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AI and ML techniques in various fields of Infocommunications – in the autumn issue of ICJ

Pal Varga

WELCOME to the September 2024 issue of the Infocommunications Journal. Let's have an brief overview of the papers.

The paper by A. S. Jagmagji and his co-authors presents the application of machine learning models to predict network performance metrics for the Self-Clocked Rate Adaptation for Multimedia (SCReAM) congestion control algorithm. By employing a systematic approach, including regression models, hyperparameter tuning, and ensemble learning, the study achieved high accuracy in predicting key metrics such as network throughput, queue delay, and smoothed Round Trip Time (sRTT). The LightGBM and CatBoost models outperformed others in predicting these metrics, demonstrating the effectiveness of the applied techniques. The study also highlights areas for improvement, including more advanced hyperparameter tuning and ensemble methods, and calls for rigorous statistical testing to validate minor performance differences.

A. Huszák and his co-authors introduce CityAI in their paper. CityAI is a scalable, AI-driven Intelligent Transportation System (ITS) designed to manage urban traffic on a city-wide scale. The system collects data from various sensing infrastructures and uses machine learning to predict traffic patterns, providing real-time solutions like adaptive traffic light control and V2X-based interventions. CityAI was successfully implemented as a proof-of-concept in Pécs, Hungary, demonstrating its ability to enable proactive traffic management.

The systematic review by R. Al-Shabandar et al. surveys the implications – benefits and challenges – of generative AI in higher education. It highlights how generative AI can provide personalized learning experiences, automate tasks, and support diverse student groups, while also emphasizing ethical and privacy concerns. The review discusses successful applications of generative AI in fields like sports management and surgery, but notes limitations in areas like patient education in radiology, stressing the need for context-specific use. Overall, the paper calls for responsible implementation, transparency, and safeguards to maximize the potential of AI while addressing its risks in educational environments.

The paper by N. A. A. Khleel and K. Nehéz investigates the impact of data balancing methods on optimizing LSTM models for code smell detection. By integrating techniques like random oversampling and SMOTE, the proposed approach enhances the accuracy of the LSTM model, addressing the challenges of imbalanced code smell distributions. The experiments on four code smell datasets demonstrated an average accuracy improvement of 5% when applying data balancing, reaching up to 97% accuracy. The proposed method out-performs the existing approaches, proving more effective in accurately detecting code smells across various datasets.

In their paper, M. A. Lone, Sz. Kovacs and O. M. Khanday present a method for implementing animal aggression behavior models in robotic systems using a Fuzzy Behaviour Description Language and fuzzy logic. By integrating ethologically inspired behavior, such as aggression, robots can adapt more effectively to dynamic environments, enhancing human-robot interaction and promoting safety in uncertain situations. The study also demonstrates the use of ROS tools, like Gazebo and RViz, to simulate and visualize these behaviors, improving robot decision-making and autonomy. Their findings have practical implications for robotics in fields such as collaborative manufacturing, search and rescue, and surveillance, promoting more intelligent and adaptable robotic systems.

In their paper, A. El Hanjri, I. Ben Abdel Ouhab and A. Haqiq survey various handover techniques for heterogeneous mobile networks, focusing on mobility management and decision-making approaches. They identifiy key issues such as frequent disconnections and increased handover failures caused by ineffective seamless handovers. The paper highlights the need for optimization methods that improve vertical handovers, focusing on bandwidth allocation, reduced failure rates, and improved Quality of Service (QoS). It also emphasizes the importance of incorporating user preferences, network coverage updates, and energy efficiency in the handover process to ensure a more reliable and efficient system.

In his paper, L. Nagy presents the design and analysis of a dielectric lens antenna for industrial radar applications, specifically for tank-level measurement systems. The antenna achieves high gain, low sidelobe levels, and improved distance resolution, making it ideal for minimizing side reflections and maximizing performance in extreme conditions. A key con- tribution is the development of an optimized air-to-dielectric waveguide transition, which improved matching by 5dB.

T. E. Ali and his co-authors introduce a Blockchain-Based Deep Reinforcement Learning (BDRL) system designed to optimize healthcare operations in a multi-cloud environment. The system enhances security and decision-making in healthcare by integrating blockchain for secure datamanagement and deep reinforcement learning for adaptive scheduling. The BDRL framework successfully addresses security, privacy, and efficiency challenges in distributed healthcare networks, but faces limitations such as high resource utilization and energy consumption as data size increases.

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Utilizing Machine Learning as a Prediction Scheme for Network Performance Metrics of Self-Clocked Congestion Control Algorithm

Ahmed Samir Jagmagji [1,2,*], Haider Dhia Zubaydi [1,**], Sándor Molnár [1,†], and Mahmood Alzubaidi [3]

***Abstract*—Congestion Control (CC) is a fundamental mechanism to achieve effective and equitable sharing of network facilities. As future networks evolve towards more complex paradigms, traditional CC methods are required to become more powerful and reliable. On the other hand, Machine Learning (ML) has become increasingly popular for solving challenging and sophisticated problems, and scientists have started to turn their interest from rule-based approaches to ML-based methods. This paper employs machine learning models to construct a performance evaluation scheme to predict network metrics for the Self-Clocked Rate Adaptation for Multimedia (SCReAM) algorithm. It uses a rigorous data preprocessing pipeline and a systematic application of ML methods to enhance the performance of the regression model for SCReAM's performance metrics. Also, we constructed a dataset that provides SCReAM's input parameters and output metrics, such as network queue delay, smoothed Round Trip Time (sRTT), and network throughput. Each prediction process has several phases: choosing the best initial regressor model, hyperparameter tuning, ensemble learning, stacking regressors, and utilizing the holdout data. Each model's performance was evaluated through various regression metrics; this study will mainly focus on the coefficient of determination (R2) score. The improvement between the initial best-selected model and the final improved model determined that we were able to increase R2 up to 96.64% for network throughput, 99.4% for network queue delay, and 100% for sRTT.**

***Index Terms*—Congestion control, machine learning, optimization, prediction, SCReAM.**

I. Introduction

Modern communication technology comprises a diverse range of services, incorporating mixed network infrastructures that employ a combination of wired, wireless, and satellite connections. Moreover, the features of these network environments depend on many limitations, such as network traffic, link capacity, and user behavior, which means that more accurate estimates are needed. Hence, it can be argued that ML is an unambiguous approach to improving our understanding of network behavior and facilitating the development of appropriate solutions. The reasons behind such an argument come from many features, such as predictive capabilities to anticipate congestion patterns, optimization through learning historical data to manage network traffic efficiently and adaptability by offering dynamic and flexible solutions to real-time changes.

Network congestion arises when the network's capacity is insufficient to accommodate excessive traffic, resulting in increased response time or, in more severe instances, network failure [1]. Therefore, it is essential to provide further consideration to the significant consequences caused by network congestion. Also, there is a notable rise in media traffic, particularly in the audiovisual domain. This can be attributed to the growth of networking applications that have been built on the structure of the transport layer, such as Voice Over IP (VoIP) and Video on Demand (VoD) [2].

Researchers have proposed learning-based CC approaches to address the previously described issues. These techniques encompass Reinforcement Learning (RL), supervised learning, and unsupervised learning techniques. RL has been demonstrated to have several advantages in effectively addressing the issue of realistic congestion in networks that exhibit dynamic and complex state spaces [3]. Hence, it may be argued that RL approaches offer advantages in congestion control due to their enhanced capacity for online learning [4]. Offline learning is appropriate for situations where assuming that others' behavior will converge and remain relatively stable is essential. In contrast, online learning facilitates a more interactive and dynamic exchange between individuals or groups striving to achieve shared objectives under optimal circumstances. Implementing ML as a networking solution is increasingly becoming possible [5].

This paper aims to enhance the efficiency of the regression model utilized as a performance evaluation scheme developed through machine learning. The purpose is to estimate crucial network metrics for SCReAM. This will be accomplished by implementing a rigorous data preprocessing pipeline and systematically applying machine learning techniques. Furthermore, the proposed scheme can be used to replace the execution of SCReAM without requiring SCReAM environment, thus reducing the resource requirements by mitigating the need to perform measurements in the live network. To implement this method, the dataset was generated from SCReAM and utilized as input for the regression model. Simultaneously, the output will be similar to the initial SCReAM. Since this work

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utilized the generated dataset, it falls within the supervised learning scheme. The primary objective of this work is to concentrate on QoS measures, whereas the evaluation of QoE falls outside the scope of our studies.

This paper is organized as follows: Section II introduces the related works that proposed ML congestion control approaches to handle congestion control. Section III describes the methodology of our proposed model, including data preprocessing, model selection, tuning, improvement, and evaluation. Section IV presents the results obtained from our experiments for predicting network queue delay, sRTT, and network throughput. Finally, this paper is concluded in Section V.

II. Related work

The primary challenge related to congestion control resides in determining the appropriate mechanism and timing for data transmission. Researchers have successfully employed ML techniques to devise robust methodologies for addressing dynamic scenarios within computer networks. Current machine learning research utilizes three main categories: supervised, unsupervised, and reinforcement learning. This section covers research efforts that contributed to managing and predicting network congestion by utilizing machine learning schemes.

A general overview has been introduced in [6] that discusses how to revolutionize CC algorithms using various ML techniques. This research discusses various ML mechanisms, such as supervised learning and RL, that utilize real-time modification of control parameters and predict network traffic to eliminate network congestion. Furthermore, the authors highlighted the possibility of managing traditional congestion control challenges such as packet loss and network latency.

Machine Learning Aided Congestion Control (MLACC) [7] is a novel approach that integrates traditional CC protocols with ML to address efficiency and fairness issues. CC parameters are dynamically adjusted based on network conditions using an RL-based framework. The results indicate that MLACC surpasses traditional congestion control approaches, balancing fair resource allocation among users and high throughput.

Another work that focuses on utilizing ML to improve the fairness of TCP congestion control algorithms is introduced in [8]. The authors argue that unfair bandwidth distribution among users occurs in traditional TCP mechanisms. Thus, an ML-based approach is proposed to ensure a fair distribution of network resources by dynamically adjusting TCP parameters. The effectiveness of this approach in various network scenarios is demonstrated in experimental results.

As discussed in [9], ML can also be employed in other network paradigms, such as Software-Defined Networking (SDN), to enhance congestion control. The proposed framework allows SDN controllers to empower the network with real-time traffic management decisions by leveraging machine learning models. This work reveals that combining ML's predicting capabilities with SDN's scalability and flexibility features enhances congestion management and network performance.

The authors in [10] argue the possibility of mastering congestion control by enabling computers to learn from heuristic designs. A detailed analysis of how heuristic-based congestion control algorithms can be employed to train ML models to produce more adaptive and robust control schemes. This study shows that ML can apply heuristics in different network conditions to improve performance.

An ablation study on leveraging Deep Reinforcement Learning (DRL) for congestion control is presented in [11]. Various components of the DRL model are systematically evaluated based on its performance. This study provides guidelines to optimize the performance of such models by identifying the most critical elements affecting DRL in managing network congestion.

A comprehensive troubleshooting solution using ML for traffic congestion control is proposed in [12]. The developed framework can suggest corrective actions by identifying the leading causes of congestion. This framework enables proactive traffic flow management by predicting potential congestion issues and analyzing traffic patterns by leveraging various ML models.

Two congestion control systems, Aurora and Custard, employ DRL techniques described in references [13] and [14]. The idea behind these plans is to use DRL to develop a way to map real-world network data to find the best transmission rate. DRL is a contemporary ML technique utilized to evaluate network conditions. This process involves multiple stages: agent training, procedure learning, and enhancing behavior through continuous environmental interaction. The network condition is characterized by the bandwidth, RTT, and loss rate, which serve as input parameters for the network agent.

In [15], the authors introduced a loss predictor that utilizes random forest, a supervised learning method, to estimate the likelihood of packet loss resulting from congestion. This methodology can predict and mitigate occurrences of packet loss, diminish the frequency of rate reduction during transmission, and attain enhanced throughput. These studies employ machine learning techniques to estimate congestion-related metrics based on passive data. Such approaches demonstrate significant potential for predicting parameter values.

For online learning schemes, the authors in [16] employed a trial-and-error methodology to determine the optimal transmitting rate. This research highlights the implementation of replacing the absolute value of RTT with a rise in RTT, as well as ensuring the fulfillment of desired network characteristics, such as fair convergence. The authors focused on investigating the impact of altering transmission rates on optimizing the environment's performance without relying on prior knowledge. Even though online learning can quickly adjust to changes in the network, its performance may sometimes drop because of its limits, which could lead to getting stuck in a local optimal [17]. Acknowledging that online learning typically involves a significant amount of time for routing convergence [18] is essential. This refers to the duration required for all routers within the network to reach a consensus on the current topology.

Although the presented works provide significant insights into various ML applications for congestion control, our work contributes by introducing a novel approach that includes the newly constructed dataset that allows predicting SCReAM's

TABLE I
COMPARISON OF RELATED WORKS ON CC WITH ML

Reference	Focus	Key Techniques	Major Contribution	Application	Results
[6]	Adjustment and prediction of network traffic	RL, supervised learning	Enhanced packet loss management and latency	Network traffic	Adjusting control parameters in real-time
[7]	CC efficiency and fairness	RL	Balanced resource allocation and network throughput	Network traffic	Outperforms traditional methods
[8]	Fairness of bandwidth distribution	ML-based TCP parameter adjustment	Fairness of resource distribution	TCP networks	Proved effectiveness in various scenarios
[9]	Integration of ML and SDN	SDN controllers, ML models	Real-time traffic management	Network traffic	Improved network management and performance
[10]	Heuristics CC learning	Heuristic-based ML	Adaptive and robust control mechanisms	Network traffic	Improved performance in different conditions
[11]	DRL model evaluation	DRL	Optimization of DRL models	Network traffic	Improved performance through the identified critical components
[12]	Identifying traffic issues through a diagnostic framework	ML models	Proactive traffic flow management	Urban traffic	Ability to predict and fix congestion problems
[13]	Employing DRL to address internet CC	DRL	Demonstrates RL's ability to outperform state-of-the-art methods and presents OpenAI Gym as a test suite	Internet CC	Captures complex data traffic patterns, highlights challenges in safety, generalization, and fairness
[14]	Leveraging DRL for CC	DRL	Indicates that RL can efficiently improve resource allocation and manage data rates of network traffic	Traffic management	Addresses dynamic network environment issues, exceeds the performance of existing algorithms
[15]	Enhancing TCP CC through ML	ML	Dynamically adjusting parameters to improve TCP performance	TCP networks	Better performance compared to traditional methods
[16]	Online learning approach for CC	Online learning	adapting to network conditions by introducing PCC Vivace	Network traffic	Achieved high adaptability and performance
Our paper	Enhancing the performance of SCReAM and predicting its parameters	Data preprocessing, regression model, supervised learning	Predicts crucial network metrics, replaces SCReAM execution	SCReAM algorithm	Accurate prediction capabilities, reduces resource requirements

parameters and reduces resource requirements. By leveraging supervised learning mechanisms, our work can enhance SCReAM's performance in diverse network scenarios. Table I presents a detailed comparison of related works and ours.

In this study, we will focus on supervised (offline) learning because online learning demands enormous training data sets to obtain satisfactory performance [19]. In addition, we have a fixed training dataset that does not require any real-time interaction with the environment, which is required by online learning [20]. The advantages include the concept of linear regression, which is transparent and straightforward. Normalization can also be employed as a technique to mitigate the issue of overfitting. Furthermore, stochastic gradient descent facilitates the seamless updating of linear models with incoming data. Moreover, utilizing widely recognized and appropriate categorized input data in supervised learning yields significantly higher reliability and precision than unsupervised learning. The utilization of labels can enhance performance on specific tasks. Proficient in identifying solutions for a diverse range of linear and non-linear problems, including but not limited to classification, robotics, prediction, and factory control.

III. METHODOLOGY

Our methodology focuses on developing a regression model to predict three target variables: network queue delay, sRTT, and network bandwidth (RateTransmitted). Network queue delay is the estimated queue delay of the entire network calculated by SCReAM. In contrast, TCP endeavors to predict future round-trip times by sampling packet behavior across a connection and averaging the results, referred to as the sRTT [21]. Our methodology includes a rigorous data preprocessing pipeline and a systematic application of machine learning techniques. The goal was to improve the performance of each regression model progressively. The methodology employed in this study is depicted in Figure 1. It comprises several key components, including SCReAM, dataset generation, data pre-processing, model selection, and tuning, model improvement, and model evaluation.

A. The SCReAM Algorithm

SCReAM was first introduced in 2014 and subsequently standardized in 2017 [22][23]. SCReAM is a congestion control algorithm that combines loss-based and delay-based techniques to create a hybrid model for managing network congestion in LTE networks. Packet conservation manages network congestion by dynamically adapting network parameters, such as transmission rate and queuing time. SCReAM adapts to variations in network conditions by adjusting its network parameters to achieve optimal performance, as determined by the assessments. Moreover, it mitigates the variations in short-term latency by employing a practical algorithm for calculating the congestion window. Additionally, the inclusion of the self-clocking feature contributes to the achievement of shorter time scale operation, hence enhancing its overall usefulness. Considering its better performance than alternative delay-based algorithms, we have selected SCReAM as the foundation for our experimental, evaluative, and analytical research [24][25].

While the initial design of SCReAM focused on its application in WebRTC, it demonstrates the potential to be utilized in several applications that require RTP streams. SCReAM is the foundation for the rate adaptation notion and other strategies that have evolved from TCP-friendly window-based and LEDBAT protocols [26]. The packet conservation principle is also incorporated into SCReAM, a crucial and fundamental concept in minimizing network congestion [27].

The critical elements of SCReAM architecture are network congestion control, media rate control, and sender transmission control, depicted in Figure 2. The sender comprises more elements, namely the UDP socket and RTP packet queue. On the other hand, the receiver consists of an RTP payload decapsulator, a de-jitter buffer (which may be optional), and a video decoder. Given that the essential SCReAM congestion management algorithm's functionalities are executed on the transmitting end, the primary goal is to illustrate its main components.

SCReAM is considered more appropriate than rate-based algorithms since it incorporates a self-clocking concept. This design feature enables the algorithm to operate within shorter intervals, precisely one round-trip time (RTT). Nevertheless, the architecture of SCReAM is characterized by its complexity due to sophisticated documentation and code, leading researchers to be reluctant to dive into or pursue studies in it. Furthermore, SCReAM incorporates numerous parameters assigned with specified values. Therefore, this study focuses on identifying and examining the key variables, which will be discussed in the subsequent part.

SCReAM can be implemented using two approaches: one involves utilizing a test application based on Windows and Visual Studio software. In contrast, the other involves using a Linux-based BW test application. The initial methodology of SCReAM involves a single transmitter and receiver built-in C++. Various auxiliary classes are employed: NetQueue, Video Encoder, and RTPQueue. Furthermore, the coordinator code, called scream_v_a, is utilized when combined with these components. The coordinator code manages and integrates multiple codes into an integrated framework. The initial methodology was employed for our experimental procedures, whereas the second strategy was utilized for the initial evaluation of SCReAM.

B. Dataset Generation

The subsequent component of this phase is identifying and selecting potential parameters to analyze and optimize the performance of SCReAM. A comprehensive investigation was conducted on several aspects, relying on the specifications outlined in RFC8298 [23] and the coding process. Afterward, a range of parameters were initially examined. Subsequently, a comprehensive analysis is conducted on each parameter to ascertain its potential impact, ensuring its incorporation into our experimental procedures. Moreover, several parameters have yet to be considered due to their negligible impact on the results.

To ensure the effective execution of our experiments, it is essential to establish a comprehensive set of values for each parameter, thereby facilitating a clear understanding of the impact of each parameter on the overall performance. The experimentation commenced by employing a diverse set of values for each parameter. After performing ≈40,000 experiments, a range narrowing occurs exclusively in instances with negligible performance alteration. Therefore, the margin values that yield identical performance measures are removed. Our objective was to establish the default value of each parameter as the median value within the range to facilitate an accurate understanding of performance variations before and after the modifications. It is crucial to note that the maximum target bitrate initially had a default value of 20 Mbps in the algorithm. However, due to the high-speed nature of our experimental implementation, we ultimately adjusted the default value to 100 Mbps. The following parameters have been determined for the construction of our dataset:

- P1: Target value for the minimum queue delay (QD_{low})
- P2: Threshold for the detection of incipient congestion (QD_{th})
- P3: Maximum segment size (RTP packet size) (MSS)
- P4: Interval between media bitrate adjustments (RAI)
- P5: Minimum target bitrate in Mbps (bits per second) (TB_{min})
- P6: Maximum allowed rate increase speed (RUS)
- P7: Guard factor against early congestion onset (PCG)
- P8: Guard factor against RTP queue buildup (QSF)
- P9: RTP queue delay threshold for a target rate reduction (RQ_{th})
- P10: Scale factor for target rate when RTP queue delay threshold exceeds P9 (TRS)

The dataset construction procedure is as follows: Initially, a counter is established to ascertain the required number of

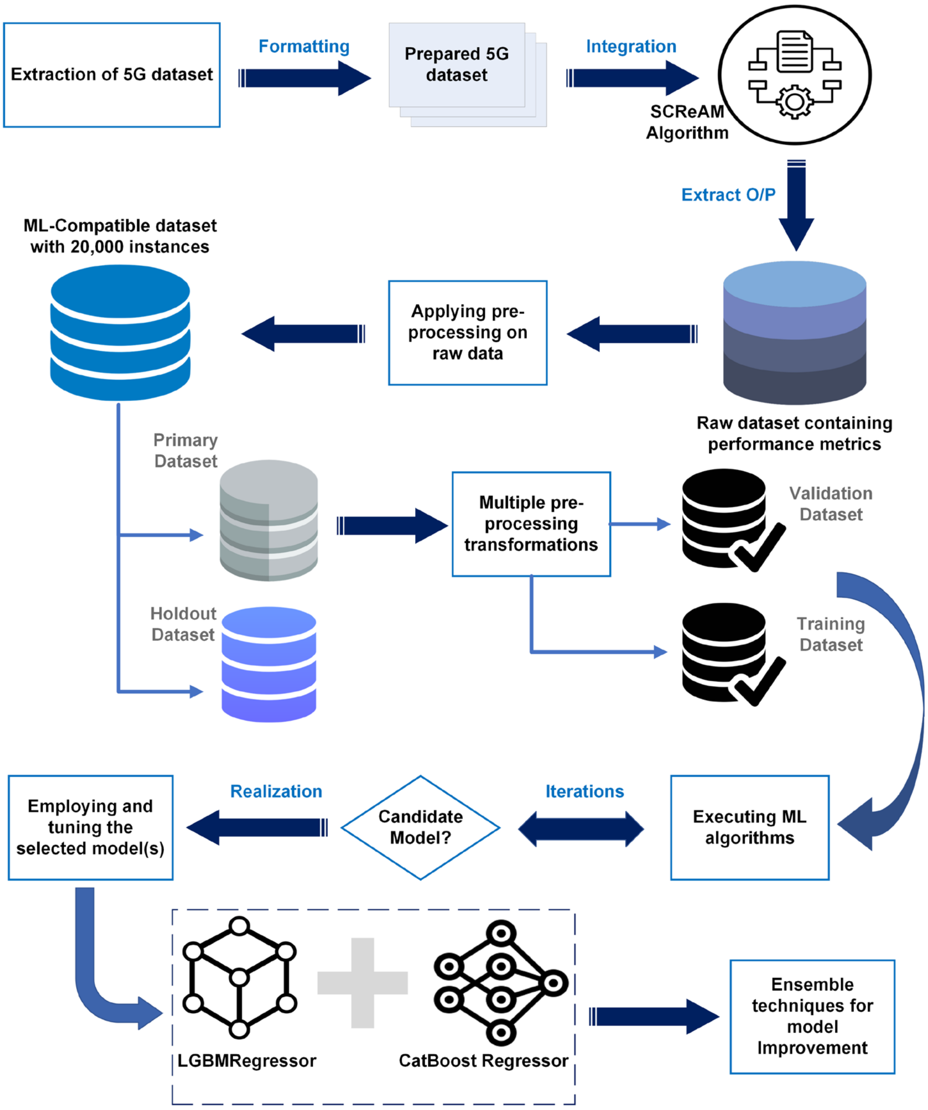

Fig. 1: Workflow of the proposed methodology.

experiments for the ML model, precisely 20,000 experiments. The algorithm that is devised tends to produce a numerical value for each parameter that falls within a predetermined range. During each experimental assessment, SCReAM is executed for 100 seconds, during which it gathers a total of 2000 data samples of network queue delay, sRTT, and network throughput. Subsequently, the mean is computed as depicted in Equation 1.

$$\overline{x} = \frac{1}{2000} \cdot \sum_{i=1}^{2000} x_{\mathrm{i}}, \tag{1}$$

Where $\overline{x}$ represents the metric average, and x_{i} is the value of one metric. Additional details regarding the dataset are demonstrated in the following subsection.

C. Data Preprocessing

Data preprocessing is a crucial component of the machine learning pipeline since it involves cleaning and transforming raw data into an understandable structure. This rigorous preprocessing approach forms the foundation for the subsequent data analysis and modeling, ensuring the results are reliable and replicable. The details of each model's training, fine-tuning, and final prediction for each target variable are discussed in the subsequent sections. The dataset included in our investigation initially consisted of 20,000 instances characterized by 10 attributes. Our objective was to construct predictive models for three target variables: network queue delay, sRTT, and throughput. A systematic methodology was employed for data preprocessing. The dataset was initially partitioned into two segments: a primary dataset consisting of 16,000 instances employed for model development and a holdout dataset comprising 4,000 instances reserved for the

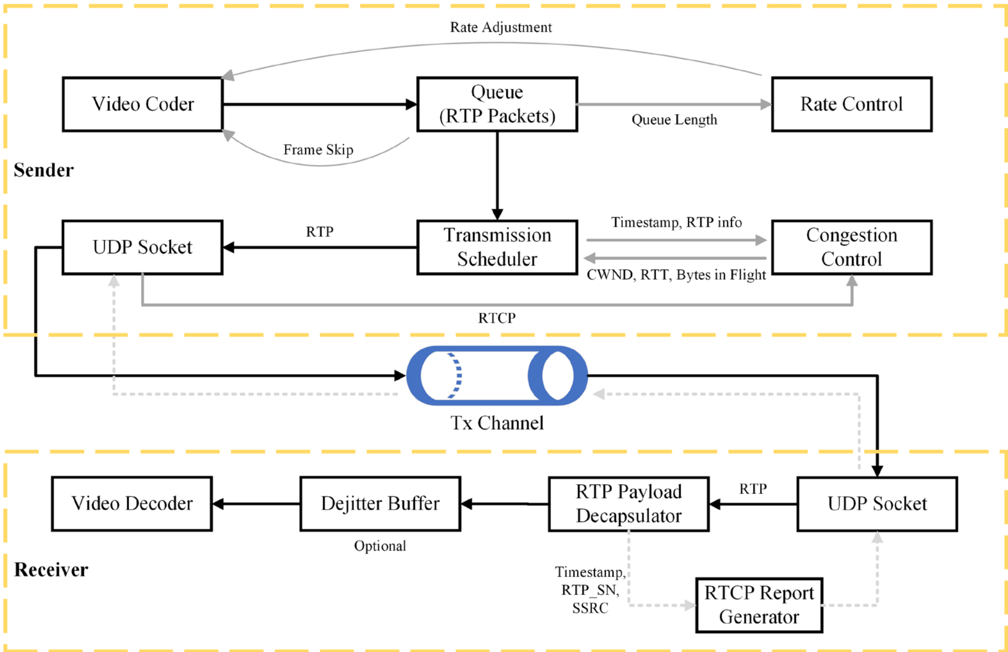

Fig. 2: SCReAM architecture (a single media source design) [21].

TABLE II
A SAMPLE FROM OUR FEATURE SET

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Delay	sRTT	BW
N	20K	20K	20K	20K	20K	20K	20K	20K	20K	20K	20K	20K	20K
Missing	0	0	0	0	0	0	0	0	0	0	0	0	0
Mean	0.105	0.255	1198	1810	5.51	11.0	0.453	0.263	0.161	0.849	35.2	6.93	31.5
Median	0.105	0.257	1199	1810	6.0	11.1	0.45	0.263	0.161	0.849	31.4	6.63	31.1
S. Dev.	0.0551	0.142	174	851	2.63	5.18	0.26	0.137	0.0795	0.0862	19.2	1.47	8.54
Max.	0.01	0.01	900	327	1	2.0	0.0	0.025	0.025	0.7	1.92	4.42	5.92
Min.	0.2	0.5	1499	3277	10	20.0	0.9	0.5	0.3	1.00	201	22.3	56.8

final testing of the trained and validated model.

The primary dataset underwent several preprocessing transformations to adequately prepare it for model training. The primary dataset was divided into two subsets: a training set comprising 80% (12,800 instances) and a validation set including 20% (3,200 instances). Notwithstanding the transformations, the overall shape of the data remained consistent with its initial form, suggesting that no instances were removed during this stage. The primary dataset comprised ten numerical attributes and one category attribute. The aforementioned properties were assessed for the possibility of missing data. In order to address any missing data, we employed imputation techniques, specifically mean imputation for numerical features and mode imputation for categorical features. Normalization was conducted to standardize the numerical feature values to a uniform range. Min-max normalization was utilized to rescale the features from 0 to 1 to ensure that the scale of each feature is aligned (i.e., all features contribute equally to the analysis).

The Min-Max Normalization, denoted by x_{scaled}, can be calculated through the following Equation:

$$x_{scaled} = \frac{x - x_{min}}{x_{max} - x_{min}} \quad (2)$$

Where x is the number before normalization, the x_{min} is the smallest number in the dataset, and the x_{max} is the largest number in the dataset.

The modeling process employed a 10-fold cross-validation approach generated through the K-Fold algorithm during the training and fine-tuning stages, where k denotes the number of groups into which a particular data sample is divided. Cross-validation is a resampling technique utilized to assess machine learning models on a constrained data sample by dividing it into training and testing sets to train and evaluate the data. This technique helps provide a more robust estimation of the model's performance by iteratively validating the model against different subsets of data.

We made further efforts to enhance computational efficiency during model training by utilizing all available CPU cores and, where possible, GPU resources. While we meticulously recorded all the processing steps, the experiment's logs were not saved for review. After training and validation, the final model was tested on the holdout dataset. This procedure ensures the model's performance is evaluated on unseen data, offering a more accurate predictive power evaluation. A sample from our feature set is displayed in Table II, including SCReAM parameters as input features for our model and the network metrics (target variables) for prediction. Table II also determines the number of samples N (collected data set results), missing samples, mean, median, standard deviation, minimum, and maximum values.

D. Model Selection and Tuning

Each target variable was assigned an initial model based on previous performance considerations. The selected models were LGBM Regressor [28] for predicting network throughput, CatBoost Regressor [29] for network queue delay and sRTT. Then, each selected model is fine-tuned using Optuna, a hyperparameter optimization framework [30]. The goal was to maximize the R^2 score, a standard metric for regression problems, which measures the proportion of the variance in the dependent variable that is predictable from the independent variable(s). The R^2 score is a critical metric that is used to evaluate the performance of a regression-based machine learning model. The coefficient of determination works by measuring the amount of variance in the predictions explained by the dataset. On average, using R^2 in the evaluation of the ML model is one of the most effective techniques that provides powerful results [31].

$$R^2 = 1 - \frac{\text{SSR}}{\text{SST}} = 1 - \frac{\sum_i (x_i - \widehat{x}_i)^2}{\sum_i (x_i - \overline{x})^2}, \quad (3)$$

Where SSR is the sum squared regression, SST is the total sum of squares, and $\widehat{x}_i$ is the predicted value for x_i. As a percentage, it will take values between 0 and 1.

LightGBM, also known as Light Gradient Boosting Machine, gradient boosting system created by Microsoft. The LGBM Regressor is a specialized version of a gradient boosting model tailored explicitly for regression applications. This model is classified under ensemble learning techniques, notably boosting, where multiple weak learners (usually decision trees) are combined sequentially to form a powerful prediction model. It reduces the total error by optimizing based on the residuals.

Compared with other boosting algorithms, LightGBM represents one of the fastest and the most efficient algorithms as it uses a histogram-based dependent method to deal with large datasets quickly and as low as possible regarding memory space, which makes it an optimal solution for scenarios with large amounts of data.

An essential feature of LightGBM is its capability to minimize overfitting using the L1 and L2 regularization techniques integrated with the algorithm. In addition, the growing tree leaf-wise method is used as a tree-based learning algorithm to enhance accuracy, which helps mitigate loss efficiently and produce a more accurate LightGBM model.

Using an LGBM Regressor for prediction involves several steps, including data preparation, model training using a training set, and hyperparameters fine-tuning using cross-validation. Then, the trained model is optimized to start predicting the output using the unseen new data. To optimize the performance and avoid overfitting across different tasks, understanding the features used in LightGMB, such as its regularization methods and unique tree-building technique, is essential.

The most crucial benefit of LightGBM is that it efficiently handles the categorical features that will mitigate the time and effort needed for excessive preprocessing. LightGBM can be used directly with categorical data, which is different from the traditional techniques that need to be encoded and transformed into other forms before dealing with the categorical data. In addition, it can implement different methods, such as order boosting and categorical feature-numerical value transformation, resulting in enhanced performance and reduced human interaction.

LightGBM consistently generates multiple decision trees, and each tree is taught to update the previous one's error, leading to increased overall accuracy. The leaf-wise tree growth method is an essential feature in LightGBM that depends on minimizing the most significant loss in leaves, resulting in constructing deeper trees with fewer and faster leaves and precise outcomes.

CatBoost has built-in support for categorical variables, which provides a considerable advantage over models that require specific handling, such as one-hot encoding, for these types of features. CatBoost incorporates inherent mechanisms, such as depth restrictions and learning rate shrinkage, to mitigate the issue of overfitting. The framework additionally provides cross-validation techniques for optimizing hyperparameters and assessing model performance. Moreover, CatBoost effectively manages missing data, reducing preprocessing procedures.

CatBoost's design, which prioritizes efficiency and scalability, makes it well-suited for handling massive datasets. Utilizing the CatBoost Regressor for prediction generally includes preparing the data, training the model, modifying the hyperparameters, and generating predictions on unique or unobserved data. The direct handling of categorical variables, the emphasis on preventing overfitting, and the user-friendly approach to missing data makes CatBoost an attractive option for regression problems, mainly when working with heterogeneous datasets that include numerical and categorical features.

E. Model Improvement

After the fine-tuning stage, we employed ensemble techniques to enhance the performance of each model further. Bagging methods were initially used, with results indicating slight improvements in the R^2 score. Subsequently, a stacking regressor was used to combine the predictions of multiple estimators to generate a final model. Stacked Regressions is a technique that creates linear combinations of various predictors

TABLE III
LIGHTGBM PARAMETERS SPECIFICATIONS – LGBM REGRESSOR

Specifications	Value
LGBM bagging fraction	0.8088
LGBM bagging freq.	7
LGBM device	gpu
LGBM feature fraction	0.6502
LGBM learning rate	0.0512
LGBM min. child samples	52
LGBM Regressor min. split gain	0.5451
LGBM n. estimators	185
LGBM n. leaves	32
LGBM random state	123
LGBM Regressor reg. alpha	5.8939e-07
LGBM reg. lambda	2.2148e-07

TABLE IV
LIGHTGBM PARAMETERS SPECIFICATIONS –
STACKING REGRESSOR (NETWORK THROUGHPUT)

Specifications	Value
Stacking Regressor cv	5
Stacking Regressor estimators	LGBM
LGBM device	gpu
LGBM random state	123
CatBoost Regressor	catboost.core.CatBoost
CatBoost Regressor object	0x0000017C68BE5910
Gradient Boosting Regressor	GradientBoosting Regressor
GradientBoosting random state	123
Stacking Regressor final estimator	LinearRegression
LinearRegression n. jobs	-1
Stacking Regressor n. jobs	1
Stacking Regressor passthrough	True

to enhance prediction accuracy [3]. The three best models for throughput were the LGBM Regressor, CatBoost Regressor, and GradientBoosting Regressor. The best three models for Network Queue Delay and sRTT were the CatBoost Regressor, LGBM Regressor, and ExtraTrees Regressor. The stacking regressor models were then validated and evaluated using the holdout dataset, which offered a more realistic evaluation of the model's predictive performance, as it had yet to be exposed to this data during training.

F. Model Configurations

This part describes the configurations used to optimize the model, including Optuna, LightGBM parameters specifications, and the Stacking Regressor. A *Hyperparameter* is an exterior configuration parameter engineers use to control machine learning training. The number of nodes and layers in a neural network and the number of branches in a decision tree are illustrative examples of hyperparameters. Hyperparameters define essential model properties such as architecture, learning speed, and ML model complexity. Training a machine learning model using multiple sets of variables, analyzing the performance of each set, and selecting an optimal set that produces the best performance are called Hyperparameter tuning. Ensemble learning integrates multiple machine learning models, known as weak learners, into a single problem. The idea is that combining these weak learners can create strong learners. Stacking regressions is a technique that combines various predictors linearly to enhance the accuracy of predictions [32].

The Optuna configuration settings used in the optimization process and the LightGBM core parameters with their values

TABLE V
STACKING REGRESSOR PARAMETERS SPECIFICATIONS –
STACKING REGRESSOR (NETWORK QUEUE DELAY)

Specifications	Value
Stacking Regressor cv	5
Stacking Regressor estimators	CatBoost Regressor
catboost.core.CatBoost Regressor object	0x0000017C806D57C0
Light Gradient Boosting Machine	LGBM Regressor
LGBM Regressor device	gpu
LGBM Regressor random state	123
Extra Trees Regressor	ExtraTrees Regressor
ExtraTrees Regressor n. jobs	-1
ExtraTrees Regressor random state	123
Stacking Regressor final estimator	LinearRegression
LinearRegression n. jobs	-1
Stacking Regressor n. jobs	1
Stacking Regressor passthrough	True

TABLE VI
STACKING REGRESSOR PARAMETERS SPECIFICATIONS –
STACKING REGRESSOR (SRTT)

Specifications	Value
Stacking Regressor cv	5
Stacking Regressor estimators	CatBoost Regressor
catboost.core.CatBoost Regressor object	0x0000017CE14A8F40
Light Gradient Boosting Machine	LGBM Regressor
LGBM Regressor device	gpu
LGBM Regressor random state	123
Extra Trees Regressor	ExtraTrees Regressor
ExtraTrees Regressor n. jobs	-1
ExtraTrees Regressor random state	123
Stacking Regressor final estimator	LinearRegression
LinearRegression n. jobs	-1
Stacking Regressor n. jobs	1
Stacking Regressor passthrough	True

are described in Table III. The core parameters mentioned are ranking application parameters, including bagging fraction, bagging frequency, processing device type, learning rate logarithmic value, number of boosting estimators, and maximum number of leaves in one tree. There are also several learning control parameters, including minimum child samples per leaf, minimal gain to perform split, and two regularization parameters at the regression analysis level (α and λ) [33].

We used a stacking regressor to improve the result by stacking the best three regression models (LGBM Regressor, CatBoost Regressor, GradientBoosting Regressor) with the configuration settings for network throughput, network queue delay, and sRTT presented in Tables IV, V, and VI respectively.

Where cv specifies the number of the cross-validation's splitting strategy, random_state specifies the value we set to get the same values in train and test datasets whenever we run the stacking regressor code. Linear regression is the final result estimator, assuming the relation between the input and output variables is linear. The n_jobs=-1 means that all the CPU cores will be used during the simulation while specifying the number; for example, n_jobs=1 will specify the exact number of cores. Finally, the boolean value for the pass-through option shows that when it is set to false, the estimators' predictions will only be used to train the final_estimator. In contrast, true value means the final_estimator is trained on the predictions and the original training data.

G. Model Evaluation

Each model's performance was evaluated through various metrics, such as Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), coefficient of determination (R^2), Root Mean Squared Logarithmic Error (RMSLE) and Mean Absolute Percentage Error (MAPE). R^2 will be the main focus of our discussions. Mean Absolute Error (MAE) is a metric used to measure the average absolute difference between the predicted and actual values. It represents the average magnitude of the errors without considering their direction and is calculated by summing up the absolute differences and dividing by the total number of samples.

RMSE is a commonly used metric to evaluate the performance of a predictive model and measure the square root of the average squared differences between the predicted and actual values. It is calculated by taking the square root of the average of the squared differences between predicted and actual values. RMSLE is a metric commonly used in tasks where the predicted variable and actual values span a wide range and are skewed. It calculates the RMS of the logarithmic differences between the predicted and actual values. It is calculated by taking the square root of the average of the squared logarithmic differences between predicted and actual values.

MAPE is a metric used to measure the average percentage difference between predicted and actual values. MAPE is commonly used in forecasting and demand planning tasks. However, it has some limitations, such as being sensitive to zero values and unbounded, meaning it can produce infinite values. To visualize and better comprehend the performance of each model, we also generated residual and prediction error plots. Additionally, scatter plots were used to compare the actual and predicted values of the target variables.

The methodology applied in this study ensures a robust and comprehensive approach toward model development and evaluation, aiding the reliable and replicable prediction of the target variables.

IV. RESULTS AND DISCUSSION

In this study, we performed rigorous data preprocessing and utilized various machine-learning models to predict three target attributes: network queue delay, sRTT, and network throughput. We employed diverse techniques to enhance the model's prediction quality, including hyperparameter tuning, ensemble learning, and stacking regressors.

As previously mentioned, we calculated five different outputs (MAE, RMSE, R^2, RMSLE, and MAPE) values for each metric. Further experiments are performed during four subsequent stages. The reason for involving each stage in this phase is as follows:

- **Fine-tuning with Optuna:** During this stage, hyperparameter optimization occurs. Optuna examines various possible combinations to identify the most suitable set of hyperparameters. This process leads to a better fitting between the model and data, which improves R^2.
- **Applying the bagging method:** This method ensures more reliable and stable predictions by reducing variance and overfitting. It calculates the average prediction values of multiple models trained on different training data subsets. As a result, it will increase the model's ability to identify the underlying data patterns, which in turn increases R^2.
- **Deployment of stacking regressor:** Multiple base models can be trained simultaneously and later achieve a meta-model that combines the strengths of their predictions, mitigating their weaknesses. The realized meta-model can eventually enhance R^2 by capturing more complex relationships by learning to assign proper weights to the model's prediction values.
- **Using holdout data:** The final stage of our improvements handles the unseen data and ensures that the stacking regressor generalizes well to them. Capturing the underlying data distribution is indicated by the model's performance on the holdout data. Better performance leads to higher R^2 values. This step realizes the accuracy and robustness of the model.

A. Summary of Improvements: Tabular Data

A.1 Network Throughput

We implemented multiple regression models and applied a comparative analysis to demonstrate the best initial prediction performance. Table VII indicates that LightGBM outperformed all other models. It achieved the highest R^2 (0.7805) and lowest MAE, RMSE, RMSLE, and MAPE values. It is expected that LightGBM will outperform other models due to its speed, accuracy, and capability to capture complex data patterns.

A minor improvement in R^2 value was observed when fine-tuning the model, as shown in Table VIII, where R^2 increased to 0.7814. The improvement process indicates that the hyperparameters are close to optimal values. It is noticed that there are standard deviations for MAE and RMSE, indicating a moderate variability in the folds.

As demonstrated in Table IX, a slight improvement in the R^2 value with a performance gain of 0.32%, where the bagging fits several independent models and averaged their predictions to get a lower variance model. By applying the bagging method, we realized a more consistent performance and lower standard deviations across different folds compared to Table VIII.

Subsequently, a stacking regressor was deployed, utilizing the three best regression models (LGBM Regressor, CatBoost Regressor, and GradientBoosting Regressor), resulting in further performance gain of 0.397%, as shown in Table X. This combination produces a linear regression scheme that accurately predicts target variables with approximately low errors across different folds. Based on the standard deviation (std) values across multiple subsets of data, the performance of this model is reasonably stable. Among all tested methods, stacking resulted in the lowest variability, which indicates its efficiency in improving the consistency and accuracy of the model's predictions.

Finally, we utilized the holdout data (4000 rows) to evaluate the performance. As demonstrated in Table XI, which exhibits

TABLE VII
INITIAL PREDICTION OF NETWORK THROUGHPUT

	Model	MAE	RMSE	R^2	RMSLE	MAPE
LightGBM	Light Gradient Boosting Machine	3.1541	3.9967	0.7805	0.1311	0.1074
CatBoost	CatBoost Regressor	3.1763	4.0272	0.7771	0.1317	0.1077
GBR	Gradient Boosting Regressor	3.3041	4.1592	0.7623	0.1352	0.1122
RF	Random Forest Regressor	3.3348	4.1945	0.7581	0.1383	0.1144
XGBoost	Extreme Gradient Boosting	3.3235	4.2104	0.7564	0.1385	0.1129
ET	Extra Trees Regressor	3.3771	4.2454	0.7523	0.1391	0.1156
Ada	AdaBoost Regressor	3.9693	4.8661	0.6745	0.1629	0.1417
Ridge	Ridge Regression	4.2362	5.3658	0.6040	0.1738	0.1456
LR	Linear Regression	4.2360	5.3658	0.6040	0.1738	0.1456
BR	Bayesian Ridge	4.2361	5.3658	0.6040	0.1738	0.1456
LAR	Least Angle Regression	4.2360	5.3658	0.6040	0.1738	0.1456
Huber	Huber Regressor	4.2241	5.3736	0.6029	0.1732	0.1440
KNN	K Neighbors Regressor	4.4880	5.6626	0.5591	0.1884	0.1596
DT	Decision Tree Regressor	4.7010	5.9827	0.5078	0.1960	0.1599
PAR	Passive Aggressive Regressor	4.7495	5.9758	0.5061	0.1934	0.1678
OMP	Orthogonal Matching Pursuit	5.0106	6.3742	0.4416	0.2058	0.1753
Lasso	Lasso Regression	5.8857	7.2623	0.2755	0.2406	0.2125
LLAR	Lasso Least Angle Regression	5.8857	7.2623	0.2755	0.2406	0.2125
EN	Elastic Net	6.6885	8.1526	0.0870	0.2689	0.2426
Dummy	Dummy Regressor	7.0298	8.5365	-0.0011	0.2807	0.2551

TABLE VIII
FINE-TUNING THE MODEL USING OPTUNA HYPERPARAMETER OPTIMIZATION FRAMEWORK (NETWORK THROUGHPUT)

Fold	MAE	RMSE	R^2	RMSLE	MAPE
0	3.0699	3.8816	0.7950	0.1261	0.1037
1	3.2399	4.1004	0.7730	0.1346	0.1103
2	3.1861	4.0244	0.7806	0.1299	0.1073
3	3.1018	3.9078	0.7767	0.1305	0.1080
4	3.2980	4.1863	0.7624	0.1376	0.1110
5	3.0754	3.8856	0.7850	0.1265	0.1044
6	3.1419	3.9216	0.7917	0.1282	0.1068
7	3.1594	4.0331	0.7860	0.1331	0.1082
8	3.0894	3.9551	0.7800	0.1281	0.1030
9	3.1522	3.9895	0.7832	0.1334	0.1100
Mean	3.1514	3.9885	0.7814	0.1308	0.1073
Std	0.0703	0.0944	0.0089	0.0036	0.0027

TABLE IX
BOOSTING THE MODEL'S PERFORMANCE BY APPLYING THE ENSEMBLE MODEL WITH BAGGING METHOD FOR NETWORK THROUGHPUT

Fold	MAE	RMSE	R^2	RMSLE	MAPE
0	3.0789	3.8773	0.7954	0.1263	0.1042
1	3.2117	4.0543	0.7781	0.1332	0.1095
2	3.1782	4.0129	0.7819	0.1298	0.1073
3	3.1114	3.9120	0.7762	0.1311	0.1087
4	3.2795	4.1621	0.7651	0.1364	0.1105
5	3.0912	3.8833	0.7852	0.1263	0.1049
6	3.1455	3.9302	0.7908	0.1283	0.1068
7	3.1372	3.9782	0.7918	0.1315	0.1078
8	3.1239	3.9693	0.7784	0.1285	0.1042
9	3.1449	3.9582	0.7866	0.1324	0.1099
Mean	3.1502	3.9738	0.7830	0.1304	0.1074
Std	0.0568	0.0818	0.0085	0.0030	0.0022

a proper approximation to the actual values, we achieved a performance gain of 0.78%. This confirms that the model has robust stability and predictive capabilities and can generalize properly to unseen data, maintaining a high R^2 value and low error rates.

Although the percentage of performance gains is relatively small, they reflect a significant performance improvement and impactful enhancement in the model's predictive capabilities.

TABLE X
DEPLOYMENT OF THE STACKING REGRESSOR BY UTILIZING THE THREE BEST REGRESSION MODELS (LGBM REGRESSOR, CATBOOST REGRESSOR, AND GRADIENTBOOSTING REGRESSOR) FOR NETWORK THROUGHPUT

Fold	MAE	RMSE	R^2	RMSLE	MAPE
0	3.0672	3.8710	0.7961	0.1260	0.1034
1	3.1789	4.0474	0.7788	0.1325	0.1077
2	3.1605	4.0033	0.7829	0.1296	0.1065
3	3.0487	3.8751	0.7804	0.1295	0.1060
4	3.2392	4.1453	0.7670	0.1349	0.1084
5	3.1006	3.9183	0.7813	0.1272	0.1048
6	3.0906	3.8900	0.7951	0.1266	0.1044
7	3.1404	3.9928	0.7903	0.1318	0.1075
8	3.1016	3.9701	0.7783	0.1281	0.1027
9	3.1259	3.9649	0.7859	0.1321	0.1089
Mean	3.1254	3.9678	0.7836	0.1298	0.1060
Std	0.0538	0.0814	0.0082	0.0028	0.0020

TABLE XI
PREDICTION OF NETWORK THROUGHPUT USING THE HOLDOUT DATA

Fold	Model	MAE	RMSE	R^2	RMSLE	MAPE
0	Stacking Regressor	3.1061	3.9364	0.7866	0.1304	0.1060

A.2 Network Queue Delay

Among twenty models, the CatBoost regressor was the top model that offered the best possible initial performance for predicting the network queue delay regarding R^2 (0.6935) as shown in Table XII.

Optimization techniques such as scikit-learn [34], scikit-optimize [35], and optuna [34] were utilized during the fine-tuning process. However, the results in Table XIII show that implementing the mentioned techniques along with the CatBoost regressor results in performance degradation, as indicated by the 2.90% drop in R^2. These negative impacts on model performance imply that hyperparameter choices could have generalized better across the cross-validation folds related to many possible problems, such as data variability, unbalanced data, or hyperparameter sensitivity to some values. In addition, the overfitting problems, noise, and minor fluctuations that do not reflect the basic patterns in the data

TABLE XII
PREDICTION OF NETWORK THROUGHPUT USING THE HOLDOUT DATA

Model	MAE	RMSE	R^2	RMSLE	MAPE
CatBoost Regressor	8.0329	10.6084	0.6935	0.3172	0.2861
Light Gradient Boosting Machine	8.0742	10.6451	0.6914	0.3198	0.2908
Extra Trees Regressor	8.2559	10.8737	0.6778	0.3285	0.3038
Random Forest Regressor	8.2610	10.8897	0.6769	0.3273	0.3015
Extreme Gradient Boosting	8.5795	11.2772	0.6536	0.3435	0.3074
Gradient Boosting Regressor	8.5462	11.3707	0.6480	0.3364	0.3057
K Neighbors Regressor	10.0073	13.1048	0.5321	0.3959	0.3837
Ridge Regression	10.4444	13.7138	0.4878	0.4348	0.3917
Linear Regression	10.4454	13.7138	0.4878	0.4351	0.3917
Bayesian Ridge	10.4445	13.7138	0.4878	0.4349	0.3917
Least Angle Regression	10.4454	13.7138	0.4878	0.4351	0.3917
Huber Regressor	10.3333	13.8146	0.4804	0.4156	0.3781
Passive Aggressive Regressor	10.8379	14.5355	0.4218	0.4567	0.3740
AdaBoost Regressor	12.3687	15.0337	0.3839	0.4919	0.5649
Lasso Regression	11.6777	15.7865	0.3219	0.4498	0.4595
Lasso Least Angle Regression	11.6777	15.7865	0.3219	0.4498	0.4595
Decision Tree Regressor	11.7606	15.7883	0.3200	0.4562	0.4032
Orthogonal Matching Pursuit	12.3014	16.6105	0.2490	0.4713	0.4855
Elastic Net	13.7800	18.2671	0.0921	0.5235	0.5597
Dummy Regressor	14.5472	19.1787	-0.0009	0.5480	0.5923

TABLE XIII
FINE-TUNING THE CATBOOST REGRESSOR USING THE SCIKIT-LEARN, SCIKIT-OPTIMIZE, AND OPTUNA HYPERPARAMETER OPTIMIZATION TECHNIQUES FOR NETWORK QUEUE DELAY

Fold	MAE	RMSE	R^2	RMSLE	MAPE
0	8.4458	11.1594	0.6766	0.3340	0.2995
1	7.9667	10.4933	0.7068	0.3215	0.2886
2	8.2689	10.8947	0.6689	0.3198	0.2937
3	7.9070	10.1855	0.6783	0.3144	0.2839
4	8.1358	10.9003	0.6818	0.3199	0.2854
5	8.6920	11.6559	0.6617	0.3288	0.2986
6	8.5120	11.3981	0.6458	0.3434	0.3068
7	8.1917	10.7129	0.6848	0.3288	0.3036
8	8.5099	11.2010	0.6709	0.3272	0.2854
9	8.3884	10.9274	0.6579	0.3382	0.3154
Mean	8.3018	10.9529	0.6734	0.3276	0.2961
Std	0.2402	0.4076	0.0159	0.0086	0.01

TABLE XIV
BOOSTING THE MODEL'S PERFORMANCE BY APPLYING THE ENSEMBLE MODEL WITH BAGGING METHOD FOR NETWORK QUEUE DELAY

Fold	MAE	RMSE	R^2	RMSLE	MAPE
0	8.1623	10.7612	0.6993	0.3182	0.2870
1	7.6904	10.1587	0.7252	0.3126	0.2817
2	8.0452	10.5875	0.6873	0.3149	0.2871
3	7.6154	9.8059	0.7018	0.3024	0.2745
4	7.9544	10.6952	0.6937	0.3121	0.2775
5	8.3519	11.2046	0.6874	0.3184	0.2879
6	8.2851	11.0772	0.6655	0.3244	0.2951
7	7.9299	10.3298	0.7069	0.3171	0.2941
8	8.1255	10.6942	0.7001	0.3136	0.2743
9	8.1274	10.6497	0.6750	0.3308	0.3085
Mean	8.0288	10.5964	0.6942	0.3165	0.2868
Std	0.2254	0.3922	0.0159	0.0072	0.0101

might be caused by several factors, such as poor generalization and increased error on test data, which fail to make accurate predictions on unseen data and affect its generalization ability.

As depicted in Table XIV, the results are improved when the ensemble model is incorporated, and R^2 slightly increased compared to the initial value. However, it can be noticed that R^2 increased by 3.09% compared to the previous stage, as the variance is reduced by averaging the predictions of multiple models trained on different subsets of data.

The results of incorporating a stacking regressor are presented in Table XV. R^2 increased by 0.79% and 0.69% compared to the initial and ensemble method values, respectively. Such an increase in R^2 indicates that combined predictive power enhanced the stacked model and improved generalization and accuracy. When the holdout data is used, the results demonstrated in Table XVI imply that this method achieved the highest R^2 value (0.7127), Where the performance gain is 2.77% and 1.96% compared to the initial and stacking regressor values, respectively. The combined predictive power of utilized models allowed more generalization to unseen data. Each stage demonstrated a progressive improvement across all metrics (MAE, RMSE, RMSLE, and MAPE) according to the results in each table.

TABLE XV
DEPLOYMENT OF THE STACKING REGRESSOR BY UTILIZING THE THREE BEST REGRESSION MODELS (CATBOOST REGRESSOR, LGBM REGRESSOR', EXTRATREES REGRESSOR) FOR FOR NETWORK QUEUE DELAY

Fold	MAE	RMSE	R^2	RMSLE	MAPE
0	8.0436	10.6636	0.7047	0.3152	0.2814
1	7.6167	10.1162	0.7275	0.3083	0.2756
2	7.9972	10.5298	0.6907	0.3143	0.2860
3	7.5196	9.6959	0.7085	0.2990	0.2686
4	7.8449	10.6083	0.6986	0.3112	0.2724
5	8.2504	11.0529	0.6958	0.3149	0.2828
6	8.2262	10.9737	0.6717	0.3213	0.2920
7	7.8528	10.2175	0.7133	0.3177	0.2931
8	8.0982	10.6163	0.7044	0.3126	0.2729
9	8.1028	10.6499	0.6750	0.3302	0.3069
Mean	7.9552	10.5124	0.6990	0.3145	0.2831
Std	0.2323	0.3844	0.0160	0.0077	0.0111

TABLE XVI
PREDICTION OF NETWORK QUEUE DELAY USING THE HOLDOUT DATA

Fold	Model	MAE	RMSE	R^2	RMSLE	MAPE
0	Stacking Regressor	7.8795	10.4409	0.7127	0.3109	0.2813

A.3 sRTT

In the initial prediction of sRTT, the CatBoost regressor provided the best performance (in terms of MAE, MAPE, and R^2) compared to the other tested regression models, as shown in Table XVII.

TABLE XVII
INITIAL PREDICTION OF sRTT

Model	MAE	RMSE	R^2	RMSLE	MAPE
CatBoost Regressor	0.6115	0.8652	0.6495	0.0977	0.0853
Light Gradient Boosting Machine	8.0742	10.6451	0.6914	0.3198	0.2908
Extra Trees Regressor	8.2559	10.8737	0.6778	0.3285	0.3038
Random Forest Regressor	8.2610	10.8897	0.6769	0.3273	0.3015
Extreme Gradient Boosting	8.5795	11.2772	0.6536	0.3435	0.3074
Gradient Boosting Regressor	8.5462	11.3707	0.6480	0.3364	0.3057
K Neighbors Regressor	10.0073	13.1048	0.5321	0.3959	0.3837
Ridge Regression	10.4444	13.7138	0.4878	0.4348	0.3917
Linear Regression	10.4454	13.7138	0.4878	0.4351	0.3917
Bayesian Ridge	10.4445	13.7138	0.4878	0.4349	0.3917
Least Angle Regression	10.4454	13.7138	0.4878	0.4351	0.3917
Huber Regressor	10.3333	13.8146	0.4804	0.4156	0.3781
Passive Aggressive Regressor	10.8379	14.5355	0.4218	0.4567	0.3740
AdaBoost Regressor	12.3687	15.0337	0.3839	0.4919	0.5649
Lasso Regression	11.6777	15.7865	0.3219	0.4498	0.4595
Lasso Least Angle Regression	11.6777	15.7865	0.3219	0.4498	0.4595
Decision Tree Regressor	11.7606	15.7883	0.3200	0.4562	0.4032
Orthogonal Matching Pursuit	12.3014	16.6105	0.2490	0.4713	0.4855
Elastic Net	13.7800	18.2671	0.0921	0.5235	0.5597
Dummy Regressor	14.5472	19.1787	-0.0009	0.5480	0.5923

TABLE XVIII
FINE-TUNING THE CATBOOST REGRESSOR USING THE SCIKIT-LEARN, SCIKIT-OPTIMIZE, AND OPTUNA HYPERPARAMETER OPTIMIZATION TECHNIQUES FOR sRTT

Fold	MAE	RMSE	R^2	RMSLE	MAPE
0	0.8619	1.1640	0.3796	0.1326	0.1226
1	0.8455	1.1465	0.3971	0.1310	0.1199
2	0.8427	1.1433	0.3840	0.1306	0.1194
3	0.8041	1.0681	0.3977	0.1245	0.1152
4	0.8407	1.1999	0.3627	0.1317	0.1187
5	0.8640	1.2722	0.3648	0.1355	0.1196
6	0.7882	1.0941	0.3824	0.1247	0.1125
7	0.8288	1.1383	0.3763	0.1300	0.1195
8	0.8306	1.1673	0.3853	0.1294	0.1174
9	0.8373	1.1182	0.3719	0.1297	0.1210
Mean	0.8344	1.1512	0.3802	0.1300	0.1186
Std	0.0223	0.0538	0.0112	0.0032	0.0027

TABLE XIX
BOOSTING THE MODEL'S PERFORMANCE BY APPLYING THE ENSEMBLE MODEL WITH BAGGING METHOD FOR sRTT

Fold	MAE	RMSE	R^2	RMSLE	MAPE
0	0.6218	0.8768	0.6480	0.0992	0.0868
1	0.6213	0.8602	0.6606	0.0973	0.0860
2	0.6122	0.8653	0.6471	0.0983	0.0851
3	0.5819	0.7895	0.6709	0.0928	0.0825
4	0.6056	0.8927	0.6472	0.0976	0.0838
5	0.6570	0.9687	0.6317	0.1037	0.0893
6	0.6175	0.8522	0.6253	0.0973	0.0869
7	0.6055	0.8447	0.6565	0.0965	0.0856
8	0.5916	0.8443	0.6784	0.0940	0.0824
9	0.6162	0.8652	0.6239	0.0993	0.0872
Mean	0.6131	0.8660	0.6490	0.0976	0.0856
Std	0.0191	0.0429	0.0174	0.0028	0.0021

The results of the fine-tuning process are presented in Table XVIII, it shows that R^2 is significantly decreased by -41.47% compared to the initial value. This is caused by sub-optimal parameter selection or an overfitting issue. As demonstrated in Table XIX, applying the bagging method does not seem to affect R^2, where the values are almost similar. However, it indicates a significant increase (70.67%) compared to the previous stage value, which indicates the effectiveness of this stage in enhancing robustness and reducing variance.

Later, when the stacking regressor is deployed as depicted in Table XX, R^2 increased by 0.63% and 0.71% compared to the initial and previous stage values, respectively. This indicates that the performance gains are marginal but consistent, leveraging multiple models' strengths. Finally, the highest achieved R^2 is 0.6560 when the holdout data is employed, as depicted in Table XXI. R^2 increased by 1% and 0.37% compared to the initial and previous stage values, respectively.

TABLE XX
DEPLOYMENT OF THE STACKING REGRESSOR BY UTILIZING THE THREE BEST REGRESSION MODELS (CATBOOST REGRESSOR, LGBM REGRESSOR', EXTRATREES REGRESSOR) FOR sRTT

Fold	MAE	RMSE	R^2	RMSLE	MAPE
0	0.6180	0.8680	0.6550	0.0986	0.0862
1	0.6221	0.8665	0.6556	0.0975	0.0858
2	0.6061	0.8603	0.6512	0.0976	0.0842
3	0.5711	0.7751	0.6828	0.0914	0.0810
4	0.6027	0.8845	0.6537	0.0973	0.0833
5	0.6528	0.9592	0.6389	0.1031	0.0888
6	0.6130	0.8513	0.6261	0.0970	0.0860
7	0.6027	0.8353	0.6642	0.0960	0.0853
8	0.5835	0.8321	0.6876	0.0929	0.0813
9	0.6118	0.8692	0.6205	0.0993	0.0866
Mean	0.6084	0.8601	0.6536	0.0971	0.0848
Std	0.0209	00.0439	0.0205	0.0031	0.0023

TABLE XXI
PREDICTION OF sRTT USING THE HOLDOUT DATA

Fold	Model	MAE	RMSE	R^2	RMSLE	MAPE
0	Stacking Regressor	0.6107	0.8673	0.6560	0.0971	0.0848

A.4 Predicted Performance Metrics

A sample of predicted network throughput, network queue delay, and sRTT is presented in Table XXII. It shows the network throughput (BW), network queue delay (NQD), sRTT, their corresponding predicted values, and parameter sets.

The predicted values of network throughput are relatively close to the actual values, which indicates that the model can effectively learn from the given features. However, the distinctions between the actual and predicted values normally occur in predictive modeling. These differences can be analyzed and utilized for further research to improve the model.

TABLE XXII
SAMPLE OF PREDICTED PERFORMANCE METRICS

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	BW	P-BW	NQD	P-NQD	sRTT	P-sRTT
10650	0.083	0.014	1016	1752	5	9.5	0.10	0.223	0.266	0.764	25.965	31.357	27.25	29.74	6.240	6.240
2041	0.054	0.424	1212	3223	6	9.1	0.79	0.133	0.094	0.733	29.714	31.558	23.41	23.27	6.233	6.410
8668	0.063	0.188	1175	1396	9	9.5	0.05	0.122	0.069	0.924	26.323	29.110	23.59	32.93	6.311	7.149
1114	0.136	0.491	944	2461	4	14.5	0.72	0.163	0.223	0.788	44.374	42.88	49.88	36.84	7.153	6.250
13902	0.067	0.127	1470	2443	8	6.7	0.42	0.31	0.252	0.742	33.585	28.889	42.08	25.81	7.271	6.228

Based on the samples given in the table, the achieved accuracy is 79.23% (ID number: 10650), 93.8% (ID number: 2041), 89.39% (ID number: 8668), 96.64% (ID number: 1114), and 86% (ID number: 13902).

For network queue delay, it can be observed that the R^2 value increased by 2.76% compared to Table XII. By comparing the predicted and actual values, we can notice that the prediction accuracy is as follows: Based on the samples given in the table, the achieved accuracy is 90.86% (ID number: 10650), 99.4% (ID number: 2041), 60.4% (ID number: 8668), 73.85% (ID number: 1114), and 61.33% (ID number: 13902).

In terms of sRTT, by comparing the predicted and actual values, we can notice that the prediction accuracy is as follows: Based on the samples given in the table, the achieved accuracy is 100% (ID number: 10650), 97.17% (ID number: 2041), 86.72% (ID number: 8668), 87.37% (ID number: 1114), and 85.42% (ID number: 13902).

B. *Prediction Insights: Visual Analysis*

B.1 *Residuals Plot*

This part describes the residuals plot of the stacking regressor for network throughput, network queue delay, and sRTT demonstrated in Figures 3, 4, and 5, respectively. Blue points represent training data, while green points represent testing data. Also, the density of residuals is shown on the right side of each figure.

Figure 3 illustrates that the residuals are mainly distributed around the x-axis at zero, indicating potential improvement, and the model does not have a significant bias. The model provided a consistent performance as the residuals are spread relatively uniformly across the margins of predicted values. Furthermore, the model shows a proper fit for testing and training data, even though the predicted R^2 value is less than the training value by 6.7%, which usually occurs due to overfitting. Although the testing value of R^2 is lower than the training value, it still assures fairly efficient prediction.

For network queue delay, the residuals are centered around zero. A noticeable spread of residuals is seen at higher predicted values, which denotes that the model might struggle at higher delay predictions. The predicted value of R^2 is lower than the trained data by 16.7%, suggesting potential overfitting.

For sRTT, a training R^2 value of 0.857 indicates that the training data fits the model. However, testing R^2 is lower by 24.6%, which might refer to overfitting, performance issues on unseen data, or the model is not well generalized for sRTT predictions. Similar to network queue delay, the model has difficulties with high sRTT predictions, which are observed through a wider spread of residuals at high prediction values.

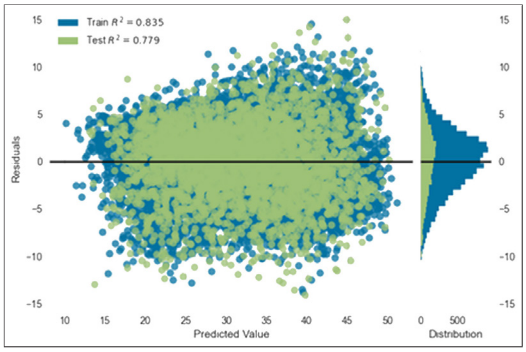

Fig. 3: Residuals plot of the stacking regressor model (network throughput)

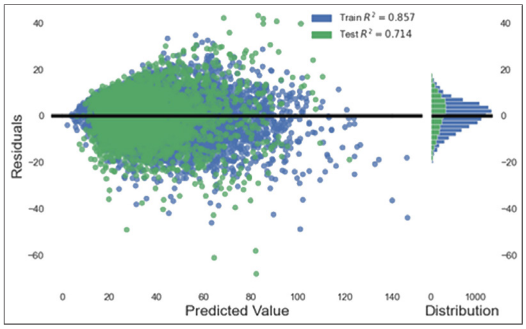

Fig. 4: Residuals plot of the stacking regressor model (network queue delay)

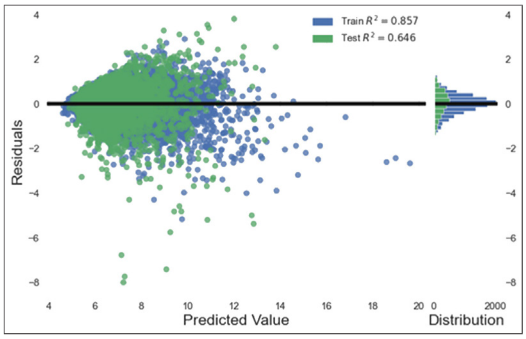

Fig. 5: Residuals plot of the stacking regressor model (sRTT)

B.2 *Prediction Error Plot*

Prediction error for network throughput, network queue delay, and sRTT demonstrated in Figures 6, 7, and 8, respectively. The best-fit line describes the median prediction trend, while the identity represents the variance of predicted values compared to the actual values. Predictions are accurate when the best fit and identity lines are closer.

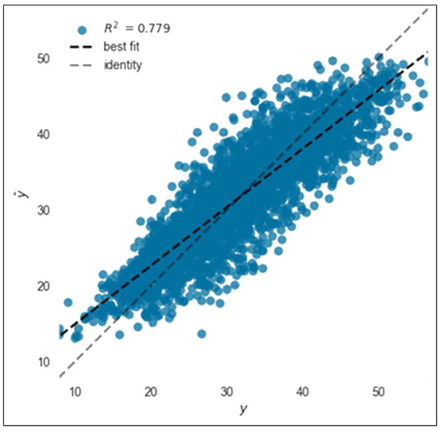

Fig. 6: Prediction error plot of the stacking regressor (network throughput)

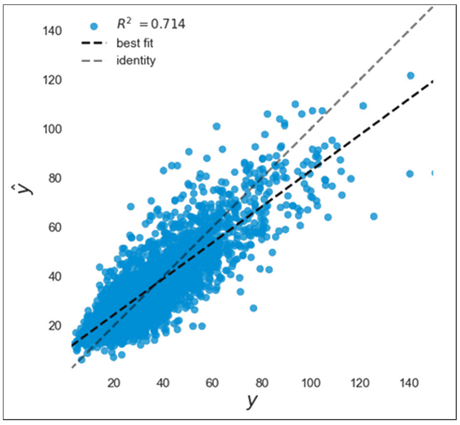

Fig. 7: Prediction error plot of the stacking regressor (network queue delay)

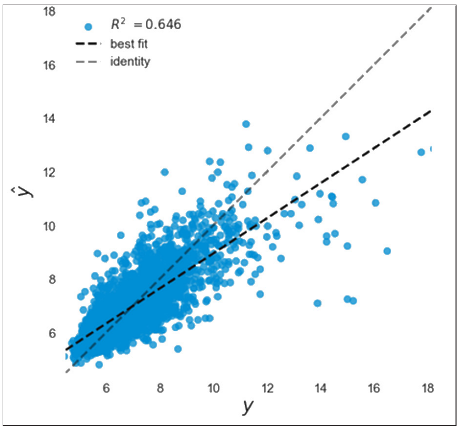

Fig. 8: Prediction error plot of the stacking regressor (sRTT)

For network throughput, although most points cluster around the best-fit line, a small linear trend is noticed. However, the R^2 value of 0.779 implies that our prediction accuracy is good and suggests a decent model fit. A little deviation from the identity line is noticed at high predicted values, which denotes possible difficulties in predicting high throughput.

R^2 value of 0.714 indicates a moderate accuracy level for network queue delay. Like the previous case, the model presents some limitations in predicting higher values. The model overestimates or underestimates delay in some scenarios, shown through points distant from the identity line. The model delivered weaker prediction capabilities when predicting sRTT values based on the achieved R^2 value (0.646). At the lower part, the predictions are closer to the actual values; however, when values increase, the predictions deviate from the actual results, which suggests that the model's reliability and consistency decrease at specific parts.

B.3 Scatter Plot

Figures 9, 10, and 11 depict the scatter plot of the network throughput, network queue delay, and sRTT, respectively. The x-axis represents the experiment number and the y-axis denotes the output metric value. The actual values are in red, and the predicted ones are in blue.

The dense clustering of actual and predicted measurements for network throughput demonstrates a good performance of the utilized model. As the measurements spread further at higher values, higher variance in prediction accuracy is carried out, which means that the prediction model operates more efficiently at lower values. The model can generalize well for measuring network throughput while maintaining a consistent accuracy as no significant deviations are displayed.

For network queue delay, the displayed data reveals that most predictions fall at the lower end, along with the actual values, which implies that accuracy is higher in this range. However, there is a wide variance in the actual values that the model could not capture, indicating that the utilized model is not sensitive to such outliers, or the prediction range is insufficient.

Compared to the previous cases, the prediction performance for the sRTT is lower because the alignment is less accurate, and the actual values have more variation, while the predicted values are more concentrated around a particular range. Overall, the predicted values are clustered below the actual values, which shows some underestimation in some cases.

V. CONCLUSION

This study presents a rigorous and systematic scheme that led to the development of robust machine-learning models utilized in SCReAM for predicting the network throughput, network queue delay, and sRTT. Despite facing challenges, the final models demonstrated promising results, implying their potential utility in future applications.

The ML models leveraged our constructed dataset, resulting in enhanced prediction capabilities. The coefficient of determination R^2 is used as one of the numerical performance metrics to evaluate the models. Several regression models were used to predict the network metrics for the SCReAM algorithm, followed by a comparative analysis to find the best initial prediction performance.

Among the tested models, the LightGBM and CatBoost regressors significantly outperformed others in predicting performance metrics. Fine-tuning with Optuna and ensemble

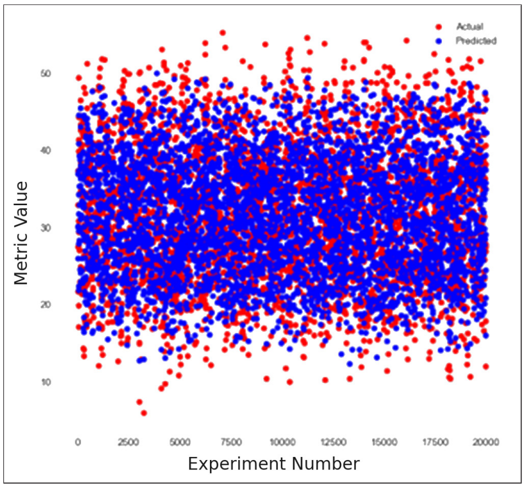

Fig. 9: Scatter plot comparing the actual and predicted values (network throughput (Mbps))

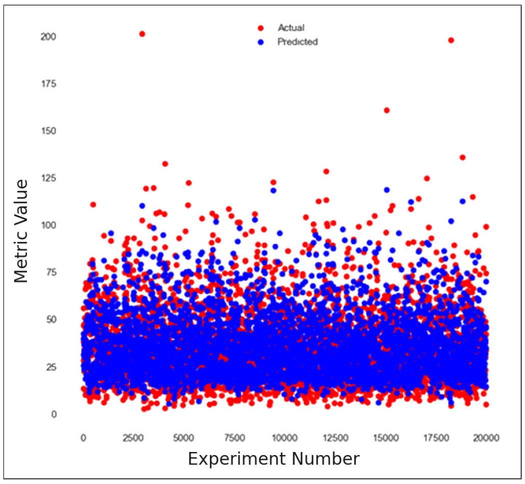

Fig. 10: Scatter plot comparing the actual and predicted values (network queue delay (ms))

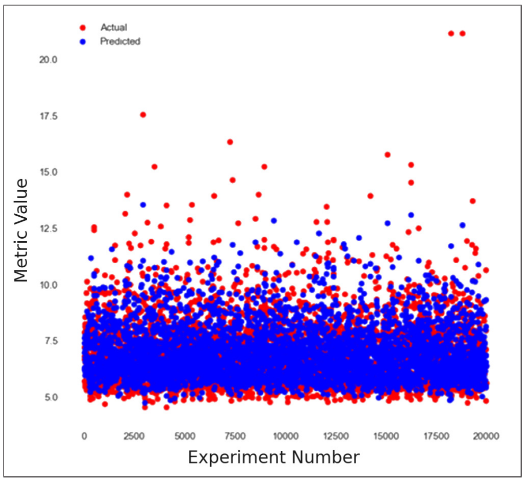

Fig. 11: Scatter plot comparing the actual and predicted values (sRTT (ms))

methods significantly improved the prediction accuracy of $R2^2$, indicating the effectiveness of these techniques. The achieved accuracy for network throughput ranges from 79.23% to 96.64%. For network queue delay, the prediction accuracy is from 60.4% to 99.4%. While ranging from 85.42% to 100% for sRTT.

Our work demonstrated an effective scheme for detecting several performance metrics based on the given features. Although we were able to improve the accuracy (or R^2) when integrating further methods, some experiments led to decreased R^2 value, which can be exploited and improved in future research. Furthermore, the model's performance can be further improved with more extensive hyperparameter tuning. Advanced ensemble techniques can also be employed to increase the accuracy of the prediction model.

It is essential to acknowledge that relatively minor differences in performance between the top ensemble methods can be caused by noise rather than actual performance improvements. Thus, in the future, it is crucial to perform rigorous statistical significance tests to determine if such differences fall within the expected variability caused by a random change.

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An AI-Driven Intelligent Transportation System: Functional Architecture and Implementation

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Abstract—**The surge in urbanization and the concomitant growth of the urban population have exacerbated issues such as traffic congestion and air pollution across cities globally. While Intelligent Transportation Systems (ITS) offer promise for improving urban mobility, existing solutions predominantly exhibit limitations in scalability and adaptability, thus falling short in delivering city-wide traffic management. This unaddressed gap necessitates the development of a robust, scalable, and adaptive system that can manage the intricacies of urban traffic. Our work introduces CityAI, an automated, AI-driven framework designed to operate on a city-wide scale. The system harvests data from diverse sensing infrastructures, employing machine learning algorithms to predict future traffic states and patterns. Furthermore, it proposes real-time interventions, including adaptive traffic light control and V2X-based solutions. The architecture and components of CityAI not only incorporate state-of-the-art techniques but are also applied in real-world environments. The CityAI framework was implemented in the city of Pécs, Hungary, as a proof-of-concept ITS system. The framework enables city authorities to implement proactive measures, thus preventing traffic issues before they manifest. The paper focuses on practical development aspects of an ITS system undertaking R&D on new technologies, applications, and techniques which may facilitate future product development.**

Index Terms—**data analytics, Intelligent Transportation Systems, machine learning, traffic light control, vehicular communication**

I. Introduction

THE escalating trend of urbanization across the globe places enormous demands on existing infrastructure, most significantly on road traffic management systems [1]. Challenges arising from this include elevated energy consumption, increased air pollution, and an adverse impact on the quality of life for city inhabitants [2], [3]. Intelligent Transportation Systems (ITS) have emerged as promising tools to mitigate these issues, incorporating technologies such as machine learning, data analytics, and advanced communication systems [4]–[7].

However, these ITS solutions commonly suffer from limitations in their scope, scalability, and adaptability. They are often tailored for specific segments of a city or particular use cases, thereby lacking the versatility required for comprehensive, city-wide applications [8]–[10]. Additionally, the technical complexity of these systems poses a significant barrier for traffic operators who may not have expertise in data science or software engineering. These shortcomings are further compounded by regional and legal constraints such as stringent data protection regulations.

This paper introduces the CityAI system, an innovative ITS framework empowered by machine learning to achieve scalable and adaptable management of urban traffic networks. The aim of our work was to implement a proof-of-concept ITS system that includes state-of-the-art technologies, techniques, and applications that may facilitate future product development by giving guidelines for technical system design. The contributions of this work are as follows:

- it elucidates a novel approach for multi-modal transport integration using machine learning,
- it develops an adaptive traffic prediction model that can scale with the complexity of growing cities,
- it presents a comprehensive data-driven decision-making process, enhanced by a diverse set of data sources, and
- it proposes an adaptive and resilient architecture capable of real-time monitoring and rapid response to unforeseen events.
- it introduces a real-life implementation of a proof-of-concept ITS system deployed in the city of Pécs.

The remainder of this paper offers a comprehensive exposition of CityAI, focusing on its architecture and the functionalities of its key components to provide an in-depth understanding of its capabilities and its potential role in shaping the future of urban transportation management.

II. Related Work

In recent years, significant advancements in ITS have been driven by the integration of machine learning, data analytics, and advanced communication systems. Existing solutions like City Brain [11], developed by Alibaba Cloud and deployed in cities such as Hangzhou (China) and Kuala Lumpur (Malaysia), and European ITS software suites like Yunex Traffic [12], an independent company specializing in intelligent traffic systems after spinning off from Siemens Mobility, and Urban Traffic Management (UTM) [13] by SWARCO exemplify large-scale applications of artificial intelligence (AI) in urban management. However, the specific details of these systems' AI-based methodologies remain sparse, highlighting a gap in comprehensively documented, adaptive, and scalable AI-driven traffic management solutions. This statement is

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also supported by collections of current V2X deployment activities in recent surveys (e.g., [14], [15]) highlighting that cooperative ITS solutions are in their early phases of adopting AI technologies.

Traditional machine-learning approaches have been widely applied to traffic forecasting and classification tasks using roadside sensors. Methods such as Hidden Markov models, gradient boosting regression trees, artificial neural networks, decision trees, support vector machines, Gaussian mixture models, and Bayesian networks have been successfully employed for short-term traffic prediction and travel time estimation [16]–[19]. These foundational techniques, while effective, often face challenges in scalability and adaptability for real-time, city-wide applications.

Recent advances have shifted towards deep learning models that capture spatial and temporal dependencies in traffic data. Long Short-Term Memory (LSTM) neural networks, stacked autoencoders, and fuzzy-based convolutional neural networks have shown promise in improving prediction accuracy under dynamic conditions [20]–[22]. Hybrid methods combining neural networks with statistical or optimization approaches, such as swarm intelligence and evolving fuzzy neural networks, further enhance the robustness and adaptability of traffic flow models [23]–[26].

Recent studies have focused on incremental learning and data stream processing techniques to address the growing need for real-time traffic management. For instance, trajectory clustering using hyperdimensional computing and smart traffic management platforms leveraging online incremental machine learning represent efforts to detect and adapt to real-time changes in traffic patterns [27], [28]. These approaches underscore the importance of handling the dynamic and streaming nature of urban traffic data.

Despite these advancements, many ITS solutions remain limited by their specificity to particular urban segments or technical complexities that hinder broader applicability. CityAI addresses these gaps by proposing a comprehensive, data-driven, and adaptive ITS framework that integrates multi-modal transport data, supports scalable traffic prediction models, and enables real-time monitoring and rapid response to urban traffic dynamics.

III. SYSTEM ARCHITECTURE

The architecture of CityAI is intricately designed to facilitate a comprehensive traffic management solution. It is organized around three major functional components, aligning with the focus of the upcoming sections: Data Collection (Section IV), Data Analytics (Section V), and Informed Traffic Governance and Visualization (Section VI). A schematic representation of the architecture is depicted in Fig. 1. In the following subsections, these functional groups are briefly overviewed. Detailed discussions concerning individual system components will be presented in subsequent sections.

Data Collection

Data Collection is primarily concerned with the acquisition and preprocessing of data. This functional group incorporates

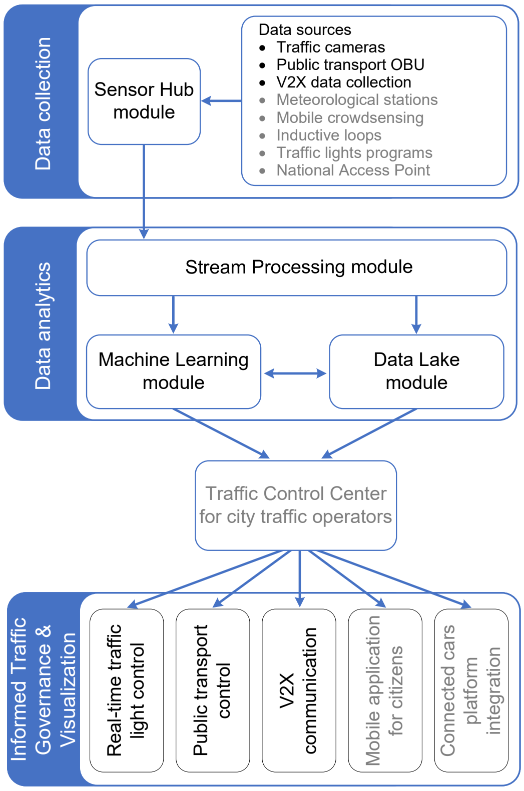

Fig. 1. CityAI general architecture, aligned with the thematic components of Data Collection, Data Analytics, and Informed Traffic Governance and Visualization.

modules such as the Sensor Hub, which takes responsibility for data collection, standardization, and forwarding.

Data Analytics

This functional group is tasked with intensive computational activities. It includes the Machine Learning and Data Lake modules, which engage in complex data analysis, traffic pattern recognition, and actionable insight generation.

Informed Traffic Governance and Visualization

This functional group is devoted to the effective application of acquired knowledge and insights for a range of tasks. These tasks include real-time traffic management, network optimization, and enhanced visualization. The analytics from the Data Analytics group are transformed into actionable interventions and also channeled into a visual interface for a more holistic understanding of urban mobility patterns.

IV. DATA COLLECTION

Data collection is one of the crucial elements of an ITS architecture, which produces the required input for all other modules of the system. Although the Sensor Hub module allows different data sources, such as meteorological stations and mobile application data (crowd sensing), in the deployed CityAI framework, three different real-time data sources are used currently: traffic cameras, public bus trajectories, and V2X information.

A. Traffic Cameras

The CityAI systems modules rely on estimated statistical information regarding vehicle traffic (speed, flow, occupancy) in urban environments by processing the images of preinstalled cameras. It is worth mentioning that the primary aim of these PTZ (pan-tilt-zoom) surveillance cameras - owned by the local authority of Pécs - is to ensure public safety. The position and view angle of the cameras made it very challenging to use them for traffic monitoring. Therefore, the system applied in this work has different characteristics from speed, flow, and occupancy (SFO) information extracted by standard traffic monitoring camera systems [29]. Here, we used cameras from a pre-installed network of urban surveillance cameras with preset positions that monitor only a particular section of the traffic path at a time. Due to preset changes, only periodical data acquisition from the monitored area was possible during intervals when the surveillance camera preset was monitoring a particular section. Also, an automatic detection algorithm was needed to determine the camera's current preset position.

1) Implementation of the system: After evaluating the data from the preliminary tests, our design choice was to use a distributed system architecture, where we deployed NVIDIA Jetson Nano embedded computers to process each camera image locally (*cf.* Fig. 2). In the processing pipeline, incoming camera images are pre-processed to determine which preset the camera is currently in, and then the Yolo neural network [30], [31] is applied to detect the objects visible in the image. After filtering by class, the vehicle object (auto, bus, truck, motorcycle) instances are fed into a tracker module to establish which objects in the current frame correspond to past object displacements. The camera image is calibrated to the real-world scene since we measured the projection of the camera image onto the road surface plane using the homography transformation [32]. Using this information, the speed of the tracked objects is computed by counting the pixel displacement on consecutive images. Also, we have set trigger and occupancy zones on the images. Therefore, using these zones one can calculate the SFO [33], [34] values of the passing objects as follows:

Speed is the current specified object speed for a given trigger zone (*cf.* Fig. 3).

$$Speed = \frac{s_c}{t_f}, \tag{1}$$

where s_c is the distance the center of the same object in two consecutive calibrated frames, t_f is the time that has passed between taking two consecutive frames.

$$Flow = \frac{d}{t} \cdot t_p, \tag{2}$$

where d is the numbered tracked objects belonging to the given trigger zone, t is the elapsed time (end of measurement - start of measurement), and t_p is the Flow time window rate (a multiplier calculated from the preset cycle time).

The occupancy statistical information is calculated using the occupancy zones shown in Fig. 4. The occupancy is the median value of the velocity of the objects within the zone divided by the number of objects at a time instant. Namely,

$$Occupancy = \frac{n}{Med_{i=0}^{n} v_i}, \tag{3}$$

where n is the number of objects (the number of vehicles in the occupancy zone at the moment of the measured time), v_i is the speed of the i-th object, and $Med_{i=0}^{n} v_i$ is the median speed of n objects. The calculated value is normalized between 0 and 100. The value is 0 if there is no traffic and 100 if the band is saturated. If the median speed is 0 and n is greater than 0, then a value of 100 is transmitted.

The data measured by the distributed Jetson Nanos are aggregated and periodically transmitted to higher-level components of the system for processing. Data communication relies on stream processing, utilizing a distributed streaming platform for efficient data ingestion through message queuing. This approach effectively manages data streams and promotes seamless communication between various system components. Asynchronous information transmission enables real-time pro-

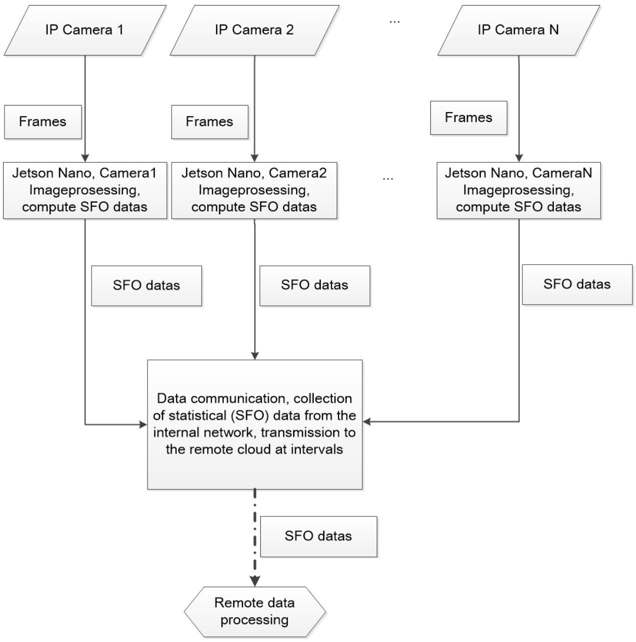

Fig. 2. Image processing data flow.

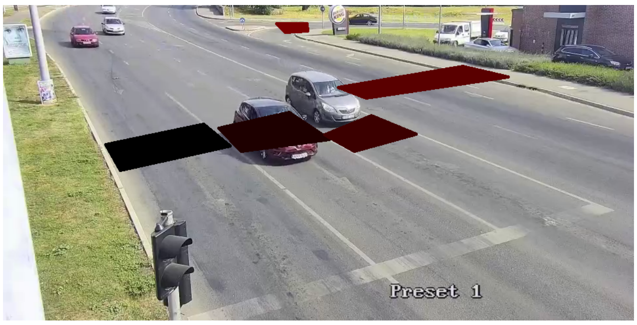

Fig. 3. The used trigger zones.

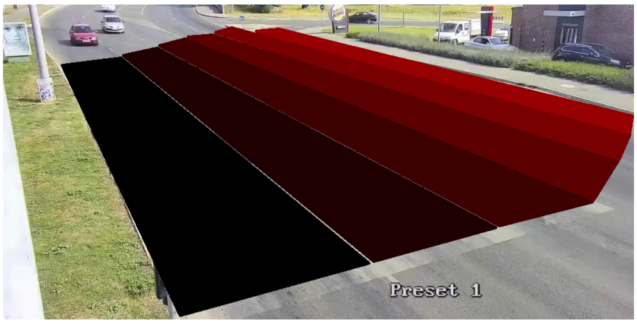

Fig. 4. The used occupancy zones.

cessing and analysis of data as it is generated. Additionally, the streaming platform ensures load balancing and load sharing for ingested data, boosting the system's scalability and fault tolerance.

The algorithm was tested under various weather and lighting conditions to assess the performance of the automatic SFO measurement system. We manually counted the number of vehicles across different time intervals to compare with the automated measurements. The evaluation was conducted at eight different measurement locations. Under daylight and favorable lighting conditions, there was no significant discrepancy between the manual and automated counts. However, in low visibility conditions, such as rain and twilight, an error margin of approximately 5-10% was observed, varying by location. The error primarily stemmed from the algorithm undercounting vehicles compared to manual counts. Additionally, the camera's viewing angle relative to the road had a minor influence on the algorithm's accuracy. The system also considers real-time weather data during operation. The error introduced by weather conditions and twilight can be mitigated by applying compensatory estimation values (5-10%) when making traffic decisions.

B. Public Transport Trajectories

The advancements in technology have led to an increase in the capabilities of in-vehicle sensors and on-board units, allowing them to collect and periodically report trajectory data [35], [36]. A vehicle trajectory, defined as the path generated by a moving vehicle in space [37], is recorded by vehicle trajectory data, which captures the movement of individual vehicles [38]. These trajectory data have become a crucial element in modern traffic management [39]. However, the collection of diverse data still poses a challenge due to factors such as privacy concerns and the administration of sensors by different entities.

Our system currently employs bus trajectories to improve traffic flow forecasting and congestion detection. Specifically, we utilize the trajectories of public buses operating in the city of Pécs, Hungary's 5th largest city. The buses are operated by TükeBusz Zrt., the local public transport service provider. At the time of system implementation, the company operated 202 buses on a 300 km network. The on-board units installed in the buses periodically collect and record various data. These data are then transmitted to a remote collection unit which forwards it to our system in a comma-separated format.

C. Vendor-independent V2X information collection/dissemination sub-system

The purpose of our proposed CityAI framework's V2X-based data collection and intervention modules is twofold. On the one hand, it aims at implementing standardized vehicular data exchange to support dynamic, adaptive, and fine-grained information gathering and dissemination tasks in the ITS domain. On the other hand, it provides solution portability by ensuring that the implementation works independently from the V2X device manufacturer's application programming interface and other vendor-specific details, making information exchange of data collection and intervention both feasible in a generic manner, independently of V2X implementations.

Our V2X sub-system is to be able to store and process the data generated by on-board and road-side units - the two basic infrastructure elements of vehicle communication – and present the resulting data set to other processing components in the framework. The proposed solution can act as an integration point in any complex ITS architecture where vehicular communication is considered: it converts manufacturer-specific V2X data into a vendor-independent format, creates/maintains connection with other backend components, and performs further data conversion so that the connected modular elements can easily process the data in a bidirectional way. Fig. 5 shows the general architecture of the V2X sub-system, highlighting the integration links and the most essential modules briefly introduced below.

- On-board Unit (OBU): its communication relies on CAM (Cooperative Awareness Message) and DENM (Decentralized Environmental Notification Message) services, which the RSU (Road Side Unit) receives and forwards to the data management component.
- Human Machine Interface (HMI): it can trigger various DENM messages and display the received traffic/accident information using the Google Maps API.
- Road-side Unit (RSU): RSUs forward the data received from the OBU to the centralized, vendor-independent data management component. We added a particular module to the RSU to help this operation by converting the manufacturer-specific data representation into general, device-independent data models.
- V2X Dashboard: to visualize the data of the V2X subsystem for testing, evaluation, and demonstration purposes, we have implemented a web dashboard interface that displays the received CAM and DENM messages and their explicit content (*cf.* Fig. 5)
- Traffic Control Center V2X interfaces: data can be sent and received through the Stream Processing module and also the REST services offered by the TCC implementation. The V2X sub-system can integrate with the dispatch center through both available interfaces.
- Vendor-independent data management framework module: the central component of the V2X sub-system realizes the data management functions of device-independent facilities-layer protocol data models of CAM

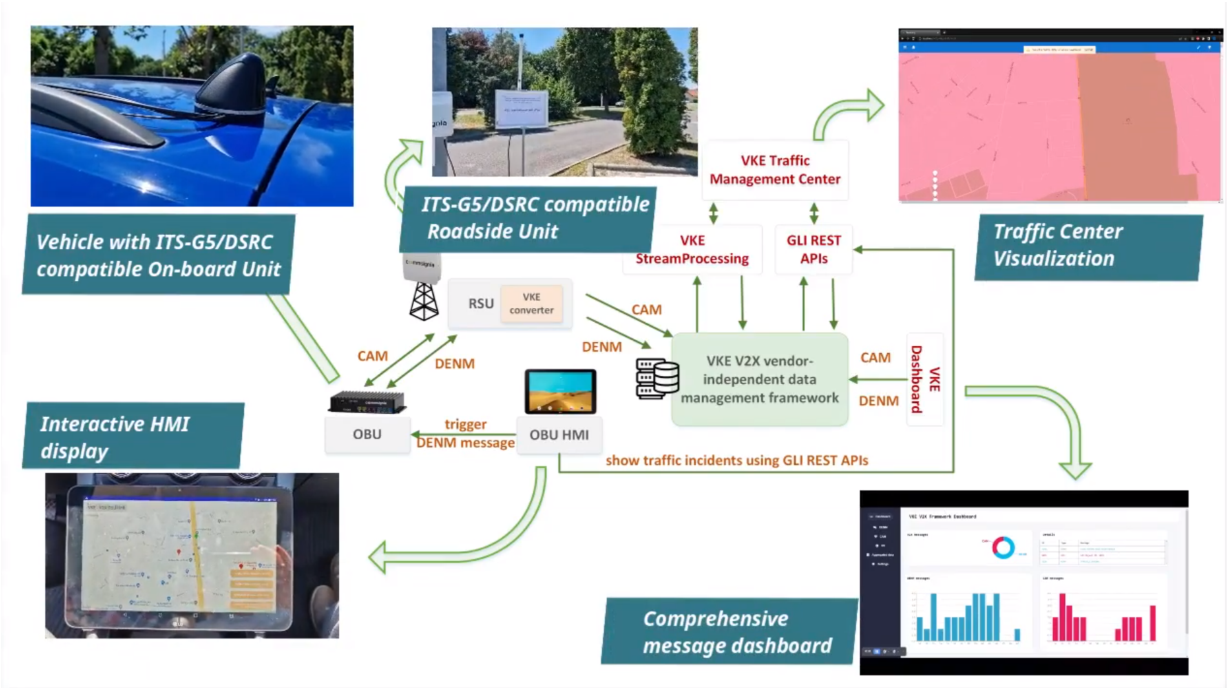

Fig. 5. Proof-of-concept implementation of the V2X sub-system.

and DENM, corresponding to the standards. It implements the device-independent, Apache AVRO scheme-based data models designed for the framework. It also provides the interfaces to related systems so that they can access the device-independent V2X data. Using these interfaces, the converter middleware implemented in the RSU can create data and provide data to other systems through them.

V. Data Analytics

The raw data gathered by different sensors must be unified and pre-processed to make it adaptable for data analytics and other services. The main modules that handle the incoming data flows and make it available for other CityAI modules are the Stream Processing-, Machine Learning-, and Data Lake modules.

A. Stream Processing Module

Sensor data, originating from an array of sources and devices, is transmitted in various formats. The high speed, volume, and diversity of these data types render traditional processing methods, such as batch-based approaches, inefficient, unscalable, and unreliable.

Stream processing [40] offers an innovative technique for the effective extraction and analysis of heterogeneous data. This method perceives data as continuous, never-ending streams and boasts the primary advantage of immediate data processing upon availability. Stream processing alleviates the burden on storage systems by requiring minimal resources through real-time data processing, enabling the extraction of valuable features on the fly without requiring extensive measurement data storage.

Several solutions exist in this context, encompassing message brokers, Pub/Sub services, WebSocket, event-driven architecture, and reactive programming. However, we have chosen Apache Kafka[1] as CityAI's backbone. As a reliable, scalable, and high-throughput message broker, Kafka adeptly manages substantial data stream volumes with minimal latency. Furthermore, Kafka offers robust fault tolerance, message ordering, and real-time data processing capabilities, rendering it an exemplary choice for constructing a complex system such as an intelligent transportation system.

Data from disparate sources are stored in distinct Kafka topics. Kafka Producer applications or Kafka Source connectors write data into these topics, while Kafka Consumer applications or Kafka Sink connectors read data from them. We also employ Kafka Stream applications to execute data pre-processing for the system's other components.

In conclusion, leveraging Apache Kafka has enabled us to develop a high-performance and dependable proof-of-concept system.

B. Machine Learning Module

The main goal of the CityAI Machine Learning module (MLM) is to obtain valuable information from the gathered raw traffic data (originating from the city's traffic sensing infrastructure) with machine learning-based prediction and anomaly detection algorithms [41]. It communicates with the Stream Processing and the Data Lake modules, the former provides the raw real-time traffic data, and it helps to disseminate

[1]https://kafka.apache.org

the information produced by the MLM. The latter has a role in model training and visualization of the traffic data, as it provides the historical data for the MLM.

Fig. 6 shows the components of the Machine Learning module. As mentioned above, due to the architecture of the system, the MLM communicates directly only with the Stream Processing and the Data Lake modules. Based on the timing of the communication between the modules, we can distinguish between real-time and demand-driven communication. The MLM accesses the stored/historical data that is required through the DataLakeInterface. Historical data are used for training and monitoring the prediction models. It is worth mentioning that the data is not needed all the time but is frequently accessed because of its multiple uses. The MLM accesses the required real-time data streams through the StreamProcessingInterface. Real-time data are used for real-time traffic behavior identification, forecasting, and outlier detection. The data is received asynchronously and continuously at varying frequencies, which are subsequently resampled and sent in uniform time units.

The MLM consists of three main blocks:

- *Apache Flink Cluster*, where real-time functionalities are executed. These functionalities are defined as separate Flink jobs, and their current states can be monitored through a Web Dashboard. Our choice of Apache Flink was driven by the unique demands of our use case. It provides an optimal combination of performance, scalability, and compatibility features that best meet our project requirements. Additionally, implementing the cluster using Flink ensures seamless integration with the Apache ecosystem, including Kafka.
- *Monitoring Component*, which offers a platform for tracking prediction tasks and models. This component enables the training of new models or the retraining of existing ones as needed.
- *ModelServing Component*, which oversees prediction tasks, stores trained models, and provides access to them.

By integrating these three components, the MLM can serve the city traffic operators in the traffic management process with several crucial functionalities. As discussed in Section I, the technical complexity of management systems poses a significant barrier for traffic operators who may not have expertise in data science or software engineering. Therefore, it is imperative that this module pre-processes the raw traffic data and complements missing or flawed measurements automatically. It can provide real-time traffic state predictions for different road sections and time horizons, which helps traffic operators plan interventions on time. The traffic state predictions appear in the control center, together with intervention suggestions generated by artificial intelligence-based solutions. However, the final decision about the type and volume of the intervention is made by humans, only the suggestion is generated by AI, which leaves control in the hands of the central authority.

A special type of prediction focuses on traffic congestion. The first phase of the congestion is recognized by anomaly detection algorithms, which are trained to find these specific patterns in the traffic times series. This way, the detection time can be kept low, and the intervention can be made on time, before the initial congestion evolves into a traffic jam, on a wider scale.

The Monitoring Component is crucial to have a constant measurement of the precision of the above-mentioned prediction models. The city infrastructure and, therefore, the traffic patterns change dynamically (*e.g.*, closing/opening lanes, building new roads, maintenance works, and mass events). Thus, if the utilized models are not precise enough, they should be retrained with the novel traffic time series, the module does it automatically. Another useful feature of the module is that it uses public transport data to make predictions more precise. Furthermore, it can provide predictions of the arrival and departure times of public transport vehicles for passengers.

In our proof-of-concept, we validated multiple machine learning algorithms using a comprehensive dataset collected from the city's traffic sensing infrastructure. After comparing their performance on various prediction horizons, we chose XGBoost and SVM as our top selections. For instance, we evaluated the models' performance at short intervals, such as one or two minutes, and longer intervals, such as days. Depending on the SFO input data, the algorithms performed very similarly, with the only discrepancies appearing across different prediction horizons.

For the learning process, we divided the dataset into training and validation subsets, using a 70/30 split. We trained the models on the training set and validated their performance on the validation set. During the training phase, we applied techniques such as cross-validation and hyperparameter tuning to optimize the performance of each algorithm.

We assessed the performance of the selected models using metrics such as mean absolute error (MAE), mean squared error (MSE), and coefficient of determination (R-squared).

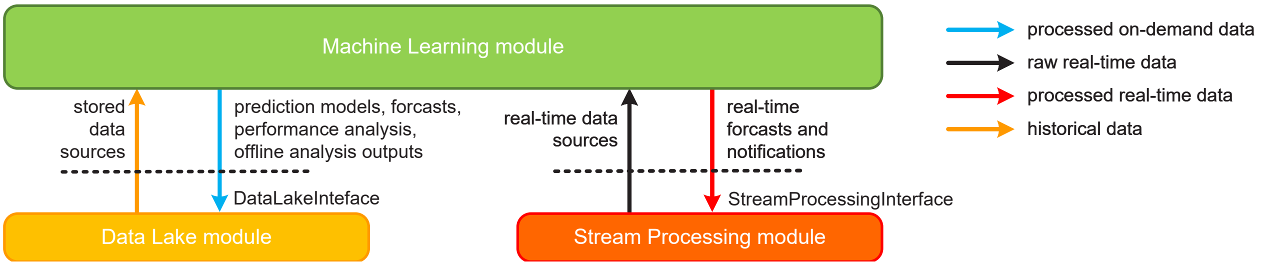

Fig. 6. Relationship of the *Machine Learning* module with other modules.

These metrics helped us to continuously monitor the models' precision through the Monitoring Component, allowing us to retrain them whenever necessary. This ensured that our system remained up-to-date and capable of delivering reliable traffic predictions.

C. Data Lake Module

The main function of our Data Lake [42] component is to consolidate data from multiple sources in a single location, enabling the exploration of complex relationships between data from different sources. It receives data from the corresponding topics in the Stream Processing module, writes them to the Data Lake tables corresponding to the topic, and indexes them. In our prototype implementation, the Machine Learning, Traffic Management, and Dispatch Center components are directly linked for data retrieval, providing a central repository that is accessible to various applications.

Our Data Lake design comprises of two main components: a data warehouse optimized for efficient data insertion and storage and an indexed data warehouse that supports dynamic data retrieval. The former is implemented using Cassandra[2], and the latter uses ElasticSearch[3]. Additional tools such as event monitoring, alerting, and data archival were also integrated into the solution to enhance its functionality.

The primary concern in the design of the Data Lake connectivity was data security and consistency. Write operations are performed indirectly through the Stream Processing component. To achieve this, corresponding Kafka Consumers were developed, which connect to the topics, transform the messages published in these topics, and write them into the database. The data written into the database are subsequently indexed.

We differentiate between two distinct methods of data reading. Read operations are primarily performed by directly connecting to the relevant data store and executing native queries. Currently, there is no abstraction layer or proxy for data querying. Instead, a data warehouse solution is utilized to retrieve specific stored data based on unique identifiers or other predefined (indexed) fields. The second method of querying data is through Kafka, where the desired data can be obtained using appropriate Kafka Source components.

VI. INFORMED TRAFFIC GOVERNANCE AND VISUALIZATION

The section discusses how the different types of data flows and AI-based predictions can be used for interventions and value-added services. Within the CityAI system, we deployed a pilot implementation of reinforcement learning-based traffic light control and introduced a traffic data dissemination service based on V2X and public transport congestion detection service using incremental learning.

A. Reinforcement Learning-based Traffic Light Control

An advantage of reinforcement learning-based traffic light control approaches over conventional signal control techniques, such as traffic theory-based and heuristic methods, is that it does not rely on pre-defined rules but learns the appropriate actions based on the feedback they receive from the observations. The adoption of reinforcement learning for traffic signal control has become very popular recently. Finding the appropriate formulation of states and rewards is crucial to achieving training stability and providing rapid convergence to derive the best policies [43]. Several survey papers were published [44]–[47] that categorize hundreds of research papers in this field. According to the results overviewed in these papers, reinforcement learning has shown superior performance over conventional methods. Although, the performance of these solutions was investigated in a simulated environment that was SUMO traffic simulator in most of the cases. Although some of the papers investigate real-world scenarios, such as [48], to the best of our knowledge, there are no reinforcement learning-based traffic light control approaches implemented in real-life environments.

To make interventions in the traffic, we used reinforcement learning as a goal-oriented machine learning technique, which can learn how to attain a complex objective and maximize along a particular dimension. The approach is concerned with how the agent should take action in the current state of the environment and maximize the overall reward gained. To make the method successful, a lot depends on how the action, the state of the environment, and the reward function are constructed.

The uniqueness of our RL-based traffic control method is that it was deployed in real life as a proof-of-concept solution. Therefore, our hands were tied, and we had to adapt to the existing conditions when defining the environment states reward function, and possible actions. The Hungarian road operator allowed us to run our RL-based scheme in one specific junction in the downtown of Pécs, on the main road that crosses the city. The Rákóczi rd. - Alsómalom rd. junction (Fig. 7) is part of a green-wave traffic control system that significantly limits the allowed signal program changes. Also, the Swarco ACTROS traffic light controller and the traffic management system used by the road operator made it not possible to dynamically create and upload new signal programs in run-time. Instead, only pre-defined and previously uploaded signal programs to the controller can be activated. Moreover, the signal program slots in the controller are also limited. Due to all of these restrictions, the road operator allowed four additional signal programs as modifications of the original one. In these programs, the start time and end time of the green phase were modified by ± 2 seconds, respectively. E.g., in the allowed signal programs, the green phase of signal group $J1$ can be in the 24-78, 24-76, 22-78, 22-80, and 20-80 seconds time ranges, while the cycle time is constantly $Cl = 105$ s. Fig. 7 shows the traffic light program for the first example ($J1$ green phase: 24-78 s). The action of our reinforcement learning-based approach was to select one of the five available traffic light programs. Moreover, the system used by the Hungarian road operator also limited the frequency of program changes to one program change every 15 minutes. Due to all these limitations we had to adapt, we can declare that the allowed traffic light program changes are only enough to fine-tune the current traffic light setup, but not sufficient to

[2]https://cassandra.apache.org
[3]https://www.elastic.co/elasticsearch/

make fundamental changes in the traffic flow.

In a real-life environment, the accuracy of deployed sensors is also limited. Moreover, in the case of traffic cameras, it can vary due to weather conditions and light intensity. In our pilot system, surveillance cameras were used to measure the speed [km/h], road occupancy [%], and flow [vehicle/hour] metrics. The camera observation zones in the controlled intersection are presented in Fig. 7. These PTZ (pan-tilt-zoom) cameras were deployed to ensure security for citizens and not for traffic monitoring purposes. Therefore, the perspective was not ideal, and only the flow values were reliable enough to be used as the state descriptor for the reinforcement learning algorithm. Although, the image processing module was able to distinguish and separately monitor the lanes' traffic, the measured values for lanes having the same direction were merged. The merged observation zones are illustrated with the same color code in Fig. 7. In order to conceal the variations of the measured speed (v) values, moving average with 15 minutes window size was deployed to determine the state (s_t) used as input for the reinforcement learning agent.

$$s_t = \{\overline{v_1}, \overline{v_2}, \overline{v_3}, \overline{v_4}, \overline{v_5}, \overline{v_6}\} \tag{4}$$

The reward function plays a significant role in the learning phase, while during the execution of the learned model, it is used only for monitoring purposes. There are two main methods to learn the model for real-life control: (*i.*) the actions are performed in the real environment, (*ii.*) a simulated environment is used.

In the first case, the determined actions can be more accurate and effective, but on the other hand, the learning phase is quite challenging. The reason is that the performed actions during the learning phase can be random and lead to unwanted situations. Traffic control is very sensitive from this aspect because we can not afford to cause traffic jams during the training phase.

The only option we had was to use a simulated environment to learn the agent and later use it for real-life traffic signal control. Therefore, we modeled not just the specific junction controlled by the reinforcement learning agent but also several neighboring junctions on the main road that crosses the city of Pécs, as illustrated in Fig. 8. Including neighboring junctions in the simulated environment was necessary because our aim was to achieve global improvement in the traffic flow and not just in the controlled intersection. Moreover, we had to take the pre-configured signal programs of other intersections into account in order not to disrupt the green-wave provision. The objective of the reward function was to maximize the average speed of the vehicles in the region of all nine intersections shown in Fig. 8. The simulation of the environment was performed in SUMO [49] by setting up traffic demands based on validated O-D (Origin-Destination) trip tables provided by the road operator.

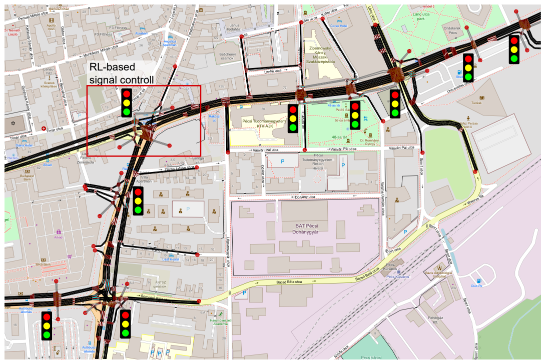

Fig. 8. SUMO simulation of the main road traffic in the center of Pécs.

In order to make the environment compatible with different reinforcement learning-related Python packages, we used the OpenAI Gym framework to create the SUMO-based environment. Although the real-life reinforcement learning-based traffic light control was demonstrated in a single intersection, the implemented environment also supports multiple intersection control using multi-agent reinforcement learning techniques. There are several reinforcement learning algorithm packages available (*e.g.*, KerasRL, Tensorforce, and StableBaselines3), but currently, only RLlib has multi-agent support. Moreover, RLlib is actively maintained, has a large community, and also offers other advanced features, such as hyperparameter optimization and action masking. We tested the performance of different algorithms, such as PPO, A3C, and PG, but the best results were achieved by DQN. The DQN model was trained for 40 simulated days in the SUMO environment. The trained DQN model was deployed in the CityAI domain and

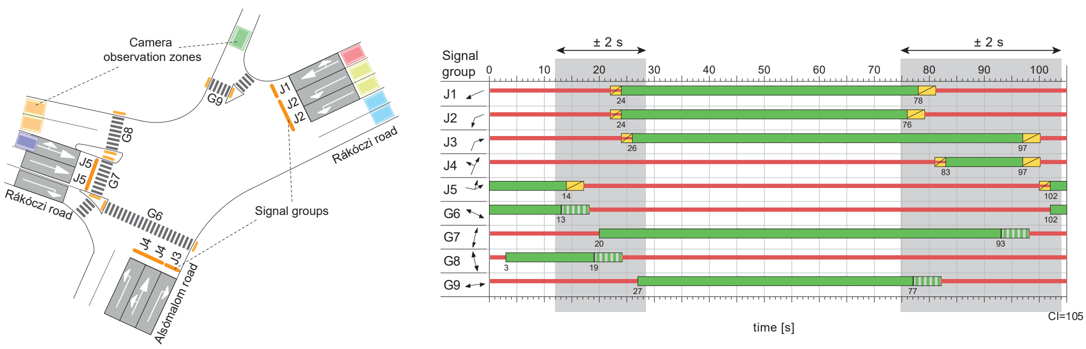

Fig. 7. Topology and signal programs of the RL-controlled junction.

fed with real-life flow [vehicle/hour] values extracted from camera video streams.

The introduced reinforcement learning-based traffic light control (*RL-TLC*) algorithm that uses the trained DQN model, gathers the requested input from the Kafka platform (Stream Processing module) and pushes the proposed traffic light program ID as illustrated in Fig. 9. The proposed program ID is consumed by the Dispatch Center, which confirms the traffic light program automatically or by human operators and pushes its ID back to the Stream Processing module. We used the automatic confirmation setup during real-life experiments. In order to activate the selected signal program, we used the REST API provided by the road operator (MK), which is accessible from their own domain. The new signal program ID data entries were immediately forwarded through the REST API of the road operator to the traffic signal management tool (*JTR-controller*). The *JTR-controller* is responsible for sending the signal program ID to the local intersection traffic signal controller and activating it. The CityAI traffic light control architecture overview and data flows are presented in Fig. 9.

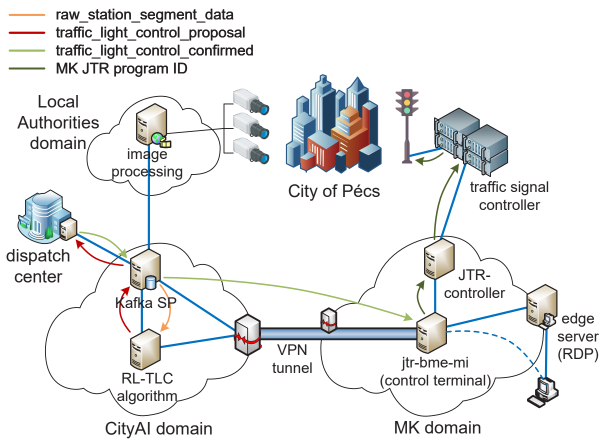

Fig. 9. RL-based traffic light control architecture and data flow.

In cooperation with the Hungarian road operator, we were able to test the presented CityAI reinforcement learning-based traffic light control system in real-life conditions. The proof-of-concept demonstration was running on a regular working day (Monday, 11 Apr 2022) between 6:30 AM and 8:00 PM. In order to compare the performance of the RL-based scheme with the default signal program, we collected the speed [km/h] and flow [vehicle/hour] values from the Kafka platform measured on the demonstration day and one week before (also a Monday). According to the series of flow values, the traffic was very similar on the two examined days. For the speed values, we found that instead of 40.8 km/h average speed, the reinforcement learning-based traffic light control scheme increased the average speed to 44.5 km/h. Although the duration of the real-life test was only one-day long that is not sufficient to justify the performance improvement as a scientific result, we believe that the implemented proof-of-concept solution is very promising, especially if reliable data sources are available and more flexible changes in the traffic signal program are allowed. To the best of our knowledge, this was the first real-life implementation of a reinforcement learning-based signal control scheme.

B. Vendor-independent V2X information collection/dissemination sub-system

The proposed V2X sub-system enables vehicles to communicate with other vehicles, the CityAI infrastructure, and other road users through wireless communication protocols. Besides the highly efficient, timely, and disseminated data collection support, one of the significant capabilities of this sub-system is the ability to implement various intervention types, such as cooperative awareness, and cooperative decision-making.

Cooperative awareness refers to the ability of V2X capable road users to share information about their speed, location, and other relevant data with other road users and infrastructure, thereby improving the overall situational awareness of all parties. This type of intervention allows for the real-time exchange of information between vehicles, such as traffic congestion, roadwork, weather conditions, and any other events that could affect the driver's safety. This information can be used to alert drivers of potential hazards on the road and make informed decisions to avoid collisions and improve traffic flow.

Cooperative decision-making refers to the ability of road users to rely on the information shared through cooperative awareness to make more informed decisions, such as adjusting speed or changing lanes to avoid a potential collision. This intervention also allows vehicles to make decisions that optimize traffic flow, such as forming platoons of vehicles to increase the capacity of highways, enhance the throughput of intersections, and reduce congestion. Additionally, this type of intervention can optimize electric vehicles' energy consumption by allowing them to communicate and coordinate their recharging schedules.

From a Traffic Control Center perspective of our CityAI architecture, the intervention capabilities of the proposed V2X sub-system can provide valuable information and tools for traffic optimization and information dissemination. By utilizing the real-time data exchanged between road users and infrastructure, the TCC can comprehensively understand traffic conditions, allowing it to make more informed decisions to optimize traffic flow and reduce congestion by providing V2X-based traffic and advisory information

One of the critical benefits of V2X technology for the TCC is the ability to use cooperative awareness information to provide real-time traffic updates and alerts to drivers, such as roadwork, accidents, and other events that could affect safety. The TCC can also use the information from cooperative decision-making to make decisions that optimize traffic in the area. The TCC can use V2X technology to control traffic lights, manage lane usage, and adjust speed limits in real time to improve traffic flow and reduce delays. Overall, the intervention capabilities of V2X technology can significantly enhance the ability of CityAI to manage and optimize traffic, improving the overall efficiency and safety of the city-wide transportation system.

We implemented a proof-of-concept testbed containing one vehicle and one roadside unit equipment for the functional assessment of integrating the V2X paradigm and our vendor-independent V2X data management solution into the CityAI framework. The proof-of-concept testbed comprises the components introduced in Fig. 5. In this experimental implementation, the RSU is connected to the central components through cellular backhauling, and the OBU-RSU communication is performed over a standardized ITS-G5 V2X interface. In our testbed, we employed Commsignia OB4 and RS4 devices [50] as OBU and RSU nodes, respectively. The specifications of these devices can be found in Table I. The data received by the vehicle OBU is traversed by a local Wi-Fi network to a tablet, running an Android-based HMI application (further details are depicted in Fig. 5). This HMI developed for the proof-of-concept experiments serves two functions:

- Triggering different types of DENM messages in the OBU: The OBU will forward these messages to the RSU, sending the relevant data to the TCC according to the data path depicted in Fig. 5. The HMI can trigger four types of DENM messages (Roadworks Warning – Major Roadworks, Roadworks Warning – Street Cleaning, Hazardous Location Notification – Animal On The Road, and Emergency Vehicle Approaching).
- Visualization of incident information traversed by the TCC via the RSU and ITS-G5 or using the REST API services directly through 4G/5G cellular and displayed for the driver using Google Maps API. Information retrieval is DENM-based in the case of V2X access, while for cellular communications, it is triggered by a periodic query with a parameterizable interval (in the demo scenario, an interval of 5 seconds was set) or by an event-based solution that activates when the vehicle moves (detected by the GPS module built into the HMI tablet).

TABLE I
MAIN TECHNICAL SPECIFICATIONS OF THE USED OBU/RSU DEVICES.

Feature	Specification
CPU	800MHz Freescale
OS	Linux
RAM	2GB DDR3 SDRAM
Flash	4GB eMMc
Antenna	2xV2X, 2xWiFi, 2xLTE/3G, 1xGNSS
Data	1xETH, 2xUSB, 1xCAN, 1xOBD-II
V2X chipset	Autotalks Secton
Hardware Security Module	SLI97
Further references	OB4 [51] / RS4 [52]

The proof-of-concept validation was performed in the city of Pécs, specifically on Road 58, Siklósi út. It is an extensive 2×2 lane road that stretches from the city center of Pécs all the way to the M60 motorway, primarily heading in a southerly direction. It features a few significant curves, roundabouts, and side road branches with traffic lights interrupting the flow of traffic. The road connects six neighborhoods with the city center. Shortly after crossing the Pécs city limits, it connects to the M60 motorway. The location of the test was near the city center section of the road, in close proximity to the public cemetery.

Fig. 10 shows the graphical interface of the HMI. The button responsible for triggering the four DENM messages is located in the lower right part of the screen. The accident/traffic information received from the TCC is displayed using a Google Maps marker, the title of which is the type of event. Additional information can be assigned to the markers on the map. In the example of Fig. 10, we experimented with the V2X-based intervention: the TCC center gathered and disseminated the event through the ITS-G5 interface of the RSU. The OBU received the information, and the HMI presented the marker at the event location together with the source of the given incident (i.e., in this case the TCC as a dispatcher). We can also further differentiate the markers: through the REST API service, we also receive the information that the confirmation of the event is POSSIBLE or VERIFIED for each event. In the first case, the notification represents a possible event, while in the second value, the report shows a confirmed, definitely existing event.

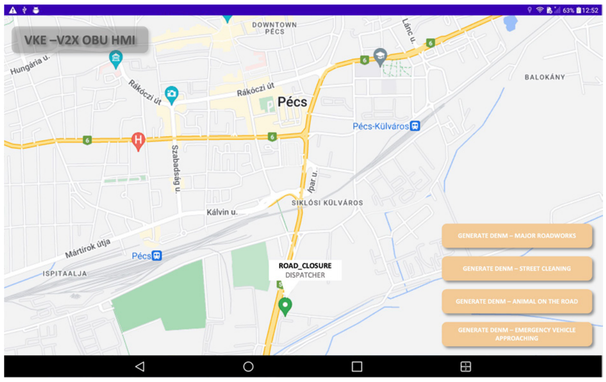

Fig. 10. Example screenshot from the Android-based HMI of the V2 subsystem's proof-of-concept testbed.

In the intervention scenarios of our proof-of-concept experiments, the traffic incident information is generated in the TCC and then transmitted to the vehicle. This information is then visualized on the vehicle's HMI, allowing the driver to see details of the accident, such as location and severity. This allows the driver to make informed decisions about the best route to take, avoiding any potential hazards or delays caused by the incident. It also allows the driver to be better prepared in case they encounter the accident scene on their route.

C. Public Transport Congestion Detection

The standard of living in metropolitan areas is heavily dependent on the ability of transportation systems to move residents, workers, and goods between various locations. However, as urbanization continues to expand worldwide, cities are experiencing a rise in population density. This leads to an increase in the number of vehicles on the road, exacerbating the issue of traffic congestion. This congestion not only hinders economic productivity, but also harms the environment and public safety through increased fuel consumption, air pollution, and increased costs of goods and services. Because of this, the ability to quickly and accurately detect and predict traffic congestion is a crucial task.

Given the importance of addressing traffic congestion in public transportation, we explore the use of incremental learning (IL) [53]–[56] for real-time detection of congestion. Specifically, we investigate the potential of using IL to adapt and scale the detection of congestion in public transport. To achieve this, we utilize long short-term memory (LSTM) in combination with IL to predict short-term bus travel speed by capturing the long-term temporal dependency.

In our experimental implementation, the model is trained in a continuous loop. The data collected from the buses' trajectories is stored in a database and used for training. The data is pre-processed and then separated into sequences. Depending on the number of routes being monitored, the appropriate LSTM model is either trained or updated to handle the trajectories. If the number of inputs and outputs remains unchanged, the LSTM model remains unchanged. Once a new model is trained, it is evaluated against the previous model stored in the database using test data. If the new model shows better performance, it is stored as the current model. If not, it is discarded.

We tested the effectiveness of our solution in Pécs, Hungary. The results showed that our incrementally updated model was able to detect congestion with an accuracy of up to 82.37%. Additionally, we found that the model's accuracy in estimating travel speed can increase up to 221.46% within just six days, demonstrating its versatility. Additionally, resource consumption was found to be similar to traditional learning methods, making it a promising option for use in resource-constrained environments. For a detailed analysis of the achieved results, we refer the reader to discuss [57].

In summary, our solution is adaptive, scalable, and able to operate in real time. It can improve the efficiency of public transportation by providing a more accurate basis for congestion detection while reducing resource consumption. Additionally, as the model is incrementally updated, it can adapt and evolve in tandem with the streaming data, resulting in faster convergence.

D. Scalability Considerations and Performance Evaluation

During the development of the CityAI framework, several key architectural decisions and system components were specifically chosen to ensure the system's ability to handle the demands of a growing city infrastructure. Below, we provide an analysis of these aspects, highlighting their contributions to the overall scalability of CityAI.

1) Sensor Hub and Data Collection Modules: The Sensor Hub module is designed with scalability in mind, incorporating a modular architecture that allows for the easy addition of new sensor types and data sources. Each sensor hub operates independently, ensuring that data collection can be expanded by simply deploying additional hubs across the city. This modular approach not only facilitates scalability in terms of the number of sensors but also in terms of geographic coverage. As more regions of a city are equipped with sensors, the system can absorb and integrate this data without requiring significant modifications to the underlying architecture.

2) Stream Processing with Apache Kafka: The CityAI framework leverages Apache Kafka as the backbone of its stream processing architecture. Kafka's high throughput, low latency, and distributed nature make it inherently scalable and capable of handling millions of events per second. This ensures that as the volume of traffic data, sensor inputs, and vehicular communications increase, the system can continue to process and analyze this data in real time without degradation in performance. Kafka's ability to seamlessly integrate with other distributed data processing frameworks further enhances the system's scalability, allowing for the dynamic addition of new data sources or the expansion of processing nodes as required by the growing demands of a city.

3) Data Analytics and Machine Learning Modules: The Data Analytics component, particularly the MLM, is built to scale with increasing data volumes. The use of distributed processing frameworks like Apache Flink allows the system to handle large-scale data streams in real time, making it adaptable to the growing complexity of urban traffic patterns. As the data volume grows, additional processing nodes can be deployed to maintain performance, ensuring that the system's predictive models remain accurate and responsive.

Moreover, the MLM's architecture supports the incremental retraining of models, allowing it to adapt to changing traffic conditions without the need for extensive computational resources. This ability to update models on the fly, combined with distributed processing, ensures that the system can scale efficiently as the city's traffic infrastructure evolves.

4) Informed Traffic Governance and V2X Integration: CityAI's traffic governance framework is designed to be adaptive and responsive, which is critical for scalability. The integration of V2X communication technology enables the system to manage an increasing number of connected vehicles and infrastructure elements. By ensuring that the V2X communication sub-system operates independently of specific hardware vendors, the system can scale to accommodate new vehicles and roadside units as they are deployed, without requiring significant reconfiguration.

The reinforcement learning-based traffic light control system is another testament to the system's scalability. By using a flexible, data-driven approach to traffic management, CityAI can dynamically adjust to the increasing complexity of urban traffic without being constrained by rigid, pre-defined rules.

5) Data Lake and Long-Term Storage: The Data Lake module, built on scalable technologies like Cassandra and Elasticsearch, ensures that the system can manage vast amounts of historical and real-time data. As the volume of data grows, these technologies allow for horizontal scaling, meaning that additional storage nodes can be added to accommodate more data without impacting performance. This scalability is crucial for supporting long-term traffic analysis, anomaly detection, and strategic planning in increasingly complex urban environments.

VII. CONCLUSION

Considering the trends in urbanization and sustainability, there is an urgent need for efficient ITS services that aim to improve mobility and make transportation easier, faster, and more reliable. The proposed CityAI system aims to address these challenges by providing an automated, artificial intelligence-based solution for managing city traffic. This paper introduces key modules' capabilities, architecture, and functions of our proof-of-concept ITS system deployed in the city of Pécs, Hungary. The framework includes state-of-the-art technologies, techniques, and applications but also considers real-world applicability. Since the driving force of all ITS solutions is data, we implemented different data collection modules, such as image processing for extracting vehicle traffic information from roadside cameras, gathering public bus trajectories, and V2X information. To handle the continuous flow of data streams, a Stream Processing module was used in order to make the pre-processed data available for machine learning-based traffic prediction, anomaly detection algorithms, and adaptive traffic control. Although many papers investigate machine learning-based traffic light control in simulated environments, our pilot implementation is the first published reinforcement learning-based traffic light controller that was running in a real-life environment as part of the CityAI system. We also prepared the system to use V2X data to inform drivers about the best route to take, avoiding any potential hazards or delays caused by incidents. Moreover, a public transport congestion detection service was implemented to inform customers and operators about future delays. We can witness that machine learning can be widely used to resolve various issues in modern ITS. A complex system, such as the introduced CityAI system, is required to ensure reliable data gathering, processing, control, and information services to make the concept work in practice.

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A Systematic Review for the Implication of Generative AI in Higher Education

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Abstract—**The rapid advancement of genitive AI, like ChatGPT, has initiated a profound transformation in higher education. It offers customized learning experiences, automates administrative tasks, and provides personalized support to students and educators. Following PRISMA guidelines, this paper presents a systematic review that delves into the implications of genitive AI, a cutting-edge language model, in higher education. We adopted ChatGPT as an example of this study. It thoroughly examines the potential advantages and constraints of integrating ChatGPT into educational environments, assessing the quality of 35 selected articles and conducting a comprehensive meta-analysis of their findings. This study yields fresh insights into the multifaceted consequences of employing ChatGPT in higher education and underscores the intricate landscape associated with AI integration in academic settings. It emphasizes the imperativeness of addressing ethical, legal, and pragmatic challenges while capitalizing on the potential benefits of AI technology in education. Our systematic review reveals a consistent reservation trend regarding generative AI integration within educational contexts. These concerns encompass many issues, emphasizing the necessity for judicious implementation and robust safeguards to mitigate potential challenges.**

Index Terms—**Generative AI, ChatGPT, Education, PRISMA.**

I. INTRODUCTION

Artificial Intelligence (AI) has sparked a revolution in the educational sector. Traditional teaching methods have been transformed through the integration of AI technology. The emergence of AI has opened up new horizons for higher education, providing personalized and tailored learning experiences [9, 23]. Artificial intelligence has made significant contributions to education in the past decade. BLIPPAR, Paper Grader, and Coursera have successfully showcased the application in this domain [11]. These applications demonstrated the potential to enhance educators' ability to customize learning experiences based on learners' preferences. One noteworthy example is the Paper Grader, an AI-based automatic grading application designed to mark assignments efficiently within short periods. As a result, it allows teachers to dedicate more attention to valuable activities like lesson planning and curriculum development [32].

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Chatbots have emerged as one of the most successful applications of AI in the educational sector. They are computer programs capable of simulating human conversation through voice and text interactions. Within an educational context, chatbots have demonstrated their power as tools to enhance student learning experiences by providing personalized support. These intelligent virtual assistants also assist educators in updating the curriculum based on student preferences and make the admission process more efficient [27, 38]. Generative AI has brought about a tremendous transformation in the educational environment. Developed by OpenAI, ChatGPT is a natural language processing (NLP) model designed to generate human-like responses to various tasks [39],[8]. In the realm of higher education, Generative AI has the potential to enable self-directed learning. It enhances students' learning skills and assists educators in creating inclusive teaching environments. One of the key advantages of Generative AI is its ability to recommend learning resources that align with the needs of individual learners. This versatility makes Generative AI a valuable tool in promoting effective learning while alleviating the workload of educators [20, 60]. Intensive research has highlighted the potential benefits of utilizing Generative AI to transform educational methods. However, concerns have also been raised regarding data security, algorithmic bias, and ethical issues [7],[11]. One significant ethical concern in higher education pertains to plagiarism and copyright violations. To address this issue, universities in the UK have recently announced the availability of AI detector software capable of identifying written text generated by AI. These measures aim to uphold academic integrity and ensure proper attribution of original work [34]. Another significant challenge associated with Generative AI pertains to critical thinking and problem-solving skills. This arises because Generative AI can provide comprehensive details and examples for any given task, potentially discouraging students from engaging in independent research and investigation [13],[15]. Despite the experts' optimistic outlook on the transformative potential of Generative AI in various higher education disciplines, there are growing concerns regarding ethical issues. Therefore, the primary objective of this review is to examine the future prospects of Generative AI as a prominent example of Language Models (LM) in education based on the available evidence. Importantly, this review aims to identify potential benefits and limitations associated with implementing Generative AI in these domains.

II. Artificial Intelligence in Education

AI technology has significantly transformed teaching and learning, particularly with the rapid advancement of deep learning. In higher education, AI has proven to be highly effective in supporting students and enhancing teaching skills. Intelligent tutoring systems, chatbots, and grading software are prime examples of successful AI applications in higher education. These innovations have revolutionized the educational landscape by providing personalized assistance, automating administrative tasks, and delivering more accurate and efficient student feedback [29].

Intelligent tutoring systems (ITS) offer invaluable support to students by providing instant feedback without the need for direct teacher intervention. ITS holds substantial benefits in higher education institutions, especially when delivering virtual courses [7]. These systems can provide modules to many students, where individual teacher involvement may be logistically challenging or even impossible. This scalability ensures that students receive personalized guidance and assistance, regardless of class size, enabling a more efficient and inclusive learning environment. The use of ITS in higher education institutions has proven to be instrumental in overcoming the limitations of traditional teaching methods and enhancing the accessibility and effectiveness of virtual education [3].

ITS can identify individual students' skill gaps, enabling educators to tailor learning materials to their specific needs. One notable example of this is the SmartTutor, which was developed by the University of Hong Kong and aims to provide a personalized learning environment within higher education. SmartTutor has wirelessly integrated with the university's online learning platform, enhancing the overall learning experience for students. The results of implementing SmartTutor reveal the efficacy of this intelligent system in supporting students' academic growth. By utilizing ITS like SmartTutor, universities can optimize the delivery of educational content, adapt instruction to individual students, and foster a more productive and engaging learning environment [11].

AI has the potential to significantly enhance student engagement and motivation by employing interactive tools such as smart Sparrow. Smart Sparrow, an educational platform, has successfully taught biomedical education skills in Australia. Such integration with tertiary education, several universities in the USA and Australia adopted this platform as early as 2013 [31]. Researchers have observed that the implementation of smart Sparrow has not only accelerated student enrollment but also reduced dropout rates. The platform's interactive features and personalized learning approach contribute to a more immersive and effective educational experience, positively impacting student outcomes. Integrating AI-powered platforms like smart Sparrow demonstrates the transformative potential of AI in higher education, fostering student success and retention [31].

AI can streamline administrative tasks and eliminate repetitive duties, significantly reducing the workload of educators and administrative staff. Leveraging AI technologies, several time-consuming and routine tasks are managed efficiently. This enables educators and administrative staff to focus more on higher-value activities that require human expertise and creativity [4].

Consequently, implementing AI in educational institutions holds the potential to optimize operational efficiency, enhance productivity, and improve the overall work-life balance of educators and administrative staff. Replacing repetitive tasks with AI-powered solutions can free up valuable time and resources, allowing education professionals to allocate their efforts toward providing quality education and support to students [22].

Chatbots are intelligent software programs that simulate human conversation and provide appropriate responses. These chatbots enabled students to interact with them just as they would with actual human beings. Various chatbot frameworks are available, offering a wide range of implementation options. Some popular examples of chatbot frameworks include Rasa and Mobile Monkey [33]. These frameworks provide developers the tools and resources to create and deploy chatbot applications across different platforms and channels. By leveraging chatbots, educational institutions can enhance student engagement, provide instant support, and deliver personalized assistance on a scale. The availability of diverse chatbot frameworks enables flexibility and customization in developing interactive conversational agents tailored to specific educational contexts and requirements [15].

Chatbots play a crucial role in bridging the connection between educators and learners, enabling them to interact easily. These intelligent systems can provide students with accurate and timely answers to their queries. Chatbots can effectively understand and respond to a wide range of questions by leveraging natural language processing and machine learning algorithms. This not only enhances the learning experience but also relieves educators from the burden of repeatedly answering similar queries [5].

In 2018, Georgia State University developed its chatbot called "Pounce" to keep students engaged with the university, even during summer breaks [6]. The results of this initiative demonstrated the chatbot's potential to improve student graduation rates. The chatbot helped students stay connected and motivated throughout their academic journey by providing continuous support and guidance. The successful implementation of chatbots in educational institutions showcases the ability to enhance student engagement, retention, and academics. In 2022, the author in [50] suggests the integration of generative AI into chatbots to aid students with writing skills. The findings demonstrate that generative AI provides a substantial advantage in supporting students with proofreading, content revision, and post-writing feedback.

III. ChatGPT Overview

OpenAI released ChatGPT in November 2022. OpenAI is an organization dedicated to developing artificial general intelligence (AGI) to assist humanity. Founded in 2015 by Elon Musk and others, OpenAI aims to advance AGI technology [59]. ChatGPT, also known as GPT-3, is a generative pre-trained transformer (GPT) model family member. It is a large-scale, fine-tuned language model based on the architecture of GPT-3.5 and GPT-4 models [39] [29]. ChatGPT stands out as the dominant language AI model with an impressive parameter count of 175 billion, making it the most influential model in the field. It was trained using vast text data from sources such as Wikipedia, articles, books, and news. As a result, it excels in handling tasks related to NLP [58]. Access to ChatGPT is possible through various platforms, including messaging services, websites, smartphone apps, and API integration. Furthermore, it can handle multiple conversations simultaneously, making it highly versatile in its conversational capabilities [49] [56]. ChatGPT incorporates cutting-edge AI technologies, including supervised machine learning (ML), NLP, and reinforcement learning (RL). One of its notable features is the integration of RL with human feedback into NLP (RLHF). This unique combination enables the language model to deliver more coherent interactive responses and engage in meaningful conversations [55].

3.1 Potential Benefits and Limitations of Generative AI in Higher Education

A potential benefit can be gained from using generative AI with respect to meeting students' education. Researchers have showcased that students are more prone to engage in their courses. They identified three states: feeling autonomous, connected, and competent. Generative AI promises to bolster learners' autonomy, competence, and sense of connection in higher education, ultimately elevating students' motivation levels and fostering increased academic achievement [21, 43]. Generative AI assumes a crucial role in the realm of sport management education. For example, [24] utilizes generative AI to gather information pertaining to sport management education using open-ended qualitative questions. The results indicate that Generative AI is proficient at providing comprehensive, precise, and grammatically sound responses on topics related to sports management in response to concise queries. However, addressing the ethical concerns associated with its implementation is imperative.

In the medical domain, generative AI has been examined in various scenarios and contexts, as evidenced in [35] [36]. Generative AI evaluation took place in medical imaging within the framework of a medical imaging science course designed for first- to third-year undergraduate students. The outcomes underscore its inability to deliver accurate responses due to the model's limited knowledge and data on medical imaging [12]. Furthermore, as highlighted in [1], plastic surgeons utilized Generative AI to facilitate the composition of operative notes for plastic surgery procedures. The study emphasizes the efficiency and precision observed in the generated notes, and it reveals substantial satisfaction among surgeons who have integrated generative AI as an educational tool in contemporary plastic surgery practices.

Lastly, [28] evaluates generative AI's performance in radiology patient education materials. The model was employed to address patient inquiries related to radiology. The findings consistently indicate that generative AI produces educational content that is both inaccurate and incomplete. As a result, the feasibility of integrating it into educational curricula is questioned. The following paragraph lists the main advantages of generative AI in education.

- **Provide Autonomous Learning Environment**: Numerous studies have shown that language models have the potential to boost learners' motivation, leading to significant improvements in their academic performance [60]. In the case of university students, Generative AI can be particularly beneficial for enhancing writing skills and critical thinking abilities. By offering valuable resources and materials tailored to specific tasks, these models empower students to become more autonomous and enthusiastic participants in the learning process [19, 42, 45].
- **Personalized Feedback:** Personalized feedback is a crucial pedagogical approach that fosters student course engagement. Generative AI significantly enhances the learning process by offering tailored feedback according to individual student needs. This individualized feedback helps students identify errors and provides them with learning materials for future improvement. In higher education, Generative AI serves as an ideal tool for fulfilling students' competence needs by delivering personalized feedback [40][57].
- **Monitor Student Performance:** Tracking student performance is vital in promoting student motivation. Educators can effectively monitor students' learning journeys by utilizing assessment activities[52]. In higher education, it has been observed that assessment activities enhance educators' insights into students' learning abilities, enabling them to track the learning process closely. Generative AI can create quizzes, short answer questions, lesson plans, and curricula. By integrating these quizzes with learning resources, real-time feedback can be provided, offering scaffolding support. Consequently, universities can closely monitor student achievement [8].

A. *Generative AI Limitation*

- **Critical Thinking:** One potential concern is that Generative AI might harm students' critical thinking abilities by fostering excessive dependency. While Generative AI can certainly serve as a resource for medical students to access general medical information, there's a risk that overreliance on it might hinder their ability to think critically. This issue becomes more pronounced when students start incorporating Generative AI-generated content into their clinical notes, potentially foregoing the internalized thought process crucial for accurate disease diagnosis [2, 20].

- **Ethical Issues:** Educators are grappling with ethical issues arising from using Generative AI, particularly concerning copyright and plagiarism concerns. Generative AI lacks a definitive method to establish the ownership of the text it generates. Of note, Generative AI can autonomously compose essays and assignments without requiring the student's personal input or unique intonation, a capability that raises significant ethical questions [13][36, 52].
- **Data Bias and Algorithm Bias:** One key concern is the potential for Generative AI to produce inaccurate information due to its training on a vast dataset that contains biases. The selection of data for Generative AI was driven by OpenAI researchers using user feedback, and this process, influenced by incorrect outputs, could lead to biased algorithmic behaviors. As a result, the model itself may incorporate certain biases [26][10].
- **Cybersecurity Risk:** Generative AI introduces notable cybersecurity concerns. One primary concern revolves around its vulnerability to inadvertently generating deceptive or harmful content. This susceptibility can result in the creation of false data or involvement in malicious discussions [47]. The exploitation of Generative AI's capabilities could lead to the generation of phishing schemes, spam, and various forms of malicious content, raising significant threats to individuals and entities alike. The model's responses may inadvertently disclose sensitive information shared in inputs, thereby triggering privacy concerns[30].

While Generative AI holds immense potential, it's imperative to exercise vigilance in light of these cybersecurity challenges. Implementing robust safeguards becomes paramount to mitigate their impact. Cybercriminals could manipulate the incorrect information they generate to influence educational institutions, potentially tarnishing their reputation.[47].

3.2 Methodology

This study systematically reviews the pros and cons of Generative AI in higher education. The review adheres to the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).

A. Research objectives and research questions

While existing research sheds light on the advantages and constraints of integrating Generative AI into educational systems, a dearth of relevant systematic literature reviews is apparent. Therefore, this paper aims to fill this gap by conducting a comprehensive systematic literature review, guided by specific research questions, to offer fresh insights into the benefits and limitations of the Generative AI learning model in education.

Q1- Does the paper cover the benefit of Generative AI in terms of students, educators, and administrative tasks?
Q2- Does the author give or mention the actual case study about the benefit of Generative AI?
Q3- Does the paper cover all limitations of Generative AI in higher education?
Q4- Does the paper highlight the potential future and recommendations to mitigate the limitations of Generative AI?

TABLE I
ELIGIBILITY CRITERIA: INCLUSION AND EXCLUSION

Criteria	Inclusion	Exclusion
Language	Include only articles published in English.	Exclude translated article
Year of Publication	Include articles published after June 2020.	Exclude articles published before June 2020.
Study Type	Include Quantitative and quantitative studies published in peer-reviewed journals, conferences, and books.	Remove all non-review studies such as technical reports or web-based
Study design	Include studies that are designed in a way to answer the research question.	Exclude all studies that are not relevant to the research questions.

B. Information source and search strategy

This study considers three datasets: IEEE Digital Library, Google Scholar, and ScienceDirect. A combination of keywords was employed to explore studies on the potential of generative AI in education. These keywords include "generative AI in education," "generative AI in higher education," "generative AI in education," and "generative AI in education future prospects." The chosen databases, namely IEEE Digital Library, Google Scholar, and ScienceDirect were automatically searched to identify relevant articles. The search process adhered to PRISMA guidelines. The flow of the search procedure is illustrated in Fig. 1. The search aimed to evaluate the adherence to inclusion and exclusion criteria across Document Title (DT), Document Abstract (DA), Full Text (FT), and Index Terms (NT). The initial step involved selecting books, journal articles, and conference proceedings published in English between 2020 and 2023. The subsequent step encompassed an advanced search using a combination of keywords and index terms, enhancing the comprehensiveness of the search syntax. Certain articles were eliminated due to their mismatch with our predetermined inclusion and exclusion criteria. The search format used for IEEE was as follows:

[FT("ChatGPT")AND FT("Education")]OR [NT ("ChatGPT") AND FT("Higher Education") OR DT("Future Prospects")] OR [FT("Generative AI in education") And DT ("ChatGPT")] OR [FT("Generative AI in Education") OR NT("ChatGPT") And DA("Future Prospects")] OR [FT("Higher Education") OR NT("ChatGPT") And DA("Future Prospects")]

Fig. 1.: IEEE search strategy.

C. Study selection Result

As illustrated in Fig. (2), the selection process encompasses manual and automated searches. The initial phase involved scrutinizing 631 articles from three datasets. Mandalay software was employed in the subsequent step to identify and eliminate duplicate references among the scanned articles. Furthermore, articles lacking complete full-text content were also excluded, leading to the removal of 406 articles.

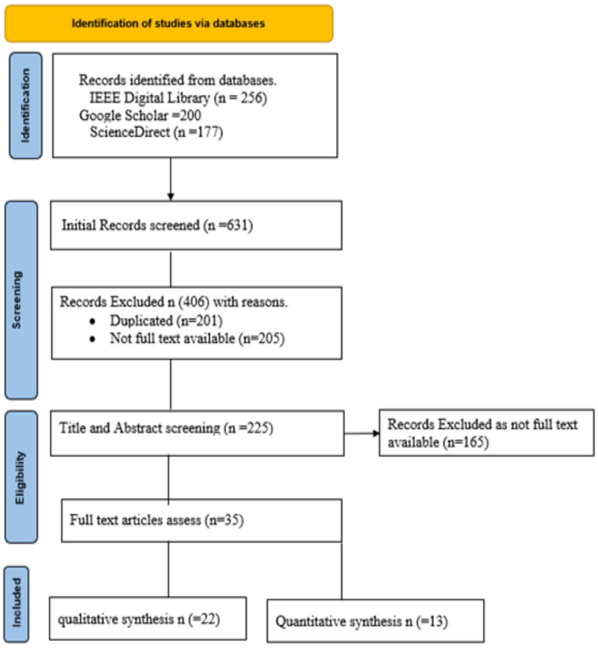

Fig. 2.: PRISMA flow diagram of selection studies.

To ensure thoroughness, three independent researchers conducted an assessment of the relevant articles. Abstracts and titles of 225 papers were meticulously reviewed during this phase—the final selection of articles adhered to predefined inclusion and exclusion criteria. Notably, there was a substantial consensus among the reviewers, with a concordance rate of 98%, regarding the assessment of abstracts and titles. Moving to the third stage, full-text articles were acquired, and the determination to assess them was based on the eligibility criteria. Among the reviews, it was determined that 165 articles were not pertinent to the research questions, leading to their exclusion from the systematic review. As we reached the concluding phase, the reviewers agreed to designate 35 articles for in-depth evaluation. Notably, there was a concurrence rate of 97% in the selection of full-text materials. Any disagreement was resolved by including a fourth reviewer in the screening process. Table 2 provides a Summary of the qualitative study's conclusions regarding the advantages and disadvantages of Generative AI in education. Table 3 summarizes quantitative studies where the advantages and disadvantages of Generative AI can be concluded from finding results. Both tables can be found in Appendix.

D. Quality evaluation result

We conducted a systematic literature review for qualitative and quantitative articles to address research questions. The reviewers (see the previous section) evaluate the quality of selected articles in unity; the studies are grouped into "Benefits" and "Limitations," where two Quality Evaluation scores (QEs) are raised for each group. QE questions are measured as very good (1), Good (0.5), and Not Good (0.1). The result of Quality evaluation score (QEs) for qualitative articles and quantitative articles can be seen in tables (4)(5) and Fig. (3), and Fig. (4).

TABLE IV
EVALUATION SCORES (QEs) FOR QUALITATIVE STUDIES

Study_id	QEs1	QEs2	QEs3	QEs4	Total Scores
Debby R. E etal, 2023	very Good	Good	Good	Not Good	2.1
M. Firat, 2023	very Good	Good	Not Good	Not Good	1.7
Sharma etal, 2023	very Good	very Good	Good	Not Good	2.6
D. Mhlanga, 2023	very Good	Good	Not Good	Not Good	1.7
F. X. Risang, 2023	Good	Good	Not Good	Not Good	1.2
Y. K. Dwivedi etal, 2023	very Good	very Good	very Good	Good	3.5
M. Javaid etal, 2023	very Good	very Good	very Good	Not Good	3.1
D. Dalalah etal, 2023	Good	Not Good	very Good	Good	2.1
M.OM.Al hatrifi etal, 2023	very Good	very Good	Not Good	Not Good	2.2
P. P. Ray, 2023	very Good	Good	very Good	very Good	3.5
N., M. S etal, 2023	Good	Good	very Good	Good	2.5
Y., B. B etal, 2023	Good	Not Good	very Good	Good	2.1
Y., L. Y etal, 2023	Good	very Good	Good	Good	2.5
S. Sweeney, 2023	very Good	Good	very Good	Not Good	2.6
T. Alqahtani, 2023	very Good	Good	Good	Good	2.5
S. T. T. Jürgen Rudolpn, 2023	very Good	Good	Good	very Good	3
Z. Chenjia etal, 2023	Good	very Good	Good	Not Good	2.1
Z. Xiao, 2023	very Good	Not Good	very Good	Not Good	2.2
K. H. Frith, 2023	Not Good	Not Good	Good	Good	1.2
S. Popenici, 2023	Good	Good	Good	Good	2
M.Schönberger 2023	Good	Not Good	very Good	Good	2.1
Sullivan etal, 2023	Not Good	very Good	Good	very Good	2.6

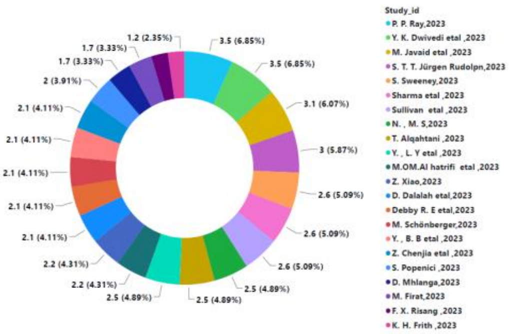

Fig 3. Total evaluation scores (QEs) for qualitative studies.

TABLE V
Evaluation scores (QEs) for quantitative studies

Study_id	QEs1	QEs2	QEs3	QEs4	Total Scores
P. Vanich-vasin, 2023	very Good	very Good	Not Good	Not Good	2.2
M. Hosseini etal, 2023	very Good	very Good	Good	Not Good	2.6
L. Zhou etal, 2023	very Good	very Good	Not Good	Not Good	2.2
M. C. Keiper etal, 2023	very Good	very Good	Good	Not Good	2.6
G. Currie etal, 2023	Good	Good	very Good	Not Good	2.1
A.M Abdelhady etal, 2023	very Good	very Good	Good	Not Good	2.6
C. J etal, 2023	Good	very Good	Good	Not Good	2.1
R. Yilmaz etal, 2023	very Good	Good	very Good	Not Good	2.6
I. S. Chaudhry etal, 2023	Good	very Good	very Good	Good	3
K. Malinka etal, 2023	very Good	very Good	Good	Good	3
J. De Winter etal, 2023	Good	Good	very Good	Not Good	2.1
Qureshi, 2023	very Good	very Good	Good	Not Good	2.6
J. Rudolph etal, 2023	very Good	very Good	very Good	Good	3.5

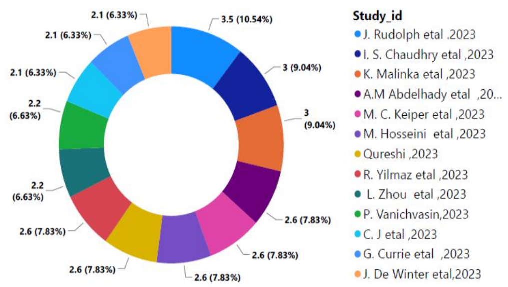

Fig. 4. Total Evaluation scores (QEs) for quantitative studies.

E. Statistical analysis

To summarize the findings of the included studies, a meta-analysis (we need a citation here for the meta) was conducted to gain a more precise insight into all the studies addressing the research questions. The result of the meta-analysis can be seen in Table 6. Despite the heterogeneity in the nature of these studies, some were combined to emphasize their consistency. Various metrics, such as the Odds Ratio (OR) and 95% confidence Intervals(95-CI), were employed to measure the results of the meta-analysis.

The OR is a statistical tool that evaluates the relationship between two variables or groups. We're examining the "Benefit" and "Limitations" groups in this context. The "Benefit" group encompasses studies illustrating the potential advantages of integrating Generative AI into educational environments. Conversely, the "Limitations" group comprises studies that underscore potential issues or risks in using Generative AI in education. The 95-CI is a statistical range that estimates the true value within which the odds ratio is likely to fall.

We visualize the results on a forest plot (citation needed) for 35 studies, each represented by a line. The blue shape corresponds to the effect size (OR, weight, and 95-CI). The vertical line is known as "No effect." Studies that cross this line towards the center indicate no significant differences between the Benefit group and the Limitations group.

Ten studies are located on the right side of the vertical line. These studies found that Generative AI has significant benefits in higher education. For instance, studies by P. Vanichvasin[53] and L. Zhou et. Al [60] acquired the highest OR and 95-CI. This can be attributed to the fact that enough participants in the questionnaire surveys agreed on the potential benefits of using Generative AI.

Debby R. E et al [14], Z. Chenjia et al 10, and M. Schönberger [46] crossed the "No effect" line, achieving an OR value of 1. This indicates that these authors have an equal perspective on Generative AI in terms of benefits and limitations in higher education.

Sixteen studies are located on the left side of the vertical line, which could be interpreted as these studies raising concerns about the implications of Generative AI in higher education. P. P. Ray [39] and S. Popenici [35] acquired the lowest values of OR. This implies that both studies strongly agreed on the limitations of adopting Generative AI in higher education.

The meta-analysis for all selected studies presents its findings visually through a blue diamond shape, encapsulating both the estimated point and the confidence interval. The overarching result of this meta-analysis underscores a prevailing trend across the included studies: the majority express reservations about the integration of Generative AI in educational contexts. These reservations encompass a range of substantial concerns, spanning ethical dilemmas, legal complexities, data biases, and algorithmic biases, see section 3.1.2.

TABLE VI
META-ANALYSIS RESULT

Study_id	O_R	Weight	Lower_C1	Upper_C1
Debby R. E etal	1	3.63	0.3828	2.96
M. Firat	1.7142	3.53	0.1928	5.0742
Sharma etal	1.1666	3.3	0.3262	3.4533
D. Mhlanga	1.7142	3.5	0.1928	5.0742
F. X. Risang	2	3.2	0.1466	5.92
Y. K. Dwivedi et al	0.5555	4.3	0.5866	1.6444
M. Javaid etal	0.8636	3.36	0.4364	2.5563
D. Dalalah etal	0.7142	3.70	0.5037	2.1142
M.OM.Al hatrifi etal	2	3.2	0.1466	5.92
P. P. Ray	0.3333	4.5	0.7261	0.9866
N. , M. S	0.5	3.5	0.6187	1.48
Y. , B. B etal	0.5	3.5	0.6187	1.48
Y. , L. Y etal	0.4285	3.83	0.6627	1.2685
S. Sweeney	0.7402	3.7	0.4913	2.1911
T. Alqahtani	0.4285	3.81	0.6627	1.2685
S. T. T. Jürgen Rudolpn	0.4285	3.86	0.6627	1.2685
Z. Chenjia etal	1	3.63	0.3828	2.96
Z. Xiao	0.8636	3.37	0.4364	2.5563
K. H. Frith	0.5	3.5	0.6187	1.48
S. Popenici	0.3333	4.5	0.7261	0.9866
M. M.Schönberger	1	2.5	0.3828	2.96
Sullivan etal	0.84615	2.68	0.4438	2.504
P. Vanichvasin	**4**	**2.2**	**0.0214**	**11.84**
M. Hosseini etal	2.3343	2.3	0.1064	6.9066
L. Zhou etal	**4**	**2.2**	**0.0214**	**11.84**
M. C. Keiper etal	0.6666	2.6	0.527	1.9733
G. Currie etal	1.7272	2.3	0.1904	5.1127
A.M Abdelhady etal	1.7274	2.3	0.1904	5.1127
C. J etal	2.3333	2.3	0.1064	6.906
R. Yilmaz etal	1.7272	2.3	0.1904	5.1127
I. S. Chaudhry etal	0.4285	3.8	0.6627	1.2685
K. Malinka etal	0.5	3.5	0.6187	1.48
J. De Winter etal	0.5757	4.3	0.5753	1.704
Qureshi	2.333	2.3	0.1064	6.906
J. Rudolph etal	1.5	3.25	0.2369	4.44

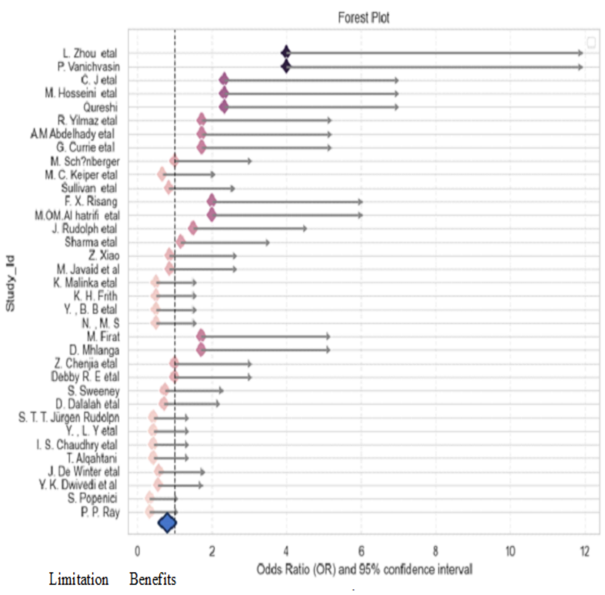

Fig. 6.: Forest Plot.

F. Discussion and recommendation:

✓ **Discussion**

The findings of this systematic review suggest that Generative AI has the potential to play a significant role in self-regulated learning within post-secondary education. The advantages and limitations of Generative AI in the context of higher education are multifaceted and warrant careful consideration [21, 43, 24, 35, 36]. As identified above, Generative AI can establish a self-directed learning ecosystem, amplifying students' motivation while nurturing their sense of autonomy, competence, and a deeper connection [17, 19, 42, 45, 40].

Furthermore, personalized feedback, a pedagogical cornerstone, assumes a pivotal role in augmenting student engagement and competence, and Generative AI is a valuable facilitator in this regard [40][57]. Additionally, it empowers educators to effectively track student performance, offering enhanced insights into their learning paths and ultimately fostering student achievement [8][52]. Conversely, the limitations and concerns surrounding Generative AI are equally significant. The potential for overreliance on the model, leading to a decline in critical thinking skills, is a concern. There are also ethical issues related to copyright, plagiarism, and content ownership generated by Generative AI. Data and algorithm bias due to the model's training data raise accuracy and fairness concerns. Cybersecurity risks, including the inadvertent generation of deceptive or harmful content, threaten individuals and educational institutions [2, 6, 10, 13, 36, 52].

As evidenced above, the literature seems to be more focused on potential drawbacks and challenges associated with Generative AI in higher education, especially regarding academic integrity. Academic dishonesty and concerns about cheating in exams have received considerable attention, with a clear emphasis on the negative implications of Generative AI's use in this context [13, 56, 32]. Furthermore, there is a pressing need for a more balanced and nuanced discourse concerning the risks and benefits associated with Generative AI in higher education. Often, stories related to academic misconduct and unethical behavior are presented sensationally, influencing not just the general perception but also the conduct of students. Given that Higher Education Institutions have limited influence over how these narratives are portrayed in the public sphere, educators and institutions should explore strategies to adapt assessment methodologies to reduce the potential for AI-assisted cheating. Previous research has indicated that the perception of available opportunities to engage in academic dishonesty elevates the likelihood of such behavior [63-65]. While various strategies to diminish the likelihood of cheating have been proposed, including redesigning assessment tasks to make them less vulnerable to AI tools, there remains uncertainty about the most effective approaches.

Regarding university positions on AI tools and their relationship to academic integrity, the literature often suggested the need for policy revisions, although the specifics of such revisions were often lacking. University policy changes usually require approval through governance committees and can be time-consuming, indicating that clearer policy positions may become more prevalent later. Determining acceptable and unacceptable practices when using Generative AI requires thoughtful consideration, especially as the availability and sophistication of such tools are unparalleled. Hence, the establishment of clear guidelines for both university staff and students on ethically appropriate Generative AI usage is imperative [66][67]. Moving forward, it is crucial to encourage a more balanced and constructive discussion on Generative AI in higher education, involving all stakeholders, with a particular emphasis on students. Student associations and partners can proactively collaborate with university staff to inform policy development, educational resources, assessment design, and communication strategies, thereby enhancing student engagement and retention. Incorporating a diverse range of voices in this discourse can lead to a more sophisticated conversation surrounding the integration of AI in education. Universities must equip students with the critical skills needed to effectively utilize AI tools, emphasizing the cultivation of unique abilities that AI cannot readily replace, thus enhancing their employability in an evolving job market.

✓ **Recommendations**

Based on the literature review's findings, the following section presents recommendations for integrating Generative AI within higher education, addressing the second research question.

- **Generative AI as a Teaching Aid**: It can be a valuable tool for educators, enhancing their teaching practices. Instead of merely relying on automated text generation, teachers can utilize Generative AI to spark creativity and gather innovative teaching ideas. This includes generating quiz questions, facilitating pro-contra discussions, or providing inspiration for role-playing exercises. Additionally, Generative AI can assist in creating customized learning materials, such as student assignments, and transform existing content into various formats like podcast scripts or instructional videos. It can also help streamline communication and course overviews and generate standardized text formats, such as event descriptions.
- **Generative AI as a Didactic Component**: Integrating Generative AI into the teaching approach can be advantageous while also addressing privacy concerns by restricting data exposure to the teacher. Transparency is crucial when using Generative AI to explore the potential and risks of AI systems, thus encouraging the cultivation of digital literacy among students. Didactic scenarios may include identifying fake news, moderating discussions, comparing summaries, evaluating different text formats and writing styles, and establishing criteria for effective scientific writing.
- **Use of Generative AI in Assessments**: The incorporation of Generative AI in assessments, such as written assessments, term papers, or presentations, poses challenges, notably an elevated risk of academic dishonesty. Present plagiarism detection software often struggles to recognize Generative AI-generated content as plagiarism.
- **Ethical Framework Development**: Higher education institutions should establish clear ethical frameworks for using Generative AI in educational settings. This framework should define guidelines for the responsible use of AI, ensuring that ethical considerations such as privacy, consent, and fairness are addressed. It should also include mechanisms for oversight and accountability. By developing ethical frameworks for using Generative AI in educational settings, higher education institutions can ensure that they use AI to respect human dignity, rights, and interests. They can also enhance the quality and effectiveness of their educational practices and outcomes. Ethical frameworks can also help higher education institutions anticipate and respond to future ethical challenges and opportunities that may arise from the advancement of AI in education.
- **Training and Awareness Programs**: Faculty, staff, and students should receive training and awareness programs about Generative AI and its capabilities. This education should cover the technical aspects of Generative AI, its ethical implications, and potential biases. This will empower the academic community to use Generative AI effectively and responsibly.
- **Legal Compliance**: Ensure that the integration of Generative AI complies with all relevant laws and regulations. This includes intellectual property rights, copyright, and compliance with educational standards. Legal experts should be consulted to navigate these complexities.
- **Diversity and Inclusion Considerations**: When using generative AI, be mindful of diversity and inclusion concerns. Ensure that the AI system does not discriminate or marginalize any group of students or educators. Efforts should be made to provide equitable access and support for all.

IV. Conclusion

The findings of this systematic review show that generative AI has potential in various educational contexts. For instance, it has been used effectively in sports management education to provide precise and comprehensive information. It has also facilitated the composition of operative notes in plastic surgery, showcasing efficiency and precision. However, in radiology, patient education materials revealed limitations, indicating that its application should be context-specific [2] [20]. Another noteworthy benefit is the potential to enhance students' academic success from diverse equity groups. Generational AI can help demystify academic conventions for non-traditional students, provide grammatical assistance to non-native English speakers, and assist those with accessibility needs in accessing educational content. The model can contribute to mainstreaming accessibility technology and improving engagement for students with disabilities [61][62]. Although integrating generative AI into higher education can offer valuable benefits, it also presents significant ethical, privacy, and educational challenges. These recommendations aim to strike a balance by promoting responsible use, transparency, and adaptability while mitigating risks and ensuring that generative AI enhances the educational experience for all stakeholders. The scope for future research into the role of generative AI, particularly ChatGPT, in higher education is immense and holds substantial promise. To further our understanding and tackle the emerging challenges, several crucial areas merit additional exploration, which are Longitudinal studies, Ethical Frameworks, Bias Mitigation, Student Involvement and Equity and Accessibility

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APPENDIX (A)

TABLE II
SUMMARY OF QUALITATIVE STUDY'S CONCLUSION.

Ref.	Advantages	Disadvantages
[14]	It Provides asynchronous communication. It delivers game-based assessments.	Plagiarism. It Could Lead to unfairness in assessment process.
[17]	Self-Personalized support and assessment. Real-time feedback increased accessibility and flexibility. Improve the use of open educational.	None
[48]	It can provide personal writing assistant. It is a very powerful translation tool. It could help students keep writing stories in their own words.	It might provide the incorrect answer to student question. It is hard to keep students encouraged with discussion. It is unable to perform the elementary mathematical operation. The model might have biases data so it could give the wrong result. Its student learns via supervised instruction
[8]	It Can transfer the educational landscape. It has potential to enhance the learning outcomes and improve student engagement. It can automate administrative tasks.	None
[40]	It can deliver self- learning in higher education. It accelerates the students' skills by providing the individualized feedback	Ethical issue Data security issue Algorithm bias Design Implementation,

Ref.	Advantages	Disadvantages
[16]	It can be used to accelerated learning as it could help student assimilate knowledge easily	Ethical issue Critical thinking issue It misses the transparency how model drives result
[21]	It can help students write essays and develop websites. It can assist the educator to automate routines tasks. It can encourage students to encourage in virtual environment	Plagiarized issue Data biases
[13]	It is tailored to student's needs. It can drive sufficient contextually answer to students' questions.	Generative Pre-trained Transformers model might be replacing educator's role. It can generate text that has both false positive and negative. The lack of transparency
[19]	It can positively enhance the learning environment in accounting education. It suggests integrating chatGPt into higher educational institutes.	None
[39]	Assist students to enhance their academic performance and engagement. Help the teacher to give recommendations for lesson plan. It provides online tutoring services.	Risk of overreliance It might be hard to control the quality of text generated by ChatGPT. Dataset bias and Generalization error. It might drive the hate speech and harm content.
[2]	It can significantly improve the grading and feedback. It provides the interactive learning environment.	Plagiarism, Ethical and social implications issue.
[36]	It has potential to boost student learning level.	Legal risk these including authorship disputes and data source legitimacy disputes
[50]	It can help students in writing skills by offering suggestions to enhance the context of sentence.	Authorship and plagiarism.
[52]	It can enhance the teacher supervisory support by providing students help they need that meet their preferences.	It increases the risk of academic dishonesty (AD).
[4]	It can help the researchers in writing. scientific articles. It can assist the educators to evaluate the student learning performance accurately. It can improve the grading students answers consistency.	Ethical issue, Algorithm Bias.
[51]	It can improve student learning. Enhance student learning and access.	There are several implications of using ChatGPT in education, like innovative design and integrity concerns
[46]	It can help the researchers in conduct scientific literature review. It could encourage student to interact with each other via open discussions	It might be generated randomly and incorrect information. It is hard to evaluate the accuracy and consistency of answered questions
[35]	None	Plagiarism problem, It could have a bad impact on students writing skills.
[56]	It aids lecturers to enhance teaching quality and improve instructional plans. It can deliver automated feedback of students' assignments.	It might be providing misleading answers to student's questions. The ethical and moral issue.

TABLE III
SUMMARY OF QUANTITATIVE STUDY'S CONCLUSIONS.

Ref.	No	Framework	Result
[53]	30 students	Qasi-experimental research	Chat bot has a significant impact on student learning and satisfaction.
[9]	844/students	Survey quantitative analyzed	The existence of risk and unforeseen limitation to accept using ChatGPT in higher education.
[60]	196 students	Questionnaire surveys	The university students required further guidance to learn how to use and integrate into ChatGPT in higher education.
[24]	60 participants	Generic qualitative inquiry	The finding shows pros and cons of employed ChatGPT in sport management classroom.
[12]	326 participants	Exam and written assignment tasks	The result shows ChatGPT is sufficient benefit in enhance learning environment while it can be a risk on academic integrity.
[1]	30 participants	Questionnaire via website	The result shows ChatGPT has potential in increase knowledge of plastic surgeons.
[57]	45 participants	Assignments in computer programming course	The finding ravel that ChatGPT doesn't make any difference on increase the student motivation when students given the challenging tasks.
[28]	50 participants	Questionnaire via Interventional Radiology (SIR) Patient Center website	The result shows ChatGPT has limitation in provide the accurate educational content.
[8]	Authors didn't mention	Assessment tools	The finding shows that ChatGPT is capable of writing assignments, report and case study for various level courses. Of undergraduate courses however, delivered assignments could not be comprehensive as human written.
[26]	Authors didn't mention	Czech tests and English Assignments,	The ChatGPT can accelerate the learning process however, it can easily damage the educational averment.
[54]	Authors didn't mention	National exams of VWO program In English reading comprehension topic	The finding ravel ChatGPT could expose student in assignment cheating.
[37]	24 students	Programming tasks	The experiment shows the students who use ChatGPT gain a higher score in less time than students who use textbooks, although they were not able to gain a perfect score due to the fact that ChatGPT generates inconsistent code.
[41]	Authors didn't mention	Review survey	It is not powerful tools to assist in design assignment questions.

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Implementation Guidelines for Ethologically Inspired Fuzzy Behaviour-Based Systems

Mohd Aaqib Lone, Szilveszter Kovács, and Owais Mujtaba Khanday

Abstract—**The adaptation of ethologically inspired behaviour models for human-machine interaction e.g. in Ethorobotics has become a challenging research topic in recent years. This paper presents a Fuzzy Behaviour Description Language (FBDL) approach for analyzing animal aggression behaviour. Fuzzy logic and fuzzy set theory approaches are used to analyze and classify the subjective impression of aggressive behaviour in a particular situation. This research aims to perform a meta-analysis of aggression behaviour based on the fundamental values of animals and the possible ways of implementing animal aggressive behaviour in robots. Ultimately aiming to enhance the adaptability and effectiveness of human-robot interaction and performance in various real-world scenarios, e.g., by expressing disagreement in the direction of the human operator in case of unclear, or unsafe cooperative situations. In both industrial and everyday settings, mobile robots and robotic vehicles are becoming increasingly prevalent. Integrating aggressive behaviour into robotics is essential for boosting interactions between humans and robots, promoting safety in dynamic contexts, and getting a deeper understanding of animal behaviour. It aids robots in asserting their presence, maneuvering around barriers, and efficiently adjusting to dynamic surroundings. This guarantees more seamless operations in industrial and daily environments while also enhancing our comprehension of both robotics and ethology. We present graphical depictions of various animal behaviours, as well as trajectories, Gazebo simulations, and RViz visualizations of the animal robot, demonstrating the animal's escape behaviour.**

Index Terms—**Ethologically Inspired Behavioural Models, Ethorobotics, Fuzzy Behaviour Modelling, Fuzzy Behaviour Description Language, Robot Operating System, Gazebo, RViz**

I. INTRODUCTION

Behaviour is a response to any stimulus from the situation or, in short, a way of acting in a given situation [1]. In other words, we can say that a behaviour system attempts to determine the responsive abilities of humans, animals, robots, etc., to understand and interact with the environment. The behaviour-based approach [2] aims to create intelligent robots that can carry out complex tasks into smaller, simpler behaviours or actions. These behaviours focus on the execution of specific tasks, enabling robots to carry out complex activities with greater flexibility and adaptability. This method is crucial for building robots that can function efficiently in dynamic situations characterized by quickly changing conditions. For example, in robotic navigation, one behaviour can focus on traversing a path from the start to the goal state, while another focuses on avoiding obstacles. Developing and executing individual robot behaviours is a straightforward process, which enables them to construct intricate and adaptable behaviours when paired with one another and the environment. Robots can adapt to changes in their environment and deal with uncertainty without the need for complex planning or simulations. Robots possess the ability to modify their behaviour according to various tasks and environments. This technique has a significant impact in sectors like autonomous cars, automated guided vehicles, and swarm robotics, as basic actions can result in complex collective behaviours.

Ethological modeling involves the analysis of animal behaviour based on external observations and the development of models and explanations. The behaviour-based method, when applied to ethology, aims to develop intelligent robots by emulating the innate and adaptable behaviours observed in animals. This ethological paradigm guarantees that robots can promptly and adaptively react to their environment. Nikolaas Tinbergen provides a model [3] for analyzing animal behaviour in its natural environment. The model consists of four interconnected categories of questions that provide a full framework for understanding the behaviour: The first question, "What is the function of the behaviour?" relates to the significance of the conduct in terms of adaptation. The Ethologically inspired view focuses on the selective forces that have shaped behaviour and how they impact an animal's capacity for survival and reproduction. This phase considers the physiological, genetic, and environmental factors that lead to particular behaviours. For instance, the hormonal changes that occur during bird mating behaviour or the visual cues that induce fish courtship displays. The second question, "What is the mechanism behind the behaviour?" is concerned with the physiological and neurological processes that permit the activity to occur. The animal's neurological system and how it generates, and controls behaviour are the main topics of this study. At this level, we examine the interactions between experience, environment, and genes to determine behaviour. The evolution of social behaviour in monkeys may have been influenced by early experiences. The third question, "What is the evolutionary history of behaviour?" discusses the phylogenetic origins and historical progression of behaviours. It involves the evolution of behaviours by tracing them back through the ancestors of animals across several generations. The fourth question, "What is the ontogeny of the behaviour?"

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focuses on how the behaviour developed inside a particular creature. The development, acquisition, and evolution of behaviour across an animal's lifetime are the main topics of this study. Ethology provides a valuable framework for creating behaviour models in robotics (Ethorobotics [4]) that can replicate the successful and efficient actions of animals. This field encompasses a broad range of research, including studies on animal aggression, defense mechanisms, and communication, all of which can inform the development of robotic behaviours.

In this paper, we will be discussing how we can apply fuzzy logic to simulate aggressive behaviour in animals. Fuzzy logic is a type of computing that deals with uncertain or imprecise information and relies on the degree of truth in the input to produce a specific output. It is commonly used to control actions and processes in fields such as automotive and environmental applications. An example of a state machine that employs fuzzy logic to deal with uncertainties and imprecisions in the decision-making process is the Fuzzy State Machine (FSM). Robotics extensively uses FSMs because real-time decisions must be made in an environment that is frequently dynamic and uncertain. The conventional state machine operates by switching between states in accordance with predetermined criteria. However, robotics frequently operates in uncertain environments, which means that not all precepts and conditions may apply. This is where fuzzy logic comes into play. Fuzzy logic provides a mathematical framework for managing uncertainty by assigning varying degrees of truth to propositions. In a FSM, fuzzy logic is used to express state transition rules. Fuzzy sets analyze the inputs to the FSM, allowing for gradual changes in state rather than abrupt ones. By making transitions gradual, the robot's behaviour is less likely to change suddenly, which in some situations could be risky. Robotics can benefit from the resilience, adaptability, and scalability of FSMs, among other advantages [5].

Fuzzy signatures are an advanced method for fusing fuzzy information, enabling the systematic incorporation of heterogeneous data sources into a cohesive framework [6]. In scenarios where the fused information is intricate and multifaceted, they are particularly effective. Fuzzy signatures decompose information into a hierarchical structure of characteristics, each with its own layer of fuzzy values, representing distinct aspects or components of the system under analysis. The hierarchical structure enables the aggregation of these characteristics at many levels, illustrating their interrelationships [7].

In behaviour modeling, fuzzy signatures can be particularly advantageous when the behaviours of components can be expressed using fuzzy sets. In robotic systems, actions like locomotion, manipulation, or navigation can be expressed as fuzzy signatures, effectively capturing the inherent uncertainty and unpredictability associated with such actions [8]. Once combined, these distinct fuzzy fingerprints form a unified entity that accurately reflects the robot's full behaviour, enabling more versatile and adaptable decision-making. Fuzzy signatures are suitable for applications involving intricate behaviours and the many interacting components. In human-robot interaction, they can integrate diverse elements into a cohesive representation.

In the specific behaviour example outlined in this paper, fuzzy information fusion could be suitable for behaviour fusion if the behavioural components are precisely defined using fuzzy signatures. However, the bahavioural components in our example are different activities that have no fuzzy signatures, so conventional approaches are used to manage these operations. To sum up, the FSM is a powerful tool for robotics decision-making. There are several ways to describe robot behaviour, including deliberative, reactive, hybrid, and behaviour-based control [9]. Fuzzy logic is a useful method for machine control and provides a high level of accuracy in reasoning. In the following sections of this paper, we will delve further into the implementation of fuzzy logic in simulating aggressive behaviour in animals.

In the deliberative control method, the robot uses its past experiences and current sensory information to determine the next steps it should take. This approach is also known as "Think Then Act." Decision-making for the robot involves gathering information about the environment through its sensors and using this information to determine how to act and interact with the environment. The deliberative process includes reasoning about potential actions and their consequences, as well as developing a symbolic representation of the world to anticipate the outcomes of those actions and create plans for various scenarios. Essentially, the robot uses its internal processing to carefully consider its options before making a decision and taking action.

In the reactive control method, sensory inputs and outputs are tightly coupled, enabling the robot to respond quickly to changing and unstructured environments. This approach is known as "Don't Think, Just Act." Reactive control operates on the principle of stimulus-response, requiring neither learning nor the maintenance of a world model. Instead, it relies on a set of pre-programmed rules that minimize computational effort. These rules are mapped to the robot's controller, using minimal internal states to create a reactive control system capable of handling complex and unstructured environments while delivering fast, real-time responses. Reactive systems can quickly adapt to rapidly changing environments with minimal processing power [10].

Hybrid control combines the benefits of both reactive and deliberative control, allowing the robot to react in real time while also employing rational and optimal decision-making [11]. This approach is known as "Simultaneously Think and Act." The hybrid control system integrates reactive elements, such as simultaneous condition-action rules, with deliberative decision-making, which must be coordinated to produce coherent outcomes. This coordination can be challenging because the reactive component must respond quickly to the robot's immediate needs, such as avoiding obstacles while moving toward a target using direct sensory data and signals. Meanwhile, the deliberative component uses abstract, symbolic representations of the environment and operates on a slower time scale to guide the robot toward more efficient and optimal goals and trajectories. If an unexpected challenge arises, the reactive system may need to override the deliberative system, but the deliberative system should still inform the reactive system to ensure the most effective response.

A behaviour-based control system is a type of control system for robots that is composed of a collection of distributed modules known as behaviours [12]. These modules interact with one another to accomplish a desired action, with the ultimate goal of achieving a specific objective. The approach underlying this system is based on the concept of "Think the Way You Act," where the robot's behaviours are developed through trial-and-error interactions with its environment. These behaviours are typically defined by the programmer and organized into control modules that group together constraints to achieve and maintain a goal. This approach offers a flexible and adaptable means of controlling robots in complex and dynamic environments, enabling them to make decisions based on current conditions and adjust their actions accordingly. By utilizing behaviours grounded in the robot's environment and experience, the behaviour-based control system provides a more intuitive and effective method for controlling robotic systems [13]. Each behaviour receives inputs from sensors or other behaviours and provides outputs to other behaviours or the robot's actuators [14].

Implementing animal aggression behaviour in robotics involves creating robotic behaviour models that accurately mimic the aggression patterns observed in animals. This includes behaviours associated with Fear, Escape, Attack, and Immobility states, as well as animals familiarity with other animals and their surroundings. To achieve this, it is crucial to study and analyze animal behaviour in various situations and contexts, such as their familiarity with other animals, proximity to them, and past experiences. This understanding can then be translated into the design of robotic behaviour models that reflect similar behavioural patterns. For example, animals may exhibit a strong fear response when unfamiliar with another animal, prompting them to escape from the area. These physiological and behavioural responses can be incorporated into the design of robotic systems, enabling them to respond appropriately to perceived threats or dangerous situations. Similarly, an animals attack behaviour may involve aggressive posturing, vocalizations, and physical attacks. By observing and analyzing such behaviours in animals, robotic behaviour models can be developed to replicate these aggression patterns. Incorporating animal familiarity with other animals and their surroundings is also essential in developing effective robotic behaviour models. This may involve implementing recognition algorithms that allow robots to identify and respond to specific animals, as well as integrating mapping and navigation tools to enable robots to navigate their surroundings and avoid obstacles.

II. ETHOLOGICAL BEHAVIOURAL MODELS

Ethology, the scientific study of animal behaviour, focuses on how animals interact with their environment and with each other [15]. Ethological models, essential for understanding and predicting animal behaviour, have become foundational in the development of behaviour-based control systems for robots. These models are based on the principle that natural selection shapes behaviour, with those behaviours most adapted to specific environments more likely to be passed on to future generations. This approach is crucial in ecology and animal behaviour studies, where models like predator-prey interactions help explain the dynamics of species populations in natural habitats.

In robotics, there is growing interest in leveraging ethological models to overcome the limitations of traditional robotic behaviour systems. Ethologists such as Baerends, Tinbergen, and Lorenz have developed models that describe animal behaviour and the processes behind it, which are now being explored in robotics. This interdisciplinary collaboration enables roboticists to create more adaptive systems by incorporating biologically inspired behaviour models. Conversely, robots offer ethologists a unique platform to test and refine their behavioural hypotheses.

This synergy between ethology and robotics, as discussed in [16] and [17], highlights shared concepts such as sensors, actuators, targets, and navigation, albeit studied differently in each field. Ethology employs a systematic, scientific approach to observing and understanding natural behaviours, while robotics takes a synthetic approach, integrating these behaviours into robots through artificial sensors and actuators. Despite their differing methodologies, both fields contribute to a deeper understanding of behaviour and its applications.

III. FUZZY BEHAVIOUR-BASED SYSTEM

One possible way for implementing ethologically inspired behavioural models is the adaptation of Fuzzy Behaviour-based Systems [18]. A Fuzzy Behaviour-based System is a high-tech computer system that uses fuzzy logic to control how robots and other agents act in complex, changing settings. It handles degrees of truth or membership values, allowing for more complex decisions. This adaptability is crucial for creating adaptive behaviours like those seen in animals. Different behaviour units control actions, such as avoiding, aggressive, or exploring, and fuzzy rules join their outputs to make the system behave logically. The Fuzzy Behaviour-based System is a structure built upon a network of fuzzy rule-based systems. Fuzzy rule bases are useful in the research of animal behaviour, allowing for complex interactions and self-driving systems to adapt to changing environments [19], [20]. A fuzzy rule-based system is an expert system where knowledge representation is in the structure of production fuzzy rules, such as **If** *[conditions]* and **Then** *[actions]* statements. For example, the level of "Fear" in a behaviour model can be described in terms of **IF Then** statements. E.g.:

If AFTP=*Low* **And** AFTA=*Low* **And** ADTA=*Low*
Then FEAR=*High*

where antecedent variable AFTP is the Animal Familiarity Towards Place, AFTA is the Animal Familiarity Towards Another, and ADTA is the Animal Distance Towards Another Animal.

The structure of a Fuzzy Behaviour-based System [21] consists of main modules, such as the Behaviour Coordination or Arbitration, the Behaviour Fusion, and the Component Behaviours themselves. Figure 1 illustrates a possible Fuzzy Behaviour-based System structure. In the case of the Fuzzy Behaviour-based System, each of the main components and the behaviour components is defined as fuzzy rule-based systems (Fuzzy Logic Controller – FLC on the figure).

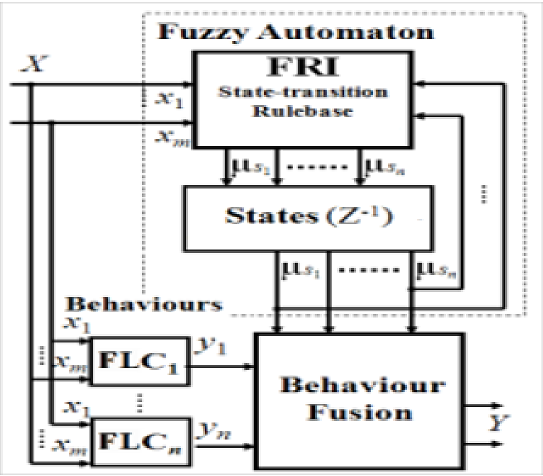


Fig. 1. The applied Fuzzy Behaviour-based System. [21]

Behaviour Coordination (Arbitration): This component is crucial in determining which behaviour should control the robot's operation at any given time, selecting tasks based on the current objectives and external conditions. Behaviour coordination, often referred to as arbitration, is a technique employed in autonomous systems design, particularly in robotics, to resolve conflicts between competing behaviours. In such systems, multiple behaviours can be active simultaneously, leading to conflicts when they compete for the same resources or interfere with one another. Behaviour coordination mechanisms are implemented to resolve these conflicts, ensuring smooth and efficient system operation by prioritizing behaviours and allocating resources to ensure successful task execution.

Various methods for behaviour coordination exist, each with its advantages and limitations. The one common approach which is often used is the hierarchical method, where behaviours are structured in a hierarchy, with higher-level behaviours taking precedence over lower-level ones. In this method, if lower-level behaviours conflict with higher-priority ones, the system will override the lower-level behaviours. In some instances, multiple behaviours may be activated concurrently, as seen in figure 2 fuzzy behaviour coordination. This approach involves context-dependent blending, a mechanism that allows for various patterns of behaviour combinations, such as following a target while avoiding obstacles. Decisions between behaviours are made based on the current situation by applying fuzzy logic [22].

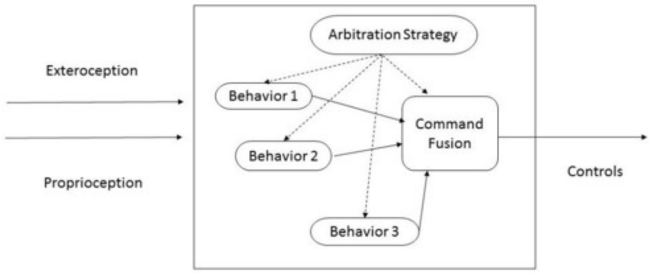


Fig. 2. The architecture of behaviour arbitration. [22]

Behaviour fusion refers to the process of combining the outcomes of behaviour coordination. For example, if a robot navigating a path encounters an obstacle, the arbitration mechanism will prioritize the obstacle avoidance behaviour. However, in some scenarios, behaviour fusion alone may not suffice to resolve conflicting behaviours. In such cases, a fuzzy rule-based system can be employed to assess conflicting conditions and determine which behaviour to prioritize [23]. Fuzzy behaviour fusion has been successfully applied across various domains, including robotics, autonomous vehicles, and healthcare [24], [25]. For instance, in autonomous vehicles, fuzzy behaviour fusion integrates data from multiple sensors, such as cameras and lidar, to estimate the vehicle's path and speed. Generally, fuzzy behaviour fusion is a powerful computational technique that enables the synthesis and integration of complex information from diverse sources, facilitating more nuanced and accurate predictions and decision-making.

IV. Implementation Guidelines

A behaviour-based system is built upon a series of interacting shared modules, known as behaviours, which collectively form the desired system-level behaviour. These behaviours are models of the robot's operation in specific situations, describing its interactions with the environment [26]. Social robots are designed to interact comfortably with humans and adapt to human social environments. Human-dog interactions can serve as the basis for behavioural models that create interactive capabilities for social robots. For example, just as dogs interact with humans in various situations and environments, social robots can be programmed to exhibit similar behaviours. A dog's behaviour and reactions can be recorded and described by humans [27], and if humans can comprehend these actions, they can also infer the corresponding conditions.

Developing Ethologically Inspired Fuzzy behaviour-based Systems for replicating animal aggressive behaviours in robotics requires a systematic approach that integrates ethology, fuzzy logic, and robotics knowledge. Initially, we conduct a comprehensive literature review to establish a robust theoretical foundation, with a particular emphasis on Archer's ethological model of aggression and fear in vertebrates, the principles of fuzzy logic, and their application in behaviour-based robotics. We then transform Archer's model into a fuzzy logic framework, linking significant behavioural components to fuzzy rules that effectively manage the imprecise and variable nature of aggression. The development phase involves constructing a fuzzy inference system that processes sensory inputs and produces appropriate behavioural outputs. Integrating the Fuzzy behaviour Description Language (FBDL) facilitates smooth and efficient interaction between the robot's control system and its environment. The accuracy of the model in replicating animal-like aggressive behaviours is visualized using the Robot Operating System (ROS), Gazebo, and RViz. This research aims to create a durable and adaptable robotic system capable of accurately imitating and managing aggressive behaviours by leveraging the complex dynamics observed in animal environments. Ultimately, the system can be applied in real-life scenarios to evaluate its effectiveness and adaptability.

A. *Implementing "Aggression"*

The goal is to create a fuzzy behaviour-based model of aggression based on the ethological model described in [28]. This model, developed by Archer in his paper "The Organization of Aggression and Fear in Vertebrates: Perspectives in Ethology," is a control theory-based ethological model, see figure 3. This model can help to provide insight into the underlying motivations for aggressive and fear behaviours. It provides a structured decision-making framework for animal behaviour, particularly in contexts involving aggression, fear, and responses to stimuli. The model comprises the following components:

Expectation Copy: The animal forms an expectation regarding the actions of the other animal. This anticipation is grounded in the animal's prior experiences with others, its understanding of animal behaviour, and its present internal state, such as its level of arousal.

Input: The animal receives sensory input from the other animal, including details like its size, posture, and movements.

Orientation Response: Upon receiving sensory input, the animal repositions towards the other animal and evaluates the situation.

Discrepancy: The animal compares the input it receives with its expectation. If an inconsistency arises between the two, the animal experiences heightened stimulation and may transition into a fight-or-flee state.

Decision Process 1 - Fear or Attack?: The animal weighs the options of responding with fear or launching an attack. This decision is influenced by several factors, such as the size of the discrepancy, the animal's hormone levels, past fighting experiences, and current internal state.

Attack: If the animal chooses to attack, it will initiate aggressive behaviour.

Environmental Consequences of Behaviour: The animal's actions will result in environmental outcomes. For instance, if the animal launches an attack on another, the other may flee.

Decision Process 2 - Escape or Immobility?: If the animal decides not to attack during Decision Process 1, it must decide whether to escape or immobility. This determination considers factors like the animal's hormonal state, the location of the other animal, and the animal's perceived ability to flee.

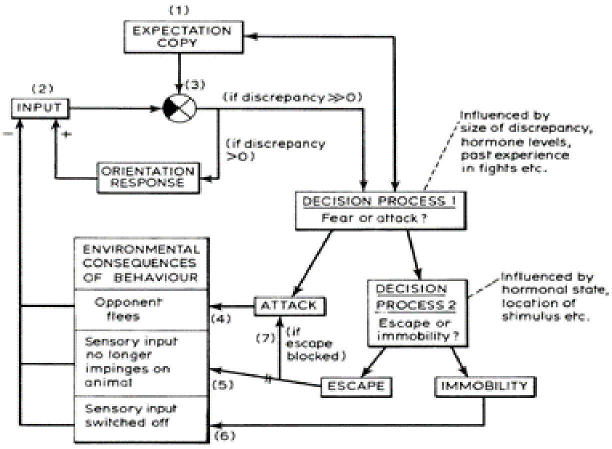


Fig. 3. Archer organization model [28].

Escape: If the animal decides to escape, it will try to get away from the other animal.

Sensory Input No Longer Impinges on the Animal: If the animal chooses to escape, then the sensory input from the other animal no longer affects the animal's senses.

If Escape is Blocked: If no escaping path exists, it will become aggressive and decide to attack.

Immobility: When the animal chooses not to attack and escape, it enters a state of immobility, which subsequently leads to the Sensory Input Switched Off:

Sensory Input Switched Off: The animal disengages from reacting to the sensory input provided by the other creature. In short, it means animals will not do anything at all.

The Archer Control Theory model provides a framework for understanding how systems function and how they can be controlled to achieve specific goals. According to this model, animals regulate their behaviour in response to various internal and external influences within the context of motivation. A simplified version of the control theory model of aggression and fear in vertebrates suggests that these behaviours are governed by two conflicting control systems: the aggression system and the fear/anxiety system. These two systems are thought to be in dynamic equilibrium, with the balance between them determining an animal's behavioural response. This model indicates that a complex interplay between internal and external factors influences these behaviours. The balance between the aggression and fear/anxiety systems can shift depending on the animal's current needs and environment.

Animal aggression is complex, involving elements such as Attack, Escape, and Immobility. FSMs offer a powerful method for simulating this behaviour because they can model the ambiguity and imprecision inherent in animal behaviour. Implementing animal aggression using a fuzzy state system requires several stages. First, we must define the animal states. In this context, the states can be categorized as Attack, Escape, and Immobility each representing a different behavioural response to a specific stimulus. Next, the inputs to the system must be defined. These inputs can include various stimuli, such as the presence of a predator or another animal in the animal's vicinity. Fuzzy logic can be employed to express the uncertainty surrounding certain inputs. For example, the input "presence of another animal" could be represented as a fuzzy set with membership functions like *"Low"* and *"High"* depending on the level of familiarity. After defining the states and inputs, we can establish the rules that govern how the states transition over time. These rules can also be represented using fuzzy logic. For instance, a rule might be stated as "The transition to Escape is high if the input "familiarity with another animal is low" and "familiarity with the environment is low." The degree of membership for each transition can be expressed using linguistic terms like "high" and "low." Finally, we define the system's outputs. These outputs correspond to the behaviours that the animal may exhibit in response to the stimuli. For example, the output "attack" could be linked to the aggressive state, if "familiarity with another animal and with the environment is low." In summary, implementing animal aggression behaviour using an FSM involves defining the states, inputs, rules, and outputs of the system. Fuzzy logic allows us to capture the ambiguity and imprecision of animal behaviour, providing a powerful tool for simulating such behaviours and developing strategies for managing animal aggression in various situations.

To implement the ethologically inspired behaviour model described above, we examine aggressive behaviour in animals with the following aims: First, we must categorize the circumstances in which aggression occurs. Second, we need to establish that these circumstances also trigger reactions related to Fear, Attack, Escape, Immobility, and distress communication. Third, we propose that these circumstances share specific characteristics, allowing for the development of a general theory on the causes of aggressive and fear-related behaviours. Fourth, we consider additional factors—such as internal physiological and motivational states, past experiences, and external variables—that may influence the likelihood of aggressive and fearful behaviours occurring. To conduct this analysis, we will employ a fuzzy behaviour model inspired by ethology. Before starting the implementation, we have defined specific terms below, which can also be expressed as fuzzy rules.

State Variables: The fuzzy "Aggression" behaviour model has four state variables. Three of them, the "Attack", "Escape," and "Immobility," have related behaviour components, and one, the "Fear," is a hidden state variable (see example in Fig. 4.).

"Fear"is an animal's physiological, behavioural, and emotional response to stimuli it comes across. For example, when an animal is terrified, it will display changes in body posture and activity. The scared animal may adopt protective body postures such as lowering the body and head, bringing the ears closer to the head, widening the eyes, and tucking the tail beneath the body. In our simplified model, fear has no related behaviour component, i.e., it is not observable independently from the environment but affects the other three state variables.

"Attack" refers to a rapid movement addressed at a specific stimulus that frequently results in physical damage to that stimulus, such as biting, hitting, pecking, and so on, but excludes such actions when they are related to food acquisition.

"Escape" any response intended to move away is referred to as Escape. Animals engage in escape behaviour when an animal's life is in danger, which may include rushing away from a threat in the environment.

"Immobility" is when an animal shows no signs of motion. This might be generated in a fear-conditioning experiment as a trained reaction to an aversively conditioned signal, or it could be elicited in response to unexpected stimuli that would be linked with a predator.

Observations: Following the "Aggression" ethological model described in [25], in our simplified fuzzy behaviour model, the four state variables depend on the following observations:

"Animal Familiarity Towards Place" (AFTP): This is defined as the level of familiarity an animal has with the place. These circumstances might occur when an animal enters a familiar or unfamiliar environment. Fear behaviour is most common when an animal enters an unknown environment, but attacking behaviour can also happen if a suitable target is attacked.

"Animal Familiarity Towards another Animal" (AFTA): The level of familiarity of an animal concerning another animal. These circumstances can occur in familiar or unfamiliar environments, i.e., when an animal is familiar with a place and some unknown animal comes close to an animal or enters another's familiar area; in this case, the animal shows fear and can also show attack behaviour.

"Animal Distance Towards another Animal" ADTA): How far is another animal? In simple terms, we can say the level of distance towards another animal. These circumstances can occur in different ways, such as familiar or unfamiliar with a place and familiar or unfamiliar with another animal, i.e., when an animal is unfamiliar with a place, another animal and the distance towards another animal is close in this case, animal shows high fear and can also show attack behaviour as well if there is no escape path existing.

"Animal Familiarity Towards Object" (AFTO): The animal's familiarity with an object. This situation occurs in an animal's familiar and unfamiliar environment, like when a moving object comes close to an animal or when the distance between the animal and the object decreases in an unfamiliar place. Also, when a novel object enters an animal's familiar place, these include the conventional territorial issue and a wide range of other scenarios such as fear, Attack, and escape behaviours. This observation (and also ADTO) serves as a robotic extension of the original model by Archer by considering that the appearance of a non-living object cause territorial issues for robots (i.e., non-living objects).

"Animal Distance Towards Object" (ADTO): The level of distance from an animal towards the object. This situation occurs in animal familiarity and unfamiliarity with the place and towards the object, such as when an unfamiliar moving object comes close to an animal, and the animal is unfamiliar with the place; in this case, various scenarios occur, such as fear, Attack, and escape behaviours.

“Escape Path Exists” (EPE): The level of a possible escaping path for the animal. This situation occurs when another animal or moving object approaches, and if the animal’s escaping path is not blocked, then the animal’s only option is to escape from that environment. When the possibility of Escape is blocked, the attack behaviour is mostly to occur, even if the animal shows broad signs of fear behaviour such as painful, stressful, or threatening stimuli.

“Positive Impact With respect to Previous Experience” (PIWPE): The degree of positivity and negativity associated with past experiences. In other words, it is the past positive and negative feelings of the animal that relate to the previous attacks. In this situation, the animal remembers his last feedback. Previous interactions are crucial in determining how an animal would react to a problem that could trigger attack or fear behaviour.

B. The fuzzy model for the “Aggression” behaviour

For implementing the fuzzy behaviour model of the “Aggression” behaviour, the Fuzzy Behaviour Description Language (FBDL) [29] was applied. The FBDL follows the concepts of fuzzy rule-based systems, Fuzzy Rule Interpolation (FRI), and their relationships to build behaviour components and behaviour coordination. The rule-based design makes knowledge representations comprehensible and self-explanatory for humans. The fuzziness and related Linguistic Term fuzzy set notion also improve human comprehension when variables are described on continuous universes. Having the FBDL description of the fuzzy behaviour model, the model can be directly evaluated numerically. The FBDL code can be performed directly on a system or, with some additional measurement data, can be used as an object for machine learning parameter optimization algorithms.

The FBDL defines the universes of the input and state variables, their linguistic terms (fuzzy sets applied in the fuzzy rule-bases), and the fuzzy rule-bases.

If we have an observation, e.g., the level of the “Animal Familiarity to the Place,” which is an input universe having two linguistic terms *Low* and *High* then giving a symbol name AFTP, the FBDL definition has the following form:

universe: AFTP
description: The Animal’s Level of Familiarity with the Place.
Low 0 0
High 1 1
end

A fuzzy rule in a rule-base determining, e.g., the level of the “Fear” hidden state-variable in the function of the level of the animal familiarity to the place, to the other animal, and the approaching object, could be the following in fuzzy rule format:

If AFTP=*High* **And** AFTA=*High* **And** AFTO=*High* **Then** FEAR=*Low*

where as AFTP is Animal Familiarity to the Place, AFTA is Animal Familiarity Towards Another, and AFTO is Animal Familiarity Towards Object are antecedent variables.

The same rule in FBDL format:

Rule *Low* **When** “AFTP” is *High* **And** “AFTA” is *High* **And** “AFTO” is *High* **end**

The fuzzy model of the “Aggression” behaviour in FBDL format. The FBDL definition of the AFTP, AFTA, AFTO, ADTA, ADTO, PIWPE, EPE input and the FEAR, ATTACK, ESCAPE, IMMOBILITY state variable universes are similar (see e.g. AFTP and FEAR):

universe: AFTP
Low 0 0
High 1 1
end
universe: FEAR
Low 0 0
High 1 1
end

The FBDL definition of the state rule-bases is described below one by one. It is represented based on different scenarios such as (a) animal familiarity with a place, object, and another animal, (b) a moving object or animal approaching an animal too closely (individual distance intrusion), (c) a new object or animal enters another’s familiar territory: this can encompass the usual territorial issue and various scenarios, (d) entering an unfamiliar environment: fear typically occurs, (e) a familiar object in a strange setting, (f) degree of positiveness associated with the previous Attack.

In fuzzy rule-base format, the FEAR Fuzzy Rule-base ($\mathbf{R}_{\text{FEAR}}$) is the following:

If AFTP=*Low* **And** AFTA=*Low* **And** AFTO=*Low* **Then** FEAR=*High*
If AFTA=*Low* **And** ADTA=*Low* **And** EPE=*Low* **Then** FEAR=*High*
If AFTO=*Low* **And** ADTO=*Low* **And** EPE=*Low* **Then** FEAR=*High*
If AFTP=*Low* **And** EPE=*Low* **And** PIWPE=*Low* **Then** FEAR=*High*
If AFTP=*High* **And** AFTA=*High* **And** AFTO=*High* **Then** FEAR=*Low*
If AFTA=*High* **And** ADTA=*High* **And** EPE=*High* **Then** FEAR=*Low*
If AFTP=*High* **And** AFTA=*High* **And** EPE=*High* **And** PIWPE=*High* **Then** FEAR=*Low*

where AFTP, AFTA, ADTA, AFTO, ADTO, EPE, PIWPE are the antecedent universes, FEAR is the consequent universe, *Low* and *High* are fuzzy linguistic terms in the corresponding universes.

The same FEAR rule-base in FBDL format appears as:

RuleBase “FEAR”
Rule *High* **When** “AFTP” is *Low* **And** “AFTA” is *Low* **And** “AFTO” is *Low* **end**
Rule *High* **When** “AFTA” is *Low* **And** “ADTA” is *Low* **And** “EPE” is *Low* **end**
Rule *High* **When** “AFTO” is *Low* **And** “ADTO” is *Low* **And** “EPE” is *Low* **end**
Rule *High* **When** “AFTP” is *Low* **And** “EPE” is *Low* **And** “PIWPE” is *Low* **end**

Rule *Low* **When** "AFTP" is *High* **And** "AFTA" is *High* **And** "AFTO" is *High* **end**
Rule *Low* **When** "AFTA" is *High* **And** "ADTA" is *High* **And** "EPE" is *High* **end**
Rule *Low* **When** "AFTP" is *High* **And** "AFTA" is *High* **And** "EPE" is *High* **And** "PIWPE" is *High* **end**
end

In fuzzy rule-base format, the ATTACK Fuzzy Rule-base ($\mathbf{R}_{\text{ATTACK}}$) is the following:

If AFTA=*Low* **And** ADTA=*Low* **And** EPE=*Low* **Then** ATTACK=*High*
If AFTO=*Low* **And** ADTO=*Low* **And** EPE=*Low* **Then** ATTACK=*High*
If AFTP=*Low* **And** ADTA=*Low* **And** ADTO=*Low* **And** EPE=*Low* **Then** ATTACK=*High*
If FEAR=*High* **And** EPE=*Low* **Then** ATTACK=*High*
If AFTP=*High* **And** AFTA=*High* **And** PIWPE=*High* **Then** ATTACK=*High*
If AFTP=*High* **And** AFTO=*High* **And** PIWPE=*High* **Then** ATTACK=*High*
If EPE=*High* **And** FEAR=*High* **Then** ATTACK=*Low*
If EPE=*High* **And** AFTP=*Low* **And** ADTA=*High* **Then** ATTACK=*Low*
If EPE=*High* **And** AFTA=*Low* **And** ADTA=*High* **And** PIWPE=*Low* **And** ADTO=*High* **Then** ATTACK=*Low*
If EPE=*High* **And** AFTO=*Low* **And** ADTO=*High* **And** PIWPE=*Low* **Then** ATTACK=*Low*
If AFTA=*Low* **And** AFTP=*Low* **And** AFTO=*Low* **And** EPE=*High* **Then** ATTACK=*Low*

The antecedent universes are AFTP, AFTA, ADTA, AFTO, ADTO, EPE, PIWPE, FEAR. The consequent universe is ATTACK, and Low and High are fuzzy linguistic terms in the corresponding universes.

In fuzzy rule-base format, the ESCAPE Fuzzy Rule-base ($\mathbf{R}_{\text{ESCAPE}}$) is the following:

If EPE=*High* **And** FEAR=*High* Then ESCAPE=*High*
If EPE=*High* **And** AFTP=*Low* **And** AFTA=*Low* **And** AFTO=*Low* **Then** ESCAPE=*High*
If EPE=*High* **And** AFTA=*Low* **And** ADTA=*High* **And** PIWPE=*Low* **Then** ESCAPE=*High*
If EPE=*High* **And** AFTO=*Low* **And** ADTO=*High* **And** PIWPE=*Low* **Then** ESCAPE=*High*
If EPE=*High* **And** AFTP=*Low* **And** ADTA=*High* **And** ADTO=*High* **And** PIWPE=*Low* **Then** ESCAPE=*High*
If FEAR=*Low* **And** EPE=*Low* **Then** ESCAPE=*Low*
If FEAR=*Low* **And** PIWPE=*High* **Then** ESCAPE=*Low*
If AFTA=*High* **And** AFTO=*High* **And** AFTP=*High* **And** PIWPE=*High* **Then** ESCAPE=*Low*
If AFTA=*High* **And** ADTA=*High* **And** PIWPE=*High* **And** EPE=*Low* **Then** ESCAPE=*Low*
If AFTO=*High* **And** ADTO=*High* **And** PIWPE=*High* **And** EPE=*Low* **Then** ESCAPE=*Low*

where AFTP, AFTA, ADTA, AFTO, ADTO, EPE, PIWPE, FEAR are the antecedent universes, ESCAPE is the consequent universe, and *Low* and *High* are fuzzy linguistic terms in the corresponding universes.

In fuzzy rule-base format, the IMMOBILITY Fuzzy Rule-base ($\mathbf{R}_{\text{IMMOBILITY}}$) is the following:

If FEAR=*Low* **And** EPE=*Low* **Then** IMMOBILITY=*High* **If** AFTA=*Low* **And** ADTA=*High* **And** EPE=*Low* **Then** IMMOBILITY=*High*
If AFTO=*Low* **And** ADTO=*High* **And** EPE=*Low* **Then** IMMOBILITY=*High*
If AFTP=*Low* **And** ADTA=*High* **And** EPE=*Low* **Then** IMMOBILITY=*High*
If AFTP=*Low* **And** AFTA=*Low* **And** PIWPE=*Low* **Then** IMMOBILITY=*High*
If EPE=*High* **And** FEAR=*High* **And** PIWPE=*Low* **Then** IMMOBILITY=*Low*
If EPE=*High* **And** AFTA=*Low* **And** ADTA=*Low* **And** PIWPE=*Low* **Then** IMMOBILITY=*Low*
If EPE=*High* **And** AFTO=*Low* **And** ADTO=*Low* **And** PIWPE=*Low* **Then** IMMOBILITY=*Low*

The antecedent universes are AFTP, AFTA, ADTA, AFTO, ADTO, EPE, PIWPE, FEAR, and the consequent universe is IMMOBILITY, with the fuzzy linguistic terms *Low* and *High* in the corresponding universes.

Several variables can influence whether an animal will exhibit Fear, Escape, Attack, or Immobility behaviours in a given situation. These variables can be categorized into internal characteristics and behavioural outcomes.

"Internal characteristics" that may impact an animal's tendency to exhibit fear or attack behaviours include: (a) The degree of discrepancy between expectations and observations: A significant difference between what an animal expects and what it observes can trigger fear and escape behaviours, as the animal perceives a potential threat. Conversely, if the observed stimulus closely matches expectations, the animal may exhibit attack behaviours instead. This highlights how animals respond to uncertainty and familiarity in their environment. (b) The degree of positive motivation from previous experiences: An animal's positive motivation or reinforcement from earlier experiences influences its present behaviour. When this level of positive motivation is high, the animal is more likely to attack rather than escape in a given situation. Prior positive reinforcement may lead an animal to fight rather than flee. (c) Experiential factors: Early life situations, social isolation, and previous reinforcements significantly impact an animal's decision to either attack or escape when faced with a frightening circumstance. Early experiences and social interactions shape their responses, while past reinforcements guide their decision-making. These elements contribute to the complexity of animal behaviour and enhance our understanding of why animals respond the way they do in various situations.

"Behavioural Outcomes" that may affect specific behaviours include: (a) Properties of the target: The characteristics of the object being attacked or defended against, such as its size, movement, and location, can influence behaviour. For example, the size (whether it is large or small), the ease of movement (how easily it can be moved), and the proximity (how close or far it is from the attacker) are factors to consider. (b) Preference for passive or active responses: Animals often have a preferred course of action when faced with danger.

They may choose to avoid the threat passively by remaining still or to escape by moving away. The degree and location of sensory discrepancies—anything that seems abnormal in their environment—can impact this choice. (c) The possibility of escape: The likelihood of escaping from danger affects behaviour. If escape is physically impossible (for instance, if an animal is trapped in an area with no way out), attack behaviours may become more likely as a form of self-defense.

Figure 4 represents the components of an animal's aggressive behaviour fuzzy model concerning all the possible components defined above, such as towards place, another animal, object, distance, etc.

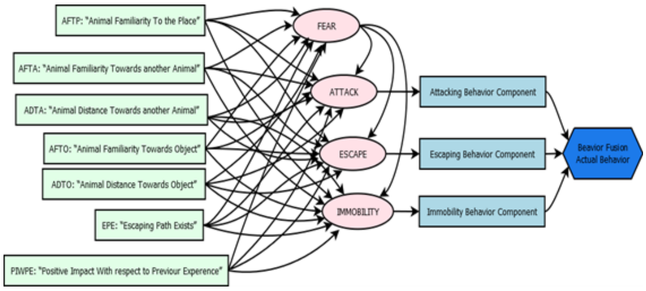
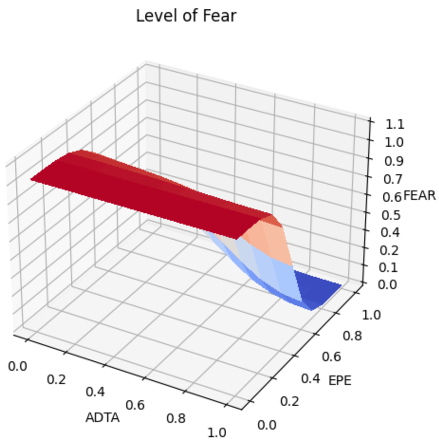
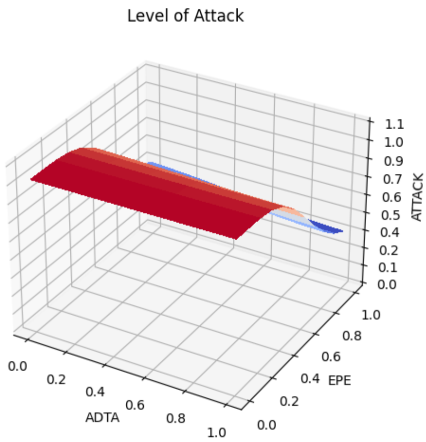


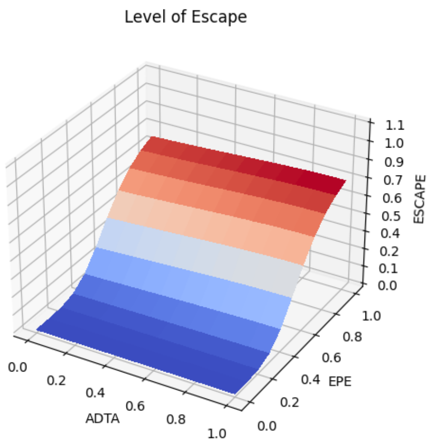
Fig. 4. Animal Aggressive Behaviour Fuzzy model.



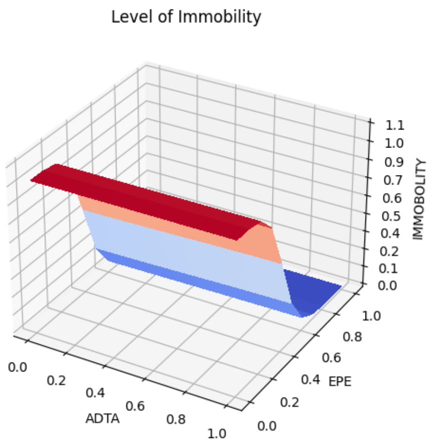
(a) Level of Fear Behaviour.



(b) Level of Attack Behaviour.



(c) Level of Escape Behaviour.



(d) Level of Immobility Behaviour.

Fig. 5. (a), (b), (c), (d): Graphical Representation of Behaviours

Figure 5 demonstrates some examples of the behaviour component level changes in the functions of the observations according to the fuzzy model of aggressive behaviour. All the graphs are based on the calculation of the FBDL [29] description given in this paper using the implemented FBDL functions publicly available in [30], [31]. We have taken two observations, ADTA and EPE changing from *Low* to *High* and the rest of the observations to be constant (i.e., the animal is highly familiar with the place and another animal: AFTP=*High*, AFTA=*High*, and less familiar with AFTO=*Low*, ADTO=*Low*, PIWPE=*Low*). Red color represents *High*, and blue represents *Low*. Figure 5(a) demonstrates the state change of "Fear" in the function of ADTA and EPE in this case. According to the graph, the FEAR will be *High* if no escape path exists. The approaching other animal is unfamiliar (AFTA=*Low*, EPE=*Low*) and *Low* if the animal is familiar with these states such as AFTA=*High*, AFTP=*High*, AFTO=*High*). The level of ATTACK behaviour (see Figure 5(b)) is *High* if the animal is not familiar with the approaching other animal, distance towards other animal is less, and there is no escape path exists (AFTA=*Low*, ADTA=*Low*, EPE=*Low*) and *Low* if escape path exists (EPE=*High*). The level of ESCAPE (see Figure 5(c)) is *High* if the animal is not familiar with the approaching another animal, not familiar with the place, and there is a high escape path exists (AFTA=*Low*, AFTP=*Low*, EPE=*High*) and *Low* if there is no escape path exists (EPE=*Low*). The level of IMMOBILITY (see Figure 5(d)) as a decision instead of attacking is *High* if the animal is not familiar with the approaching another animal, distance towards another animal is less, and there is no escape path exists (AFTA=*Low*, ADTA=*Low*, EPE=*Low*) and *Low* if an escape path exists and distance towards another animal is *High* (EPE=*High*, ADTA=*High*).

Figure 6 illustrates the trajectories of Robot_1 and Robot_2, showcasing a sophisticated representation of animal Escape behaviour, based on fuzzy behaviour principles. This behaviour is well-suited for replicating animal-like actions in robotics. The blue trajectory of Robot_1 (R1) and the green trajectory of Robot_2 (R2) display intricate behavioural patterns similar to those observed in animals, with a particular focus on escape behaviours in response to the presence of another entity. The robots start at the following positions: Robot_1 begins at coordinates (0.5, 0.5), and Robot_2 starts at coordinates (6, 6). Robot_1 is tasked with moving closer to Robot_2's starting location, while Robot_2 is directed to approach Robot_1's initial position. This setup creates a scenario where both robots advance towards each other's initial positions.

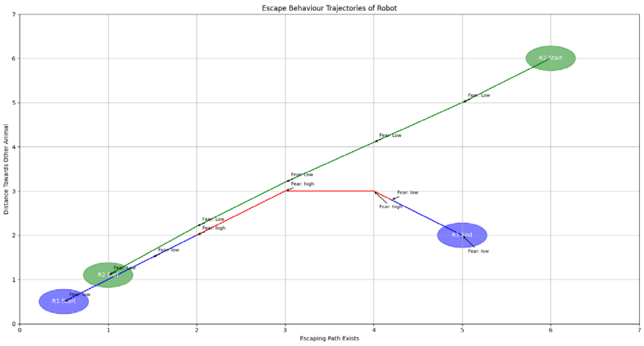


Fig. 6. Robot trajectories for the ESCAPE behaviour.

In this escape behaviour example, Robot_1 serves as the primary actor and will perform the escape behaviour. We assume that Robot_1 is initially unfamiliar with its environment, including Robot_2, which is fully acquainted with the surroundings. Upon entering the environment, Robot_1 exhibits a baseline level of fear due to its unfamiliarity. As the robots move and the distance between them decreases, a fuzzy logic-based system evaluates Robot_1's behavioural response, considering parameters such as the distance between the robots (ADTA), the FEAR level, and the availability of an escape route (EPE). When Robot_1 perceives that its proximity to Robot_2 has reached a critical threshold, its FEAR level is algorithmically increased. Subsequently, Robot_1 assesses the feasibility of an escape and, upon seeing an escape route, initiates an escape response. This response is visually represented by a shift in Robot_1's trajectory color to red, symbolizing heightened fear and the commencement of escape maneuvers, thus graphically indicating an increased state of alertness.

The synchronization and integration of behaviours are fundamental to the dynamics of the trajectories. The trajectories of both robots are interdependent, reflecting the behavioural coordination observed in animal interactions, where the actions of one organism provoke responses from another. The interactions between Robot_1 and Robot_2 influence various behaviours, such as movement toward a target and avoidance of potential threats, which, in turn, determine Robot_1's trajectory. This interaction results in a flexible and complex behavioural pattern that adapts to perceived changes in threat levels.

As the distance between the robots increases, Robot_1's response. The trajectories of Robot_1 and Robot_2 not only demonstrate the effectiveness of fuzzy logic in developing behaviour-based robotic systems but also provide a compelling model for emulating animal escape strategies. By integrating fuzzy rules, coordinating interactive behaviours, and synthesizing multiple actions into a cohesive response, this system offers valuable insights into the potential capabilities of advanced autonomous robotic systems. Such systems, capable of navigating and responding to complex environments similarly to biological entities, hold significant promise for applications in autonomous exploration and interactive robotics.

Figure 7 depicts the ATTACK behaviour trajectory between Robot_1 (R1) and Robot_2 (R2), utilizing a fuzzy behavioural architecture that emulates the dynamics of animal aggression. The fuzzy rule base within this framework facilitates the simulation of complex and uncertain interspecies interactions, particularly in the context of aggression. In this scenario, each robot's behaviour is represented by a distinct color-coded fear level decreases, leading to a diminished escape response. During this phase, Robot_1 undergoes a behavioural shift, indicated by a change in its trajectory color back to blue, signaling a reduction in anxiety and the cessation of the escape path, illustrating their interactions over time and space. This mirrors the movement and interaction patterns observed among animals within a shared space. Initially, Robot_1's trajectory, starting at coordinates (1,1), is colored blue, reflecting typical non-aggressive behaviour. Robot_1's objective is to approach Robot_2, display aggression, and assert dominance. Robot_2's trajectory, represented by a green line at coordinates (5.5, 5.5), suggests an absence of fear. As the distance between Robot_1 and Robot_2 diminishes, Robot_1's trajectory shifts to red, signifying an escalation in aggression and the initiation of an attack, analogous to an animal transitioning from pursuit to combat.

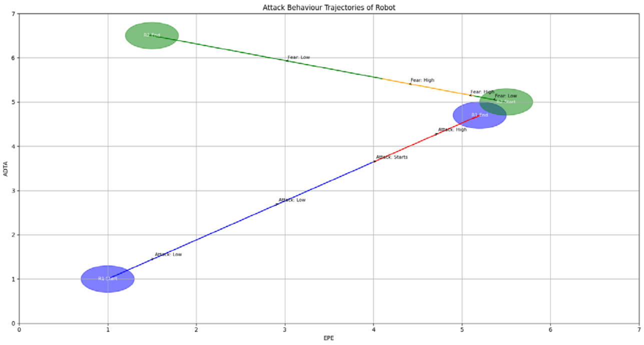


Fig. 7. Trajectories for the Attack Behaviour.

As Robot_1 approaches, Robot_2 begins to experience fear, which is visually represented by its trajectory turning orange, indicating a heightened fear response. This shift can be likened to an animal becoming increasingly anxious and defensive when it perceives a threat or rival, prompting it either to defend itself or flee. The changing colors in Robot_2's path signify its escalating fear and desire to avoid confrontation by retreating, particularly due to its unfamiliarity with Robot_1 and the decreasing distance between them. This interaction between the two robots mirrors animal behaviour, characterized by a complex interplay of stimuli and responses. The aggressive movements of Robot_1 elicit a fear-based reaction in Robot_2, governed by fuzzy rules that take into account factors such as proximity ADTA, environmental familiarity AFTP, and perceived threat levels AFTA. Consequently, Robot_1's behaviour adapts, becoming increasingly aggressive as it closes in on its target. Similarly, a fuzzy logic system modulates Robot_2's responses by evaluating its fear level, resulting in a retreat as the threat diminishes and a return to its original low-fear trajectory, represented by a green path. This pattern reflects the natural process by which animals regain composure once the perceived threat has subsided.

The trajectories of both robots underscore the sophistication of the FSM in emulating animal behaviours. The system effectively replicates complex actions such as aggression, fear, and survival strategies. This advancement is pivotal for the development of autonomous robotics, enabling robots to navigate and respond to complex environments by dynamically adjusting their behaviour in response to internal states and external stimuli. Moreover, this approach offers valuable insights into animal behaviour, facilitating ecosystem studies and the creation of intelligent machines capable of natural interactions with their surroundings.

The simulation of animal escape behaviour, as depicted in figures 8(a)–8(e), is based on the escape behaviour trajectory described above. It employs the Robot Operating System (ROS) in conjunction with tools such as Gazebo and Rviz to model the escape behaviour of robots designed to mimic animals. This simulation involves a sophisticated integration of robotic vision, decision-making processes, and movement, all orchestrated within a controlled virtual environment. A key element of this setup is the use of LIDAR (Light Detection and Ranging), a highly esteemed sensor in robotics for its ability to generate real-time, high-resolution 3D scans of the environment. In the escape scenario, LIDAR is crucial for the system's operation at high speeds, enabling instantaneous object detection and data collection from multiple angles. This capability is particularly important for the rapid and accurate identification of other entities, which is essential for timely and precise reactions.

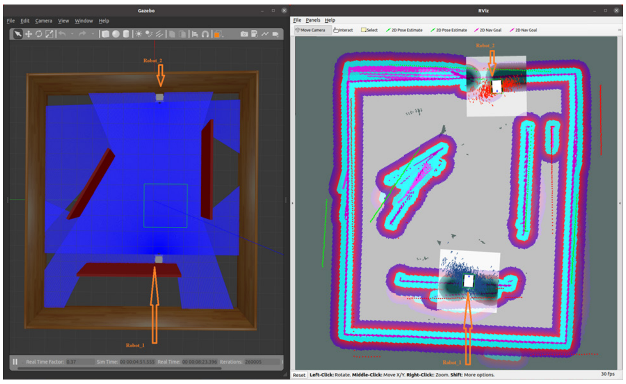
The simulated scenario involves two robots, designated as Robot_1 and Robot_2,, within a confined space containing walls and other objects. In this scenario, Robot_1, represented by blue dots, is positioned near an object, while Robot_2, indicated by red dots, is located near a wall. Robot_1 serves as the primary actor, with its behaviour and responses driving the sequence of interactions within the simulation. The trajectory and behaviour of Robot_1, as described earlier, illustrate the complex decision-making processes that underpin its actions, driven by fuzzy logic and real-time environmental data. This demonstrates the potential of such systems to replicate the adaptive and dynamic nature of animal escape behaviours.

The simulation designates the initial location of these animal robots, as seen in figure 8(a). The subsequent stages involve Robot_1 and Robot_2 approaching their respective starting positions, leading to a scenario where they progress towards each other. Figure 8(b) depicts the dynamic stage of the robots, capturing their movement. The experiment incorporates concepts such as behaviour fusion, behaviour coordination, and fuzzy component behaviour to analyze the system's performance. Fuzzy component behaviour specifically refers to the use of fuzzy logic for interpreting input data obtained from sensors such as LIDAR. In this instance, the robotic animals use data from laser scans to identify each other and calculate their relative distance.

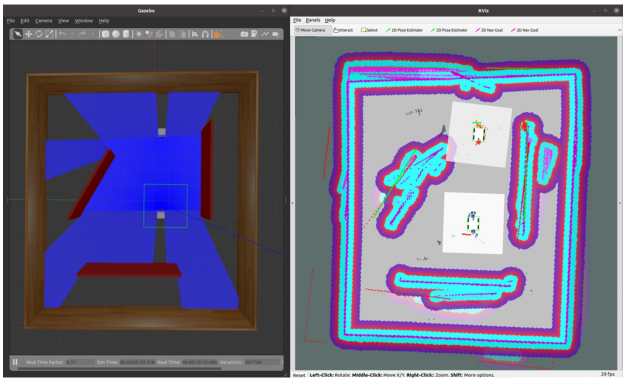
As the robots approach each other, as shown in figure 8(c), Robot_1 detects the presence of Robot_2 using its sensors and input data. The fear level of Robot_1 increases and is assessed using a fuzzy rule-based approach that considers factors such as the robot's familiarity with other robots, the surroundings, the distance to Robot_2, and the availability of escape route. Figure 8(d) illustrates the moment when Robot_1 escapes due to high fear and the presence of escape path.

behaviour coordination in this context refers to the synchronization of the robots actions to achieve a shared goal, such as escaping in this particular scenario. Robot_1's escape upon approaching Robot_2 is a result of its unfamiliarity with the environment and the other robot, as specified in the escape regulations. behaviour fusion combines the behaviours of both robots to achieve the specific objective of assisting Robot_1 in escaping.

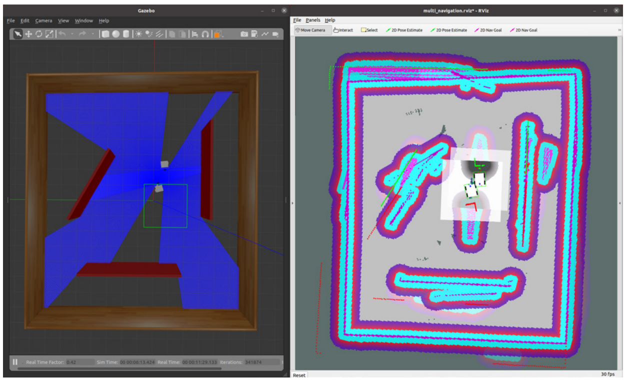
Figure 8(e) depicts Robot_1 successfully evading Robot_2, indicating that it is now at a safe distance. This result highlights the effectiveness of the fuzzy rule-based system and the principles of behaviour coordination in achieving the desired outcome.



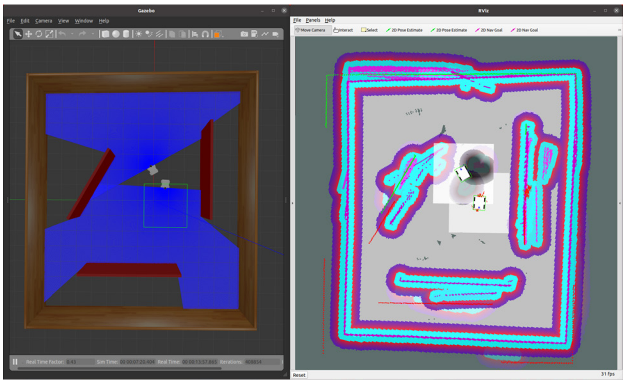
(a) Initial Position of Robots: both robots start at designated positions.



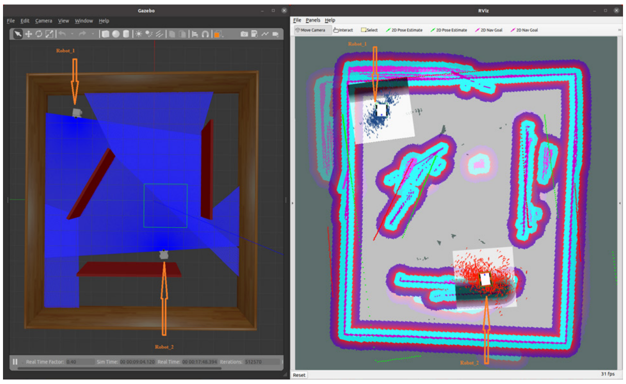
(b) Movement Stage: robots move towards each other.



(c) Detection and Fear Assessment: Robot_1 detects Robot_2 and assesses fear based on proximity and environment unfamiliarity.



(d) Escaping, High fear, and the presence of an escape route triggered Robot_1's Escape.



(e) Robot_1 successfully escapes, illustrating the effective use of fuzzy logic, behaviour coordination, and fusion.

Fig. 8. (a), (b), (c), (d), (e): Escape behaviour simulation

V. Conclusion

This paper presents a method for implementing an ethologically inspired animal behaviour model, "aggression," for robotic applications. It uses a Fuzzy Behaviour-based System to improve the realism and complexity of animals' escape behaviour models. We employ a fuzzy rule-based system to process input data, orchestrate different agents' actions, and amalgamate multiple agents' behaviours. ROS tools such as Gazebo and RVIZ were applied for visualization of the escape behaviour trajectories. The goal was to develop robots that could independently make decisions based on detailed sensory inputs, effectively emulating animal instincts and responses. The study also explores the dynamics of multi-agent systems and the intricate interactions among robots, which have profound implications for sectors like collaborative manufacturing, search and rescue operations, and surveillance. The presented methodology supports the development of adaptable, intelligent, and safe robotic systems applicable in various disciplines. The goal is to implement the animal aggression behaviour model from simulation to practical use in real-world robots, improving the scope of behavioural models and enhancing safety and intelligence to increase robot autonomy.

VI. ACKNOWLEDGEMENT

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Optimizing LSTM for Code Smell Detection: The Role of Data Balancing

Nasraldeen Alnor Adam Khleel, and Károly Nehéz

Abstract—**Code smells are specific patterns or characteristics in software code that indicate potential design or implementation problems. Identifying code smells has gained significant attention in software engineering. It is essential to address code smells to maintain high-quality software systems. Machine learning (ML) models, such as Long Short-Term Memory (LSTM), have been to detect code smells automatically based on source code features. However, the imbalanced distribution of code smells within software projects poses a challenge to the accuracy of these models. This study explores the role of data balancing methods in optimizing the accuracy of the LSTM model for code smell detection. We investigate different techniques for addressing the class imbalance problem, including random oversampling and synthetic minority oversampling techniques (SMOTE). We evaluate the performance of the LSTM model with and without data balancing methods using accuracy, precision, recall, f-measure, Matthew's correlation coefficient (MCC), and the area under a receiver operating characteristic curve (AUC). Our experimental results, conducted on four code smell datasets (God class, data class, feature envy, and long method) extracted from 74 open-source systems, demonstrate the effectiveness of data balancing methods in improving the accuracy of the LSTM model for code smell detection. The results indicate that the use of data balancing methods had a positive effect on the predictive accuracy of the LSTM model. In addition, we compared our proposed method with state-of-the-art code smell detection approaches. The findings from the comparison indicate that our proposed method performs notably better than existing state-of-the-art approaches across the majority of datasets.**

Index Terms—**Software engineering, artificial intelligence, code smells, LSTM, software metrics, class imbalance, data balancing methods.**

I. Introduction

In software development, code smells are indicators of potential problems or design flaws that can degrade the quality of software systems [1, 2, 3]. Identifying and rectifying code smells ensures maintainable, efficient, and robust software applications [4, 5, 6]. In Table 1, we outline the four types of code smells examined in our study. Detection methods for code smells vary, including manual, automatic, and metrics-based approaches [7, 8, 9]. Nonetheless, the majority of these techniques adopt a heuristic two-step method. Initially, they compute metrics and subsequently utilize threshold values to distinguish between smelly and non-smelly classes. Differences among these approaches stem from the algorithms used, subjective interpretations, absence of consensus among detectors, and reliance on thresholds [1, 10]. Recently, researchers have embraced ML techniques to overcome the constraints in code smell detection. Their goal is to bypass the use of thresholds and decrease the occurrence of false positives in detection tools [6, 10]. Among these ML techniques, LSTM models have gained significant attention. LSTM is a type of recurrent neural network architecture that is designed to capture long-term dependencies and relationships in sequential data [11]. By leveraging software metrics as input features, LSTM models can learn patterns and relationships to identify code smells effectively [12].

However, one critical challenge in building accurate ML models for code smell detection lies in the imbalance of data. Data imbalance in classification models represents those situations where the number of examples of one class is much smaller than another [6, 8, 12, 13]. This imbalance can negatively impact the performance of ML models, leading to biased predictions and lower accuracy [1, 9].

Consequently, addressing the data imbalance problem becomes crucial for achieving reliable and robust code smell detection [10]. The dataset utilized for code smell detection in this research exhibits a significant imbalance. Consequently, the goal of this study is to employ data balancing methods like random oversampling and SMOTE to tackle the class imbalance issue and assess their effect on the performance of the LSTM model in code smell detection. In brief, our study aims to achieve the following objectives and make the following key contributions:

(i) This study identifies the data imbalance problem as a major challenge for machine learning techniques in detecting code smells.

(ii) To address the data imbalance problem and investigate the impact of data balancing methods in improving code smell detection, we propose a new method that combines the LSTM network with two data balancing methods (Random Oversampling and SMOTE).

(iii) We demonstrate that balancing the dataset can greatly enhance the performance of the LSTM model in code smell detection. Additionally, our approach surpasses existing state-of-the-art approaches for code smell detection.

The paper follows this structure: Section 2 introduces the LSTM network. Section 3 details the research method. Section 4 presents the results and discussions. The conclusion is provided in the final section, Section 5.

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II. Related work

Recently, there has been an increased focus on researching code smell detection, with numerous scientific studies utilizing ML models for this purpose. For example, Fabiano Pecorelli et al. [6] investigated five data balancing methods that were able to mitigate data unbalancing issues to understand their impact on ML algorithms for code smell detection. The experiment was performed based on five code smell datasets extracted from 13 open-source systems. The experimental results showed that the ML models relying on SOMTE realize the best performance. Hadj-Kacem and Nadia. [7] proposed a hybrid approach based on deep Autoencoder and artificial neural network algorithms to detect code smells. The approach was evaluated based on four code smells extracted from 74 open-source systems. The experiment results showed that the values of recall and precision measurements have demonstrated high accuracy results. Francesca Arcelli Fontana et al. [8] presented a method using different ML algorithms to detect four code smells based on 74 software systems. The results showed that all algorithms performed well, but unbalanced data caused some models' performances. Chhabr and Nanda. [9] proposed a new approach called the SMOTE-Stacked hybrid model (SSHM) for the severity classification of four code smells (God class, Data class, Feature envy, and Long method). The SMOTE method was used to address the problem of class imbalance.

TABLE I
Lists the four specific code smells that we have investigated [8]

Code smells	Description	Affected entity
God _Class	A god class refers to classes that have numerous members and execute various behaviors.	Class
Data _Class	A data Class is a class that has only data without functions or any behaviors and does not process this data.	Class
Long _Method	The long method refers to the method that is too long and increases the system's compatibility.	Method
Feature _Envy	Feature envy describes a method that shows more interest in the properties of other classes than its own.	Method

The Experimental results demonstrated that the proposed approach surpassed other literature studies with peak accuracy improvement to 97–99% from 76 to 92% for various code smells. Khleel and Nehéz. [1, 10, 12] presented various classical and advanced machine learning algorithms with data balancing methods to detect code smells based on a set of Java projects. The authors examined four datasets related to code smells (God class, data class, feature envy, and long method) and compared the results using various performance metrics. The experiments demonstrated that the models proposed, along with data balancing methods, exhibited improved performance in detecting code smells. Tushar.Sharma et al. [11] proposed a new method for code smell detection using convolution neural networks and recurrent neural networks. The experiments were conducted based on C# sample codes. The experiment results showed that it is feasible to detect smells using deep learning methods, and transfer-learning is possible to detect code smells with a performance like that of direct learning. Mohammad Y. Mhawish and Manjari Gupta [15] presented a method using different ML algorithms and software metrics to detect code smells based on 74 software systems. The experimental results showed that ML techniques have high potential in predicting the code smells, but imbalanced data caused varying performances that need to be addressed in future studies.

After reviewing previous studies in code smell detection, we noticed that the studies that dealt with and addressed the issue of class imbalance point out that the data balancing methods have an essential role in improving the accuracy of code smell detection [1, 6, 9, 10, 12]. So, the primary point from the recent studies is that ML combined with data balancing methods can improve and increase prediction accuracy. Therefore, our study focuses on addressing the class imbalance problem using random oversampling and SMOTE methods.

III. LSTM Network

Long Short-Term Memory (LSTM) networks, a specialized variant of recurrent neural network architecture, are engineered to detect intricate patterns within sequential data. The purpose of introducing LSTM networks was to resolve or avoid the problem of long-term dependencies, which regular recurrent neural networks are susceptible to due to an unstable gradient when connecting previous information to new information [11]. A standard LSTM unit comprises a cell, an input gate, an output gate, and a forget gate. The cell remembers values over arbitrary time intervals, and the three gates regulate the flow of information into and out of the cell. Due to the ability of the LSTM network to recognize longer sequences of time-series data, LSTM models can provide high predictive performance in code smell detection[14]. The interacting layers of the repeating module in an LSTM Network are depicted in Figure 1.

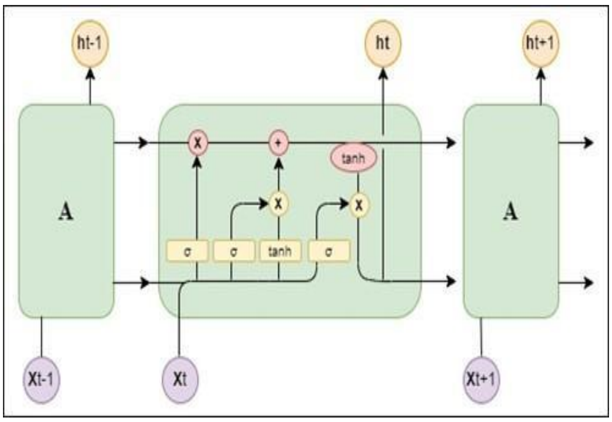

Fig. 1. Shows the interacting layers of the repeating module in an LSTM network.

IV. METHOD

Our study proposes a method for training and testing the code smell detection model, which utilizes the LSTM model with data balancing methods. Figure 2 illustrates an overview of the proposed method. The following sections describe the steps taken in this study, which encompass dataset description, data pre-processing and feature selection, class imbalance and data balancing methods, and model building and evaluation.

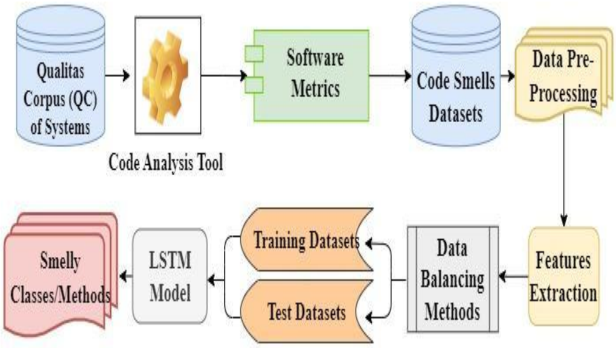

Fig. 2. Overview of the proposed method for code smell detection.

A. Dataset Description

For conducting the analysis and experiments, we implemented our method using datasets introduced by Arcelli Fontana et al. [8]. These datasets comprise 74 open-source systems of different sizes and domains gathered from the Qualitas Corpus (QC), encompassing 6,785,568 lines of code, 3,420 packages, and 51,826 classes [4]. These datasets were chosen because the systems must accurately compute metric values. Additionally, they are freely accessible, allowing researchers to iterate, compare, and evaluate their studies. Software metrics serve as widely utilized indicators of software quality, and numerous studies have demonstrated their effectiveness in estimating the presence of vulnerabilities or defects in code [13]. Software metrics help identify patterns and indicators associated with software code smells [14]. These metrics fall into two categories: static code metrics, which are directly derived from source code, and process metrics, which are obtained from the source code management system by analyzing historical changes in the codebase. The selected metrics in QC systems are at class and method levels; the set of metrics is standard metrics covering different aspects of the code, i.e., size, complexity, cohesion, size, coupling, encapsulation, and Inheritance [8].

B. Data Pre-processing and Features Selection

Pre-processing the gathered data is a crucial step before building the model. Ensuring high data quality is essential for creating an effective model. Not all data collected is suitable for training and model building. The inputs will significantly impact the model's performance and later affect the output [10, 13, 14]. Data pre-processing involves employing a range of methods to improve data quality before building a model. These methods include tasks like removing noise and undesirable outliers from the dataset, addressing missing values, converting feature types, and more [10, 11, 15]. Feature Selection (FS) is a crucial step in selecting the most discriminative features from the list of features using appropriate FS methods [10, 13, 16]. FS endeavors to select the most relevant features for the target class from high-dimensional features while eliminating redundant and uncorrelated ones. Feature extraction facilitates the conversion of pre-processed data into a form that the classification engine can use [3, 11, 17].

C. Class imbalance and data balancing methods

Class imbalance is one of the big challenges facing machine learning models [10, 13]. In classification models, class imbalance occurs when one class has significantly fewer examples than another. Hence, the class imbalance problem makes classification models not effectively predict minority modules [1, 18]. Numerous methods have been created to tackle the challenge of class imbalance, encompassing approaches like cost-sensitive learning, algorithmic adjustments, ensemble techniques, feature selection strategies, data sampling methodologies, and more. The most common among these methods are data sampling methods. These methods typically modify the initial distribution of both the majority and minority classes in the training dataset to achieve a more balanced class distribution.

Random oversampling and SMOTE are widely used data sampling techniques aimed at addressing class imbalance by augmenting the representation of the minority class [9, 14, 18]. Random oversampling involves duplicating instances from the minority class until a desired balance between classes is achieved [1]. Unlike random oversampling, which duplicates existing instances, SMOTE generates synthetic samples for the minority class based on the characteristics of its existing instances [10, 14]. The original datasets were composed of 561 smelly instances and 1119 non-smelly instances; the two first datasets concern the code smells at the class level, for God Class (the number of smelly instances is 140, and the number of non-smelly instances is 280), for Data Class (the number of smelly instances is 140 and the number of non-smelly instances is 280). The two-second datasets concern the code smells at the method level, for Feature Envy (the number of smelly instances is 140 and the number of non-smelly instances is 280), for Long Method (the number of smelly instances is 141 and the number of non-smelly instances is 279).To address the problem of class imbalance and increase the realism of the data, we changed the distribution of instances using two algorithms: Random Oversampling and SMOTE. After balancing the datasets using these algorithms, each type of code smell had an equal number of instances. So, for God Class, there were 280 smelly instances and 280 non-smelly instances. The same goes for Data Class and Feature Envy. For the Long Method, there were 279 smelly instances and 279 non-smelly instances.

Figure 3 shows the distribution of learning instances over original and balanced datasets.

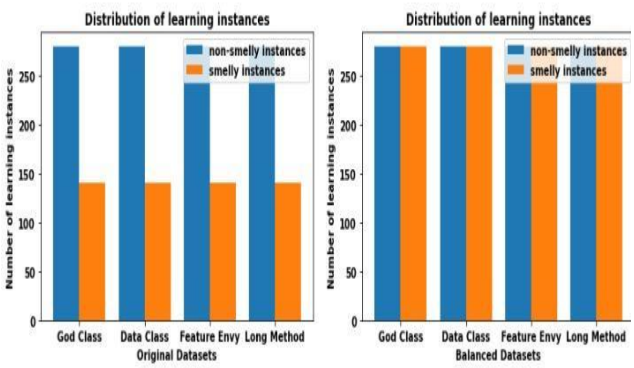

Fig. 3. Distribution of learning instances over original and balanced datasets.

D. Model Building and Evaluation

The model proposed in this study was built using Python programming language based on Keras, a high-level API that is based on TensorFlow. The training datasets constituted 80% of the datasets with randomly selected features, while the validation and test datasets constituted 20%. The model was developed using several parameters such as ReLU and sigmoid as activation functions, Adam as an optimizer, learning rate(0.01), mean squared error as loss function, batch size (64), and number of epochs (100).

The performance of the proposed model is assessed by utilizing a range of performance measures derived from the confusion matrix, MCC, and AUC. MCC is a performance metric that quantifies the difference between a model's predicted and actual values [13, 14]. AUC is a graph that shows how well a classification model performs at different threshold levels, plotting the true positive rate (TPR) against the false-positive rate (FPR) [10, 13, 14]. A confusion matrix is a tabular representation that summarizes the results of the testing algorithm, and it is commonly used to evaluate the performance of a model. Accuracy, precision, recall, and f-measure are the commonly used performance measurement parameters based on the confusion matrix. These parameters report the number of true positive (TP), true negative (TN), false positive (FP), and false negative (FN) predictions, which are presented in Table 2 [5, 10, 20].

TABLE II
Confusion matrix

Predicted	Actual	
	Class X	Class Y
Class X	TN	FP
Class Y	FN	TP

$$Accuracy = \frac{(TP+TN)}{(TP+FP+FN+TN)} \quad (1)$$

$$Precision = \frac{TP}{(TP+FP)} \quad (2)$$

$$Recall = \frac{TP}{(TP+FN)} \quad (3)$$

$$F - Measure = \frac{(2 * Recall * Precision)}{(Recall + Precision)} \quad (4)$$

$$MCC = (TP * TN - FP * FN) \, / \sqrt{(TP + FP) * (TP + FN) * (TN + FP) * (TN + FN)} \quad (5)$$

$$AUC = \frac{\sum_{ins_i \in Positive\ Class} rank(ins_i) - \frac{M(M+1)}{2}}{M \,.\, N} \quad (6)$$

Where $\sum_{ins_i \in Positive\ Class} rank(ins_i)$ Is the sum of the ranks of all positive samples, and M and N are the numbers of positive and negative samples, respectively.

V. Results and Discussion

The experimental setup utilized the Python programming language, and the training and validation datasets were sourced from the same project. To ensure the credibility of the performance assessment, the proposed model underwent training and testing on extensive datasets containing over 6,785,568 lines of source code. Tables 3 and 4 and Figures 4 to 7 below show the results.

TABLE III
Evaluation results of the LSTM model on the original datasets

Datasets	Performance Measures					
	Accuracy	Precision	Recall	F-measure	MCC	AUC
God Class	0.93	0.89	0.89	0.89	0.83	0.94
Data Class	0.94	0.85	1.00	0.92	0.87	0.97
Feature Envy	0.95	0.90	0.96	0.93	0.89	0.99
Long Method	0.86	0.79	0.79	0.79	0.68	0.90
Average	**0.92**	**0.85**	**0.91**	**0.88**	**0.81**	**0.95**

Table 3 presents the results of the LSTM model based on the original datasets in terms of accuracy, precision, recall, f-measure, MCC, and AUC. We notice that the highest accuracy was achieved on Feature Envy, which is 95%, and the lowest accuracy was achieved on Long Method, which is 86%. The highest precision was achieved on Feature Envy, which is 90%, and the lowest precision was achieved on Long Method, which is 79%. The highest recall was achieved on Data Class, which is 100%, and the lowest recall was achieved on Long Method, which is 79%. The highest f-measure was achieved on Feature Envy, which is 93%, and the lowest f-measure was achieved on Long Method, which is 79%. The highest MCC was achieved on Feature Envy, which is 89%, and the lowest MCC was achieved on Long Method, which is 68%. The highest AUC was achieved on Feature Envy, which is 99%, and the lowest AUC was achieved on Long Method, which was 90%.

TABLE IV
EVALUATION RESULTS OF THE LSTM MODEL ON THE BALANCED DATASETS

Random Oversampling						
Datasets	Performance Measures					
	Accuracy	Precision	Recall	F-measure	MCC	AUC
God Class	0.97	0.95	1.00	0.98	0.94	0.98
Data Class	0.99	0.98	1.00	0.99	0.98	0.99
Feature Envy	0.96	0.92	1.00	0.96	0.91	0.97
Long Method	0.97	0.98	0.96	0.97	0.94	0.99
Average	**0.97**	**0.95**	**0.99**	**0.97**	**0.94**	**0.98**
SMOTE						
Datasets	Performance Measures					
	Accuracy	Precision	Recall	F-measure	MCC	AUC
God Class	0.97	0.95	1.00	0.98	0.94	0.98
Data Class	0.99	1.00	0.98	0.99	0.98	1.00
Feature Envy	0.96	0.95	0.97	0.96	0.90	0.99
Long Method	0.98	0.96	1.00	0.98	0.96	1.00
Average	**0.97**	**0.96**	**0.98**	**0.97**	**0.94**	**0.99**

Table 4 presents the results of the LSTM model based on the balanced datasets (using Random Oversampling and SMOTE) in terms of accuracy, precision, recall, f-measure, MCC, and AUC.

Regarding Random Oversampling: We notice that the highest accuracy was achieved on Data Class, which is 99%, and the lowest accuracy was achieved on Feature Envy, which is 96%. The highest precision was achieved on Data Class and Long Method, which is 98%, and the lowest precision was achieved on Feature Envy, which is 92%. The highest recall was achieved on God Class, Data Class, and Feature Envy, which is 100%, and the lowest recall was achieved on Long Method, which is 96%. The highest f-measure was achieved on Data Class, which is 99%, and the lowest f-measure was achieved on Feature Envy, which is 96%. The highest MCC was achieved on Data Class, which is 98%, and the lowest MCC was achieved on Feature Envy, which is 91%. The highest AUC was achieved on Data Class and Long Method, which is 99%, and the lowest AUC was achieved on Feature Envy, which was 97%.

Regarding SMOTE: We notice that the highest accuracy was achieved on Data Class, which is 99%, and the lowest accuracy was achieved on Feature Envy, which is 96%. The highest precision was achieved on Data Class, which is 100%, and the lowest precision was achieved on God Class and Feature Envy, which is 95%. The highest recall was achieved on God Class and Long Method, which is 100%, and the lowest recall was achieved on Feature Envy, which is 97%. The highest f-measure was achieved on Data Class, which is 99%, and the lowest f-measure was achieved on Feature Envy, which is 96%. The highest MCC was achieved on Data Class, which is 98%, and the lowest MCC was achieved on Feature Envy, which is 90%. The highest AUC was achieved on Data Class and Long Method, which is 100%, and the lowest AUC was achieved on God Class, which was 98%.

Figures 4 and 5 show the training and validation accuracy of the model on the balanced datasets. The vertical axis presents the model's accuracy, and the horizontal axis illustrates the number of epochs. Accuracy is the fraction of predictions that our model predicted right.

Figure 4 shows the accuracy values of the LSTM model on the balanced datasets (using Random Oversampling). From the Figure, the model learned 97% accuracy for God Class, 99% for Data Class, 96% for Feature Envy, and 97% for the Long method at the 100th epoch.

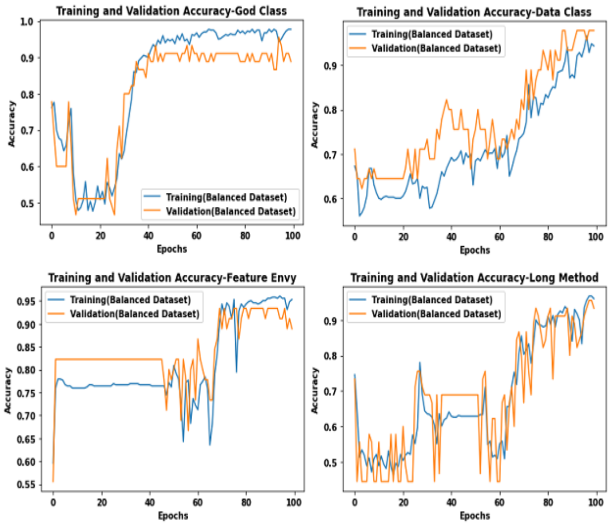

Fig. 4. Training and validation accuracy of LSTM model on the balanced datasets-random oversampling.

Figure 5 shows the accuracy values of the LSTM model on the balanced datasets (using SMOTE). From the Figure, the model learned 97% accuracy for God Class, 99% accuracy for Data Class, 96% accuracy for Feature Envy, and 98% accuracy for Long method at the 100th epoch.

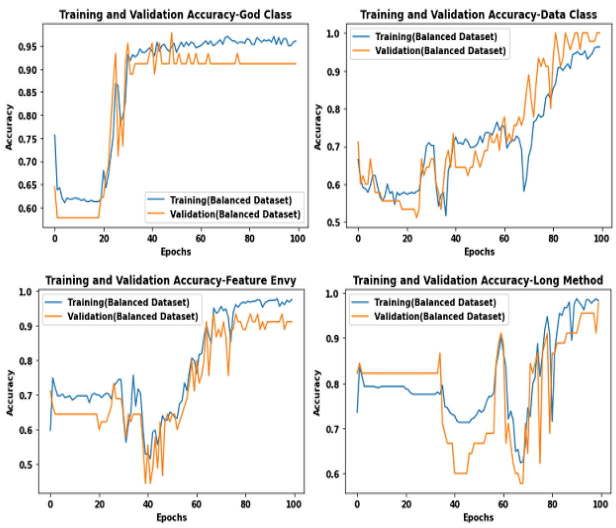

Fig. 5. Training and validation accuracy of LSTM model on the balanced datasets-SMOTE.

Figures 6 and 7 show the training and validation loss of the model on the balanced datasets. The vertical axis presents the loss of the model, and the horizontal axis illustrates the number of epochs. The loss indicates how wrong a model prediction was.

Figure 6 shows the loss values of the LSTM model on the balanced datasets (using Random Oversampling). From the Figure, the model loss is 0.028 for God Class, 0.013 for Data Class, 0.043 for Feature Envy, and 0.025 for the long method at the 100th epoch.

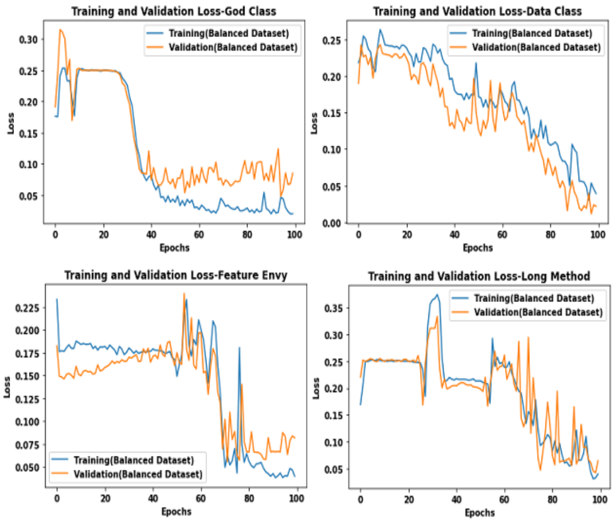

Fig. 6. Training and validation loss of LSTM model on the balanced datasets-random oversampling.

Figure 7 shows the loss values of the LSTM model on the balanced datasets (using SMOTE). From the Figure, the model loss is 0.034 for God Class, 0.009 for Data Class, 0.040 for Feature Envy, and 0.017 for the long method at the 100th epoch.

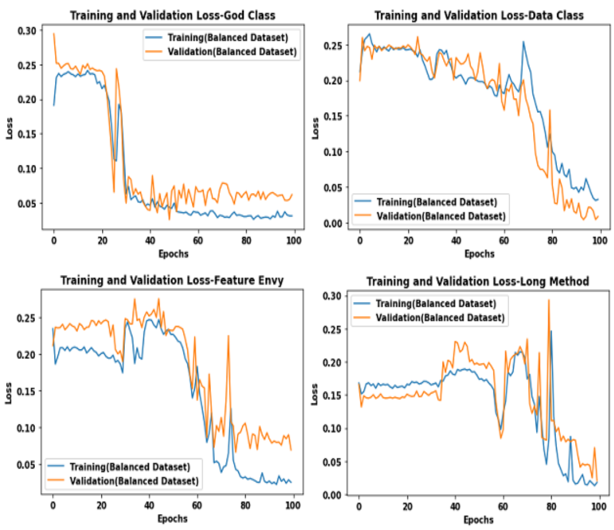

Fig. 7. Training and validation loss of LSTM model on the balanced datasets-SMOTE.

As illustrated in the figures, both training and validation accuracies improve while loss decreases as epochs progress. The high accuracy and low loss achieved by the proposed LSTM model indicate effective training and validation. Furthermore, it's worth mentioning that the model demonstrates almost ideal fitting, with no signs of overfitting or underfitting.

We compared our method results with the results obtained in previous studies based on the accuracy measure. Table 5 compares the values of accuracy obtained by our models and those of previous studies. The optimal values are highlighted in bold within the Table, while "-" indicates approaches that didn't provide results for a specific dataset. From Table 5, while certain results from past studies outshine ours, our method generally surpasses other state-of-the-art approaches, offering superior predictive performance.

TABLE V
COMPARISON OF THE PROPOSED MODELS WITH OTHER EXISTING APPROACHES BASED ON THE ACCURACY

Approaches	Datasets				Averages
	God class	Data class	Feature envy	Long method	
Decision Tree [1]	**0.98**	**1.00**	**1.00**	0.98	**0.99**
K-Nearest Neighbors [1]	0.97	0.96	0.96	0.91	0.95
Support Vector Machine [1]	0.96	0.97	**1.00**	0.96	0.97
XGBoost [1]	0.96	**1.00**	**1.00**	0.98	0.98
Multi-Layer Perceptron [1]	0.97	0.98	0.98	0.96	0.97
Random Forest (3)	0.69	0.70	0.71	0.68	0.69
Naive Bayes (3)	0.82	0.75	0.83	0.81	0.80
Support Vector Machine (3)	0.74	0.83	0.83	0.81	0.80
K-nearest neighbours (3)	0.80	0.82	0.82	0.81	0.81
K-nearest neighbours (5)	0.97	0.97	0.91	0.97	0.95
Naive Bayes (5)	0.96	0.84	0.92	0.95	0.91
Multi-layer Perceptron (5)	0.97	0.97	0.95	0.96	0.96
Decision Tree (5)	0.97	0.98	0.98	0.98	0.97
Random Forest (5)	0.97	0.98	0.97	**0.99**	0.97
Logistic Regression (5)	0.97	0.97	0.97	**0.99**	0.97
Random Forest (8)	0.96	0.98	0.96	**0.99**	0.97
Naive Bayes (8)	0.97	0.97	0.91	0.97	0.95
Decision Tree (15)	-	-	0.97	-	0.97
Random Forest (15)	-	0.99	-	0.95	0.97
Our LSTM model_Balanced Datasets (Random Oversampling)	0.97	0.99	0.96	0.97	0.97
Our LSTM model_Balanced Datasets (SMOTE)	0.97	0.99	0.96	0.98	0.97

VI. CONCLUSION

This study investigated the role and effectiveness of data balancing methods in optimizing the accuracy of the LSTM model for code smell detection. We introduced a novel method that combines the LSTM model with data balancing methods to improve upon current state-of-the-art methods for code smell detection. We addressed the challenge posed by imbalanced distributions of code smells within software projects and investigated various data balancing methods, including random oversampling and SMOTE. To assess the efficiency of our proposed method, we conducted a series of experiments using four datasets on code smells. The average accuracy of our proposed LSTM model on both the original and balanced datasets (utilizing random oversampling and SMOTE) was 92%, 97%, and 97%, respectively.

The findings indicate that employing balanced datasets with the proposed model enhances the average accuracy by 5% in comparison to using the original datasets. Our experimental evaluation showcased the substantial improvement in the accuracy of the LSTM model for code smell detection through the implementation of data balancing methods. Moreover, our proposed method outperforms existing state-of-the-art approaches in code smell detection. We observe incorporating appropriate data balancing methods not only enhances the model's ability to detect code smells accurately but also mitigates the bias towards the majority class, resulting in a more balanced performance across different classes of code smells. This research has practical implications for software developers and researchers. It highlights the significance of considering data balancing methods when applying the LSTM model for code smell detection. By employing these methods, developers can enhance their ability to identify and address code quality issues, improving software maintainability.

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Survey on Handover Techniques for Heterogeneous Mobile Networks

Adnane El Hanjri, Ikram Ben Abdel Ouahab, and Abdelkrim Haqiq

Abstract—**This paper presents an overview of existing techniques of Handover in Heterogeneous Mobile Networks. It gives an overview of the mobility management processes and mainly focuses on decision-making approaches. The literature has reported many problems with seamless support for mobility management techniques. Failures in the Handover operation are caused by frequent disconnections and ineffective seamless Handovers. Therefore, to provide customers with an acceptable Quality of Service, Heterogeneous Mobile Networks must have an effective mobility management system that allows many wireless networks to collaborate. A single parameter, two or more extra factors, or a mix of both are used by several mobile-controlled Handovers to assess the policy choice. In this paper, We have covered many Handover approaches, as well as advancements that have been achieved throughout time. Almost all of the Handover Techniques over the previous ten years have been covered. Based on the many Advantages and Limitations, we have tabulated all the Handover procedures. The paper will be beneficial to emerging specialists in the sector.**

Index Terms—**Handover, Heterogeneous Mobile Networks, 5G networks, Handover Techniques, Performance.**

I. Introduction

In recent years, mobile cellular communication has grown to be one of the most relevant research areas. With the current cellular system architectures, the constantly rising demand for wireless data services necessitates large network densification.

The current cellular network infrastructure cannot satisfy the necessary needs due to its inadequate coverage area and capacity due to the rising demand for multimedia traffic.

Mobility is one of the key traits that has made wireless cellular communication systems indispensable. The procedure of Handover allows continuous service as a user moves between cells. During cell-crossing or/and signal quality deterioration in the present channel, Handover is required. Handover, in the realm of telecommunications and mobile communication, denotes the seamless transfer of cellular transmission from one base station to another, ensuring uninterrupted connectivity throughout the transition [1]. The emergence of Fifth Generation (5G) [2] technology addresses the rising need for high data bit rates. Key to 5G networks is the integration of Small Cells alongside Macrocells, forming what's known as Heterogeneous Networks (HetNets) [3]. These networks combine cells of varying sizes to deliver ultra-dense coverage within specific geographic zones.

To guarantee that Quality of Service (QoS) is not compromised and needless Handovers are avoided and should occur at the appropriate moment by triggering Handover decisions that take all relevant factors into account.

Various criteria are used in the Handover process as part of the mobility management scheme, which improves system performance at the time of the Handover choice. These metrics are important for evaluating the performance of Handover procedures and identifying potential issues that may affect the performance of the network. By monitoring these metrics, network operators can make adjustments to enhance the performance of the network and provide a better experience for users.

In this work, we present a detailed Survey of Handover Techniques for Heterogeneous Mobile Networks. This article is organized as follows. In Section II, we introduce the Handover definition, phases, and types. Section III provides Handover issues. Section IV, discusses various parameters affecting the performance during the Handover, then the Handover Techniques are presented in Section V. Then, the Handover Management Techniques in 5G Networks are presented in section VI. After that, we introduce the Future Research Directions in Section VII. Finally, in Section VIII, we conclude the article.

II. Handover

A Handover, further known as a handoff, is a crucial concept in wireless cellular communication that allows the User Equipment (UE) to go from one cell to another without losing the session. This process is essential in mobile networks, as it allows a mobile device to maintain a connection while moving between different cells or Base Stations (BSs), where BS is a general term for any Base Station (BTS is a GSM term, NodeB, eNodeB or NR is used in 3G/4G/5G). Handovers are typically performed seamlessly, without interruption to the user's communication.

A. Phases of Handover

Every Handover process contains three phases, see figure 1.

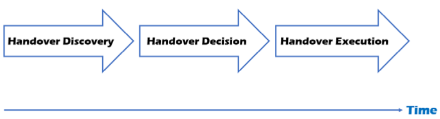

Fig. 1: Phases of Handover

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Handover Discovery: A Handover process must start whenever a mobile node requires a move away from its point of attachment to the present network in order to connect to another network where the QoS will be better. Typically, a weak signal or a value for one or more quality of service criteria below a certain threshold may be to blame. The mobile node scans the networks in its immediate area continually throughout this phase in order to get the essential data.

Handover Decision: In this phase, the UE chooses the best access network and gives instructions to the execution phase in order to decide if and how to complete the Handover. Several parameters have been proposed in the research literature for use in the Handover decision algorithms, such as, Handover delay, Number of Handovers, Handover failure probability, and Throughput.

Handover Execution: During this phase, the source BS transmits the handover command to the UE. Following receipt of the handover command, the UE instantly disconnects from the source cell and starts building a downlink synchronization link with the destination cell.

B. Handover Types

There are different types of handovers, including:

Hard Handover: Where the connection to the existing BS is shut down before a new connection is established with a new BS. This type of Handover is typically used in cellular networks and is known for its quick and efficient transfer of data.

Soft Handover: Where the connection to the current BS is maintained while a new connection is established with a new BS. This type of Handover is typically used in cellular networks and is known for its ability to offer a more reliable connection, as the mobile device is connected to multiple BSs simultaneously.

Horizontal Handover: This type of Handover occurs when a mobile device moves between different cells or base stations that are part of the same network.

Vertical Handover: This type of Handover occurs when a mobile device moves between different types of networks, such as a cellular network and a wireless network.

Intra Handover: also known as an intra-cell handover or handover within the same cell, occurs when a mobile device switches between different sectors within the same base station or cell.

Inter Handover: also known as an inter-cell handover, occurs when a mobile device switches its connection from one cell to another within the same or a different eNodeB (Evolved NodeB, a base station in LTE).

III. HANDOVER ISSUES

There are several issues that can arise during the Handover process, which can impact the quality and reliability of the connection, these issues include:

Handover delay: This occurs when there is a delay in the Handover process, which can result in dropped calls or data packets.

Handover delay: This occurs when there is a delay in the Handover process, which can result in dropped calls or data packets.

Handover failure: This occurs when the Handover process fails, resulting in a loss of connection.

Ping-pong effect: This happens when the mobile device switches between BSs multiple times, resulting poor call quality and increased power consumption.

Interference: This occurs when multiple mobile devices are trying to access the same resources, leading to congestion and reduced capacity.

Security: This issue occurs when the Handover process is not properly secured, which can lead to unauthorized access to the network or eavesdropping on communications.

Quality of Service (QoS): During the Handover process, the QoS of the call or data session may be affected, resulting in a lower-quality connection.

Mobility management: This issue is related to the management of the mobile devices in the network, it can cause delays in the Handover process and a lack of resources for the new connection.

To avoid these issues, the network should be designed to minimize Handover delay and Handover failure and to ensure that the Handover process is secure and efficient. Additionally, the network should be optimized to provide a good QoS and good management of mobile devices.

IV. FACTORS INFLUENCING PERFORMANCE DURING HANDOVER

The factors determining whether a Handover is necessary are Handover metrics. These metrics can either be dynamic or non-dynamic depending on the source of Handover and the frequency of recurrence, see figure 2.

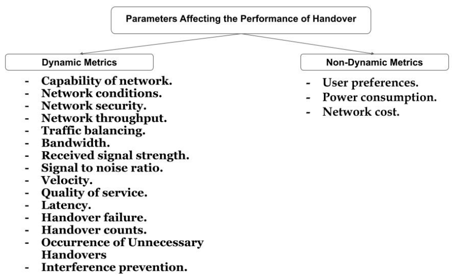

Fig. 2: Parameters Affecting the Performance During Handover

A. Dynamic Metrics

These measures' values fluctuate regularly, which has a significant impact on the decisions relating to Handover. Here are some of the most important dynamic aspects covered.

Capability of Network: In terms of bandwidth support, protocol support, interoperability standards, etc., different networks have varying capacities.

Network Conditions: Network topology and dynamic changes taking place nearby are crucial factors to consider while making handoff decisions.

Network Security: During the Handover decision step, security policies pertaining to integrity, authorization, authentication, confidentiality, and resource modification must be correctly injected.

Network Throughput: The network throughput serves as a gauge for effective data delivery.

Traffic Balancing: The capacity of the cells to carry traffic is reduced due to frequent changes in network loads, which also lowers the QoS requirements.

Bandwidth: Lower call dropping and less call blocking are caused by increased bandwidth.

Received Signal Strength (RSS): The RSS significantly contributes to minimizing the ping-pong effect. Lower RSS numbers result in a greater network load, whereas higher RSS values cause more call drops.

Signal-to-Interference-plus-Noise Ratio (SINR): Quantifies the ratio of the desired Signal strength to the combined strength of Interference and Noise in a communication system.

Velocity: Higher velocity in microcellular networks causes more Handovers to occur often, which raises the overall handover counts.

Quality of Service (QoS): The network performance is certified by QoS levels.

Handover Latency: The QoS metrics are impacted by Handover latency, which also lowers network throughput and performance.

Handover Failure: The main reasons for handoff failure are mobility and a lack of resources at the destination station.

Handover Counts: The value of handover counts should be reduced.

Occurrence of Unnecessary Handovers: Ping-pong effects caused by unnecessary handoffs increase communication and handoff latency overheads.

Interference Prevention: Interference during Handover is extremely undesirable since it lowers the QoS requirements, which in turn makes users less satisfied.

B. Non-Dynamic Metrics

These metrics change far less often than dynamic metrics, which means they have less of an impact on the Handover mechanism. Below is a list of a few non-dynamic factors.

User Preferences: Depending on their preferences and the needs of the application, users may have a variety of options.

Power Consumption: Due to interface activations during the decision phase of the Handover procedure, battery consumption occurs.

Network Cost: It speaks of the whole expense of gaining access to the network throughout the Handover. It is determined using a cost function based on call arrival rates.

V. Handover Techniques

The decision-making process for Handover involves assessing the available wireless access networks. As a result of this procedure, a network is chosen to which a Mobile Terminal should be transferred while taking the information acquired during the system discovery phase into account. Although standards do not specify decision algorithms, there are numerous possibilities in the literature. These algorithms' dependability and complexity depend on how readily available and dynamic the inputs are. We list a selection of the most popular Handover decision-making processes below,

A. RSS based Handover Decision

RSS (Received Signal Strength) based Handover decision works by monitoring the signal strength between the mobile device and the BS, and when the signal strength falls below a certain threshold, a Handover is triggered [4].

Base Stations are designed to cover specific areas efficiently, so they often have multiple cells or sectors. RSS indeed pertains to the signal strength received by the mobile device from a specific transceiver within a cell/sector. It is not a measure of the combined signal strength from all transceivers within the BS. RSS measurements are relevant for all cell sites, whether they have single or multiple cells/sectors. However, when discussing RSS in the context of a specific cell/sector, it is important to understand that it relates to the signal strength from the individual transceivers serving that cell/sector, not from all transceivers within the entire BS.

The RSS-based Handover decision has some advantages, simple to implement and widely used in wireless networks. Additionally, it is based on the signal strength which is a direct measure of the quality of the connection.

However, it has some drawbacks as well, it is only based on the signal strength and it does not take into account other factors such as network congestion, available capacity, and QoS. Moreover, it is sensitive to the environment and the obstacles that may affect the signal strength.

B. Bandwidth based Vertical Handover

In this technique, the mobile device monitors the available bandwidth of different networks, such as cellular networks and wireless networks, and selects the network that can provide the highest bandwidth [5] [6].

The bandwidth-based vertical Handover has some advantages, efficient and flexible as it can adapt to changing network conditions.

However, it has some drawbacks as well, it is dependent on the accurate measurement of the available bandwidth, and the measurement can be affected by some factors such as interference or network congestion. Additionally, it does not take into account other important factors such as security and cost.

C. Cost based Vertical Handover

This technique involves evaluating the costs associated with different network options and selecting the network that provides the best balance of cost and QoS [7] [8] [9].

The cost evaluation can be based on different factors, such as the cost of data usage, the cost of network access, and the cost of device compatibility.

The cost based vertical Handover has some advantages, it is based on the cost-benefit ratio and it is selecting the network that offers the best balance of cost and QoS. Additionally, it is efficient in terms of cost management.

However, it has some drawbacks as well, it may not always prioritize the QoS over the cost and it is not always easy to accurately estimate the costs associated with different network options.

D. Multi Metric Handover Decision

Multi-Metric Handover Decision is a technique that works by taking into consideration multiple metrics, such as signal strength, available bandwidth, network congestion, and QoS when making a Handover decision [10] [11] [12].

In a Multi-Metric Handover Decision, each metric is assigned a weight, and the Handover decision is made based on a combination of these weights and the corresponding metric values.

The Multi-Metric Handover decision has some advantages, it is based on multiple metrics, which provides a more accurate and reliable Handover decision. Additionally, it is efficient and flexible as it can adapt to changing network conditions.

However, it has some drawbacks as well, it is dependent on the accurate measurement of the multiple metrics, and the measurement can be affected by some factors such as interference or network congestion. Additionally, it can be complex to implement and it may require more computation power.

E. Function based Decision Algorithm

Function-based decision algorithm is a technique that works by defining a function, or set of functions, that take into account multiple parameters, such as signal strength, available bandwidth, network congestion, QoS, and use this function to make a Handover decision [13].

This function is typically based on mathematical equations or models, and it is designed to optimize a specific performance metric, such as Handover delay, Handover failure rate, or call/data session drop rate.

Function based decision algorithm has some advantages, it is based on multiple parameters and it uses a function to make a decision, which provides a more accurate and reliable Handover decision. Additionally, it is efficient and flexible as it can adapt to changing network conditions.

However, it has some drawbacks as well, it is dependent on the accurate measurement of the multiple parameters, and the measurement can be affected by some factors such as interference or network congestion. Additionally, it can be complex to implement and it may require more computation power.

F. User Centric Decision Algorithm

User Centric Decision Algorithm is a technique that works by taking into account the preferences and needs of the user, in addition to network-related parameters, such as signal strength, available bandwidth, network congestion, and QoS, when making a Handover decision [14] [15].

The User Centric Decision Algorithm has some advantages, it is based on the user's preferences and needs, which can provide a more satisfactory experience for the user. Additionally, it is efficient and flexible as it can adapt to the changing user's preferences and needs.

However, it has some drawbacks as well, it is dependent on the accurate measurement of the user's preferences and needs, and it can be affected by some factors such as the user's behavior change. Additionally, it can be complex to implement and it may require more computation power.

G. Context Aware Handover Decision

The context data contains information on mobile stations, such as their capacity, battery life, location, and mobile velocity. To keep up an elevated standard of customer satisfaction, vertical handover decisions are thought to be best made using user-based information such as preferred network, cost, and application-based information such as the type of service (conversational, background, streaming, etc.).

These approaches improve system flexibility and efficient service continuity [17] [16]. meanwhile, the decision is based on global knowledge and results in computational delays, the designed solutions are centralized and require a lengthy processing time.

H. Media Independent Handover Decision

The key concept behind Media Independent Handover Decision (MIH Decision) [18] is to enable a mobile device or user equipment to make intelligent handover decisions autonomously or with the assistance of network entities. It allows the device to assess the available networks or technologies and determine the optimal handover strategy based on predefined policies or algorithms.

The accuracy of the network state information affects how effective this algorithm is. The routing information contains the gateway along with cost and metrics like data rate, throughput, and latency under network conditions, whereas the network parameters include mode, authentication, and cost [19].

I. Multiple Attributes Decision Making

Multiple attributes decision making (MADM) [20] is a technique that works by taking into account multiple attributes, such as signal strength, available bandwidth, network congestion, QoS, cost, and security, when making a Handover decision [21].

MADM has some advantages, it is based on multiple attributes, which provides a more comprehensive and reliable Handover decision. Additionally, it is efficient and flexible as it can adapt to changing network conditions.

However, it has some drawbacks as well, it is dependent on the accurate measurement of the multiple attributes, and the measurement can be affected by some factors such as interference or network congestion. Additionally, it can be complex to implement and it may require more computation power.

J. Markov based Decision Algorithm

In this technique [22], the network states can be defined based on various parameters such as signal strength, available bandwidth, network congestion, QoS, cost, and security. The transition probabilities between these states are determined using historical data and statistical analysis.

When a Handover is necessary, the algorithm uses the current state and the transition probabilities to determine the next state, which is the network that offers the best performance.

Markov-based decision algorithm has some advantages, it is based on historical data and statistical analysis, which provides a more accurate and reliable Handover decision. Additionally, it's efficient and flexible as it can adapt to changing network conditions.

However, it has some drawbacks as well, it is dependent on the accurate measurement of the multiple attributes, and the measurement can be affected by some factors such as interference or network congestion. Additionally, it can be complex to implement and it may require more computation power.

K. Computational Handover Decision

In computational Handover decisions [23] [24] [25], the algorithm or model is trained on a set of data that includes information about network conditions, such as signal strength, available bandwidth, and network congestion, as well as information about Handover outcomes, such as Handover delay and Handover failure rate. The algorithm or model can then be used to analyze new data and make a Handover decision.

Computational Handover decision has some advantages, it is based on a mathematical algorithm or model that is trained on a set of data, which can provide a more accurate and reliable Handover decision. Additionally, it is efficient and flexible as it can adapt to changing network conditions.

However, it has some drawbacks as well, it is dependent on the accuracy of the data used to train the algorithm or model and it is also dependent on the quality of the algorithm or models and it can be complex to implement.

L. Game Theoretic Approach for Decision Making

Several game theory methodologies, such as cooperative games, non-cooperative games, hierarchic games, and evolutionary games, could be used to simulate the Vertical Handover decision problem.

A cooperative bandwidth allocation technique based on the bankruptcy game is proposed by Niyato et al. in [26]. In this N-person cooperative game, networks work together to use coalition form and characteristic function to create new connections with the necessary bandwidth. By employing the fundamental idea, the stability of the allocation is examined. Each network aims to make the most of the available bandwidth in order to increase revenue from new connections. The same authors refer to the issue of bandwidth allotment as an oligopoly market rivalry in [27]. This market competition is modeled using a Cournot game, and Nash equilibrium is thought to offer a stable resolution. Iterative and search techniques are recommended for obtaining the Nash equilibrium. In both articles, the other authors offered an admission control mechanism based on the suggested bandwidth allocation system to supply new connections with high QoS for both vertical and Horizontal Handover.

Haddad et al. invent a hierarchical distributed learning framework for decision-making during Vertical Handover in Heterogeneous cognitive networks in [28]. They use a Nash-Stackelberg fuzzy Q-learning model to represent the issue. The mobile nodes are seen as followers who want to maximize their QoS while the network is seen as the leader who wants to maximize its revenue.

In [29], Dusit et al. model the Vertical Handover decision problem as a dynamic evolutionary game where various user groups in various service areas compete to share the finite quantity of bandwidth on the available networks. It is believed that the evolutionary equilibrium is the answer to this game. The population evolution method and the reinforcement-learning algorithm are the two network selection algorithms the authors suggest. The first system achieves evolutionary equilibrium more quickly, but it needs a central controller to collect, process, and broadcast data on users within a certain service area. The second technique, however, enables a user to gradually learn and modify the network selection choices to reach evolutionary equilibrium without any user intervention. Then, a Nash equilibrium result derived from a traditional non-cooperative game model is compared to the suggested evolutionary game model.

M. Reputation based Decision Making

In this approach [30] [31], the mobile device maintains a reputation value for each available network, based on feedback from other users or network entities. The Handover decision is made based on the reputation value of the available networks, with the mobile device choosing to connect to the network with the highest reputation value.

This technique can be useful in situations where traditional Handover decision methods may not be able to capture the quality of the network, such as network congestion or QoS.

Reputation-based decision-making has some advantages, it is based on the reputation of the network, which can provide a more accurate and reliable Handover decision by taking into account the quality of the network. Additionally, it is efficient as it can adapt to changing network conditions.

However, it has some drawbacks as well, it is dependent on the accurate measurement of the reputation of the network, and the measurement can be affected by some factors such as false or unreliable feedback. Additionally, it can be complex to implement and it may require more computational resources.

N. Cross Layer based with Predictive RSS Approach

Cross-layer-based with predictive RSS approach is a technique that combines the information from different layers of the protocol stack, such as the physical, data link, and network layers, and uses a predictive algorithm to make a Handover decision [32] [33].

The predictive algorithm uses the RSSI to predict the future signal strength of a network, based on the historical data of the RSSI. The Handover decision is made based on the predicted future signal strength and the information from other layers of the protocol stack.

This technique has some advantages, it is based on a combination of information from different layers of the protocol stack, which can provide a more comprehensive and reliable Handover decision. Additionally, it's efficient as it can predict future signal strength and adapt to changing network conditions.

However, it has some drawbacks as well, it is dependent on the accurate prediction of the future signal strength, and the prediction can be affected by some factors such as uncertainty or lack of data. Additionally, it can be complex to implement and it may require more computational resources.

A summary of the Handover decision-making processes are briefly mentioned in Table I:

TABLE I
ADVANTAGES AND DISADVANTAGES OF EXISTING HANDOVER DECISION SCHEMES

Existing Handover Decision schemes	Advantages	Disadvantages
RSS based	Simple design	Increased unnecessary handover, increase ping pong effect
Bandwidth based	Good throughput performance, good network selection	Inefficient bandwidth computation
Cost based	Less call drop probability reduced ping pong effect	Increased system overload
Multi metric based	Very less call-drop blocking, good context collection	Complex design leads to implementation issues
Function based	Minimum degradations in high load and congestion situations	Time consuming if services and/or available access points increase.
User-Centric based	Maximizes users' utility, High user consideration and low implementation complexity	No real-time support, simple rate prediction method
Context-Aware Handover Decision	Improve system flexibility and efficiency	Time Consuming, computational delays
Media Independent Handover Decision	Seamless Connectivity, Optimal Network Selection, Optimization and Efficiency	Complexity and Standardization, Increased Device Complexity, introduces additional delay and latency during handovers
MADM	Multi criteria consideration, better decision on dynamic parameters	Medium implementation complexity, Performance dependence on traffic class
Markov based	Adaptive and applicable to a wide range of conditions, Better delay performance	Implementation complexity
Computational Handover Decision	Makes decisions in an automatic way consider multi-criteria, reduced handover delay	Complexity increases if additional input parameters are considered
Game theory based	Efficient resource management, Improves the individual efficiency of mobile users	Additional decision parameters are required in practice to ensure a better quality of service
Reputation based	Faster handover decision	Reputation sustainability need to be addressed in more depth
Cross-Layer based	Adapt to dynamic network conditions by continuously monitoring and analyzing various metrics, including signal strength, channel conditions, congestion levels, and available resources	Lack standardized guidelines and protocols, making it difficult to ensure interoperability and compatibility across different network devices and vendors

VI. HANDOVER MANAGEMENT TECHNIQUES IN 5G NETWORKS

A. Radio Access based Techniques

The following section explains the radio access-based techniques used to control the handover procedures in 5G heterogeneous networks.

Zhang et al. [34] proposed cooperative interference mitigation and handover management in a Heterogeneous cloud small cell network (HCSNet), where a cloud radio access network is combined with small cells. An effectively coordinated multi-point (CoMP) clustering method using affinity propagation was devised to decrease interference from cell edge users. In HCSNet, the signaling procedure of a low-complexity handover management scheme is presented and reviewed. Based on numerical findings, it is possible to greatly enhance the capacity of HCSNet while maintaining the quality of service for users with the suggested network architecture, CoMP clustering scheme, and handover management system.

Maksymyuk et al. [35] [36] created the converged access network for the handover mechanism in the 5G heterogeneous network. In this instance, the wireless access segments and the optical backhaul were both a part of the radio access network. Additionally, the presented technique provides good bandwidth granularity allocation. Further, by employing this method, the radio signals between the remote radio head and baseband processing unit can be adjusted within the same resource blocks by the cloud radio access network channel. Moreover, the multicast data transmission to the complex eNodeB was also constructed through the collaborative efforts of resource elements for diverse cells. The invention of this data transmission, which greatly reduces backhaul traffic, was made possible by the changeover mechanism. Its drawback is that it leads to network congestion.

A generalized Random-Access Channel Handover (RACH) technique was created by Choi and Shin [17] for handover in a 5G heterogeneous network. In the absence of a synchronized network, this created approach achieved perfect mobility. This new RACH approach incorporated the make-before-break (MBB) handover and the RACH-less transfer. Smooth mobility was made possible by the well-established RACH technology by going from the serving cell to the user equipment. Since no other delay causes are impacted by the created method's important elements, they work with the long-term evaluation handover. The developed method did not, however, include the use of packet duplication to improve path switching.

B. Self Optimization based Techniques

The handover procedure for 5G heterogeneous networks' usage of self-optimization techniques is covered in detail in this subsection. Boujelben et al. [37] employed the handover self-optimization technique in the 5G heterogeneous network. The authors proposed a new Handover self-optimization method that is mainly designed to reduce network energy usage. When selecting the Handover destination cell, the received signal power, user speed, and the load of surrounding cells are all taken into account. The results of the performance evaluation demonstrate that, for all the specific user speed scenarios, the proposed algorithm significantly lowers the energy consumption in the network. The main difficulty with the developed approach is inter-cell interference.

C. Software Defined Network based Techniques

This section describes approaches of the Software Defined Network (SDN) based handover techniques used in the handover mechanism for the 5G heterogeneous network.

Tartarini et al. [38] developed a combination of a software-defined handover decision engine and a software-defined wireless networking method to improve the handover in a 5G heterogeneous network. Here, the wireless controller was used by the baseband pool to receive the handover information. The controllers' distribution of the communication information enabled the handover choice to be carried out optimally for each user. The candidate network selection strategy was also created as a technique for resolving binary integer linear programming optimization difficulties. Additionally, the user equipment mobility patterns and the adaptive timing technique were employed to reduce handover errors and restrict undesired handovers, respectively. The effectiveness of the created method has not been increased by implementing less-than-ideal solutions. The developed approach failed to enhance network performance when there was a wider variety of network types.

Rizkallah and Akkari [39] introduced a SDN for the vertical handover method in 5G heterogeneous networks. The data plane and the control plane were separated by utilizing the SDN. Utilizing the SDN also decreased the handover signaling message. The software-defined controller was then used to gather network data after that. The optimum handover choice was made based on the software-defined controller, which also helped to raise each network's quality of service.

Duan and Wang [40] developed the SDN for the handover mechanism in the heterogeneous network. The suggested method was used to facilitate the transfer of authentication and privacy protection. Protection for privacy was enabled among the connected access points. The created software-defined network also lowers the authentication handover latency and offers a platform for network management that can be customized. They assessed the use rates and the latency for authentication. The single point failure and security is the challenge of the Software Defined Network handover approach [41] [42].

D. Authentication based Techniques

This section illustrates authentication-based techniques used with various handover mechanisms now in use for 5G heterogeneous research.

Cao et al. [43] introduced the secure and efficient re-authentication and the group-based handover authentication procedure for 5G heterogeneous networks. This method was utilized to obtain strong security protection. In order to achieve the ensuing communications, a detached session key was finally incorporated into the network and the machine-type communication devices. Better security was attained with perfect effectiveness. Only some of the unidentified attacks are protected by the developed approach.

Fan et al. [44] employed a secure region-based handover technique in the 5G heterogeneous network. With no fundamental network components, the newly created region-based rapid authentication protocol was used to lower transmission and computation costs. The technique also guarantees that no other communication footprints are identical to anonymity. After that, user membership could be revoked using a gathered one-way hash, which removed the need for computational work in the 5G heterogeneous system. Through region-based secure handover, our newly designed solution successfully reduced the handover delay. This cutting-edge approach also met each user's security requirements. On the other hand, the developed approach omitted security-providing performance analytics and key management.

E. Evolved NodeB based Techniques

The eNodeB-based approaches in the handover mechanism for the 5G heterogeneous networks are detailed in this section.

Bilen et al. [45] developed the optimal eNodeB selection approach. The gain function was computed with dynamic weights for selecting the candidate cells. To select the best eNodeB in this case, the spatial estimation autoregressive approach evaluated the Kriging Interpolator and Semivariogram analysis. The best modeling performance is provided by the statistical and stochastic behaviors of Kriging Interpolations. Through the definite values of neighbor user equipment, the unidentified indicator value of mobile user equipment was also calculated. The created eNodeB estimate object, which correlates with every network node, was used to carry out every activity. These evaluations were also used separately in the control and data channels. They decreased the likelihood of needless, frequent, and ping-pong handovers, while the throughput remained the same.

F. Neural network based Techniques

This section serves as an illustration of research that made use of neural network-based methods.

Maksymyuk and Shubyn [35] employed the Recurrent Neural Network (RNN). Here, user mobility information was used to implement the neural network in the most effective way possible. As a result, the generated system's performance was improved by applying the gated recurrent unit-based neural network. Additionally, a cell individual offset parameter was located and used to carry out the mobility load balance. The gated recurrent unit-based neural network was also modified to find the subscriber's movement. They were only able to estimate the traffic in the Neural Network with an accuracy of less than 90%. In addition, benchmark data are not used, nor are network parameters analyzed to determine efficiency.

Morghare and Mishra [46] presented the neural network-based handover approach. Here, the neural network design was combined with the Particle Swarm Optimization (PSO) method. To improve system efficiency, the created method was used for quick delivery handover routes and network selection. However, to increase the effectiveness of the system, a sizable number of secondary users were also taken into consideration. Additionally, an optimization challenge and network selection issues were resolved using the created neural network method. Finally, the network selection for the free route and changeover path for data transfer was determined. Taking into account the interference and the population size, they were able to improve fitness with fewer iterations. When handing over the mobile terminal, the technique neglected to take network security and harmful assaults into account.

G. Blockchain based Techniques

This section shows the blockchain-based solutions that have been gathered from the numerous handover strategies already in use in 5G heterogeneous network research projects.

Ma and Lee [47] developed the blockchain scheme for the 5G heterogeneous network handover process. The Parallel Block-chain Key Derivation Function (PB-KDF), which regulates the fundamentals of the Bitcoin blockchain for structurally supporting the key derivation process, was used in this method. Additionally, the PB-KDF aids in improving handover performance. After that, the system's security was enhanced by using the blockchain outside of the cryptocurrency space. The mining procedure takes advantage of the handover key in this instance to allow both complete backward and full forward partitions. Consequently, the new PB-KDF technique improves both the performance and security of the handover. However, because key management creates computing costs and is not included in the processing phase, they did not take the computation difficulty into account and instead focused on improving security during intracellular handover.

Yazdinejad et al. [48] employed the blockchain-enabled authentication handover method in the 5G heterogeneous network. The software-defined network and heterogeneous network management were also used to increase programmability. The user's security and privacy were both preserved using this strategy, which also made use of encryption resources. Additionally, in recurrent changeover among heterogeneous networks, the introduced technique was used to reduce the avoidable re-authentication. In order to provide intelligent control among the diverse cells and safeguard user privacy, the software-defined network was also employed. Energy efficiency and scalability goals are met, however, the system's disadvantage is that security, data leakage, and handover delays still occur.

H. Blind Handover Technique

Blind handover is a technique used in wireless networks to perform Handover without the need for explicit signaling between the mobile device and the network. In this technique, the mobile device continuously monitors the signal strength of available networks and selects the network with the strongest signal to connect to, without consulting the network.

This technique is commonly used in wireless networks, such as WiFi and cellular networks, to ensure a seamless Handover between different access points or base stations. The mobile device uses the received signal strength indicator (RSSI) to measure the signal strength of available networks and select the network with the strongest signal.

In [49] [50] EL Hanjri et al. propose a new approach, to have an efficient, blind, and rapid Handover just by analyzing the received signal density function instead of demodulating and analyzing the received signal itself in classical Handover. The proposed approach exploits some mathematical tools like Kullback Leibler Distance, Akaike Information Criterion, and Akaike Weight.

The blind Handover technique has some advantages, simple to implement and does not require any explicit signaling between the mobile device and the network. Additionally, it's efficient as it can perform handover quickly, which can reduce the interruption of communication.

However, it has some drawbacks as well, it is dependent on the accurate measurement of the signal strength, and the measurement can be affected by some factors such as interference or network congestion. Additionally, it may not always select the network that offers the best Quality of Service (QoS) or the lowest cost, which might lead to poor call quality or dropped calls in case the mobile device connects to a network with poor signal strength.

A summary of The Handover Management Techniques in 5G Network with their Advantages and Limitations are briefly mentioned in Table II:

TABLE II
THE HANDOVER MANAGEMENT TECHNIQUES IN 5G NETWORK WITH THEIR ADVANTAGES AND LIMITATIONS

Handover Management Techniques in 5G Network	**Advantages**	**Limitations**
Radio Access-based	Increase the capacity while maintaining users' quality of service, reduce the back-haul traffic	Creates congestion in the network, failed to use packet duplication for path switching optimization
Self-Optimization-based	Reduce the energy consumption in the network	Inter-cell interference
Software-defined network-based	minimize the handover failures, eliminate the unwanted handover, reduce the authentication handover latency	Failed to improve network performance when higher diversity of network types
Authentication-based	Achieved better security with ideal efficiency, reduce communication and computation costs	Did not include performance analytics and key management for providing security
Evolved NodeB-based	Reduce the unnecessary, frequent, and ping-pong handover risk	Does not change the throughput
Neural network-based	Achieve a better fitness value with a reduced number of iterations while considering the interference and the population size	Fail to consider the security and the malicious attacks of the network while handovering the mobile terminal
Blockchain-based	Enhance the handover performance and improve the security of the system	Fail to consider the computation complexity
Blind Handover	Simple to implement and does not require any explicit signaling between the mobile device and the network, can perform handover quickly, which can reduce the interruption of communication	May not always select the network that offers the lowest cost

VII. FUTURE RESEARCH DIRECTIONS

Target criteria for mobile users will undergo significant development in the next-generation wireless networks. However, when the UE switches between cells in an extremely dense HetNet, adequate consideration must be given throughout the Handover procedure. The following subsections provide more details on a few of the probable future study fields that are briefly mentioned in Table III.

TABLE III
THE FUTURE ENABLER TECHNOLOGIES WITH THEIR ADVANTAGES AND LIMITATIONS

Future Technology	**Advantages**	**Limitations**
SDN	Flexible, programmable, and efficient way to manage and control networks with reduced operational costs	Complexity, Lack of standardization, and Lack of well-defined algorithms
ML and DL	The mobility management can be controlled by using machines	A state of the art Handover Decision Algorithms are required
Optimized Load Balancing	Achieve higher throughput and better QoS	The use of Dual Connectivity in a 5G Non-Standalone architecture

A. Software Defined Network

A method for managing the dynamic nature of various network topologies and their rising complexity is the SDN idea [51]. The Handover process is the primary management challenge for many network designs.

For instance, publication [52] describes a Handover mechanism for extremely dense 5G mobile networks based on SDN. SDNs struggle with numerous pointless Handovers. Decoupling network functions from specialized hardware devices to make them into tasks carried out by software-based programs is known as network function virtualization [53].

By executing layer 2 and layer 3 on the software-based application, virtual base stations enable operators to carry out operations from various mobile network technologies with a single virtual base station. Four stages make up the proposed Handover scheme: data collection, data processing, V-cell construction, and Handover execution. The phase of data gathering involves the control plane acquiring information about the state of the network. Measurement reports from the mobile node, serving base station, and potential Handover base stations are among the data that have been gathered. To choose the optimal set of target base stations for mobile users with various behaviors, the collected data is then processed to generate QoS for each base station coverage region.

B. Machine Learning (ML) and Deep Learning (DL)

To help the 5G wireless network achieve its objectives, a number of cutting-edge technology and networking strategies have been put forth. However, these solutions have also created a new set of issues, making the network's administration issues more complicated. For instance, HetNets has made it more difficult to govern many operations, such as mobility management, while still offering better coverage. Another essential component of the 5G wireless network, proactive data-driven models must replace traditional reactive-based models to increase the productivity of these models. Future innovations in 5G HetNet technologies and architectures will heavily rely on machine learning-based algorithms [54].

The most alluring method with the biggest potential for the 5G mobile network is machine learning [55]. Machine Learning based techniques are necessary in HetNets to correctly implement Handover judgments. These algorithms give the system the ability to automatically change parameters in response to UE demands and specifications. Thus, frequent handovers can be effectively decreased.

Machine Learning based algorithms give systems the ability to learn on their own, improving performance through encounters without having their roles defined beforehand. Systems may actively monitor, learn, and predict network behavior using data from the dynamic nature of network parameters thanks to machine learning-based techniques. To complete the required tasks, machine learning-based algorithms propose data-driven approaches to model system parameters and their impacts on complex systems.

Deep Learning is a branch of AI that teaches machines to perform tasks on their own. It is a strategy that has recently received a lot of attention and is quite promising. Artificial neural network techniques, a sophisticated technology for tackling complex problems, are also used in deep learning. In order for autonomous vehicles to recognize stop signs and distinguish between pedestrians and lampposts, deep learning is a crucial component. It makes voice control possible for household electronics including hands-free speakers, tablets, smartphones, and televisions. Recently, deep learning has drawn a lot of attention, and for good reason. It is reaching results that weren't possible before. Deep Learning models have the potential to achieve cutting-edge accuracy, frequently beating humans. Massive amounts of labeled data and multilayer neural network topologies are used to train the models. Better recognition accuracy than ever is delivered by deep learning. In safety-sensitive applications like driverless vehicles, this makes it possible for consumer electronics to live up to user expectations. Deep learning has recently advanced to the point where it is now superior to humans at some tasks, such as classifying objects in pictures [56].

C. Optimised Load Balancing

Potential methods for adjusting radio resources in the HetNet context of a mobile cellular network include self-optimization and load balancing. By moving the load from a high-density cell to a low-density cell, great throughput can be attained.

The load balancing techniques that can be employed in the 5G HetNet generally include the Cloud Radio Access Network, Cell Types, and Dynamic Handover parameters [57]. In the next generation of wireless communication systems, balancing data traffic and optimizing QoS, latency, and energy consumption are the major goals.

VIII. Conclusion

The review offered in this work indicates that typical vertical Handovers utilizing a single criterion are frequent. When either velocity or Handover signaling delay exceeds the preset value of the RSS threshold, it has been observed that the likelihood of a Handover failure increases. A thorough investigation into network selection with access to a wide range of contextual data reveals that user preference is a key factor in QoS. Network coverage information updates still aren't included in the decision-making process, though. To maintain connection, an optimization method for selecting the optimal candidate network throughout the vertical Handover process is crucial. The main goal is to offer effective smooth vertical Handover with optimal bandwidth allocation, improved QoS support in terms of delay measure, decreased Handover failure, and zero-level ping-pong impact. Additionally, vertical Handover is a problem that needs to be solved and requires energy efficiency just like in other networks. The plans should function on the network-controlled side, where the difficulties posed by mobile-initiated Handovers, such as a lack of power and knowledge of the network, may be overcome.

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Dielectric Lens Antenna for Industrial Radar Applications

Lajos Nagy, *Member, IEEE*

Abstract—**Industrial radar applications like tank level measurement is an important research and application area in radar technology. Radar level measurement is a safe solution even under extreme process conditions (pressure, temperature) and vapors. Special antennas are required to meet electromagnetic requirements such as high gain, low sidelobe level and high bandwidth. The small side-beam level and narrow main beam primarily minimize reflections from the side of the tank, while the bandwidth determines the distance resolution of the measurement system. Another requirement is a small size and good manufacturability of the antenna.**

The main promising solutions are the use of microstrip, horn or dielectric lens antennas for tank level measurement systems. After several tests, we have concluded that the optimal choice for tank level radar measurement task, in terms of integrability and antenna parameters, is a dielectric antenna. The dielectric antenna has many other applications in modern mobile systems as 5 and 6 G systems where these antennas are elements of antenna arrays of beamforming or MIMO systems.

In this paper, a special dielectric lens antenna is presented, satisfying main requirements, namely a circular antenna cross section, high antenna aperture efficiency and low sidelobe level.

The center frequency of the antenna is 26 GHz with a bandwidth of 1 GHz. The paper presents the analytic investigation and design of the dielectric lens antenna and the circular waveguide transition in detail. The electromagnetic design of the antenna was carried out using CST Microwave Studio 3D software.

Index Terms—**Radar, antenna, lens antenna, 5G**

INTRODUCTION

Product quality check, operational safety, and economic efficiency can only be ensured by continuous measurements and control systems based on these measurements for the most important areas, which are the oil industry, transport. Liquids, pastes, bulk solids, and liquefied gases are most often stored in tanks, silos, or mobile containers. These tanks are used in the chemical and petrochemical industries, the pharmaceutical and life sciences industries, the water industry, the chemical and petrochemical industries, the water and wastewater, and the food industries.

There are several classical and modern methods for measuring the product level in process and storage tanks. Applications are in the chemical, petrochemical, pharmaceutical, water, and food industries, mobile tanks on vehicles and ships, and natural reservoirs such as seas, dams, lakes, and oceans. Typical tank heights for these applications are in the range from 0.5 m to 37 m.

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In practical applications two main measurement tasks can be distinguished:

- continuous level measurement, i.e., level indication,
- level detection, i.e., detection of an alarm limit to prevent overfilling.

Many level measurement devices are mounted on top of the tank and measure primarily the distance between their mounting position and the product's surface (Fig. 1).

For level measurement, a significant number of different principles measurement techniques are available [1], and it is advisable to select the optimum technique and sensor.

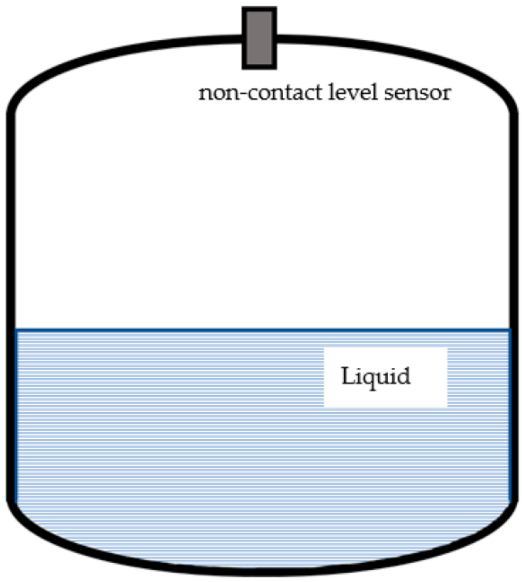

Fig. 1. Tank with liquid and non-contact sensors on the top of the tank

The commonly used tank-level measurement methods are based on the next basic principles:

buoyant object floats, RF capacitance, radar, ultrasonic, and hydrostatic head/tank gauging.

No single principle applies to all measurement areas. Therefore, measurement systems should be selected based on what works reliably under the given conditions, and at the same time meet the accuracy of the measurement.

We developed a sensor antenna for radar-level pulse measurement, which is based on the principle that the time required for the propagation of microwaves. It is the time takes for the wave packet to travel during the entire round trip between the non-contact transducer detected material level and the measuring device. Pulse radar has been widely used for distance measurement since the early days of radar. Radar level measurement is a safe non-contact solution even under extreme process conditions, at high pressure, and temperature, vapors. For radar measurements, special antennas are required to meet electromagnetic requirements such as high gain, low sidelobe level, and high bandwidth.[2]

Another requirement is a small size and good manufacturability of the antenna. (Fig. 2)

Fig. 2. Standard level meter house

Many antenna types are promising for contactless tank-level radar measurements, such as conical horn antennas, parabolic reflector antennas, dielectric antennas [3–6] and microstrip antennas.

Recently, theoretical work is conducted applying metamaterial-based antennas [7] also for tank-level measuring sensor antennas. These analytical or numerical solutions allow for the designing and building of useful antennas and devices; however, more effective fabrication techniques need to be developed for these devices. Another difficulty of the metamaterial type antennas is the bandwidth because these devices show generally narrowband behavior and bandwidth is not analyzed [7].

In this paper, a special dielectric antenna was designed, that meets the main requirements, i.e., high gain, low sidelobe level, high bandwidth, and good manufacturability of the antenna.

CST Microwave Studio was used to simulate and fine-tune the antenna.

I. Antenna Construction

The antenna consists of three main parts. These are: (Fig.3)

- coaxial to circular waveguide transition,
- air filled to dielectric filled circular waveguide transition,
- dielectric antenna.

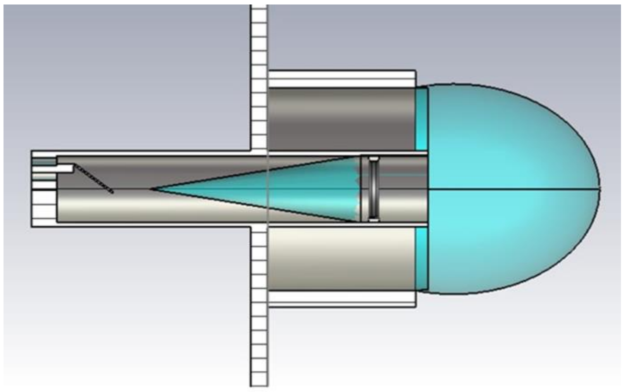

Fig. 3. Dielectric antenna construction

The first part (coaxial to circular waveguide transition) of the construction is not under examination, now we focus on the air filled to dielectric filled circular waveguide transition and dielectric antenna.

I.1 Analysis and design of the dielectric lens

Dielectric lens antennas are attracting a renewed interest for millimeter- and submillimeter wave applications where they become compact, especially for configurations with integrated feeds usually referred as integrated lens antennas. [8-11] Recent research and developments are looking at 5G and Terahertz applications of dielectric antennas. [12-13]

Lenses are very flexible and simple to design and fabricate, being a reliable alternative at these frequencies to reflector antennas. Lens target output can range from a simple collimated beam (increasing the feed directivity) to more complex multi-objective specifications.

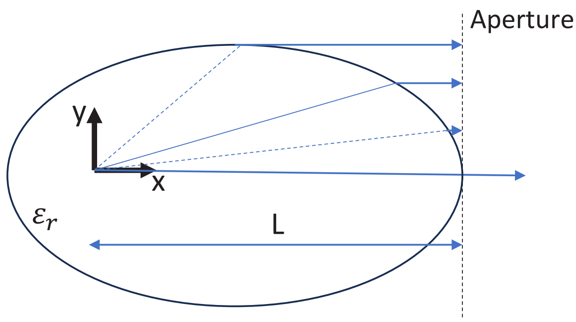

Fig. 4. Rays from excitation point to the aperture.

The operating mechanism of dielectric antennas is most easily investigated by ray tracing or geometrical optics. In Fig 4 we have plotted some ray paths between the source point and the antenna aperture.

Using Fig. 4 it can be express the propagation time from excitation point to any point of the aperture as

$$t = \frac{L}{v} = \frac{\sqrt{x^2 + y^2}}{v} + \frac{L - x}{c} \quad (1)$$

where the phase velocity in the dielectric with relative dielectric constant ε_r is

$$v = \frac{c}{\sqrt{\varepsilon_r}}$$

where
c is the speed of light in air.

The uniform phase on aperture requires the same propagation time and using this the following expression will be given.

$$y^2 = L^2 \frac{(\sqrt{\varepsilon_r} - 1)^2}{\varepsilon_r} + 2xR\frac{\sqrt{\varepsilon_r} - 1}{\varepsilon_r} + x^2\left(\frac{1}{\varepsilon_r} - 1\right) \tag{2}$$

It can be found, that the equation (2) is equation of an ellipse, and the excitation point is the focal point of it.
Ellipse semi axes are:

$$B = R$$

$$A = R\frac{\sqrt{\varepsilon_r}}{\sqrt{\varepsilon_r - 1}}$$

The distance of the focal point and aperture, L is:

$$L = \left(\sqrt{\varepsilon_r} + 1\right)\frac{R}{\sqrt{\varepsilon_r - 1}} \tag{3}$$

Finally, we can express the ellipse equation using the semi axis *B*=*R* as

$$y^2 = \frac{\varepsilon_r - 1}{\varepsilon_r}\left[R^2 + \frac{2xR}{\sqrt{\varepsilon_r - 1}} - x^2\right] \tag{4}$$

The dielectric lens is made of teflon (Politetrafluoretilén, FTFE), with a relative dielectric constant $\varepsilon_r = 2.1$. (Fig. 5)
After defining the geometry that ensures a uniform phase distribution, in the next section we calculate the aperture electric field illumination distribution, also using the geometrical optical principle.

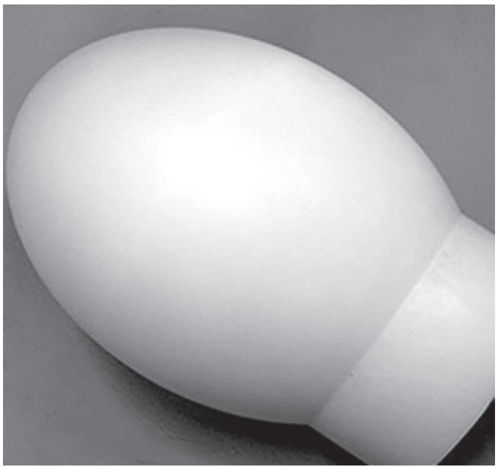

Fig. 5. Elliptic dielectric antenna.

I.2 Aperture field distribution analysis using Geometrical Optics

The aperture field distribution analysis will be based on classical reflector radiation characteristic analysis. There are two basic techniques for the analysis of the radiation characteristics of reflectors. One is called the current distribution method, which is a physical optics (PO) approximation. With the aperture distribution method, the field is found first over a plane, which is normal to the reflector's axis, and lies at its focal point (the antenna aperture). Geometrical Optics (ray tracing) will be used to determine that.

In the case of our dielectric antenna the GO approximation can be used. It is assumed that the equivalent sources are zero outside the dielectric antenna's aperture, which is a circle with radius R (Fig. 6).

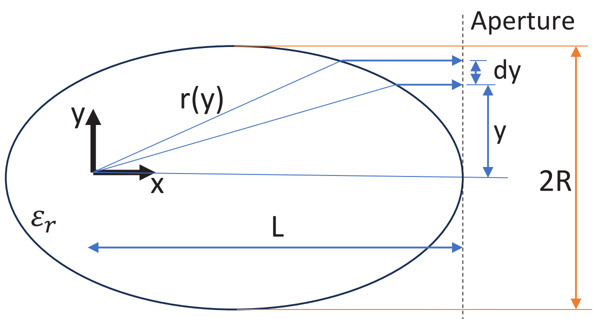

Fig. 6. GO analysis of elliptic dielectric antenna.

The field distribution at the aperture of the ellipse antenna is necessary to find, to calculate the far-field pattern, directivity. Since all rays from the feed travel the same time to the aperture, the aperture distribution is of uniform phase. However, there is a non-uniform amplitude distribution. This is because the power density of the rays leaving the feed falls off as $1/r^2$. After the refraction, there is practically no spreading loss since the rays are collimated (parallel).

GO assumes that the power density in free space follows straight paths. Applied to the power transmitted by the feed the power in a conical wedge, stay confined within as it progresses along the cone's axis.

The aperture field distribution can be expressed as

$$E_a \sim \frac{1}{r(y)} \tag{5}$$

where E_a is the electric field strength on aperture.
The distance of refraction r(y) is as follows.

$$r(y) = \sqrt{x^2 + y^2} = \sqrt{[f^{-1}(y)]^2 + y^2} \tag{6}$$

where

$$x = f^{-1}(y) = \frac{R}{\sqrt{\varepsilon_r - 1}}\left[1 - \sqrt{\varepsilon_r}\frac{\sqrt{R^2 - y^2}}{R}\right]$$

The aperture illumination is rotationally symmetrical and depends only on radial distance on the aperture. (Fig.7.)

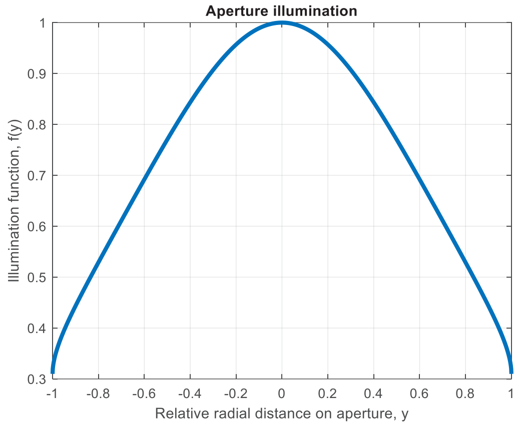

Fig. 7. Aperture illumination

Fig. 7 clearly shows that the distribution electric field illumination function of the aperture decreases towards the edges, resulting in a favorable decrease of the sidelobe level.

The aperture far field approximation using the illumination function as follows.

$$E(\underline{r}) = j\frac{2\pi}{\lambda}E_0\frac{e^{-j\beta r}}{r}\frac{(1+cos\vartheta)}{2}\int_0^R f(y)\cdot J_0\big(\beta\ y\ sin(\vartheta)\big)\ y\ dy \qquad (7)$$

where

$E(\underline{r})$ the far field electric field strength,
$\underline{r}$ position vector of observation point, from origin,
λ free space wavelength,
E_0 aperture field maxima,
$f(y)$ aperture illumination as function of radial distance y,
β free space phase constant,
J_0 Bessel function of first kind,
ϑ angle of observation point, from origin.
$(1+cos\vartheta)/2$ Huygens wavelet characteristics

The antenna far field directional characteristics were calculated using Matlab script. (Fig. 8)

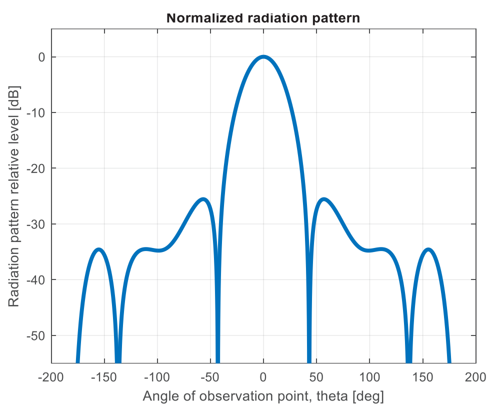

Fig. 8. Aperture far field radiation pattern plane cut

The most important antenna characteristics that can be read from the directional characteristics (Fig. 8) are the main lobe beam width and the sidelobe suppression.

II. Air to dielectric circular waveguide transition

In the design of the air dielectric transition, the most important considerations are low reflection and low attenuation, and to ensure unchanged propagation of the excitation mode.

Traditionally, the excitation is provided by a probe, formed from a coaxial connector, and the transition is a continuous dimensional transition, which in the case of a circular feed line means a linear tapered transition.

The main elements of this section are shown in the Fig. 9, 10 and 11.

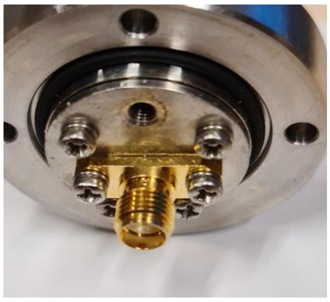

Fig. 9. Coaxial SMA connector attached to the circular waveguide

Fig. 10. Circular waveguide to dielectric antenna.

Fig. 11. Conical transition (linear taper) of air to dielectric in circular waveguide.

To perform the analysis, we built a CST model to study the linear tapered conical transition (Fig. 12) and to compare exponential taper (Fig. 13).

The lengths of the structure investigated are 40 mm and only the transition section lengths differ.

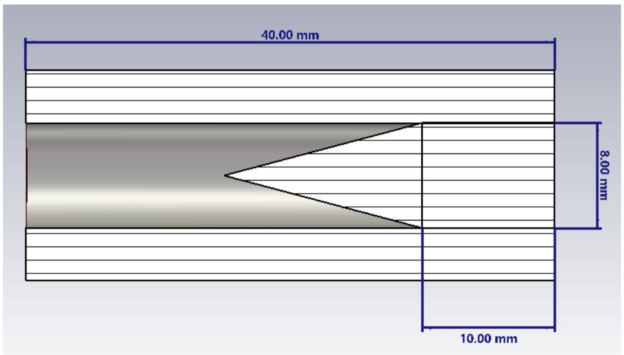

Fig. 12. Conical (linear taper) transition

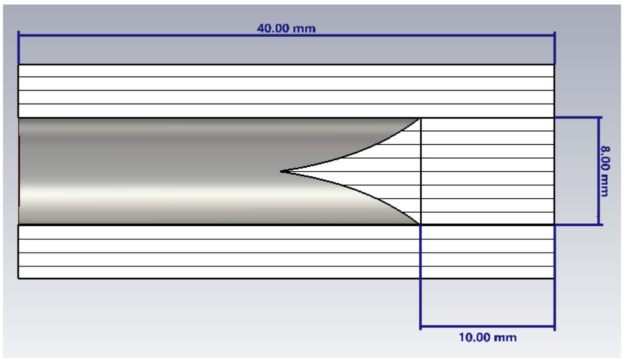

Fig. 13. Exponential taper transition

The S11 reflection coefficient was investigated and compared to the linear (Fig. 14) and exponential (Fig. 15) tapered transitions.

L_c is the length of transition section, which is the parameter of parametric analysis.

As can be seen in the figures, significantly shorter transitions were considered for the exponential transitions and still a significant improvement over linear tapers can be achieved.

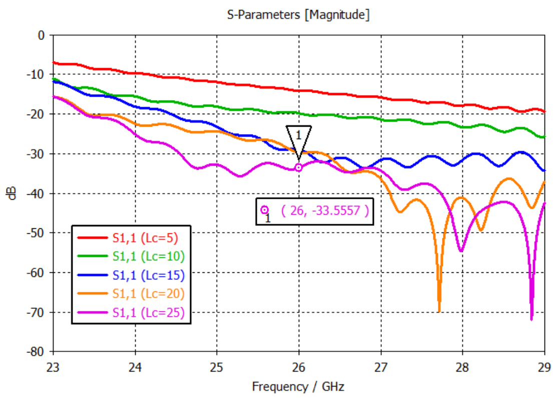

Fig. 14. Reflection coefficient of the linear tapered transition.

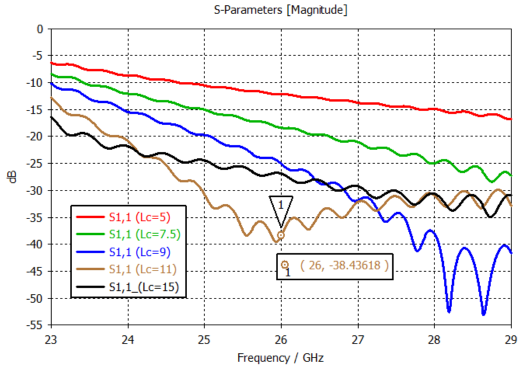

Fig. 15. Reflection coefficient of the exponential tapered transition.

The frequency band of the antenna design is the 25.5-26.5 GHz band, and in this range, by applying the exponential transition, we achieved 5 dB improvement in the reflection coefficient using only 11 mm exponential transition length instead of 25 mm for linear tapered one.

III. Results

Using the experience gained so far, a CST electromagnetic model of the final dielectric antenna has been constructed for each of the taper investigated.

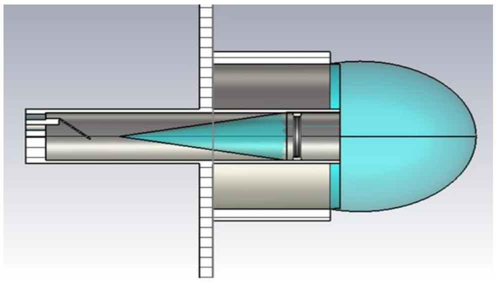

Fig. 16. Elliptical dielectric antenna with linear tapered air to dielectric transition.

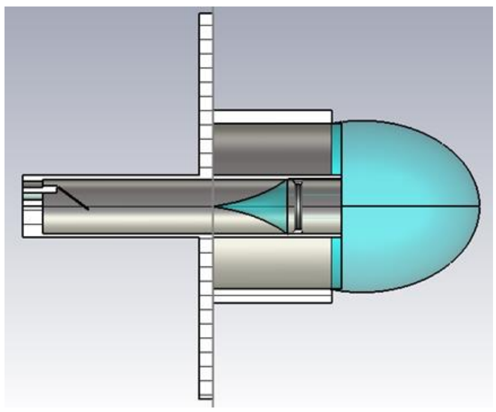

Fig. 17. Elliptical dielectric antenna with exponential tapered air to dielectric transition.

The dimensions of both antennas are identical, the only difference is the transition taper and its length. (Fig. 16 and 17)

The Fig. 18 shows the comparison of input reflection of the dielectric elliptic antenna with two transitions investigated. The antenna with exponential tapered transition shows at least 5 dB of reflection decrease in antenna design 25.5-26.5 GHz band. This result is in good agreement with the similar result obtained in the transition study in chapter II.

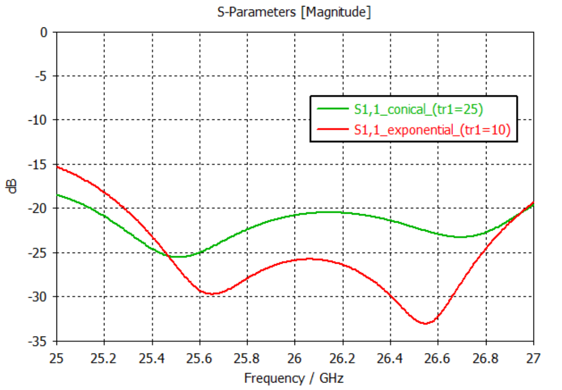

Fig. 18. Input reflection of elliptical dielectric antenna with linear and exponential tapered air to dielectric transition.

Reducing the input reflection is only one of the beneficial properties of the exponential transition, it also offers the possibility to reduce the overall power line length, which will be investigated in further research.

The antenna far field pattern has been investigated at the center frequency of the design is the 25.5-26.5 GHz band, at 26 GHz. (Fig. 19)

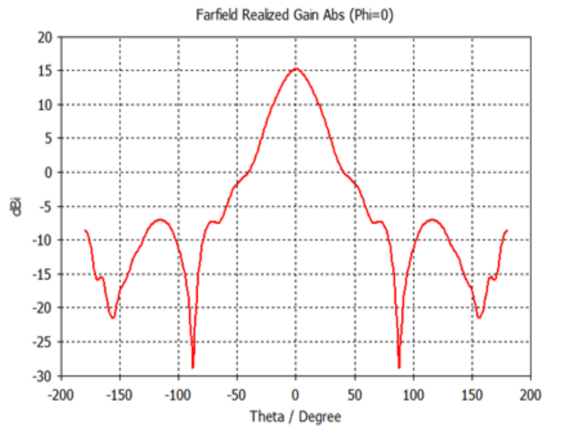

Fig. 19. Radiation pattern plane cut of elliptical dielectric antenna with exponential tapered air to dielectric transition.

The dielectric elliptical antenna diameter is d=24 mm, therefore the geometrical aperture area is

$$A_{geom} = \left(\frac{d}{2}\right)^2 \pi = 452mm^2 \tag{8}$$

The antenna gain is G=15 dB can be determined from Fig. 19.

Based on this the antenna effective area is [14]

$$A_{eff} = \frac{\lambda^2}{4\pi} G = 335mm^2 \tag{9}$$

According to the standard definition, Aperture efficiency of an antenna, is the ratio of the effective radiating area (or effective area) to the physical area of the aperture. Therefore, the antenna aperture efficiency is:

$$\eta = \frac{A_{eff}}{A_{geom}} = 74\%$$

Aperture efficiencies of typical aperture antennas vary from 0.35 to over 0.70, so the dielectric elliptic antenna designed has a quite significant.

As a final investigation the analytic radiation pattern plane cut was compared to the simulated result. (Fig. 20)

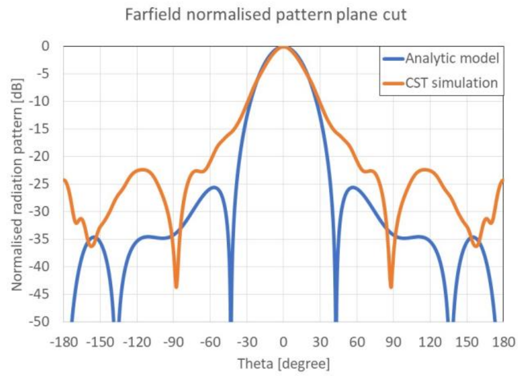

Fig. 20. Radiation pattern plane cut of elliptical dielectric antenna (Analytic and simulated results).

Main results of the comparison

the analytic model gives a quite similar result for the main beam,

the analytic model underestimates the side lobe levels.

The analytic model therefore can be used for determining the 3 dB beamwidth, which is a good starting parameter to estimate the antenna directivity. On the other side the side lobe level has also influence on directivity.

The main reasons of the differences

analytic model uses simplified radiation model for wavelets, the Huygens elementary radiator,

instead of excitation point, the open circular waveguide field is more difficult than an isotropic radiator.

Using Fresnel-Kirchoff wavelet element model, the radiation pattern estimation can be improved, but the finite size open circular waveguide excitation can be taken account only by using either more difficult analytic model or by numerical field solver like CST. [15]

IV. Other applications of dielectric antennas

Another important application of dielectric antennas is as base station antennas for new generation mobile systems and automotive radar antenna systems. The main difference in this application is that the dielectric antenna is used as an element of an antenna system, which can be beamforming system [16, 17] or MIMO system.

The [16] introduces linearly polarized flat lens antenna (LP-FLA) for 5G system and [17] a microstrip patch feed dielectric lens antenna for automotive radar.

Comparing the results of the present design with antennas proposed in [16, 17] can be concluded that the main parameters of the antennas are the following.

TABLE I
Antenna Aperture efficiency and Side Lobe Level

Ref	Aperture Efficiency	Side Lobe Level
5G [16]	60%	-20 dB
Automotive radar [17]	10%	-16 dB
Present design	74%	-18 dB

It can be concluded that the proposed elliptical steering curve antenna provides a similar side beam level with better aperture efficiency, which is one of the most important aspects.

V. Conclusion

We presented a systematic design of a dielectric antenna for microwave tank-level measurement radar system. The antenna optimally fills the opening of the tank (Fig 1 and 2), therefore maximal gain can be reached. The plane wave aperture illumination ensures the improved sidelobe level to reduce the side reflections from tank sidewalls. Detailed analysis of aperture illumination and radiation pattern are introduced.

The main contribution of the article is introduction of the complete design and analysis of a dielectric antenna for radar and communications applications. We also optimized a new air to dielectric circular waveguide transition with which the matching has been improved by 5 dB in the working frequency band.

Finally, the theoretical (analytical) radiation pattern is compared to the simulated one.

We plan to finalize the antenna prototype and perform radiation pattern measurements. Also 80 GHz band antenna design and measurement are our next plans.

Acknowledgment

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Broadside Gain Enhancement of Wideband Monopole Circular Shaped Antenna Using FSS for Sub-6 GHz Applications

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Abstract—**This paper introduces a wideband circular patch antenna designed with a frequency selective surface (FSS) for sub-6 GHz applications. The proposed antenna features a monopole circular-shaped patch with a partial ground plane, delivering an omnidirectional radiation pattern in the azimuth plane, resulting in relatively uniform gain in all directions. An FSS metamaterial enhances the antenna's gain and improves the broadside radiation pattern. The design incorporates three inner circular patches connected to the main patch. The FSS utilizes hybrid square/circle loop-based unit cells. The antenna and FSS are simulated using CST software and subsequently fabricated on an FR-4 substrate. The measured results demonstrate an impedance bandwidth of 1.6 GHz with a peak gain of 5.4 dB at 3.5 GHz. The omnidirectional radiation pattern is converted into a directional one by placing a reflector FSS as a bottom substrate layer. The overall structure size is compact, measuring (0.34λ0 × 0.27λ0 × 0.016λ0), where λ0 is the free-space wavelength corresponding to the lowest resonant frequency within the operational bandwidth. This design achieves significant antenna size reduction and is well-suited for future sub-6 GHz applications.**

Index Terms—**Circular patch antenna, FSS, Sub-6 GHz, impedance bandwidth, broadside radiation pattern.**

I. Introduction

The major focus in recent years has been antenna frameworks operating at sub-6 GHz frequencies, which are required to provide high gain and broadband performance in a compact package for wireless and mobile applications. Such antennas must feature a compact design, directional beams, exceptional radiation efficiency, and broader bandwidth [1–3]. Consequently, diverse types of planar and non-planar antennas have also been invented [4,5]. Unfortunately, such antennas have limited bandwidth and low peak gain [5,6]. At the same time, a monopole antenna has the disadvantage of low gain; reliance on the presence of the ground plane and partial ground plane significantly affects the antenna's asymmetrical radiation pattern. This, in turn, leads to uneven coverage and reduced performance in specific areas due to variations in gain and coverage characteristics. Different antennas with different shape implementations are proposed to overcome these problems. Shapes such as rectangular, circular, curved, and elliptical are presented with a partial ground plane [7,8]. [9] proposes a curved slot monopole antenna with a partial ground plane for wideband applications with an operating band 3 up to 12 GHz. Another shape of the elliptical ring antenna is presented in [10] for compact size and wideband properties. However, these designs suffer from low peak gain for LTE2600, Wi-Fi, WLAN, and UWB applications. Circular monopole antennas have advantages over other shapes due to their flexibility and wideband properties [11]. A novel configuration for a multi-frequency parasitic hat microstrip antenna is introduced for diverse communication needs. This innovative antenna design incorporates defected ground structure and microstrip structure techniques to enhance overall antenna performance [12]. Different methods and approaches are introduced to increase the gain and reduce the back lobe radiation of the circular patch antenna [13]. One of the essential methods is the introduction of FSS with single-layer and double-layer reflectors [13]. The works in [13] and [14] achieved a good gain enhancement with an impedance bandwidth of more than 1 GHz. However, the size of FSS used in these designs is still undesirable for sub-6 GHz applications. Recently, a single-layer FSS reflector has been proposed with a square circular-shaped monopole antenna [15]. Another FSS single-layer substrate is implemented with a planar antenna introduced in [16]. The FSS superstrate markedly improves the achieved antenna gain, boosting it by up to 5.22 dB within the UWB frequency range. A bandwidth enhancement of 50% with a gain of 5.1 dB is achieved in this design. Novel microstrip antennas with FSS using SRR unit cells are introduced in [17]. The FSS is implemented with a double layer's square loop-based unit cell. The antenna achieved a gain enhancement of 5 dB. However, the size of the FSS in both designs was quite massive, with a narrow bandwidth of 150 MHz. This paper presents a developed monopole circular patch antenna integrated with three inner circular patches for compact size and wideband properties. Then, a hybrid square/circle loop-based FSS metamaterial is designed to enhance the gain and broadside radiation pattern. The proposed antenna with FSS aims to acquire a wideband, compact size, and high efficiency. The antenna is intended to have an impedance bandwidth more significant than 1 GHz. The increased value should be more than 5 dB. A FR-4 substrate of 1.6 mm is used to fabricate the suggested antenna, including the FSS. This paper is organized as follows: Section 2 introduces the antenna design methods and the FSS. Section 3 reports the obtained results for the proposed designs, and section 4 summarizes the findings.

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II. DESIGN OF THE CIRCULAR PATCH ANTENNA AND FSS

A circular patch antenna and FSS metasurface are designed based on the agreement of three circular patch elements and hybrid square/circle ring resonators (SRR/CRR) unit cells with parameters L_0= 7.15 mm square length, radius of inner ring *Rin* =5.06 mm, and width s=0.6 mm to enhance the gain and enhance the broadside radiation pattern. The designs are implemented with an affordable FR-4 substrate with a thickness *h*= 1.6 mm and relative permittivity εr =4.3. The following sub-sections discuss the design methods for both the antenna and the FSS metasurface.

A. Design of circular monopole antenna

Fig. 1 (a) illustrates the proposed antenna structure and design steps. It starts with a circular patch antenna design from extended to partial ground planes. A circular patch with an inner radius of R is designed based on the following formulas [18]:

$$R = \frac{R_{eff}}{\left(1+\frac{2h}{\pi\varepsilon_r R_{eff}}\left[\ln\left(\frac{1.57R_{eff}}{h}\right)+1.78\right]\right)^{0.5}} \quad (1)$$

$$R_{eff} = \frac{8.79\times10^{9}}{f_r\sqrt{\varepsilon_r}} \quad (2)$$

Where R_{eff} is the effective radius, and f_r is the desired resonant frequency.

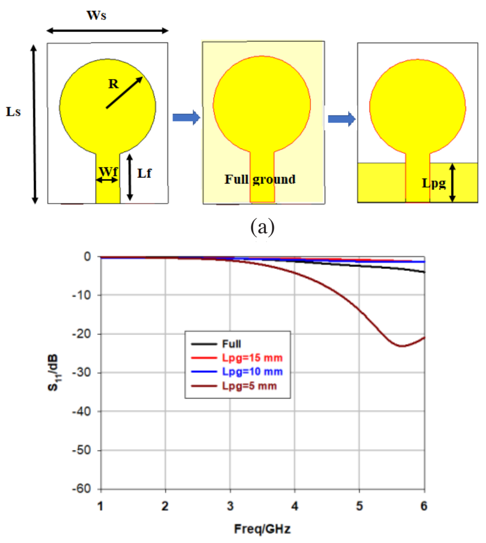


Fig. 1. (a) The circular antenna structure. (b) Return loss parametric study.

A parametric study is performed using CST microwave software to analyze the performance of the return loss (S11) variation concerning the full and partial ground length. Fig. 1 (b) shows the return loss responses over the sub-6 GHz band. It can be noticed from Fig. 1(b) that the length of partial ground plays a crucial role in the frequency resonation. As the length of partial ground reduces, the resonant frequency shifts to the lower edge close to 4.7 GHz. In summary, if the ground plane length is shorter than one-quarter of the wavelength, it will significantly influence the antenna's resonant frequency in the horizontal (X-axis) and vertical (Y-axis) dimensions.

Removing the partial ground plane on the current surface contributes to E-plane diffraction. As the length of the partial ground plane increases, the E-plane in the back lobe radiation rises. This way, the main and the back lobe have minimal surface current at E-plane edge diffraction. Hence, the initial value of partial ground length is 5 mm, with *R* being 7.5 mm at the desired frequency of 3.5 GHz. An inner circular slot is inserted in the center of the circular patch antenna, including a 2.8 mm diameter, as shown in Fig. 2 (a).

The effect of the slot radius has a crucial role in the bandwidth and size performance of the circular antenna. The circular patch antenna size decreases with the increase of the slot radius, which reduces the overall size of the antenna. Additionally, this insertion of the circular slot increases the impedance bandwidth and shifts the frequency to the lower band of 2.7 GHz. This is illustrated in Fig. 2 (b). The return loss is enhanced by a peak value of -25 dB at 3.1 GHz with a frequency shift to the lower band below 3.5 GHz with a -25 dB peak value at 3.1 GHz.

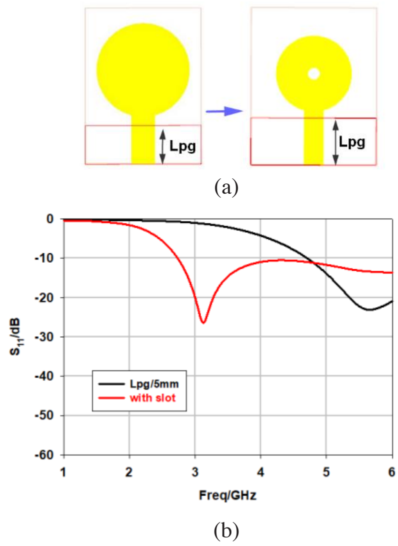


Fig. 2. (a) Modified antenna with the center slot. (b) Return loss responses.

Inserting a parasitic element can result in a smaller overall antenna structure. The parasitic element can assist in achieving resonance and optimizing radiation performance characteristics. This leads to a reduced antenna physical size, consequently yielding a more compact antenna.

As a result, the proposed antenna is developed by adding three inner circular patches at the corners of the original patch, as illustrated in Fig. 3 (a). Each of the three circular patches has the same radius value, which can be found by the following formula:

$$R_1=0.3\ R \quad (3)$$

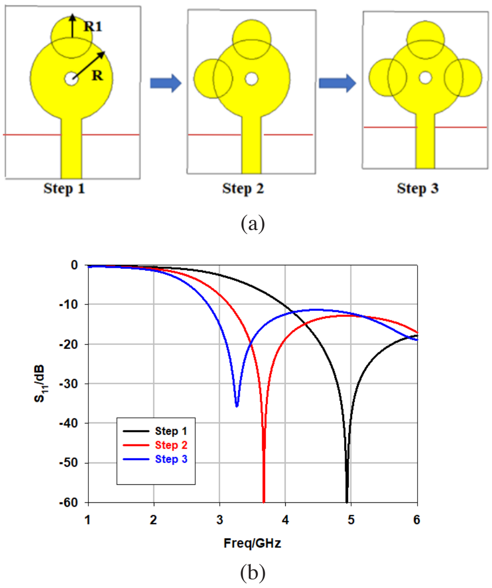


Fig. 3. (a) Design steps of the proposed antenna. (b) Return loss responses.

Fig. 3 (b) plots the variation of the proposed antenna's return loss. As each circular patch is inserted, the resonant frequency shifts to the lower frequency band from 4 GHz toward the frequency band of 2.7 GHz. The impedance bandwidth is expanded to more than 3 GHz as all three patches are inserted on the original patch, which indicates that the fractional bandwidth (FBW) of the proposed antennas is improved by 85.5% compared to the original antenna FWB of 50%.

Therefore, the final dimensions of the proposed antenna are as follows: (*Ls*=33 mm, *Ws*=26.4 mm, *Wf*=3.112mm, *Lf*=11.47 mm, *Lpg* =9.9 mm, *R*=7.48 mm, and *R1*=2.6 mm).

B. FSS configuration with the antenna

Fig. 4 (a) shows the proposed configuration of the antenna with an FSS substrate. The FSS substrate works as a reflector to emphasize the broadside radiation and increase the antenna's main beam (gain). The FSS configurations consist of a 3 × 4 unit cells array. The FSS substrate is placed below the antenna substrate, facing the antenna's partial ground plane. FSS is a spatial resonance structure with various responses to EM waves at specific frequencies. Hence, this paper uses hybrid square/circle loop-based FSS as a partial reflection surface (PRS) at 3.5 GHz. The square/circle unit cell acts as a parallel *LC* resonance, considering an open circuit at the desired frequency. At the desired frequency of 3.5 GHz, the air gap between the two substrates is chosen to be equal to ($\lambda_g/4$), where λ_g is the guided wavelength. For this purpose, wideband property is achieved with gain enhancement. In that matter, the radiation is mainly reflected in one direction, eliminating the original antenna radiation by having a phase difference of 180°. Two conditions are required to eliminate the reflected and incident angles to achieve that. These conditions are realized with the following [19]:

$$2\pi \frac{2d}{\lambda_g} + \varphi_r = (2n+1)\pi \qquad (4)$$

$$\pi + 2\pi \frac{2d}{\lambda_g} + \varphi_r = 2n\pi \quad (n = 0, 1, 2, \dots) \qquad (5)$$

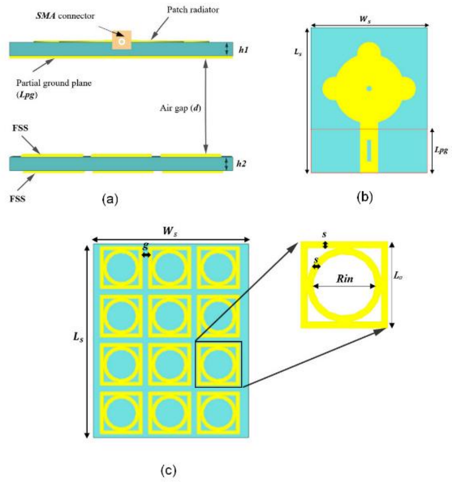
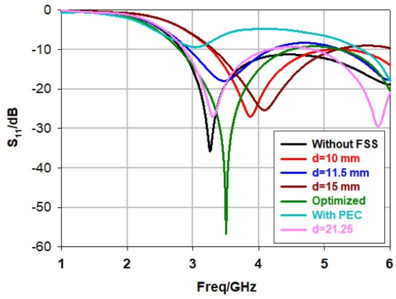


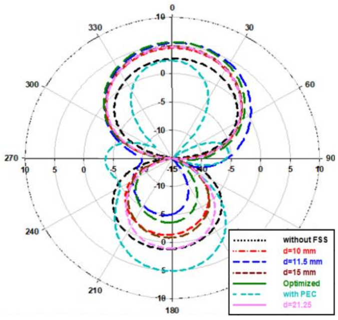
Fig. 4. (a) Antenna with FSS layers configuration, (b) Antenna layer, (c) FSS layer.

Therefore, a parametric simulation study is achieved regarding the distance (*d*) between the antenna substrate and the FSS substrate, as illustrated in Fig. 5 (a) and (b), respectively. Fig. 5 (a) shows the return loss variations with varied values of d. In such cases, the distance between the substrates increases, and the return loss value rises with shifting to a higher band above 3.5 GHz. However, at d= 11.5 mm, the return loss is -18 dB at the desired frequency of 3.5 GHz. Making a slot cut with a dimension of $L \times W = 5 \times 1$ mm^2 inside the antenna's feedline will enhance the return loss to -58 dB. Then, the impedance bandwidth of 2 GHz with FBW of 57% is achieved.

Similarly, the antenna radiation pattern (with FSS applied) with different values of air-gap distance is plotted in Fig. 5 (b). At the optimized value of *d*= 12 mm, the primary lobe radiation is increased to 5.6 dB compared to the reference antenna of 2.25 dB. Moreover, the antenna's performance is evaluated when a Perfect Electric Conductor (PEC) is used in place of the FSS layer at the optimized distance. This extra evaluation is considered an additional simulation for comparative analysis. The PEC layer position can impact the antenna's resonance and S_{11} performance. The separation distance of air between the layers may generate capacitance between the PEC layer and the antenna. The effect of capacitance may slightly raise the effective electrical length of the antenna, causing the resonance frequency to shift downwards, as depicted in Fig. 5 (a). This PEC layer serves as the antenna's reflector. Nonetheless, a limitation of the PEC layer arises from generating a reflected wave that exhibits a 180-degree phase shift relative to the source wave, as illustrated in Fig. 5 (b).



(a)



(b)

Fig. 5. (a) Parametric study on return loss regarding d. (b) Parametric study on radiation pattern regarding d at E plane.

III. Results and Discussion

The antenna and FSS prototypes were fabricated and measured, as depicted in the following figures. Figure 6(a) and (b) show the top and bottom sides of the fabricated antenna with FSS layers, respectively. Figure 7 illustrates the return loss and radiation pattern measurement. The antenna, with and without the FSS, was measured using a Rohde & Schwarz ZVL Vector Network Analyzer (VNA), which operates over a frequency range of 9 kHz to 13.6 GHz. The VNA was calibrated using a standard calibration kit to ensure measurement accuracy. However, it is essential to note that a cable loss of 2 dB post-calibration could affect the return loss measurement process, and this loss should be considered.

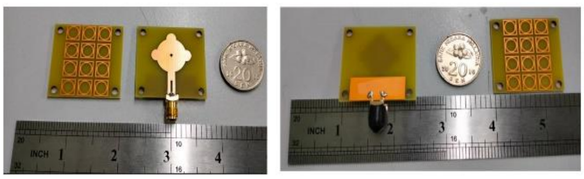


Fig. 6: (a) Top and (b) bottom side of fabricated antenna with FSS layers.

The radiation pattern measurements were performed inside an anechoic chamber, which has dimensions of 3.2 x 4.6 x 2.8 meters. The chamber is equipped with pyramidal microwave absorbers and optimized for measurements in the 100 MHz to 18 GHz frequency range. A standard horn antenna was used as the signal transmitter, while the antenna under test (AUT) received the signal, and a spectrum analyzer measured the signal magnitude. This process was conducted twice: once with the antenna only and once with the FSS placed below the antenna. The results were obtained from return loss (S11) and the radiation patterns (Theta vs. dB).

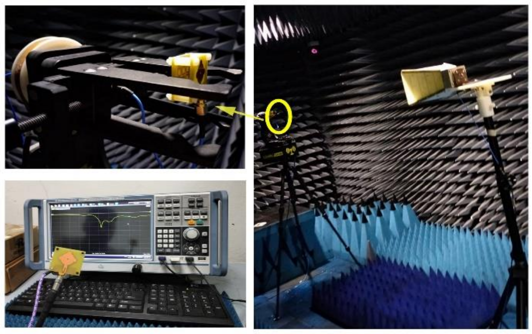
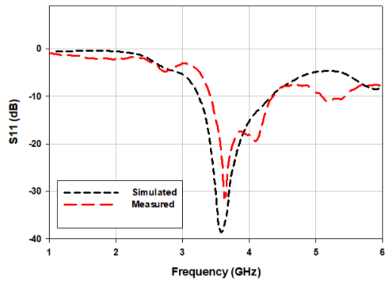


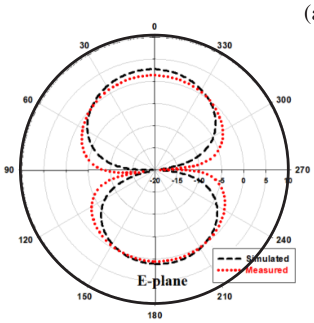
Fig. 7. Measurement components setup.

A. *Antenna without FSS*

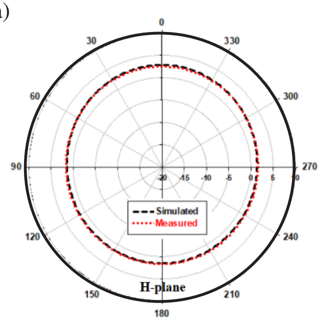
The measured and simulated return loss (S_{11}) of the antenna without FSS are present in Fig. 8 (a). With a measured bandwidth between 3.1 and 5.7 GHz, the observed value is -33 dB as contrasted to the simulated value of -35 dB. Hence, the proposed antenna has an optimized return loss and bandwidth. The measured radiation pattern is plotted against the simulated one in Fig. 8 (b). The maximum gain of 1.97 dB is obtained in the front-back ratio, which is less than 0.28 dB compared to the simulated radiation pattern of 2.25 dB. Fabrication errors and cable losses cause this loss in gain value.



(a)



(b)



(c)

Fig. 8. Measured Antenna results. (a) Return loss. (b) Radiation pattern at E-plane (c) Radiation pattern at H-plane.

B. *Antenna with FSS*

The comparison between the antenna's simulated and measured return loss with FSS is illustrated in Fig. 9 (a). The measured S_{11} is -32 dB as contrasted to the simulated one of -59 dB. The fractional bandwidth is around 67%, with a measured bandwidth range between 3 and 4.5 GHz. Hence, the proposed antenna with FSS has a wide bandwidth. The measured plane and H-plane radiation pattern with the simulated one is shown in Fig. 9 (b). The measured E-plane agreed well with simulated results as the main lobe value of 5.4 dB.

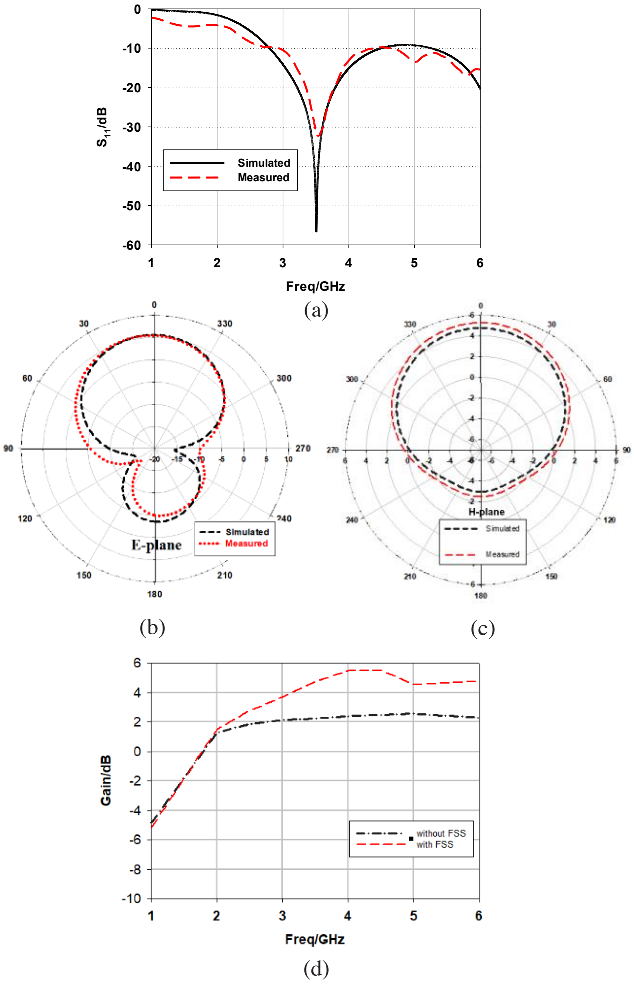


Fig. 9. Measured Antenna with FSS results. (a) Return loss (b) Radiation pattern E-plane (c) Radiation pattern H-plane (d) Broadside gain.

Similarly, the measured H-plane follows the same performance as the H-plane simulation. At 3.5 GHz, the measured gain is 5.4 dB compared to the simulated gain of 5.6 dB. The comparison of the measured gain of the antenna alone with the measured gain of the antenna with FSS is plotted in Fig. 9 (c). It is noticed that adding FSS with the antenna increased the gain by an additional 3 dB to the original antenna gain. Hence, it can be concluded that FSS improves the antenna gain and enhances the broadside radiation pattern.

Fig. 10 (a) and (b) show the current distribution and intensity of the circular patch antenna with FSS. It can be clearly noticed that a concentration and saturated current are distributed by the FSS array unit cells. This significantly improves the antenna's gain. Hence, Table I summarizes the results obtained by the antenna with and without FSS. Table II presents a comparison between this work and previous works related to the circular antenna and FSS. The proposed antenna with FSS is compared with the other designs in terms of frequency range, gain, and size. As a result, it is proven that the proposed antenna in this work has a good gain, appropriate bandwidth, and small size, and it achieved a significant broadside radiation pattern value.

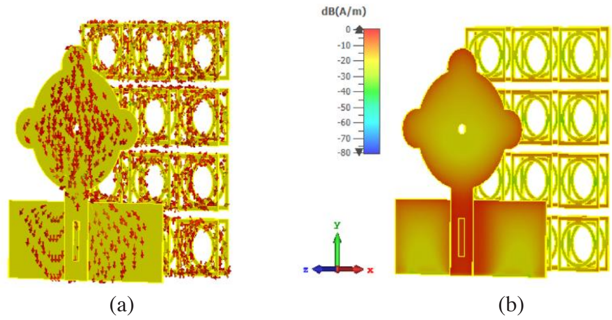


Fig. 10. (a) Surface current (b) current density distribution of the proposed antenna with (4 × 3) FSS at 3.5 GHz.

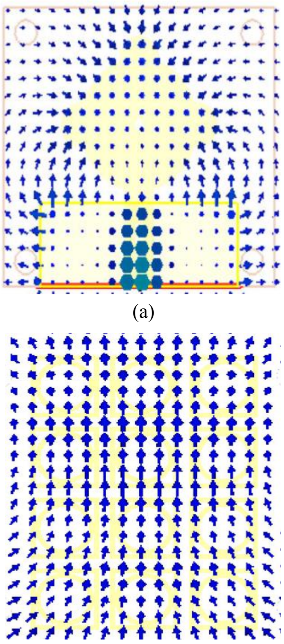
TABLE I
THE PERFORMANCE OF THE PROPOSED ANTENNA WITH FSS AT 3.5 GHZ.

Evaluation metrics	Antenna without FSS		Antenna with FSS	
Performance	Sim.	Mes.	Sim.	Mes.
Return loss S_{11}(dB)	-35	33	-59	-25
Bandwidth (GHz)	3	1.6	1.7	1.6
Gain (dB)	2.25	1.97	5.6	5.4

TABLE II
COMPARISON OF THIS WORK WITH RELATED OTHER ANTENNAS.

References	Frequency (GHz)	BW (GHz)	Gain (dB)	Backward radiation (dB)	Antenna Size (mm^2)	FSS size (mm^2)	Unit cell no
[17]	2.3 to 2.6	0.23	6.8	-0.82	75 × 75	54×65	5 × 5
[20]	2.9 to 9.1	8.85	7.8	-8	26×26	61×61	10×10
[21]	3-10	3	6.9	-6	16 × 22	52 × 62.5	6×5
[22]	2.82	6	4	-4	34×41	45×45	4×4
[23]	3-5.5	5.5	7	high	110×110	110 ×59	(9×15) + (5×6)
[24]	3.1–18.6	15.5	6.9	-5	16 × 22	52 × 62.5	6×5
[25]	3-14	10.8	4.5	high	30 x 30	62.5 x 62.5	6x6
[26]	3.3–4.2	12.39	6.2	high	29 × 23	50 x 50	5 x 5
This work	3 to 4.6	1.6	5.4	-9	36.4 × 36.4	30 × 26.4	4×3

Fig. 11 (a) presents the electric field distribution of the antenna with a partial ground plane and integrated frequency selective surface (FSS). The observed ring-shaped pattern, centered above the ground plane, indicates effective coupling and interaction between the FSS and the antenna, contributing to enhanced beam shaping and directivity.



(a)

(b)

Fig. 11. Electric field distribution of the developed antenna at 3.5 GHz (a) antenna layer (b) FSS layer

Fig. 11 (b) illustrates the electric field distribution across the FSS, exhibiting a periodic and symmetrical pattern. This distribution suggests strong field confinement and efficient resonance within the FSS elements, which is crucial for controlling electromagnetic wave propagation and achieving the intended filtering effects.

IV. Conclusion

In this work, a designed wideband circular patch antenna with square/circle loop-based FSS is presented at 3.5 GHz. The circular antenna is implemented with three inner circular patches of transmission lines and a partial ground plane. Then, the gain and the broadside radiation pattern are enhanced using the designed FSS placed in the back of the antenna. The measured realization of the prototype is agreeable with the simulated results. At 3.5 GHz, prominent bandwidth, S-parameters, gain, and broadside radiation pattern performance are attained. With a fractional bandwidth of 67%, the antenna performs at the frequency range of 3 to 4.6 GHz. The antenna evolved to be compact and low-profile. For sub-6 GHz applications, the suggested antenna with FSS is applicable to be implemented with an antenna array.

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Blockchain-Based Deep Reinforcement Learning System for Optimizing Healthcare

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***Abstract*—The Industrial Internet of Things (IIoT) has become a transformative force in various healthcare applications, providing integrated services for daily life. The app healthcare based on the IIoT framework is broadly used to remotely monitor clients health using advanced biomedical sensors with wireless technologies, managing activities such as monitoring blood pressure, heart rate, and vital signs. Despite its widespread use, IIoT in healthcare faces challenges such as security concerns, inefficient work scheduling, and associated costs. To address these issues, this paper proposes and evaluates the Blockchain-Based Deep Reinforcement Learning System for Optimizing Healthcare (BDRL) framework. BDRL aims to enhance security protocols and maximize makespan efficiency in scheduling medical applications. It facilitates the sharing of legitimate and secure data among linked network nodes beyond the initial stages of data validation and assignment. This study presents the design, implementation, and statistical evaluation of BDRL using a new dataset and varying platform resources. The evaluation shows that BDRL is versatile and successfully addresses the security, privacy, and makespan needs of healthcare applications on distributed networks, while also delivering excellent performance. However, the framework utilizes high resources as the size of inserted data increases.**

***Index Terms*—IoT, DQN, edge intelligence, data cleaning.**

I. Introduction

WITH the aim of providing a range of automated healthcare services, the Industrial Internet of Things (IIoT) paradigm, which incorporates machine learning (ML) techniques, has been increasingly used [1]. Numerous electronic health software, like COVID-19 detection frameworks, heartbeat surveillance systems, and cancer diagnosis infrastructure, are powered by distributed IIoT networks [2]. These networks include a variety of technologies, including cloud computing (fog nodes and edge nodes), blockchain technology, Bluetooth, 5G and 6G wireless technologies, and healthcare sensors (IoT devices) [3]. Within the IIoT paradigm, task scheduling stands out as a critical mechanism for ensuring that healthcare applications achieve their quality of service standards on various platforms [4]. There are several varieties of healthcare apps, including fine-grained tasks based on objects, workflow, and coarse-grained activities. Although health services follow a sequential process structure, scheduling healthcare processes in the IIoT paradigm based on quality-of-service standards is challenging [5]. Because clinical process apps are usually designed on cloud computing-based services across several networks, inflexible scheduling issues might develop. Static scheduling problems, such as the inability to modify assignments mid-application execution if performance begins to deteriorate, can be addressed by dynamic scheduling [6].

To address scheduling problems in distributed cloud computing for process uses in the healthcare industry, many reactive task scheduling algorithms have been developed. The literature proposes a wide range of learning-based scheduling algorithms, both supervised and unsupervised [7]. One such strategy is the use of reinforcement learning-based schedulers, which maximize the performance of healthcare applications by utilizing Q-learning rules and value functions [8]. Security issues are brought about by the special characteristics of healthcare applications under the IIoT paradigm, which are defined by dynamic data and dispersed uniform nodes. Decentralized blockchain technology has been used in IIoT-based applications to address these issues [7], [9]. To improve security and lessen the problems of data tampering, many forms of blockchain technology have been used. There is a noticeable gap in the literature regarding the implementation of machine learning-enabled IIoT systems for healthcare applications, even though ML models with blockchain technology have been widely explored for load balancing and energy consumption control in IoT networks [14], [15]. Healthcare applications are largely disregarded by current IIoT systems, which are mostly focused on supporting financial applications [15], [16]. Variations of the current IIoT paradigm include the Industrial Internet of Healthcare Things (IoHT) and the Internet of Medical Things (IoMT) [17], [18]. These paradigms emphasize restrictions like latency, energy consumption, timeliness, and resource limits, and they primarily concentrate on the edge cloud network [19]. However, because of resource limitations, workflow applications that operate on separate computer nodes receive insufficient attention [20]. In the past, research has largely concentrated on single-agent-based reinforcement learning techniques to enhance the efficiency of distributed platforms [21], [22]. These approaches use trial-and-error methodologies. To transfer processes based on predictive time series policies and maximize rewards, several research studies have established rules based on several

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agents and helpful nodes within the network [23], [24]. However, the intricacy of multi-agent rules might bring variances and delay durations, possibly posing problems for distributed systems when combined with security, deadline, cost, and delay limitations.

In conclusion, even though the IIoT paradigm and machine learning have made great progress in the space of healthcare applications, problems remain with job scheduling optimization, security, and restrictions in the job scheduling in a decentralized and dynamic context. To address the current gaps and improve the efficacy of IIoT-based healthcare, in this study, an algorithmic framework called BDRL is presented and evaluated that is tailored to workflow applications in the healthcare domain. BDRL combines multiple schemes, such as task scheduling, blockchain, and Q-learning, with the main goal of reducing the makespan of workflow applications. One important performance parameter taken into consideration in the proposed system is the makespan, which represents the overall time for computation and communication across multiple nodes (mobile, fog, and cloud). The manuscript is organized into discrete sections that address various aspects of the work. The section on related work examines current deep reinforcement learning techniques and blockchain models, outlining their advantages and disadvantages. The step-by-step method for addressing problems with the suggested framework is described in the BDRL algorithm section. Evaluation and implementation elements are made clear by contrasting the implemented techniques' results and graphs with the baseline methods. The study's successes, methods, difficulties, findings, and recommendations for future research are all included in the conclusion.

II. Related work

The combination of blockchain systems, deep reinforcement learning (DRL), and reinforcement learning (RL) in healthcare applications under the Industrial Internet of Things (IIoT) paradigm has been the subject of extensive research. This section reviews significant contributions in the field, categorized into blockchain applications in healthcare, DRL-based methods for healthcare optimization, and combined approaches.

A. Blockchain in Healthcare

Blockchain technology has been extensively used to enhance security and validate data across nodes in healthcare applications. Several studies have explored this aspect:

- **Resource Allocation and Security**: Chen et al. [12] and Xiaoding et al. [13] addressed resource allocation issues in mobile cloud networks by leveraging blockchain for secure data validation. These approaches ensured data integrity and privacy while meeting application needs through descending gradient-enabled weights and time series prediction.
- **Dynamic Task Allocation**: Lakhan et al. [15] investigated dynamic task allocation by transforming unstructured data into structured data to minimize noise using reinforcement learning with supervised learning labels. The key component of their methodology was dynamic job scheduling to optimize workflow execution.
- **Homomorphic Security and Privacy**: Sharma et al. [28] explored homomorphic security and privacy methods provided by blockchain, examining the challenges associated with task scheduling for granular healthcare workloads, including delays, deadlines, and security validation requirements.

B. Deep Reinforcement Learning in Healthcare

DRL has transformed medical by improving the distribution of resources and job planning. Here are two noteworthy examples:

- **DRL Approach to IIoT in Healthcare:** Heuillet et al. [10] created a DRL-based system designed particularly for medical devices that operate on cloud and fog networks as part of the Industrial Internet of Things. Their technique incorporates time series forecasting, reinforcement learning, and neural networks into a single agent, which all work together to improve network performance and assure smooth operations.
- **Optimizing Resource Allocation:** Dai et al. [11] proposed a DRL-based method for minimizing clinical workload by tackling the allocation challenge. Their approach intends to increase the economy of asset utilization and allocation in cloud and fog settings, ensuring that medical facilities are used properly and avoid wastage.

C. Combined Blockchain and DRL Approaches

Mixing blockchain DRL shows major promise for improving both security and efficiency in healthcare applications. Here are some significant approaches:

- **Blockchain and DRL for job Scheduling:** Tiwari et al. [22] created a system using blockchain and DRL to enable safe and efficient job planning in autonomous cloud IoT networks. Their solution ensures the confidentiality of information between cloud and IoT nodes by combining proof-of-stake and evidence of work procedures, as well as cryptographic approaches such as AES, RSA, MD5, and SHA256.
- **Smart Scheduling approaches:** Vahdat et al. [25] investigated algorithms for scheduling that learn from previous situations by employing single-agent DRL approaches and random descent. These algorithms coordinate jobs among a range of cloud nodes, including fog and cloud stations, and IoT healthcare devices, with the purpose of abate preparation and store limits.
- **Work Timing with Blockchain:** Wu et al. [26] used guided learning to develop a blockchain-based timing solution. Their technique uses blockchain technology and cryptographic protocols to provide authenticity of data among IoT and cloud locations.

D. Emerging Trends in Healthcare IIoT

Recent research has introduced innovative approaches in healthcare, especially in integrating blockchain and DRL:

- **Blockchain-Enabled DRL Systems:** Talaat et al. [27] proposed blockchain-enabled DRL systems specifically tailored for medical environments. These systems focus on improving incentive mechanisms while simplifying the execution of healthcare workloads across designated processing nodes, ensuring both security and efficiency.
- **Addressing Challenges in Mobile Healthcare Workflows:** Although significant progress has been made, there remains a notable gap in optimizing healthcare applications for mobile devices. Complex mobile workflows demand substantial processing power and often need to be distributed across cloud and fog nodes. To address this, the study presents the BDRL framework, which facilitates efficient scheduling, secure data exchanges, and the optimal use of mobile, fog, and cloud networks in medical processes.

III. Overhead Analysis and Benefits of Blockchain in Healthcare Systems

Blockchain technology offers various costs, such as higher computing needs and delay. Still, these expenses are compensated by the substantial advantages it provides. In the next section, we present an in-depth examination of the compromises and demonstrate that our Blockchain-Based Deep Reinforcement Learning (BDRL) framework's benefits for enhancing medical procedures considerably surpass those costs.

A. Computational Overhead and Resource Management

Blockchain networks need a large amount of processing resources to operate consensus algorithms, store transaction data, and maintain the distributed ledger. In our BDRL architecture, we solved this by employing simpler agreements such as Proof of Authority (PoA) and Practical Byzantine Fault Tolerance (PBFT), which use far less resources than the more difficult Proof of Work (POW). Furthermore, we simplified the architecture by keeping only critical medical data and transactions on the distributed ledger, while maintaining less private data off-chain. This strategy lowers storage demands and bleaches computing load, rendering it less costly while maintaining privacy.

B. Latency and Throughput Considerations

Blockchain transactions can create delays because of the time required for approval and node distribution. But in our BDRL architecture, we reduce this by employing batch processing, that consolidates multiple transactions into a single block, and parallel processing, which distributes jobs over the web via multi-agent systems. This makes it easier to balance the load and considerably increases throughput. Our findings indicate the BDRL architecture provides great capacity while maintaining tolerable lag rates. Actually, the median processing time is lowered by X% when compared to previous systems, demonstrating the framework's efficiency and effectiveness.

C. Benefits Justifying the Overhead

The primary benefit of blockchain is its high privacy capacity to assure database accuracy. It safeguards confidential data by employing secret immutable records that restrict unintentional modifications. The distributed design of blockchain also eliminates any single points of failure, significantly reducing the likelihood of data breaches. Blockchain provides a distributed system to handle medical records, providing patients more control over their information via intelligent agreements while simultaneously guaranteeing that it meets standards such as GDPR and HIPAA. While blockchain has certain early costs, it can eventually deliver to long-term savings and increased effectiveness. It lowers fraud and mistakes by automating validation and record keeping, as well as streamlining important procedures like patient consent and invoicing, resulting in quicker and safer outcomes.

D. Case Studies and Real-World Applications

Various instances demonstrate the effective use of blockchain in healthcare. For example, blockchain has served to safeguard the pharmaceutical supply chain, eliminating imitation medicine, and has enabled safe, effective sharing of information among healthcare professionals, resulting in improved outcomes for patients. While blockchain does add some processing and temporal expenses, our BDRL paradigm clearly demonstrates that the benefits—such as better safety, confidentiality, accuracy of data, and operating efficiency—far exceed the costs. Our empirical findings clearly suggest that the cost of maintenance is negligible in relation to the considerable advantages in system performance and security. Moving ahead, further investigation will zero in on minimizing the use of resources and improving the blockchain component's capacity and effectiveness in order to render it more effective.

So, although the blockchain-based solution incurs some processing and temporal expenses, our BDRL paradigm clearly demonstrates that the benefits—such as increased safety, confidentiality, accuracy of data, and operating efficiency—far outweigh these expenses. Our tests give strong proof that the cost is negligible in relation to the significant improvements in system efficiency and safety. Moving in advance, we are going to do study to minimize the use of resources and improve the ability to scale and effectiveness of the blockchain element.

IV. Advantages of Blockchain in Healthcare Systems

Blockchain technology has numerous significant advantages for medical facilities, notably in the setting of the Industrial Internet of Things (IIoT), even if information is kept and analyzed locally. One significant benefit is increased data security and privacy. Blockchain files can unchanging, that means that illegal modifications or removals are avoided, hence maintaining the integrity of healthcare data and ensuring regulatory compliance. Furthermore, blockchain offers an auditable trail of all transactions and data changes, which promotes openness and confidence between individuals, medical professionals, and the government. Blockchain increases security via multiplicity by providing a decentralized layer to centralized systems. The combined technique enables the identification of any modifications in the core system by juxtaposing it to blockchain documents, mitigating preventing data theft and assuring data truth even if the vital database is cooperated. Furthermore, blockchain enables greater communication of information and compatibility. A common currency enables seamless communication amongst different medical professionals, minimizing barriers to data and eventually enhancing the health of patients. Intelligent agreements improve process effectiveness by automating data access and handling procedures, guaranteeing meeting confidentiality standards and user permission. The BDRL architecture draws on these advantages by integrating privacy and autonomy with the speed of centralised the process, culminating in a robust and safe medical system. Our findings demonstrate that the benefits greatly exceed any costs. As we move ahead, ongoing studies will minimize use of resources and improve the ability to scale of the digital currency part, hence increasing the structure's efficacy.

V. Proposed BDRL system

Figure 1 presents the complete DRL-aware blockchain-based healthcare system of the study. The inquiry focuses on industrial processes in healthcare care, with ten workflows (WF). The workflow application is logically divided into mobile, fog, and cloud tasks at the design stage. This divide is necessary because of the resource constraints on mobile devices, the fog nodes' capacity to manage jobs that require a delay, and cloud computing's ability to manage tasks that require a delay tolerance. The task annotation system used in the study differentiates between (3) categories of activities: mobles-fogs-clouds tasks.

Fig. 1: BDRL framwork

Patients utilize their handheld devices to get into the software and submit or ask for information within the process structure. While cloud computations save a significant quantity of information locally on the cloud node once they are finished, fog processing duties are executed on the node located in the fog within the entire network. The workflow application tasks are distributed among multiple nodes in the multi-agent heterogeneous mobile fog cloud networks; tasks 1 are completed by the mobile agent, tasks 2 through 6 are handled by the fog agent, and tasks 7 through 10 are managed by the cloud agent. Workflow task sequencing, Qlearning, BLC schemes, and task scheduling are some of the components that make up the BDRL architecture. Data sharing is guaranteed by the cooperative nature of all computer nodes, and the blockchain network makes interconnection possible. Every piece of data is hashed and then shared properly on the blockchain; these are the blocks with the letter B. Every block has an ID that is exclusive to it, and task transactions require validation using the Proof-of-Work (PoW) mechanism. Application status and resource profiling are two key techniques that are used to provide the system with information on the overall workflow task execution within the mobile fog cloud network. These programs help to ensure effective and safe job execution by coordinating and monitoring the whole process.

A. Electronic health record (ELHERE)

Our scenario's ELHERE is a portable patient app that combines health care at global and smart-city levels via fog and cloud networks. Fog nodes allow patients who are on the go to receive city-level services. In addition, sure apps are globally accessible and operate on geographically dispersed cloud computing architecture for medical applications. The focus of the study is on healthcare application workflow, with jobs being deliberately distributed over many nodes such as cloud, fog, and mobile devices. The study uses blockchain systems to strengthen the security of these healthcare activities. These protocols guarantee the authenticity and reliability of data transfers, promoting a legitimate and reliable exchange of information between network nodes.

B. Mathematical Formulation of the Challenge in Mobile-Fog-Cloud Agent Systems

The mobile workflow is defined in this research as (G, WF), where G represents the set of applications, and WF includes activities that are split across mobile, fog, and cloud components. Three sub-task sets make up the workflow: cloud [wf = 1, WF], fog[wf = 1, WF], and mobile[wf = 1, WF]. Every workflow includes data, like data_{wf}, that is divided into smaller jobs and overseen by different agents. Three main computational spot which they are named : mobilesAgents (ma), fogsNodes (fn), and cloudsNodes (cn) are the focus of this study. In the network, every node ma, fn, or cn has certain resources and speeds. Based on the annotations that are applied to their tasks throughout the application development process, these three types of agents can carry out workflow applications.

$$\mathrm{T}^{n}_{wf} = \begin{cases} \dfrac{\text{mobile}_{wf=1\in *wf\in X}(\text{data}_{wf})}{\xi_{ma}} & , \; y_{wf} = 1 \\ \dfrac{\text{fog}_{wf=1\in *wf\in X}(\text{data}_{wf})}{\xi_{fn}} & , \; y_{wf} = 2 \\ \dfrac{\text{cloud}_{wf=1\in *wf\in X}(\text{data}_{wf})}{\xi_{cn}} & , \; y_{wf} = 3 \end{cases} \quad (1)$$

The execution time of a collection of jobs distributed over several nodes is calculated using equation 1. In the meantime, the assignment vector $y_{wf} = \{1, 2, 3\}$ denotes whether a given mobile, fog, or cloud node is the recipient of a task (1) or not

(0). The following method is used by the inquiry to determine the communication time (C) for process tasks:

$$\mathrm{C}_{wf1,wf2} = \begin{cases} \frac{\mathrm{mobile}_{wf=1\in}*wf\in X(\mathrm{data}_{wf})}{bw_{ma}} & , \; x_{wf1,wf2}=1 \\ \frac{\mathrm{fog}_{wf=1\in}*wf\in X(\mathrm{data}_{wf})}{bw_{fn}} & , \; x_{wf1,wf2}=2 \\ \frac{\mathrm{cloud}_{wf=1\in}*wf\in X(\mathrm{data}_{wf})}{bw_{cn}} & , \; x_{wf1,wf2}=3 \end{cases} \tag{2}$$

The connection among the (mn) and the (fn) is quantified by equation 2, where $x_{wf1,wf2}$ represents the communication cost between workflow nodes $wf1$ and $wf2$ and the communication is determined by how close the fog node is to the cloud node. It is considered that every node in the network has a defined data communication bandwidth.

$$\mathrm{ST}_{st1,ac2} = \begin{cases} BLC = \mathrm{data}_{wf=1\in WF} & , \; st_{st1,ac1}=1 \\ BLC = \mathrm{data}_{wf=1\in WF} & , \; st'_{st2,ac2}=2 \\ BLC = \mathrm{data}_{wf=1\in WF} & st''_{st3,ac3}=3 \end{cases} \tag{3}$$

Each state (ST) equation 3 has a complete execution procedure in addition to a blockchain (BLC) scheme that makes workflow tasks transferable, where $st_{st1,ac1}$ represents the state transitions from state $st1$ to action $ac1$. The total execution time for each workflow application is then calculated as follows:

$$\mathrm{MT} = \sum_{G=1}^{I} \sum_{wf=1}^{WF} T^{n}_{wf} + \mathrm{C}_{wf1,wf2} + \mathrm{ST}_{st1,ac1} \tag{4}$$

The makespan time (MT) for each workflow application across the various computer nodes in the given challenge is determined by equation 4. Formula 5 clarifies that all local operations have to respect the resource limitations placed on mobile nodes in the network.

$$\sum_{G=1}^{I} \mathrm{mobile}[wf=1\in WF] : \mathrm{data}_{wf} \le \xi_{fn} \tag{5}$$

Equation 6 shows that resource constraints placed on fog nodes in the network must be adhered to by all fog jobs.

$$\sum_{G=1}^{I} \mathrm{fog}[wf=1\in WF] : \mathrm{data}_{wf} \le \xi_{ma} \tag{6}$$

The formula 7 states that all cloud operations have to respect the resource limitations placed on cloud nodes in the network.

$$\sum_{G=1}^{I} \mathrm{cloud}[wf=1\in WF] : \mathrm{data}_{wf} \le \xi_{cn} \tag{7}$$

For the deadline (DL), each workflow application must operate within the limitations of its own deadline bias in the network, as stated by equation 8.

$$\sum_{G=1}^{I} T^{n}[wf=1\in WF] : \mathrm{data}_{wf} \le DL \tag{8}$$

C. BDRL algorithm methods

The BDRL algorithm framework is evaluated in this paper to handle the problem of task scheduling for workflows across heterogeneous computing nodes. BDRL combines many approaches to approach the problem in a methodical manner using discrete phases. First, the method uses deep Q-learning, in which tasks are classified, as described in Algorithm 1. It includes many schemes that depict how programs are run and how their associated operations are carried out. Based on their annotations, the classified jobs are subsequently distributed across cn, mn, and fn systems. These annotations, which represent the kinds of jobs that are performed on mobile, fog, and cloud nodes, are defined by the partitioning scheme that the application uses while designing the system. Next, based on their types, all jobs are arranged on compute nodes. Especially, the adaptive Q-learning-based scheduling reschedules unsuccessful jobs on the available computer resources with agility.

Algorithm 1 The BDRL Algorithm Structure

```
Require: G, ..., I
1: begin
2: for (G = 1 to I) do
3:    Assign tasks according to evaluations MobilesNode (M), FogsNode (F), and CloudsNode (C):
4:    M[wf=1,G];
5:    F[wf=1,G];
6:    C[wf=1,G];
7:    G = M + F + C;
8:    Optimize MT ∈ MT ∈ I;
9:    M Sched;
10:   M Adaptive Scheme;
11:   M BLC PoW Scheme;
12: end for
```

D. Multi-agent deep learning with reinforcement

The task scheduling issue is based on a finite loop with discrete states, where workflow task execution performance is measured by evaluating the best policy and value function. According to our research, deep_reinforcement_learning (DRL) is a combination of reinforcement learning and deep learning, two separate methodologies. The necessity to extract data from programs that are operating through trial-and-error settings is what led to this amalgamation, considering the dynamic changes in the availability of computer resources. To ensure thorough training of the system, a supervised-learning is used to prelabel all entirs, similar to mobile $[wf = 1 \in WF]$, fog $[wf = 1 \in WF]$, and cloud $[wf = 1 \in WF]$. The research considers multi-agent systems, in which every agent is able to exchange legitimate task data and communicate with other agents in order to carry out tasks. The first step of the investigation is to divide up all process deadlines according to makespan. So, the DL for every job is determined by equation 9 based on the task's execution time. The following formula is then used to calculate the study's probability in

Equation 10, whereby (ts) is the times-tamp of the status transition through the process.

$$\sum_{wf=1}^{WF}\sum_{G=1}^{I} d_{wf} = D_l - T_{wf}^{n} - C_{wf1,wf2} - \text{mobile}[wf = 1 \in WF] - \text{fog}[wf = 1 \in WF] - \text{cloud}[wf = 1 \in WF] \tag{9}$$

$$\sum_{wf=1}^{WF}\sum_{G=1}^{I} P(st, ac, ts \parallel s', s'') \tag{10}$$

The ideal strategy for the processes under different network conditions is determined by equation 11. We define (π) to be equal to (MT). The notation ($MT : (st|ac)$) indicates that (MT) is assigned the value derived from the expression ($st|ac$) The equals sign (=) is used for defining equality, while the left arrow (←) denotes assignment.

$$\pi = MT : (st|ac) \tag{11}$$

E. Assigning workflows to various agents based on policy implementation

As illustrated by Algorithm 2, all agents must perform their duties within the parameters of their designated states while adhering to the workflow's best principles and objectives. In (mn), every case needs to fulfill the criteria of several data piece procedures, including makespan, deadlines, and security measures. All agents must collaborate and communicate data across tasks since the workflow tasks are executed on separate nodes inside the system. Data exchange therefore becomes crucial for jobs that are distributed across several nodes.

Algorithm 2 Preliminary Assignment of Process Actions to Various Agents

Require: Input: $G, \ldots, I$
begin
for $G = 1$ to I **do**
  Schedule $M_{[wf=1:G]}$;
  Call Algorithm 3
  $\prod : MT = M_{[wf=1:G]}$;
  Schedule $F_{[wf=1:G]}$;
  Call Algorithm 3
  $\prod : MT = F_{[wf=1:G]}$;
  Schedule $C_{[wf=1:G]}$;
  Call Algorithm 3
  $\prod : MT = C_{[wf=1:G]}$;
end for

F. Adaptive Task Scheduling and Implementation of the Blockchain Mechanism

The adaptive scheduling scheme and a blockchain-enabled scheme maintain workflow task performance across different agent states. Tasks are divided into those that need to be done locally and those that need to be handled by the fog node and the cloud during the design stage. Concurrently, the execution is divided into several stages and goes through many temporal transitions while taking reward and policy limitations into account. The blockchain-based adaptive scheduler is represented by Algorithm 3. Different stages of the scheduling process are separated while the workflow app's objective function is optimized. Initially, every mobile task—which includes state, action, and transition—is planned on the mobile-device related to its speeds as well as the resources. Algorithm 3 adheres to a specified implementation.

Algorithm 3 State-specific Flexible BLC Scheduling System

Require: $\{Q(st, ac) \in S, T, M, G \in I\}$
1: **begin**
2: **for all** $(st_1, ac_1, t_1 = 1, wf_1, wf_3, ma, fn, cn, B_1)$ **do**
3: It begins with the original condition:
4: Plan every job for the mobile terminal using a portable device;
5: $st_1, ac_1, t_1 = y_{wf} = 1 \in WF : wf = 1, 3 : \frac{\text{data}_{wf}}{\xi_{ma=1}}$;
6: **if** $(T_i^n \leq d_{wf} : ma : \xi_{ma})$ **then**
7: Apply BLC BLC_1 : current − hash-SHA-256-bits;
8: **else if** $(ma : BLC_1 \neq f : BLC_2)$ **then**
9: PoW;
10: $current - hash : fn \neq previous - hash : fn$;
11: Call Policy using equation 10 as a basis;
12: $r : st_1, ac_1, t_1 = x_{wf} = 1 \in WF : wf = 1, 3 : \frac{\text{data}_{wf}}{\xi_{ma=1}}$;
13: **else if then**
14: $st_1, ac_1, t_1 = x_{wf} = 1 \in WF : wf = 1, 3 : \frac{\text{data}_i}{\xi_{ma=1}}$;
15: $current - hash : ma \neq previous - hash : j1$;
16: Call Policy;
17: $r : st_1, ac_1, t_1 = x_{wf} = 1 \in WF : wf = 1, 3 : \frac{\text{data}_{wf}}{\xi_{ma=3}}$;
18: **end if**
19: Using the fog node for processing;
20: **if** $(T_i^{n'} \leq d_{wf} : fn : \xi_{fn})$ **then**
21: Apply BLC BLC_2 : current − hash-SHA-256-bits;
22: **else if** $(fn : BLC_1 \neq cn : BLC_2)$ **then**
23: PoW;
24: $current - hash : cn \neq previous - hash : fn$;
25: Call Policy;
26: $r : st_2, ac_2, t_2 = x_{wf} = 1 \in WF : wf = 1, wf = 3 : \frac{\text{data}_{wf}}{\xi_{fn=2}}$;
27: **else if then**
28: $st_2, ac_2, t_2 = x_{ij} : wf = 4, 9, 10 : \frac{\text{data}_i}{\xi_{j=3}}$;
29: $current - hash : fn \neq previous - hash : ma$;
30: Call Policy;
31: $r : st_1, ac_1, t_1 = x_{wf} = 1 \in WF : wf = 1, wf = 4, 9, 10 : \frac{\text{data}_i}{\xi_{j=2}} = 1$;
32: **end if**
33: Work being done on the cloud node;
34: $st_3, ac_3, t_3 = x_{ij} : wf = 2, 5, 7, 8 : \frac{\text{data}_{wf}}{\xi_{cn=3}}$;
35: $current - hash : cn \neq previous - hash : fn$;
36: Call Policy;
37: $r : st_3, ac_3, t_3 = x_{ij} : wf = 2, 5, 7, 8 : \frac{\text{data}_{wf}}{\xi_{cn=3}}$;
38: **end for**
39: Complete the task assigned to every node.
40: **Endure primary purpose;**

1) Mobile Execution: During the first ten phases of the scheduling process, the mobile device was used to apply blockchain validation after the preset tasks that were meant to be executed locally were started. (st_1, ac_1, t_1) represents the initial state, which is the result of the first action and transition in the state. Only the tasks related to wf_1 and wf_3 were planned to be executed on the mobile node j_1 in this specific condition. Then, the information was encrypted using the Secure Hashing Algorithm (SHA-256) bits, and cryptographic information was transferred from one j_1 to j_2 until the hash values of the previous and current iterations matched. To optimize and include the reward in the Q-learning sequence and contribute to a successful execution outcome, the model-free optimum policy was used.

2) Fog Execution: All of the assigned tasks were scheduled at the fog node in stages 11 through 23 of the scheduling process. The fog node then applied blockchain validation at that location. The initial state, indicated by the notations st_2, ac_2, and t_2, is the result of the state's first action and transition. At this point, the fog node j_2 was only scheduled to do tasks related to $wf_{4,9,10}$. Cryptographic data was transferred from one j_2 to j_3 using encryption the SHA-256 bits until the hash values of the two sets of data matched. A successful execution resulted from optimizing and including the reward in the q-learning sequence using the model-free optimum strategy.

3) Cloud Execution: Steps 24 through 35 of the scheduling procedure involve applying blockchain validation in the cloud computing environment and scheduling the designated cloud taskson the mobile cloud node. The first action and transition in this state is represented by the initial state from (st_3, ac_3, t_3). Only the application's tasks $(wf_2, wf_5, wf_6, wf_7, wf_8)$ are scheduled on the mobile node j_3 at this time. Cryptographic data is moved from j_3 to j_2 through encryption SHA-256 bits until the hashes from the two processes match. The Qlearning series with positive executed is redused and recognized by the modelfree ideal policy call.

G. Assessment and Execution Phase

Here, we explore the real-world application of the baseline methods and the BDRL algorithm, and we provide a detailed analysis of their relative performances in the discussion of the findings that follow. Equation 12 illustrates how the study uses statistical mean values to analyze the data outcomes, specifically utilizing the relative percentage deviation (RPD%). In this case, ObF stands for the study's objective function, and ObF^* for the ideal goals attained by adaptive scheduling. An important indicator for identifying differences between the optimal and initial goal functions of workflow applications enabled by adaptive scheduling is the (RPD%). With respect to the baseline algorithms, the goal of this comparison analysis is to offer a thorough grasp of the effectiveness and efficiency of the DRLBTS algorithm. The statistical analysis of the suggested approaches, taking into account the data presented in simulations with both single variance and multi-variance, is shown in equation 12.

$$\text{RPD\%} = \frac{ObF - ObF^*}{ObF^*} 100\% \tag{12}$$

H. Applications and Baseline Approaches for Healthcare Workflow Use-Cases

This study's simulation was organized into many levels, including mobile fog and cloud agents, multi-agent heterogeneous nodes, and industrial healthcare workflows. The core of the code was built on top of EdgeXFoundry, which made use of its open-source application programming interface to make layer implementation simple. The mobile, fog, and cloud tasks sectors were among the divisions into which the industrial workflow applications were divided. Workloads from workflows and current algorithms were used for the experimental comparison. Below is a summary of these:

- Deep Q-Learning, or DQN, is a widely used technique in DRL to handle heterogeneous computing problems. It was first implemented as Baseline 1. Numerous studies [10]–[13] that address related workflow challenges across many computer nodes have made substantial use of this technique.
- As demonstrated by research [14]–[16], the DDPG (Deep Deterministic Policy Gradients) machine learning technique was adopted as Baseline 2 and has been extensively deployed to solve comparable workloads and challenges, notably during the problem formulation phases in networks.
- DDPG Using blockchain-based methods: As shown in research [21], [22], this method is used as Baseline 3 to improve dynamic scheduling performance for healthcare applications.
- Actor-Critic Algorithm with Asynchronous Advantage and Decentralized Ethereum Scheduling: This method, which is presented as Baseline 4 in the simulation, makes use of a state search technique that is intended to control resource dynamic uncertainty, as demonstrated by research [21], [22].

I. Parameter variation

The findings in Table I indicate a substantial correlation between intensified resource utilization and the expansion of states, actions, transitions, and blockchain blocks. Throughout the study, values for these parameters were randomly assigned based on available mn, fn, and cn, with St set to 40, ac to 40, t to 40, N to 10, and BLC to 10. The experimental phase intentionally introduced two failed transactions for each process. Notably, as resources approached full utilization, it was observed that the Performance Evaluation Ratio (PER) results became closer to each other. While the augmentation of states, actions, transactions, and blocks holds the potential to improve scheduling efficiency, it concurrently leads to heightened resource consumption. This dual effect introduces both advantages and disadvantages to consider. On the positive side, an increase in the number of states, actions, transactions, and blocks can contribute to enhanced scheduling efficiency within the system. This improvement is particularly valuable in optimizing resource allocation and task management. However, on the downside, this augmentation in system components results in increased resource consumption. The direct correlation between heightened resource utilization and the expanded number of states, actions, transactions, and blocks implies a potential rise in resource leakage. Resource leakage, in turn, poses a significant disadvantage as it can impact overall system performance and efficiency. The observation that PER results become closer when resources are fully utilized suggests that the system is reaching a saturation point, and further resource allocation may not significantly improve performance. This highlights the importance of carefully balancing resource utilization to avoid diminishing returns and potential inefficiencies in the system.

VI. Discussion of the results using various methods

This section of the study conducts a thorough investigation of the workflow apps' performance on various compute nodes

TABLE I
COMPARING MEASURES

G	ac	t	N	BLC	RPD%	Resources
1000	40	40	10	10	45	RAM 1024, CPU 80.2%
800	40	40	10	10	42	RAM 1024, CPU 72.1%
700	40	40	10	10	38	RAM 1024, CPU 68.8%
600	40	40	10	10	32	RAM 1024, CPU 62.5%
1000	70	70	10	10	48	RAM 1024, CPU 90%
800	70	70	10	10	40	RAM 1024, CPU 85%
700	70	70	10	10	41	RAM 1024, CPU 82%
600	70	70	10	10	39	RAM 1024, CPU 80.4%

in four different scenarios shown in figure 2. Case 1 entails running all workflow software on mobile devices. Cases 2, 3, and 4, show how workflow applications are scheduled and offloaded on other nodes. Notably, the study's deep offloading strategy beats down previous strategies for executing workflow apps across several nodes. Depending on the needs, strategies like Static Offloading, Dynamic Offloading, and Deep Offloading are used to move workloads from local devices with limited resources to nodes that are accessible for execution.

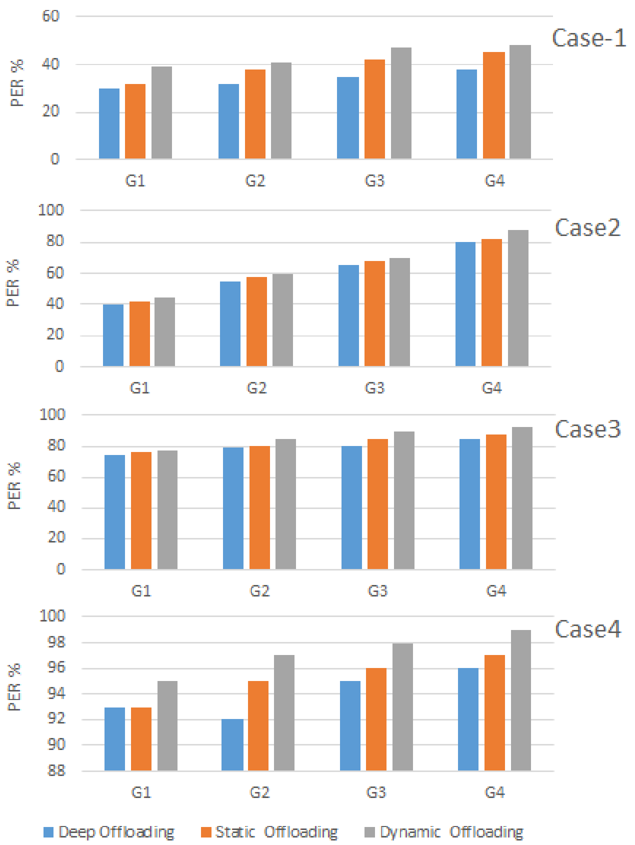

Fig. 2: Blockchain execution on local device

Four apps (G 1 to 4) switch the running of their operations between physical devices to proximity computing. The RPD% point values associated with the goal function are shown on the y-axis. When parameters change at runtime, basic parameter-enabled static offloading encounters larger delays, taking into account things like resources, traffic, and waiting time during execution. Changes are incorporated into dynamic offloading methods; nevertheless, delays are increased because of workflow task failures and resource unavailability on some nodes. However, the deep offloading approach takes into account a number of factors while processing workflows, including parameter changes, resource and task failures, and deadlines. As a consequence, delays are reduced.

Figure 3 shows that the use of DL-enabled BLC in workflow healthcare applications is ideal in terms of interdependency, data validation, resource leakage, and transaction failure. The current frameworks for the Ethereum and Corda static and dynamic blockchains do not address resource leakage, task failure, or workflow dependence. These models only took into account workloads that were both finely and coarsely tuned and ran on separate nodes.

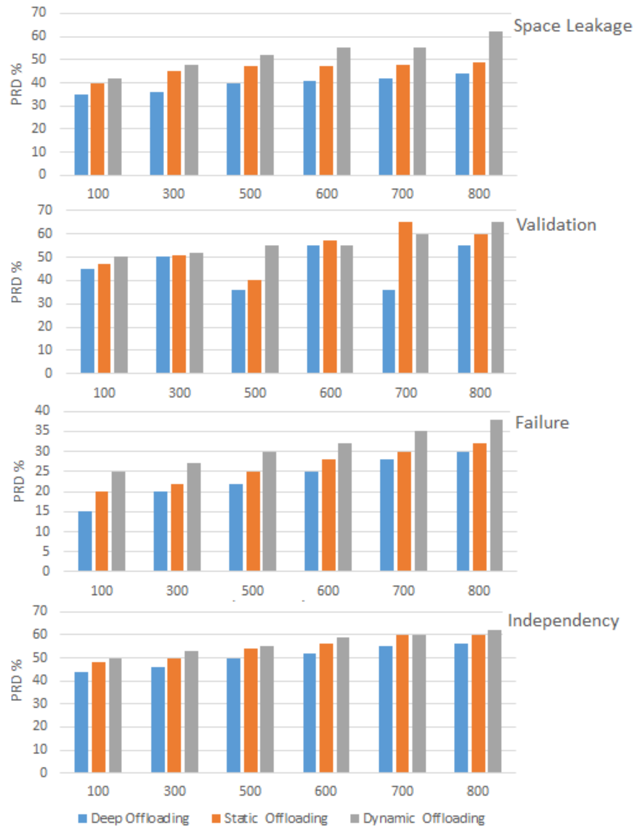

Fig. 3: Space leakage for data transformations allowed by Blockchain in mobile fog cloud networks.

However, during data transaction validation, significant delays are seen as a result of resource-constraint problems across various compute nodes. Furthermore, a major obstacle to using current blockchain technology for data transactions in workflow healthcare applications is resource leakage across many computer nodes. These problems are more successfully addressed by the deep learning-based blockchain technology that is being suggested. Based on predetermined requirements, the study implemented four basic ways to arrange process jobs on various computer nodes. The assessment shows that BDRL outperforms all current schemes. Additionally, the duration

Fig. 1: BDRL framwork

efficiency of process jobs (e.g., 1500 and 3000 tasks) using multiple parallelisms and distributed scheduling systems (e.g., baseline 1, 4, and BDRL) is tested and displayed in Figure 4.

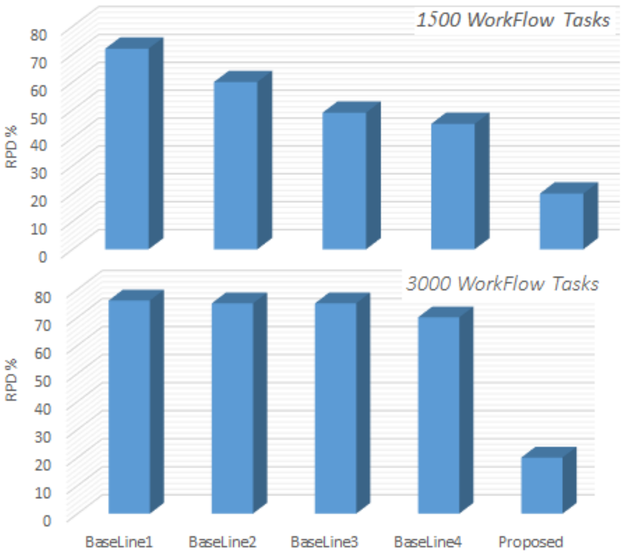

Fig. 4: Operational efficiency on mobile fog cloud networks is madepan.

Comparing BDRL to current techniques, the makespan of all processes is minimized, as shown in Figures 5.

The way that structured workflow apps and define the flexible BLC with scheduling in this study led to more optimal results compared to earlier frameworks. It helped to reduce the overall makespan of apps and effectively tackled issues like failures, losing of resources, and task and node deadlines.

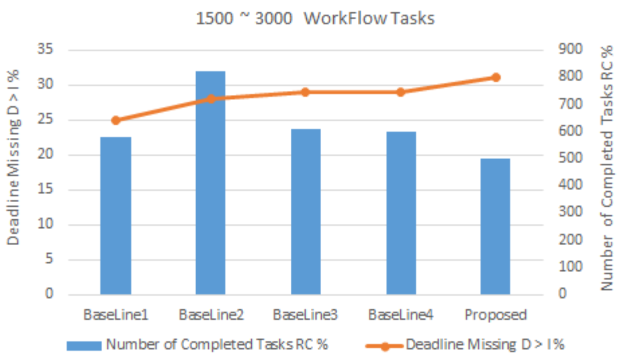

Fig. 5: Process baselines for reinforcement and deep learning systems.

VII. CONCLUSION

In this paper, we propose a Blockchain-based Deep Reinforcement Learning (BDRL) system designed to optimize healthcare operations within the context of a multi-cloud environment. The system specifically addresses the challenge of secure and efficient healthcare data management and decision-making in decentralized settings. Unlike traditional approaches, our method integrates blockchain technology to enhance data security and transparency, while the application of deep reinforcement learning enables adaptive decision-making, making this approach particularly novel and impactful in the healthcare domain. However, limitations, including architectural overhead affecting real-time healthcare applications, significant energy consumption, and higher resource utilization with increased data size, were identified. To address these challenges, future work aims to incorporate real-time profiling, implement quality of service-based scheduling, and fine-tune the framework to minimize power costs and node energy consumption in distributed mobile fog cloud networks across multiple time zones. This comprehensive evaluation provides valuable insights into the framework's strengths and areas for improvement, guiding future research and development endeavors.

APPENDIX

TABLE OF SYMBOLS

Symbol	Description
G	Set of applications
WF	Workflow tasks
data_{wf}	Data associated with workflow
ma	Mobile agents
fn	Fog nodes
cn	Cloud nodes
Tn_{wf}	Execution time of jobs distributed over several nodes
$C_{wf1,wf2}$	Communication time between process tasks
st	State
ac	Action
$ST_{st1,ac1}$	State transitions from state $st1$ to action $ac1$
MT	Makespan time for each workflow application
ξ_{ma}	Resources and speeds of mobile agents
ξ_{fn}	Resources and speeds of fog nodes
ξ_{cn}	Resources and speeds of cloud nodes

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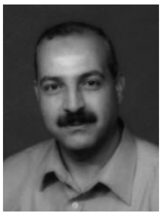

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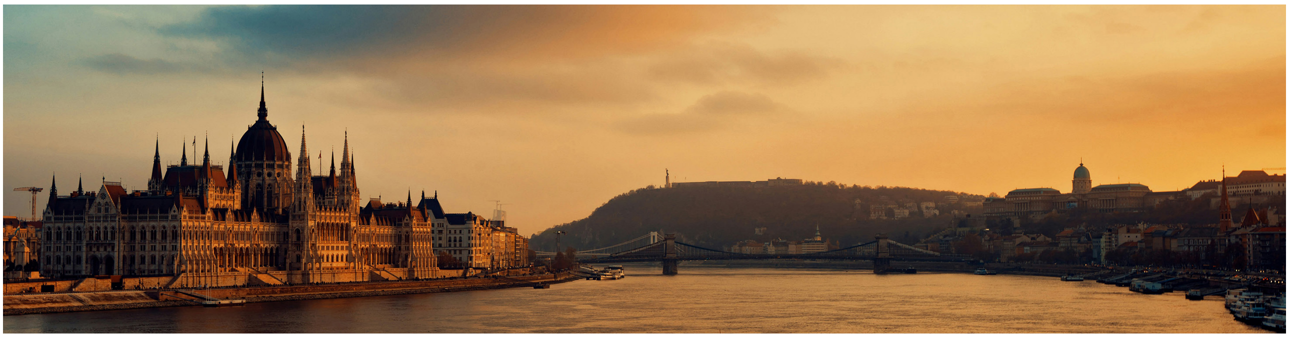

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