Short thesis for the degree of doctor of philosophy (PhD)

High Speed B5G/6G Communication Network Analysis Using Machine Learning And Queueing Techniques

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Outline

1. Introduction

The evolution of wireless communication systems has reached a critical phase with the advent of 6G networks, as it is expected to deliver unprecedented capabilities such as speed, reliability, and latency. The main goal is to address the growing demand for real-time data-driven applications, like immersive augmented and virtual reality, intelligent transportation systems, industrial automation, and large-scale machine-type communications. With promised data rates exceeding 1 Tbps, latency below 1 ms, and the ability to support ultra-dense networks [1, 2], 6G is not just an upgrade but a paradigm shift that redefines how wireless networks are conceived, designed, and managed [3, 4].

To fulfil these demanding requirements, 6G must incorporate a wide range of technological innovations spanning physical, medium access, and network layers. Including many new technologies that should be investigated before implementing them, because they might bring a lot of challenges, like the terahertz communication, intelligent reflective surfaces, cell-free architectures, integrated sensing and communication, and other technologies. However, beyond these hardware-level advancements, one of the defining features of 6G is the integration of artificial intelligence (AI) into every aspect of the network, enabling pattern recognition, predictive adaptation, autonomous decision-making, and dynamic resource optimisation. Machine learning and artificial intelligence integration are no longer considered add-ons but rather a central component that allows the system to interpret context, adapt to the dynamic environment, and evolve as the conditions change.

Despite this, the path to bring 6G to reality faces fundamental challenges [4, 5, 6]. First, the absence of real-world data makes it difficult to accurately characterise network behaviour under future scenarios. Second, the complexity of the system, which results from the interaction of multiple technologies and the dynamic nature of wireless environments, makes it hard to derive generalizable models. Third, the traditional network design process, which relies only on heavily on mathematical abstractions, needs to be complemented by data-driven tools that can extract patterns and inform decisions. The mentioned challenges require novel frameworks capable of simulating 6G scenarios, extracting meaningful features with the help of traditional mathematical techniques, analysing the system's complexity, and training intelligent agents that can adapt and operate in such environments.

My thesis proposes a multi-stage framework using different analysis techniques and integrating AI models to enhance the performance of the system. The value of this approach lies in its flexibility and modularity. By structuring the investigation into discrete but interconnected stages: simulation, feature extraction, AI learning, and reinforcement adaptation, this study lays the groundwork for early understanding and validation of 6G behaviours. My thesis provides a practical roadmap for future work, especially once real-world data becomes available. More broadly, the framework demonstrates how intelligent data processing and AI integration can bridge the current gap between theoretical design and operational readiness.

This introductory chapter provides the background and motivation for the rest of the work. The next sections will articulate the problem statement, define the research objectives, and present the overall structure of the investigation, including the grouping of results into focused thesis blocks.

The main publications related to this thesis are the following: [J1, J2, J3, J4, J5, C1, C2, C3, C4, C5, C6, C7].

2. Problem Statement and Research Objectives

To meet the ambitious performance expectations of 6G networks, like ultra-low latency, extreme data rates, massive connectivity, and intelligent resource management, the adoption of new enabling technologies is essential. These include terahertz communications [7], intelligent reflecting surfaces, and network slicing, among others. However, introducing these technologies gives rise to new technical and analytical challenges that must be anticipated and addressed during the design phase. The complexity of 6G networks should be addressed. Traditional modelling approaches and static analysis tools are no longer sufficient to capture these evolving behaviours [8]. Meanwhile, the lack of real-world 6G datasets further complicates early validation and optimisation efforts. Therefore, simulation environments remain the only feasible way to study system behaviour under realistic assumptions.

In the 6G context, integrating AI methods becomes a promising solution as a core analytical tool [9, 10, 11]. Intelligent models can identify hidden patterns and adapt to dynamic environments. After using the simulation environment to extract the 6G networks KPIs, it is very important to process them with the right advanced signal processing techniques to extract the hidden patterns and unknown behaviours KPIs before introducing the AI methods, which can offer a powerful approach to navigate the complexity of early 6G research. The aim is not only to prepare the ground for real-world deployment but also to create models that are adaptable and data-efficient.

Research objectives

- Use two aspects to extract the 6G wireless networks data: the first is the directional MAC protocol with the help of the ns-3 simulator, and the second is the Retrial Queueing System with the help of MATLAB software.

- Extract and process the 6G performance data using different techniques such as Shannon entropy and time-frequency analysis.
- Integrate different artificial intelligence techniques for learning and overcome the 6G challenges.
- Provide a theoretical foundation for future empirical studies once real-world 6G data becomes available, through a structured and modular framework.

3. Methodology

The methodology adopted follows a multi-stage approach to analyse, model, and interpret emerging behaviours in 6G wireless systems. The overall workflow is represented by a modular and extensible framework that unifies both simulation-based environments and data-driven modelling. In this chapter, all the methods presented are implemented as part of this unified modular framework, ensuring flexibility and ease of integration across different 6G use cases.

Simulation Framework and KPI Extraction

Due to the current unavailability of real-world 6G deployment data, simulations form the foundation of this research. Two complementary simulation models have been used for extracting the 6G KPIs. The first focuses on ADAPT (Adaptive Directional Antenna for Terahertz Frequencies) to emulate MAC-layer behaviour under high-frequency directional transmission scenarios. The second model, RQS (Retry Queueing System), was designed using MATLAB to simulate the retry dynamics of mobile terminals under varying access conditions and queue states.

For each simulation scenario, essential KPIs were extracted to evaluate system behaviour. These include Packet delivery rate and latency, Queue size evolution and client loss ratio, Directional transmission success rate (ADAPT-specific), and System throughput under contention.

These KPIs were then used as input signals for subsequent complexity analysis and AI integration phases. The use of ns-3 provides an environment with high flexibility for topology design, custom protocol implementation, and time-accurate tracing of communication events.

Feature Extraction and KPIs Analysis

A series of signal processing and statistical techniques were employed to extract features from the raw KPIs and analyse the behavioural complexity of the system under different configurations. These include:

i) Shannon Entropy and entropy ratios to measure.

ii) Empirical Mode Decomposition (EMD) and Ensemble EMD (EEMD).

iii) Marginal Hilbert Spectrum (MHS) analysis.

iv) Higher-order derivatives and slope-based transforms were also considered.

These methods allow for a granular and interpretable understanding of the system's dynamic states, enabling the decomposition of macro-level throughput into micro-level behaviour changes associated with specific node types or spatial configurations (e.g., normal vs. overlapped mobile terminals in ADAPT).

Multi-Level AI Integration

These analyzed KPIs were then used to train multiple artificial intelligence models:

i) *Unsupervised Learning*: DBScan clustering was employed to identify behavioural groups among the Mobile Terminals (MTs) without prior labelling.

ii) *Supervised Learning:* 3 types of Recurrent Neural Network (RNN) were trained using wavelet-transformed extracted features.

iii) *Multi-Layer Transfer-Learning model:* Multi-layer machine learning models were also evaluated with transfer learning ability for enhancing the classification across different simulation scenarios, where a new metric was introduced to quantify the performance of the used model, and choose the best one, taking into consideration various parameters.

iv) *Generative AI*: five different Generative AI methods were examined to generate synthetic KPIs data; meanwhile, six similarity metrics were used to evaluate the quality of the generated dataset.

v) *Reinforcement Learning Integration:* In the RQS algorithm, a deep Q-learning RL-based agent was introduced to learn an optimal policy for better decision-making and enhance the 6G queue performance.

Theoretical Validation in the Absence of Real-World Data

Since 6G is still in its pre-deployment stage, theoretical validation has been adopted in place of empirical benchmarking. Several validation strategies were applied: i) Comparative analysis between simulation outputs and known theoretical bounds (e.g., maximum achievable throughput under ideal channel access). ii) Internal consistency checks across overlapping data sources (e.g., entropy and EMD IMFs). iii)Sensitivity analysis of AI models to noise and unseen configurations, by using metrics to evaluate the performance. iv)Robustness tests for generalisation across mobile terminals and the topology types.

These layers of theoretical validation ensure that the proposed methods are not only operationally meaningful within simulation but also conceptually transferable to future real-world 6G environments once relevant datasets become available. This provides a coherent synthesis of applied validation strategies compensation for the absence of real-world data while preserving the methodology rigor of the study.

4. Results

The dissertation results are organized in three main thesis groups, a together eight theses.

4.1. Thesis Group I: Simulation and Data Processing

This thesis group focuses on the simulation-based exploration of 6G network behaviour and the techniques used for data analysis.

4.1.1. Thesis 1: Simulation-based characterization of directional MAC behavior and KPI extraction

With the help of the ns-3 simulator and Terasim extension [12, 13], we extracted different KPIs related to the 6G MAC-ADAPT.

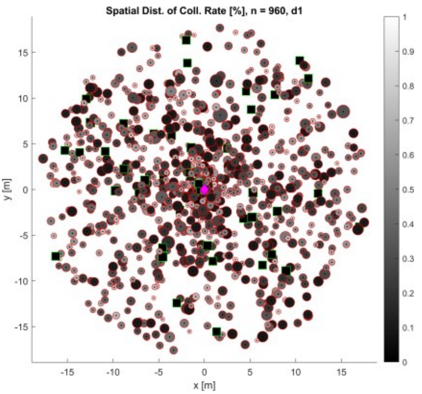

Figure 1. Spatial distribution of collision rates of MTs in centred topology (n = 960).

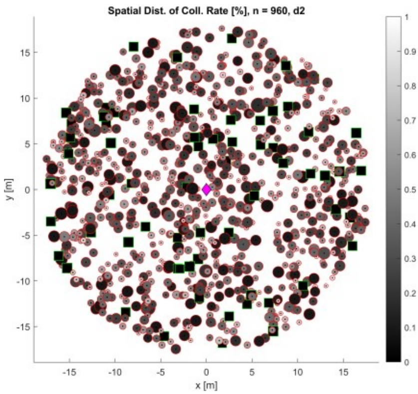

Figure 2. Spatial distribution of collision rates of MTs in uniform topology (n = 960).

By visualising it, several interesting behavioural patterns were revealed under different network conditions and parameter settings. As various simulation parameters were adjusted, such as MTs density, topology type, overlap ratio, and step size, distinct trends emerged in performance indicators like collision (see Figure 1 and Figure 2), throughput, transmission duration, received power, and packet loss. These behaviours highlighted the sensitivity of the directional MAC mechanism to spatial dynamics and protocol configuration. "*The plotted figures demonstrate how varying these parameters impacts network performance, with the overlapping ratio enhancing the coverage and the rotation step ensuring systematic access to all sectors. As observed, a higher MT population leads to an increased collision rate, while lower densities reduce collisions significantly. Correspondingly, the interactions between these parameters reveal intricate dependencies that can be leveraged to refine network strategies.*" (Discussion is in the dissertation, section IV.3, [J2, C1]). As an extension, we added two main parameters ADAPT MAC algorithm: i) overlapping ratio, ii) step size. These parameters have interesting properties, explained in detail in the dissertation (Discussion is in the dissertation, section IV.4, [J2, C2, C3]).

4.1.2. Thesis 2: Entropy-based analysis of network behavioral complexity

The second thesis explores the use of entropy-based metrics to analyse the ADAPT-MAC received power by the Access Point (AP) [30, 32]. The MTs were split into two types based on the overlapping ratio, so basically on their location in the cell. The Shannon entropy of the two subsystems was calculated, plus the total entropy of the system (see Figure 3), which we later use the three calculated parameters to calculate a so-called entropy ratio of the two subsystems to analyse the interdependence between the two MTs types. This entropy ratio allowed us to characterise the mutual influence between the MTS with different spatial opportunities for communication. By quantifying the uncertainty of subsystem interactions, this ratio provides a measurable indicator of network complexity, as higher entropy and stronger interdependence typically correspond to more complex behavioral dynamics.

In addition, two metrics were introduced: Inter-Subsystem Mutual Effect (M) and Relative Entropy Difference (R) (Figure 4) defined with the following formulae:

$$M[e] = \eta_N[e] + \eta_L[e] - 1 \quad (1)$$

$$R[e] = \eta_N[e] - \eta_L[e] \quad (2)$$

Where $\boldsymbol{\eta_N}$ and $\boldsymbol{\eta_L}$ refers to the entropy ratios of the normal and lucky MTs, respectively.

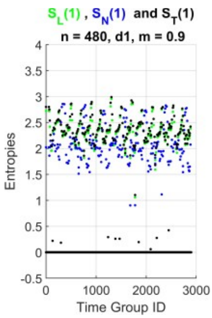

Figure 3. Entropy of subsystem interdependence.

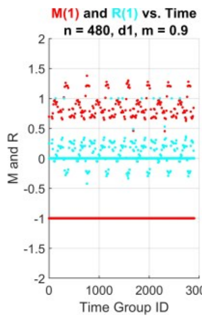

Figure 4. Entropy ratios-based metrics.

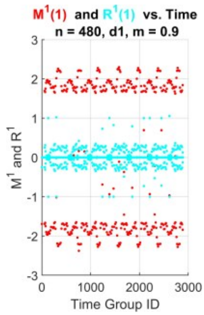

Figure 5. 1st derivative of entropy ratios-based metrics.

"The inter-subsystem mutual effect metric evaluates the interdependence level between the two subsystems. M being closer to zero indicates a high level of interdependency, conversely, more analysis is needed to study the significance of nonzero M. The Relative Entropy Difference (R) calculates the balance of the system, "R being closer to 0 declares the equilibrium of the two subsystems; this suggests that both subsystems experience similar uncertainty and variability in accessing the AP, reflecting a balanced communication opportunity. Such equilibrium minimises congestion and interference, promoting stable network performance and ensuring fair resource distribution among MTs." (Discussion is in the dissertation, section V.1) [J2, C5].

Figure 5 shows the first derivative of the introduced metrics M and R, *"One can notice, that by calculating the derivative, the scale got enlarged guarding the original pattern depending on the simulation scenario case and the parameters m, n, and d. This scale adjustment brings subtle variations into clearer focus, revealing periodic shifts and fluctuations that may otherwise be overlooked. This finding is crucial for tracking rapid changes in entropy ratios, enabling fine-tuning of parameters for enhanced adaptability and robustness in practical applications."* (Discussion is in the dissertation, section V.1) [J2, C5].

4.1.3. Thesis 3: Time-frequency behavior profiling with EMD and MHS

In this thesis, multi-processing techniques were applied to analyze two 6G-KPIs and identify anomalous behaviors, defined here as irregular patterns or deviations in throughput and received power that deviate from expected stable trends. First is the throughput, where EMD and EEMD were applied to analyze it [14]. An interesting property was found: *"Our observation from the results was that the IMFs generated by the direct and inverse methods were significantly different, despite having different amplitudes for the same IMFs. This difference was further confirmed by a correlation coefficient of less than 0.5 (c = 0.48), which indicates that EMD is direction-dependent. The experiment was repeated using EEMD with 5 percent white noise. The IMFs generated by the direct and inverse methods were identical, despite having the same amplitude. This finding was confirmed by a high correlation coefficient c = 0.994, which indicates that EEMD is direction-independent."* (Discussion is in the dissertation, section V.2) [J1]. Following, we fitted the throughput signal to extract the fitting parameters **a** and **b.** A scatter plot was generated to provide visual insight into the outcomes of parameters **a** and **b** (see Figure 6).

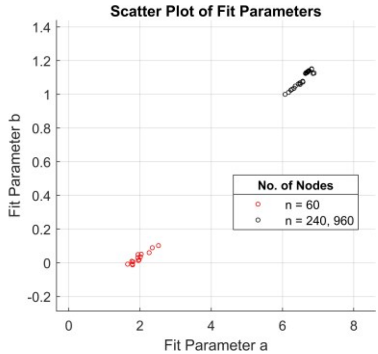

Figure 6. Scatter plot of the fit parameters.

Interestingly, the parameters clustered according to congestion levels, thereby indicating congestion as a measurable anomaly in system behavior.

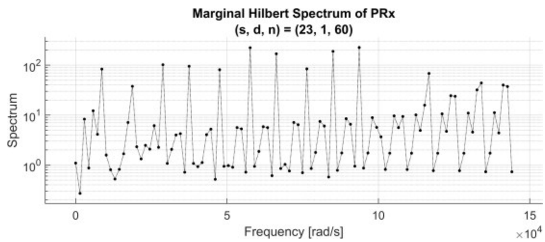

Figure 7. Marginal Hilbert Spectrum of received power (n, d, s) = (60, 1, 23).

*"These findings strongly imply that the fitting parameters, specifically parameters **a** and **b**, hold promising potential as valuable indicators for discerning and characterizing network congestion states. Such observations signify the scientific relevance and significance of the proposed methodology in understanding and quantifying the complexities of network congestion in our study."* (Discussion is in the dissertation, section V.2) [J1]. The second chosen 6G-KPI was the received

power by the AP. Where IMFs were extracted using EMD, then processed it using HHT to extract then the MHS (see Figure 7).

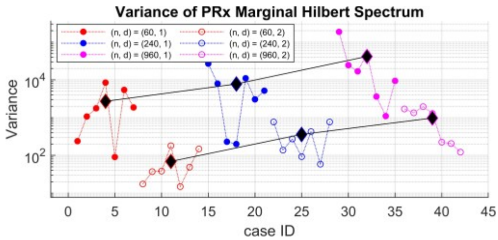

Figure 8. Mean of received power marginal Hilbert spectrum vs. scenario case ID.

It was found that *"The MHS of the received power shows varying patterns depending on the scenario. These patterns reflect how the frequency components of the signal change over time. In some cases, the spectrum may appear stable, indicating consistent received power, while in others, it may fluctuate, pointing to factors like interference or environmental changes. These variations provide valuable insights into the system's behavior, helping to identify stable periods or potential issues like interference."* (see Figure 8) (Discussion is in the dissertation, section V.3) [J3].

To compare between the MHS patterns, we decided to use four different statistical methods (Mean, Interquartile Range, variance, and skewness). The results show that these statistical methods reveal distinct clustering behaviors in the two different topologies. The results indicate that the centered topology demonstrated higher signal consistency and clustering, while the uniform topology exhibited greater variability and dispersion. This variability is interpreted as a manifestation of anomalous network conditions tied to topology. It also highlights the pivotal role of topology, with centered configurations outperforming uniform ones by 17 dB in signal variance. (Discussion is in the dissertation, section V.2) [J3].

4.2. Thesis Group II: AI Integration and Learning

This thesis group focuses on the integration of AI tools with different usages into the 6G MAC system. Building upon the extracted simulation dataset and behavior analyses presented in the previous thesis group, AI is investigated here to uncover the hidden structures, learn temporal dynamics, generalize across conditions, and even generate synthetic patterns to extend the available knowledge. This part of the thesis establishes a multi-level AI-driven framework that supports intelligence and prediction in future 6G environments.

4.2.1. Thesis 4: Unsupervised clustering of 6G behavioral patterns using DBScan

The sector efficiency was calculated within 50 simulation cases, considering both collisions and throughput. We applied the DBScan-based unsupervised machine learning on the unlabeled dataset to cluster the features [15]. Since DBScan relies on two parameters: the radius that defines the distance between two points to be neighbors, and the minimum points required to form a dense region or a cluster, *So what will be the optimal Minimum number of elements for best clusterization?* To determine the optimal configuration, we evaluate the trade-off between cluster compactness and the number of outliers. The analysis showed the best working point is the one with the lowest outliers, not equal to zero (see Figure 9), which was found to be 6 elements per cluster. Therefore, 6 different clusters were found $(C_0, C_1, C_2, C_3, C_4, C_5, C_6)$.
"The results of classifying the sector efficiency vectors using the working point are illustrated in Figure. VI-8, Given the substantial number of outliers which represents 25.5% of the data (383 out of 1500 elements) revealed with dark blue rectangles in class C_0." While DBScan labelled these as "outliers", in our simulation context they

reflect to rare behavioural patterns that deviate from dominant clustering trends, rather than erroneous data. We consider this as an important notation, as these cases may capture unusual but valid network condition that merit future study.

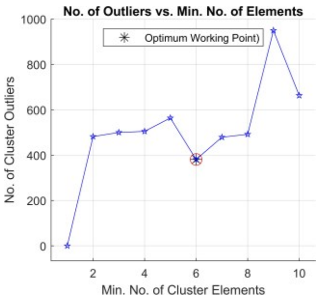

Figure 9. Dependence of Outliers Number on Minimum Number of Cluster Elements.

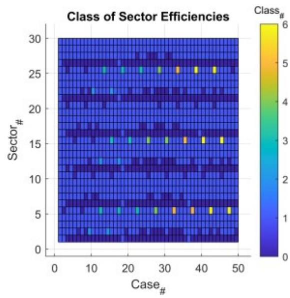

Figure 10. Classification of sector efficiency vectors at optimal working point.

"The results of classifying the sector efficiency vectors using the working point are illustrated in Figure. VI-8, Given the substantial number of outliers which represents 25.5% of the data (383 out of 1500 elements) revealed with dark blue rectangles in class C_0." While DBScan labelled these as "outliers", in our simulation context they reflect to rare behavioural patterns that deviate from dominant clustering trends, rather than erroneous data. We consider this as an important notation, as these cases may capture unusual but valid network condition that merit future study.

" Meanwhile, It is intriguing that sector efficiency vectors having the IDs 5, 15, and 25 are enrolled within the clusters C_4, C_5, and C_6. This criterion invites further investigation to understand why these sectors are enrolled in these classes in this manner, which could reveal unique characteristics or patterns specific to these cases and sectors." (Discussion is in the dissertation, section VI.1) [J2, J4, C4]. In this context, such cases should not be seen as errors or anomalies, but rather as rare patterns that deviate from dominant clusters. The grouping suggests that they

capture distinctive efficiency conditions, giving insights into hidden structural properties of the MAC mechanism that may otherwise remain unnoticed.

4.2.2. Thesis 5: Classification of 6G Behavioral Patterns Using RNNs with Wavelet-Encoded Features

The contribution of this thesis is to demonstrate that the supervised learning methods, when combined with a mathematical feature extraction method, can reliably classify 6F patterns based on MT density. With the help of the wavelet transform, we extracted the AP-MT transmission distance features for 14 different simulation cases.

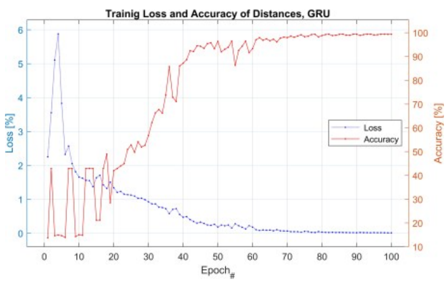

Figure 11. GRU NN learning and classification.

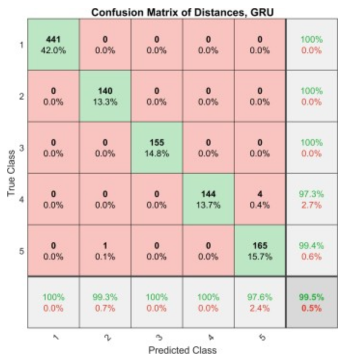

Figure 12. GRU confusion matrix.

After that, we randomly select 300 compacted sequences from the overall extracted feature, creating a so-called feature vector as follows:

$$\delta^{i} = \left(\delta^{i}_{1}, \delta^{i}_{2}, \ldots, \delta^{i}_{300}\right), i = 1, 2, \ldots, 14 \quad (3)$$

"Every sequence vector $\delta_j^i \in \mathbb{R}^{2000}, j = 1, \ldots, 300$ *has 2000 serial elements, where the vectors have been classified and mapped based on Table. IV-1 having in total 5 different classes* $(C_1, \ldots, C_5)$*, the classes are carefully chosen based on the*

mobile terminals' densities." (Discussion is in the dissertation, section VI.2) [J2, C1].

The three RNN types have been used for these classifications: LSMT, BiLSTM, and GRU. All the three methods used demonstrated strong performance from both learning and testing accuracies (Figures 11 & 12). results have the effectiveness of the methods used. "*Each model, when combined with wavelet transform for feature extraction, showed strong performance. The GRU model, for instance, achieved 99.5% accuracy and completed training and testing in a remarkably short time, highlighting its efficiency and ability to process complex data quickly. Similarly, the LSTM and BiLSTM models showed excellent accuracy, though with slight differences in training behavior. While all models demonstrated robustness in handling the given dataset, the wavelet transform required substantial computational resources. Additionally, class imbalance can affect model accuracy, especially for underrepresented classes."*(Discussion is in the dissertation, section VI.2) [J2, C1]. The results directly reflect the research objective. It enables interpretable and scalable AI-driven methods by combining AI with mathematical feature extraction methods for predicting communication performance under diverse 6G scenarios.

4.2.3. Thesis 6: Performance Evaluation of 6G RNN Models via Multi-Layer Transfer Learning and WATR Metric

This thesis aims to enhance the performance of the NN by using multi-layer transfer learning and evaluate it with a novel metric that focuses on both the accuracy and efficiency of the learning. We focused on training multi-layer transfer learning on the extracted MAC collisions for 16 simulation cases, using a novel multi-layer transfer learning approach. Four classes were considered based on the step **s** parameters; every two twin pairs belong to the same class. For the multi-layer transfer-learning [16, 17, 18], we used three types of RNN: LSTM, BiLSTM, and GRU. A novel approach was introduced by constructing two types of multi-layer NN: homogeneous models and heterogeneous models, where we took the advantage of the taught layers and untaught layers in this design (table 1).

Table 1, Neural network types.

NN Code	Transf. Learn.	Homogeneous	Taught Layers	Untaught Layers	Max. Epochs
U1	No	Yes	0	1	150
U2	No	No	0	2	150
T0	Yes	Yes	k = 1, …, 5	0	150+200·k
T1	Yes	No	k = 1, …, 4	1	150+200·k
T4	No	Yes	0	k = 1, …, 5	150+200·k

However, we tend to compare the performance of the models used because based on research that was done and to the best of our knowledge, no metric was found to quantify the goodness of learning outcomes. Therefore, we propose a metric to weight the overall performance taking into consideration the learning time, validation accuracy at a certain threshold $a = 0{,}90$, and testing accuracy, we first calculate a so-called the Accuracy-to-Tima Ratio (ATR) for both validation and testing as follows:

$$\mathrm{ATR_{valid}}(a) = \frac{\mathrm{Acc_{valid}}(a)}{\mathrm{Learn\ Time}(a)}\ [\mathrm{s}^{-1}] \tag{4}$$

$$\mathrm{ATR_{test}} = \frac{\mathrm{Acc_{test}}}{\mathrm{Learn\ Time}}\ [\mathrm{s}^{-1}] \tag{5}$$

Where $\mathrm{Acc_{valid}}(a)$ and $\mathrm{Learn\ Time}(a)$ are the validation accuracy and the learning time within the threshold a, respectively. While $\mathrm{Acc_{test}}$ and Learn Time are the testing accuracy and the learning time, respectively. Second, we calculate the Weighted Accuracy-to-Time Ratio (WATR) with weight α as follows:

$$\mathrm{WATR} = \alpha \cdot \mathrm{ATR}_{\mathrm{valid}} + (1-\alpha) \cdot \mathrm{ATR}_{\mathrm{test}}\ [\mathrm{s}^{-1}] \tag{6}$$

the weight α reflects the relative importance of validation over testing performance. In this thesis, α is defined as the ratio the $\mathrm{ATR}_{\mathrm{valid}}$ and $\mathrm{ATR}_{\mathrm{test}}$ values:

$$\alpha = \frac{\max(\mathrm{ATR}_{\mathrm{test}})}{\max(\mathrm{ATR}_{\mathrm{valid}})} \tag{7}$$

WATR metric was calculated for the proposed models, and it proved its ability in quantifying the goodness of the trained model.

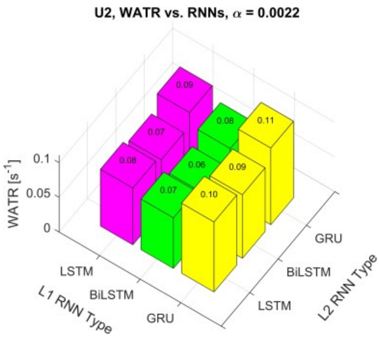

Figure 13. WATR for U2 heterogeneous RNN type.

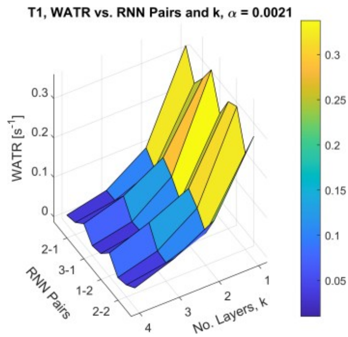

Figure 14. WATR T1 heterogeneous RNN.

For both T0 and T4 (homogeneous models), GRU performed better than other RNN types. For heterogeneous model U2, always good performance is achieved when GRU layers are used, hence the best performance is when both layers are GRU, having $WATR = 0.11\ s^{-1}$ (see Figure 13). As for T1, the performance is enhanced when the number of taught layers increases (Figure 14). *"The type of the RNN significantly influences testing accuracy and WATR performance metrics. Notably, GRU outperformed other configurations, demonstrating superior efficiency and accuracy in both homogeneous and heterogeneous setups."* (Discussion is in the dissertation, section VI.3) [J2, C2].

The expected outcome of this thesis is the good performance of the RNN models, when combined with multi-layer transfer learning, achieving superior performance in terms of efficiency and accuracy compared with the traditional NN types. Also, the performance of the GRU-based models when compared with that of LSTM and BiLSTM. Moreover, the proposed WATR metric provides a systematic and interpretable way to quantify model performance, thus addressing previous works' lack of evaluation measures.

4.2.4. Thesis 7: Synthetic data generation for rare pattern extension using Generative AI

This thesis aims to generate a synthetic entropy-based dataset to extend the rare patterns in 6G simulations, addressing the challenge of data scarcity. We expect to identify the most effective GAN method for producing realistic and reliable data that can enhance the training and evaluation of AI models in communication research.

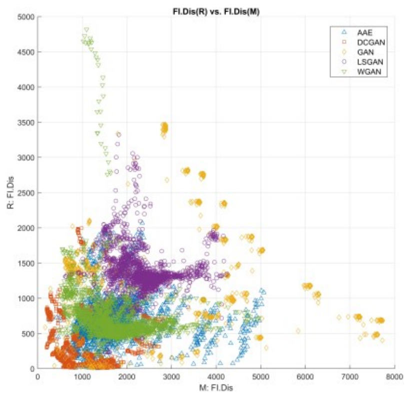

Figure 15. FID scatter plot.

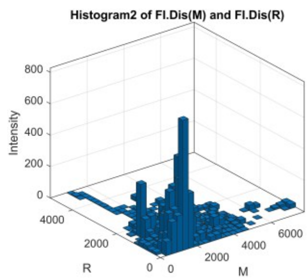

Figure 16. FID 3D histogram.

Five Generative Adversarial Networks (GANs) methods were used for generating a synthetic pattern from the Shannon entropy metrics M and R; Adversarial Autoencoder (AAE), Deep Convolutional GAN (DCGAN), Least Squares GAN (LSGAN), and Wasserstein GAN (WGAN). 20 synthetic M and R pairs were generated from each simulation case, having 70 different simulation cases. Nevertheless, an important aspect should be considered, *how can we evaluate the quality of the generated dataset?* And *which GAN method is more accurate?*

Therefore, it was decided to compare the original M and R pair dataset and the generated ones by using six well-known similarity metrics [19, 20, 21, 22]. Two types of figures were generated: a scatter plot of the M and R pair and a 3D histogram for visualization (e.g. Figures 15 and 16). The results revealed that DCGAN generated more accurate synthetic data than the rest: *"it was evident that the GAN type called DCGAN outperformed the others, proving superior synthetic data quality and better alignment with the original data. On the other hand, the traditional GAN type showed the worst performance among all methods, indicating lower quality and higher error rates. These findings highlight the importance of selecting the appropriate GAN model for specific applications."*(Discussion is in the dissertation, section VI.4) [J2, C6, C7].

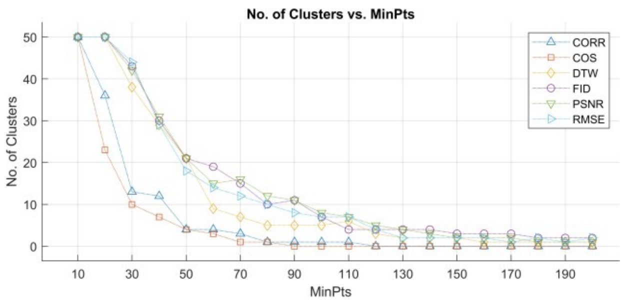

Figure 17. Dependence of the number of the clusters on the parameter MinPts of the OPTICS.

For a better evaluation, we used Ordering Points To Identify the Clustering Structure (OPTICS) method. As a result, three main clusters were observed (Figure 17): *Group 1: {FID, PSNR, RMSE}, Group 2: {DTW}, Group 3: {CORR, COS}.* *"The evaluation results proved the limitations of both correlation and cosine similarities in capturing the resemblance and quantifying the similarity level between the original entropy pair {M, R} vectors and the generated vectors in* *contrast to other used similarity metrics (DTW, FID, PSNR, and RMSE).”*(Discussion is in the dissertation, section VI.4) [J2, C6, C7].

4.3. Thesis Group III: Queueing Behavior and Reinforcement Learning

The modeling of queueing behavior for the next-generation wireless networks with the integration of RL are addressed in this thesis group. The objective is to explore how intelligent agents can earn optimal policies that improve client services rates and reduce losses under dynamic and uncertain conditions.

4.3.1. Thesis 8: Reinforcement learning for adaptive decision-making in 6G queueing environments

As the tested 6G RQS baseline model exhibited some limitations, we proposed to integrate decision-making-based DQN RL to enhance the performance. 120 simulation cases were simulated based on three variables: arrival rate (λ), queue size (K), and the scaling factor (α) for the agent reward calculation. (Discussion is in the dissertation, section VI.5) [J5]

By integrating the DQN-RL, we could observe the increase in the served MTs, a decrease in both queued MTs and orbited MTs over episodes. This was across all the simulated cases (e.g. Figure 18).

Nevertheless, calculating the Singular Value Decomposition (SVD), six clusters were detected based on the clients' arrival variable. The fifth and sixth clusters appear close to each other, suggesting similar structural characteristics under these high-load conditions. *“This is likely due to the saturation effects of the queueing system as the arrival rate approaches its upper limit. The found clustering behavior proves the strong impact of arrival rate on the learned policy and system dynamics.”*

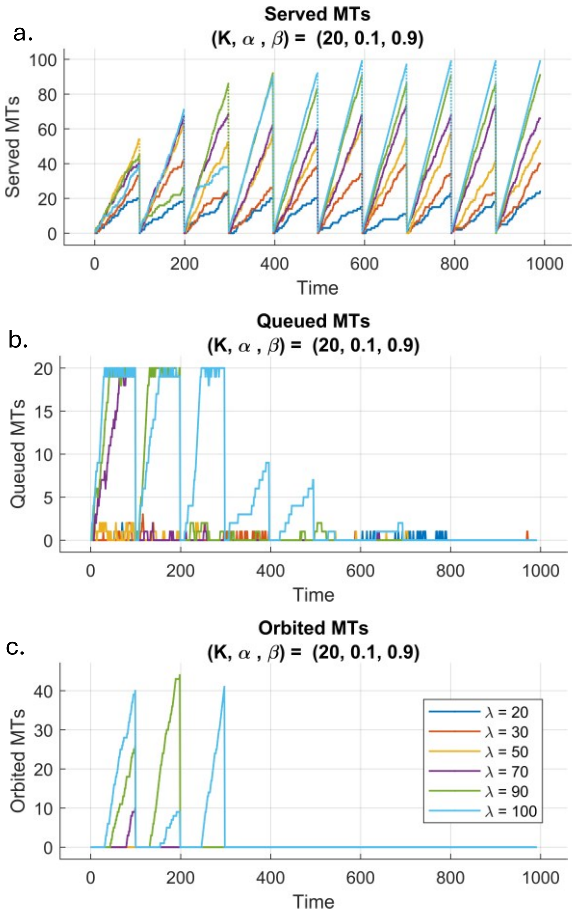

Figure 18. Performance of 6G-RQS with RL Integration: Served (a), Queued (b), and Orbited (c) MTs for (K,α,β) = (20,0.1,0.9).

"*Nevertheless, the distinct clusters reinforce the effectiveness of SVD in capturing the dominant patterns within the served MTs matrix, offering valuable insights into the fundamental structure of the learned 6G-driven RQS system dynamics."*(Discussion is in the dissertation, section VI.5) [J5].

Moreover, the most used DQN-actions during the simulation were extracted for all simulation cases (e.g. heatmap in Figure 20). These results clearly indicate that in cases when we have arrival rates between 20 and 90, the most frequently selected action was action 1 (do nothing) across all the cases, with a few exceptions.

Figure 19. SVD of the served MTs.

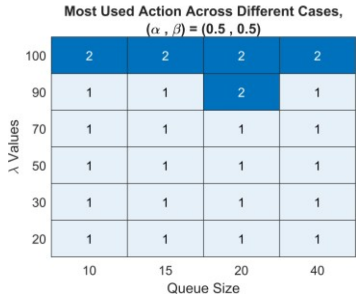

Figure 60. DQN-based most decided actions heatmap.

In contrast, for the highest arrival rate, the agent consistently favors action 2 (force to serve one MT), this can reflect that in high traffic loads, the natural service rate becomes insufficient to prevent excessive queueing and orbiting.

5. Applications of the Found Results

The practical implications of my thesis are significant for advancing the development and deployment of 6G networks. The methods and insights presented provide a roadmap for addressing key challenges in future real-world applications, offering innovative solutions to enhance network performance, reliability, and adaptability. In scenarios characterized by dynamic and high-density environments, such as urban centers or industrial IoT deployments, the ability to process complex and time-sensitive data is critical. This research supports these demands by highlighting efficient methodologies for feature extraction (findings of *chapter IV, [J2, C1, C2, C3]*), data analysis using multiprocessing techniques (findings of *chapter V, [J1, J2, J3, C5]*), clustering (findings of *sub-chapter VI.1, [J2, J4, C4]*), classifications (findings of *sub-chapter VI.2,[J2, C1]*), and predictive modeling (findings of *sub-chapter VI.3, [J2, C2]*). The proposed approaches can streamline processes such as dynamic resource allocation, anomaly detection, and collision management, enabling networks to maintain high performance even under challenging conditions.

For practical deployment, the findings suggest the importance of adaptive algorithms capable of real-time adjustments to varying network states. By incorporating robust clustering methods and predictive modeling techniques, network operators can optimize efficiency while minimizing computational overhead. Additionally, the generation of synthetic data (findings of *sub-chapter VI.4, [J2, C6, C7]*) provides an invaluable tool for testing and validating network protocols in scenarios where real-world data is limited or unavailable. This capability is crucial for simulating extreme conditions or novel use cases, ensuring the reliability of solutions before they are deployed.

The reliability and applicability of synthetic data have been reinforced through theoretical validation, which is considered a robust approach. However, stronger validation would involve aligning synthetic data with real-world benchmarks. This can only be achieved once 6G devices become available on the market. Strategies such as these, coupled with advanced metrics tailored to specific network scenarios, ensure that synthetic data accurately reflects the complexities of real-world conditions, thus enhancing its applicability in supporting innovative applications for 6G networks. Furthermore, the use of DQN-RL strategies (findings of *sub-chapter VI.5, [J5]*) demonstrates a promising approach for dynamic decision-making in queueing environments. By learning optimal retry policies in a data-driven manner, DQN-RL enhances the system's ability to handle varying loads and unpredictable user behaviors, thereby improving overall service reliability and adaptability.

To ensure the broader applicability and security of these methods, attention must be given to potential risks, such as privacy concerns and vulnerability to adversarial attacks. Employing privacy-preserving techniques, such as federated learning or differential privacy, can safeguard sensitive information while maintaining the utility of generated data. Moreover, integrating these methods into a practical 6G architecture will require collaboration across disciplines to address hardware constraints, interoperability, and scalability. The findings of this study provide a foundation for future innovations in 6G technology. They highlight pathways for optimizing network operations, ensuring scalability, and supporting diverse applications, from smart cities to autonomous systems. By bridging theoretical advancements with practical implementation strategies, this work contributes to a more actionable framework for the next-generation wireless communication networks.

Nevertheless, this study has certain limitations. The validation of some methods relied on simulated data and theoretical aspects rather than real-world 6G measurements. Future work should therefore focus on extending the evaluation with practical datasets, addressing scalability and security challenges. Developing more adaptive mechanisms would ensure robustness in diverse 6G scenarios.

Own publications

List of Own Publications Referred in the Dissertation

[J1] **Talbi, D.**, Gál, Z.: Decomposition Based Congestion Analysis of the Communication in B5G/6G TeraHertz High-Speed Networks. Infocommun. Journal 15 (Special), 43-48, 2023 **(WoS, Scopus, Q3, IF: 0.9)**.

[J2] **Talbi, D.**, & Gal, Z.: AI-driven insights into B5G/6G MAC mechanisms: A comprehensive analysis. *Internet of Things*, *31*, 101571, 2025 **(WoS, Scopus, D1, IF: 7.6)**.

[J3] **Talbi, D.**, Gál, Z.: Analysis of High-Speed Radio Communication in THz Bands: Topological Impacts and Signal Decomposition Using Empirical Mode Decomposition and Marginal Hilbert Spectrum. Lecture Notes on Data Engineering and Communications Technologies. 252, 59-71, 2025 **(Scopus, Q4).**

[J4] **Talbi, D.**, Daoui, Z., & Gal, Z. (2024). Unsupervised Machine Learning-Based Clustering of High-Frequency Radio Channel Properties: Analysis of Sector Communication Efficiency. Procedia Computer Science, 238, 306-313. (**Scopus**).

[J5] **Talbi, D.**, & Gal, Z.: Integrating Reinforcement Learning into M/M/1/K Retry Queueing Models for 6G Applications. Sensors. 25 (12), 1-30, 2025. ISSN: 1424-8220. DOI: http://dx.doi.org/10.3390/s25123621, (2024) **(Q1, IF: 3.5).**

[C1] **D. Talbi**, M. A. Korteby and Z. Gal, "Neural Network Based Analysis of Terahertz Frequency Signal Propagation for B5G/6G Wireless Networks," *2022* IEEE 2nd Conference on Information Technology and Data Science (CITDS), Debrecen, Hungary, pp. 267-272, 2022 **(Scopus)**.

[C2] **D. Talbi** and Z. Gal, "Impact of Multi-Layer Recurrent Neural Networks in the Congestion Analysis of TeraHertz B5G/6G MAC Mechanism," 2022 International Conference on Software, Telecommunications and Computer Networks (SoftCOM), Split, Croatia, pp. 1-6, 2022 **(Scopus)**.

[C3] Gál, Z., **Talbi, D.**: "B5G/6G kommunikációs csatorna torlódásának elemzése mesterséges intelligenciával = Artificial Intelligence Based Analysis of the B5G/6G

Communication Channel Congestion, " XXIII. Energetika-Elektrotechnika - ENELKO és XXXII. Számítástechnika és Oktatás : SzámOkt Multi-konferencia / szerk. Sebestyén-Pál György, Szabó Loránd. - p. 101-107, 2022.

[C4] **Talbi, D.**, Gál, Z.: "Localization Behaviour of the THz Radio Communication Based on Unsupervised Machine Learning, " Az elmélet és a gyakorlat találkozása a térinformatikában XIII.: Theory meets practice in GIS, Debrecen, 293-300, ISBN: 9789636150396, 2022.

[C5] **D. Talbi**, Z. Gal, "Entropy-Based Interdependence Analysis of the B5G/6G THz Network", Automation, Robotics & Communications for Industry 4.0/5.0 (ARCI' 2024): 4th IFSA Winter Conference, Barcelona, 170-176, (ISSN 2938-4796) ISBN: 9788409582198, 2024.

[C6] **Talbi, D.**, Gal, Z., "Analysis of the B5G/6G Communication Power Entropy Patterns Based on Generative AI Methods", 2024 IEEE 3rd Conference on Information Technology and Data Science (CITDS), Debrecen, Hungary, 2024 **(WoS)**.

[C7] Gál, Z., **Talbi, D.**, 'Analysis of Received Power Entropy Interdependence in B5G/6G Radio Cell', 2024 IEEE 13th International Conference on Cloud Networking (CloudNet), Piscataway, 1-6, ISBN: 9798350376562, 2024.

List of Own Publications not Referred in the Dissertation

[C8] Y. Mudhafar, **D. Talbi** and Z. Gal, "Neural Network Based Comparison of Real and Synthetic Data Series in TeraHertz Domain," 2022 IEEE 2nd Conference on Information Technology and Data Science (CITDS), Debrecen, Hungary, pp. 207-211, 2022 **(Scopus)**.

[C9] M. A. Korteby, **D. Talbi** and Z. Gal, "Fractals and Wavelets Based Energy Analysis of Cost-Balanced LEACH Sensor Network," 2022 IEEE 2nd Conference on Information Technology and Data Science (CITDS), Debrecen, Hungary, pp. 159-164, 2022.

[C10] **T. Djamila**, K. M. Amine, G. Zoltan, “Decomposition Based Congestion Analysis of the Communication in B5G/6G TeraHertz High-Speed Networks”, ABSTRACT, The 12th International Conference on Applied Informatics, Eger, Hungary, March 2-4,2023.

[C11] M. A. Korteby, **D. Talbi** and Z. Gal, " Effect of the Modulation on the Cluster Head Election in Cost Balanced LEACH”, ABSTRACT, The 12th International Conference on Applied Informatics, Eger, Hungary, March 2-4,2023.

[C12] **D. Talbi**, and Z. Gal, “High-Speed Communication Service Based on Low Earth Orbit Satellite Constellation ”, The meeting of theory and practice in GIS XIV. Theory meets practice in GIS, Debrecen, 291 - 301, ISBN: 9789636150846, 2023.

[C13] **D. Talbi**, M. Tourky, Z. Gál, “Localization Behavior of Swarm Intelligence Algorithms”, The meeting of theory and practice in GIS XIV. Theory meets practice in GIS, Debrecen, 303 – 311, ISBN: 9789636150846, 2023.

[C14] **D. Talbi**, Z. Gal, J. Sztrik, “Low Latency and High-Speed Communication Service with LEO Satellite Constellation”, IEEE, Information and Digital Technologies 2023, June 20th - 22nd, ISBN: 9798350305869 , p. 251-256, 2023 **(Scopus)**.

[C15] Z. Gal, **D. Talbi**, M. Tourky “On the Localization Properties of Swarm Intelligence Algorithms”, IEEE, Information and Digital Technologies 2023, ISBN: 9798350305869 , p. 97-104, 2023 **(Scopus)**.

[C16] Z. Gal, M. Korteby, **D. Talbi**, “Impact of Modulated Routing Mechanism on Wireless Sensor Network Systems: A Comprehensive Analysis”, IEEE, ICKII 2023, ISBN: 9798350323535, p. 70-76, 2023 **(Scopus)**.

[C17] Z. Gal, **D. Talbi**, L. Filep, “On the Required Iteration Number of the Representant Swarm Intelligence Algorithms Based on Coefficient of Variation”, IEEE Proceedings of 2023 9th International Conference ICOA, ISBN: 9798350312546, p. 1-6, 2023.

[C18] Gál, Z., **Talbi**, D., Korteby, M., “Entropy Analysis of Hierarchical Routing in Heterogeneous Wireless Sensor Network.” IEEE 5th Eurasia Conference on IOT, Communication and Engineering (ECICE) / Meen, IEEE-INST ELECTRICAL

ELECTRONICS ENGINEERS INC, Piscataway, 61-67, ISBN: 9798350314694, 2024. **(Scopus, Best Paper Award)**.

[C19] Gál, Z., **Talbi, D.**, "Insights into Low Earth Orbit Satellite Communication Dynamics: Quality of Service Analysis of Connection Behavior, Latency, and Doppler Shift", 2024 IEEE 4th International Conference on Electronic Communications, Internet of Things and Big Data. April 19-21, 2024 **(Best Paper Award)**.

[C20] Phoebe, G., **Talbi, D.**, Gál, Z., "Actual Trajectory and High Speed Internet Service Aspects of a Low Earth Orbit Satellite Constellation." Az elmélet és a gyakorlat találkozása a térinformatikában XV. = Theory meets practice in GIS. Debrecen, 21-29, ISBN: 9789634906193, 2024.

References

[1] HAN, Chong, WU, Yongzhi, CHEN, Zhi, et al. Terahertz communications (TeraCom): Challenges and impact on 6G wireless systems. arXiv preprint arXiv:1912.06040, 2019.

[2] WANG, Jun, WANG, Cheng-Xiang, HUANG, Jie, et al. A novel 3D non-stationary GBSM for 6G THz ultra-massive MIMO wireless systems. IEEE Transactions on Vehicular Technology, 2021, vol. 70, no 12, p. 12312-12324.

[3] TALEB, Tarik, AGUIAR, Rui Luis, GRIDA BEN YAHIA, I., et al. White paper on 6G networking. 2020.Ali, S., Saad, W., & Steinbach, D. White Paper on Machine Learning in 6G Wireless Communication Networks. White paper. 6G Research Visions, No.7, June 2020.

[4] XIA, Qing, HOSSAIN, Zahed, MEDLEY, Michael, et al. A link-layer synchronization and medium access control protocol for terahertz-band communication networks. IEEE Transactions on Mobile Computing, 2019, vol. 20, no 1, p. 2-18.

[5] GHAFOOR, Saim, BOUJNAH, Noureddine, REHMANI, Mubashir Husain, et al. MAC protocols for terahertz communication: A comprehensive survey. IEEE Communications Surveys & Tutorials, 2020, vol. 22, no 4, p. 2236-2282.

[6] JIANG, Wei et SCHOTTEN, Hans D. Full-spectrum wireless communications for 6G and beyond: From microwave, millimeter-wave, terahertz to lightwave. In: 2023 IEEE 3rd International Conference on Computer Communication and Artificial Intelligence (CCAI). IEEE, 2023. p. 353-357.

[7] AKYILDIZ, Ian F., JORNET, Josep Miquel, et HAN, Chong. Terahertz band: Next frontier for wireless communications. Physical communication, 2014, vol. 12, p. 16-32.

[8] KOENIG, Swen, LOPEZ-DIAZ, Daniel, ANTES, Jochen, et al. Wireless sub-THz communication system with high data rate. Nature photonics, 2013, vol. 7, no 12, p. 977-981.

[9] Sakar, C.O., Polat, S.O., Katircioglu, M. et al. Real-time prediction of online shoppers' purchasing intention using multilayer perceptron and LSTM recurrent neural networks. Neural Comput & Applic 31, 6893–6908, 2019.

[10] Tao Ren, Xuefeng Liu, Jianwei Niu, Xiaohui Lei, Zhao Zhang. Real-time water level prediction of cascaded channels based on multilayer perception and recurrent neural network. Journal of Hydrology, Volume 585, 2020.

[11] ALI K, Shoukath, KHAN, Arfat Ahmad, UR REHMAN, Ateeq, et al. Learned-SBL-GAMP based hybrid precoders/combiners in millimeter wave massive MIMO systems. Plos one, 2023, vol. 18, no 9, p. e0289868.

[12] Morales, Daniel & Jornet, Josep. ADAPT: An Adaptive Directional Antenna Protocol for medium access control in Terahertz communication networks. Ad Hoc Networks, vol.119, Mai 2021.

[13] Zahed Hossain, Qing Xia, Josep Miquel Jornet. TeraSim: An ns-3 extension to simulate Terahertz-band communication networks. Nano Communication Networks, vol.17, pp. 36-44, September 2018.

[14] Huang, Kai, et al.: A method for extracting fingerprint feature of communication satellite signal. Wireless Communications and Mobile Computing 2022.1 (2022): 7796017.

[15] AOUEDI, Ons, PIAMRAT, Kandaraj, HAMMA, Salima, et al. Network traffic analysis using machine learning: an unsupervised approach to understand and slice your network. Annals of Telecommunications, 2022, vol. 77, no 5, p. 297-309.

[16] ZHUANG, Fuzhen, QI, Zhiyuan, DUAN, Keyu, et al. A comprehensive survey on transfer learning. Proceedings of the IEEE, 2020, vol. 109, no 1, p. 43-76.

[17] AMEER, Iqra, BÖLÜCÜ, Necva, SIDDIQUI, Muhammad Hammad Fahim, et al. Multi-label emotion classification in texts using transfer learning. Expert Systems with Applications, 2023, vol. 213, p. 118534.

[18] LU, Huiming, WU, Jiazheng, RUAN, Yingjun, et al. A multi-source transfer learning model based on LSTM and domain adaptation for building energy prediction. International Journal of Electrical Power & Energy Systems, 2023, vol. 149, p. 109024.

[19] SATEA, Huda Dhari, IBRAHEM, Amer A., FAIQ, Maher, et al. Similarity measurement's comparison with mapping and localization in large-scale. In : AIP Conference Proceedings. AIP Publishing, 2023.

[20] SENIN, Pavel. Dynamic time warping algorithm review. Information and Computer Science Department University of Hawaii at Manoa Honolulu, USA, 2008, vol. 855, no 1-23, p. 40.

[21] BUZUTI, Lucas F. et THOMAZ, Carlos E. Fréchet AutoEncoder distance: a new approach for evaluation of generative adversarial networks. Computer Vision and Image Understanding, 2023, vol. 235, p. 103768.

[22] SARA, Umme, AKTER, Morium, et UDDIN, Mohammad Shorif. Image quality assessment through FSIM, SSIM, MSE and PSNR—a comparative study. Journal of Computer and Communications, 2019, vol. 7, no 3, p. 8-18.

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Candidate: Djamila Talbi
Doctoral School: Doctoral School of Informatics
MTMT ID: 10092775

List of publications related to the dissertation

Foreign language scientific articles in Hungarian journals (1)

1. **Talbi, D.**, Gál, Z.: Decomposition Based Congestion Analysis of the Communication in B5G/6G TeraHertz High-Speed Networks.
   Infocommun. J. 15 (Special), 43-48, 2023. ISSN: 2061-2079.
   DOI: http://dx.doi.org/10.36244/ICJ.2023.5.7
   IF: 0.9

Foreign language scientific articles in international journals (4)

2. **Talbi, D.**, Gál, Z.: AI-Driven Insights into B5G/6G MAC Mechanisms: A Comprehensive Analysis.
   Internet of Things. 31, 1-43, 2025. ISSN: 2543-1536.
   DOI: http://dx.doi.org/10.1016/j.iot.2025.101571
   IF: 7.6 (2024)
3. **Talbi, D.**, Gál, Z.: Analysis of High-Speed Radio Communication in THz Bands: Topological Impacts and Signal Decomposition Using Empirical Mode Decomposition and Marginal Hilbert Spectrum.
   Lecture Notes on Data Engineering and Communications Technologies. 252, 59-71, 2025. ISSN: 2367-4512.
   DOI: https://doi.org/10.1007/978-3-031-87784-1_6
4. **Talbi, D.**, Gál, Z.: Integrating Reinforcement Learning into M/M/1/K Retry Queueing Models for 6G Applications.
   Sensors. 25 (12), 1-30, 2025. ISSN: 1424-8220.
   DOI: http://dx.doi.org/10.3390/s25123621
   IF: 3.5 (2024)
5. **Talbi, D.**, Zahra, D., Gál, Z.: Unsupervised Machine Learning-Based Clustering of High-Frequency Radio Channel Properties: Analysis of Sector Communication Efficiency.
   Proc. Computer Sci. 238, 306-313, 2024. ISSN: 1877-0509.
   DOI: https://doi.org/10.1016/j.procs.2024.06.029

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Hungarian conference proceedings (1)

6. Gál, Z., **Talbi, D.**: B5G/6G kommunikációs csatorna torlódásának elemzése mesterséges intelligenciával = Artificial Intelligence Based Analysis of the B5G/6G Communication Channel Congestion.
   In: XXIII. Energetika-Elektrotechnika - ENELKO és XXXII. Számítástechnika és Oktatás : SzámOkt Multi-konferencia. Szerk.: Sebestyén-Pál György, Szabó Loránd, Erdélyi Magyar Műszaki Tudományos Társaság, Kolozsvár, 101-107, 2022, (ISSN 2734-6757)

Foreign language conference proceedings (6)

7. Gál, Z., **Talbi, D.**: Analysis of Received Power Entropy Interdependence in B5G/6G Radio Cell.
   In: 2024 IEEE 13th International Conference on Cloud Networking (CloudNet), IEEE-INST ELECTRICAL ELECTRONICS ENGINEERS INC, Piscataway, 1-6, 2024. ISBN: 9798350376562

8. **Talbi, D.**, Gál, Z.: Analysis of the B5G/6G Communication Power Entropy Patterns Based on Generative AI Methods.
   In: 2024 IEEE 3rd Conference on Information Technology and Data Science (CITDS), Institute of Electrical and Electronics Engineers (IEEE), Piscataway, 223-228, 2024. ISBN: 9798350387889

9. **Talbi, D.**, Gál, Z.: Entropy-based Interdependence Analysis of the B5G/6G THz Network.
   In: Automation, Robotics & Communications for Industry 4.0/5.0 ARCI' 2024 Conference Proceedings. Ed.: Sergey Y. Yurish, International Frequency Sensor Association, Barcelona, 170-176, 2024, (ISSN 2938-4796) ISBN: 9788409582198

10. **Talbi, D.**, Gál, Z.: Impact of Multi-Layer Recurrent Neural Networks in the Congestion Analysis of TeraHertz B5G/6G MAC Mechanism.
    In: 2022 International Conference on Software, Telecommunications and Computer Networks (SoftCOM), IEEE, [s.l.], 1-6, 2022.

11. **Talbi, D.**, Gál, Z.: Localization Behaviour of the THz Radio Communication Based on Unsupervised Machine Learning.
    In: Az elmélet és a gyakorlat találkozása a térinformatikában XIII.: Theory meets practice in GIS. Szerk.: Abriha-Molnár Vanda Éva, Debreceni Egyetemi Kiadó, Debrecen, 293-300, 2022. ISBN: 9789636150396

12. **Talbi, D.**, Korteby, M. A., Gál, Z.: Neural Network Based Analysis of Terahertz Frequency Signal Propagation for B5G/6G Wireless Networks.
    In: 2022 IEEE 2nd Conference on Information Technology and Data Science (CITDS). Ed.: Fazekas István, Institute of Electrical and Electronics Engineers (IEEE), Piscataway, 196-201, 2022. ISBN: 9781665496537

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List of other publications

Foreign language conference proceedings (11)

13. Phoebe, G. A., **Talbi, D.**, Gál, Z.: Actual Trajectory and High Speed Internet Service Aspects of a Low Earth Orbit Satellite Constellation.
    In: Az elmélet és a gyakorlat találkozása a térinformatikában XV. = Theory meets practice in GIS. Szerk.: Abriha-Molnár Vanda Éva, Debreceni Egyetemi Kiadó, Debrecen, 21-29, 2024. ISBN: 9789634906193

14. Gál, Z., **Talbi, D.**, Korteby, M. A.: Entropy Analysis of Hierarchical Routing in Heterogeneous Wireless Sensor Network.
    In: 2023 IEEE 5th Eurasia Conference on IOT, Communication and Engineering (ECICE) / Meen, Institute of Electrical and Electronics Engineers (IEEE), Piscataway, 61-67, 2024. ISBN: 9798350314694

15. Gál, Z., **Talbi, D.**: Insights into Low Earth Orbit Satellite Communication Dynamics: Quality of Service Analysis of Connection Behavior, Latency, and Doppler Shift.
    In: Proceedings of the 2024 IEEE 4th International Conference on Electronic Communications, Internet of Things and Big Data (ICEIB), Institute of Electrical and Electronics Engineers (IEEE), [Piscataway], 116-121, 2024. ISBN: 9798350360721

16. **Talbi, D.**, Gál, Z.: High Speed Communication Service Based on Low Earth Orbit Satellite Constellation.
    In: Az elmélet és a gyakorlat találkozása a térinformatikában XIV. Theory meets practice in GIS / Abriha-Molnár Vanda Éva, Debrecen University Press, Debrecen, 291-301, 2023. ISBN: 9789636150846

17. Gál, Z., Korteby, M. A., **Talbi, D.**: Impact of Modulated Routing Mechanism on Wireless Sensor Network Systems: A Comprehensive Analysis.
    In: IEEE 6th International Conference on Knowledge Innovation and Invention, [s.n.], [s.l.], 70-76, 2023. ISBN: 9798350323535

18. **Talbi, D.**, Tourky, M., Gál, Z.: Localization Behaviour of Swarm Intelligence Algorithms.
    In: Az elmélet és a gyakorlat találkozása a térinformatikában XIV. Theory meets practice in GIS / Abriha-Molnár Vanda Éva, Debrecen University Press, Debrecen, 303-311, 2023. ISBN: 9789636150846

19. **Talbi, D.**, Gál, Z., Sztrik, J.: Low Latency and High-Speed Communication Service with LEO Satellite Constellation.
    In: Proceedings of The International Conference on Information and Digital Technologies 2023, [s.n.], [s.l.], 251-256, 2023. ISBN: 9798350305869

20. Gál, Z., **Talbi, D.**, Tourky, M.: On the Localization Properties of Swarm Intelligence Algorithms.
    In: Proceedings of The International Conference on Information and Digital Technologies 2023, [s.n.], [s.l.], 97-104, 2023. ISBN: 9798350305869

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21. **Talbi, D.**, Filep, L., Gál, Z.: On the Required Iteration Number of the Representant Swarm Intelligence Algorithms Based on Coefficient of Variation.
In: Proceedings of 2023 9th International Conference on Optimization and Applications (ICOA), IEEE Computer Society, Washington, Piscataway, 1-6, 2023. ISBN: 9798350312546

22. Korteby, M. A., **Talbi, D.**, Gál, Z.: Fractals and Wavelets Based Energy Analysis of Cost-Balanced LEACH Sensor Network.
In: 2022 IEEE 2nd Conference on Information Technology and Data Science (CITDS). Ed.: Fazekas István, Institute of Electrical and Electronics Engineers (IEEE), Piscataway, 116-121, 2022. ISBN: 9781665496537

23. Mudhafar, Y., **Talbi, D.**, Gál, Z.: Neural Network Based Comparison of Real and Synthetic Data Series in TeraHertz Domain.
In: 2022 IEEE 2nd Conference on Information Technology and Data Science (CITDS). Ed.: Fazekas István, Institute of Electrical and Electronics Engineers (IEEE), Piscataway, 152-156, 2022. ISBN: 9781665496537

Foreign language abstracts (2)

24. **Talbi, D.**, Korteby, M. A., Gál, Z.: Decomposition Based Congestion Analysis of the Communication in B5G/6G TeraHertz High-Speed Networks.
In: The 12th International Conference on Applied Informatics - Abstracts, Eszterházy Károly Egyetem, [Eger], 1-3, 2023.

25. Korteby, M. A., **Talbi, D.**, Gál, Z.: Effect of the Modulation on the Cluster Head Election in Cost Balanced LEACH.
In: International Conference on Applied Informatics - Abstracts, Eszterházy Károly Egyetem, Eger, 1-3, 2023, (ISSN 1792-460X)

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