MINISTRY OF EDUCATION AND TRAINING
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RESEARCH ON SHORT PACKET COMMUNICATION PROTOCOLS WITH ULTRA-RELIABLE AND LOW LATENCY IN COOPERATIVE COMMUNICATIONS

Major: Electronic Engineering
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SUMMARY OF PH.D. THESIS

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This thesis was completed at HCMC University of Technology and Education

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INTRODUCTION

Research Reasons.

To date, the Internet of Things (IoT) services, including automation technologies, intelligent transport systems, tactile internet, as well as Virtual Reality (VR) and Augmented Reality (AR), are developing rapidly. Fifth-generation (5G) wireless network technology, along with its advanced versions, such as 5.5G and 6G, is opening the door to deeper integration of humans into the IoT ecosystem and a hyper-connected society. In the context of emerging networking and communication technologies, three key services are expected to make significant breakthroughs: machine-to-machine communication (mMTC), enhanced mobile broadband (eMBB), and ultra-reliable low-latency communication (uRLLC). Currently, the development of uRLLC services, characterized by high reliability and low latency, has become a primary focus in the engineering and industrial sectors. uRLLC communications require extremely high reliability and a latency of less than 1ms to meet stringent Quality of Service (QoS) standards.

At present, Short Packet Communication (SPC) is regarded as the primary communication method for improving uRLLC services within 5G networks and future network generations. Additionally, collaborative networks have proven to be a promising solution for enhancing reliability in most existing network systems, as well as in the development of next-generation networks, providing benefits such as increased channel transmission efficiency, improved reliability, and extended coverage range. Therefore, the research on SPC combined with collaborative networks presents a promising avenue for realizing uRLLC systems in next-generation 5G networks. However, to date, studies on SPC in collaborative networks have primarily focused on improving reliability, without simultaneously meeting the requirements for both reliability and latency.

Based on the above considerations, this thesis titled "**Research on Short Packet Communication Protocols with Ultra-Reliable and Low Latency in Cooperative Communications**" aims to propose new protocols using advanced techniques at the physical layer to address both reliability and latency issues in SPC, with a focus on enhancing uRLLC services.

Research Objectives

The thesis focuses on two primary objectives, which are clearly defined as follows:

- The first objective is to develop an SPC model in a cooperative communication network and optimize the system's performance to meet the requirements of uRLLC systems within the framework of next-generation network standards.
- The second objective is to investigate and apply advanced methods and techniques to enhance reliability and minimize latency, specifically through the use of techniques such as Intelligent Reflecting Surfaces (IRS), non-orthogonal multiple access (NOMA), and Deep Learning (DL) techniques.

Research Tasks

The thesis addresses four main tasks as follows:

- Task 1: Develop and evaluate the performance of the SPC model in a two-hop relay network.
- Task 2: Optimize the performance of the SPC in a two-hop relay network to meet the requirements of uRLLC systems.
- Task 3: Analyze the performance of the SPC system using IRS to enhance reliability and reduce latency in cooperative networks.
- Task 4: Estimate the power allocation for the SPC system through the application of DL techniques, aiming to comply with the criteria of uRLLC systems.

Research Scope

The thesis primarily investigates SPC in cooperative communications, two-hop relay networks, and NOMA networks.

Research Approach and Methods

Approach: Based on the analysis of research on SPC in next-generation networks, existing results and methods have been compared and evaluated, unresolved issues identified, and directions for future research proposed in the thesis.

Research Methods:

The thesis employs the following research methods:

- Analytical and Comparative Method: Studies on SPC are analyzed and compared, leading to the proposal of new models to meet the specific research objectives of the thesis.
- Statistical Analysis: Techniques such as signal analysis, calculus, probability theory, and optimization methods are applied to evaluate performance and optimize the proposed systems.
- Monte Carlo Simulation Method: This method is used to validate the results of the theoretical analysis.
- Performance Comparison: The performance of the proposed system model is compared with existing systems to demonstrate the advantages of the new model.

Research's Scientific and Practical Significance

❖ The scientific significance of this thesis lies in its contribution to the field with new solutions and advanced results regarding SPC, as follows:

- The thesis provides a novel solution for SPC in two-hop relay networks to enhance reliability and reduce latency by: i) Exploiting spatial diversity through techniques such as transmit antenna selection (TAS), partial relay selection (PRS), and maximum ratio combining (MRC); ii) Optimizing transmit power and relay node positioning.
- This thesis proposes the use of Intelligent Reflecting Surfaces (IRS) as a replacement for DF relay nodes in SPC systems, significantly improving system performance.
- For the first time, the thesis proposes the combination of wave shaping techniques and IRS in NOMA to improve SPC reliability, and employs Deep Learning (DL) to address low-latency and fast processing

requirements in future networks, focusing on predicting BLER, throughput, latency, and transmit power allocation.

Practical Significance

- The first optimized SPC model for two-hop relay networks in 5G is introduced, with features such as low transmit power, limited coverage area, short transmission distances, and high co-channel interference. This model provides a foundation for future research and design of MIMO-based networks for SPC.
- The SPC model using IRS is critical for relay networks and NOMA, proving effective for 5G and future networks, particularly in challenging transmission environments such as urban and hilly terrains, with limited transmit power and small coverage areas.
- The thesis has been published in international Web of Science journals, including the Journal of Communications and Networks (Q1) and the Institution of Engineering and Technology Communications (Q2), as well as in the RIVF 2023 and ATC 2024 international conferences, and the National Journal of Information and Communication Technology. These contributions provide valuable references for researchers and organizations in the field of wireless networking technology.

CHAPTER 1 OVERVIEW

Chapter 1 provides an overview of issues related to short packet communication in cooperative networks. These issues are evaluated and analyzed based on research from relevant international and domestic studies conducted in recent years. From this, we identify existing challenges, potential areas for development, and propose three research models, which are presented in Chapters 3 to 5.

CHAPTER 2 THEORETICAL FOUNDATIONS

Chapter 2 presents the theoretical foundation for short packet communication and cooperative communications. Specifically, it describes the structure of short packets, analyzes performance evaluation data for short packet communication, and outlines basic models in cooperative communication. Furthermore, this chapter delves into the advantages and disadvantages of short packet communication and cooperative communication in uRLLC systems. Additionally, Chapter 2 covers fundamental theories related to advanced techniques such as IRS, NOMA, and DL.

CHAPTER 3: OPTIMIZATION OF SYSTEM PERFORMANCE FOR SHORT PACKET COMMUNICATION IN TWO-HOP RELAY NETWORKS

Chapter 3 proposes a short packet transmission model in a two-hop decode-and-forward relay network, combining protocols such as TAS, PRS, and MRC. This is illustrated in Figure 3.1.

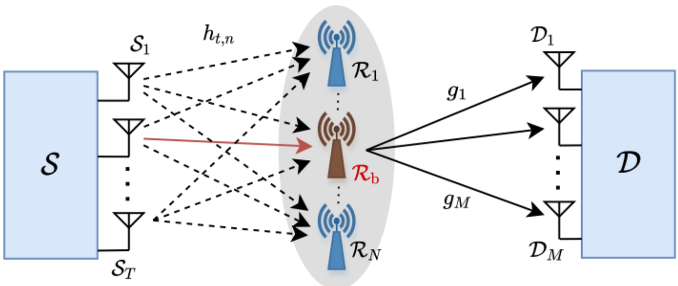

Figure 3.1: Two-Hop DF Network Model with TAS/PRS/MRC techniques in SPC

Operating Principle: The system model operates based on a time-division multiple access method with two consecutive time slots through relays $\mathcal{R}_n$. In the first time slot, the source $\mathcal{S}$ transmits the signal to the relays $\mathcal{R}_n$, where the system simultaneously employs TAS and PRS technique. According to the TAS principle, the system selects the optimal transmitting antenna of the source for the transmission process. Next, in the second time slot, the selected relay $\mathcal{R}_b$ receives the signal from the source $\mathcal{S}$, $\mathcal{R}_b$ decodes it, and forwards it to the destination $\mathcal{D}$ using the Decode-and-Forward (DF) method. To ensure signal reception reliability, the destination implements MRC protocol.

The system performance is analyzed and evaluated based on parameters such as block error rate (BLER), latency, and throughput. Mathematical expressions for these parameters are provided explicitly and validated through Monte Carlo simulation. The simulation results are presented, including the evaluation section and the optimization of system performance, with simulation parameters set for the number of transmitted bits $\beta = 256$ bits và block length $k = 256$ CUs, normalized transmit distance $D = 10$, the channel attenuation factor $\eta = 3$.

System performance evaluation: The overall system performance utilizing the Fixed Decode-and-Forward Protocol (FDF) outperforms the Selective Decode-and-Forward Protocol (SDF) across all values of the average Signal-to-Noise Ratio (SNR) $\bar{\gamma}$, as shown in Figure 3.2. Therefore, the FDF technique is selected for further investigation in the subsequent figures.

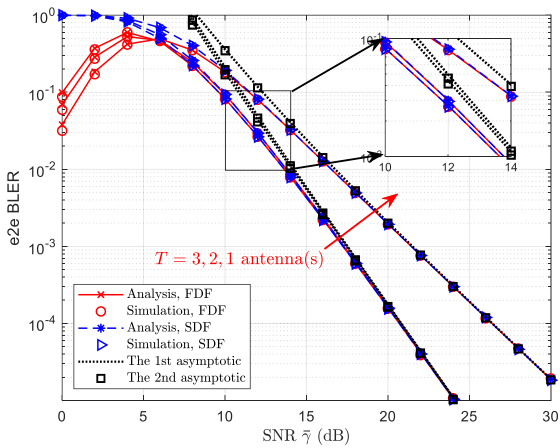

Figure 3.2: The performance comparison between the FDF and SDF schemes, with $N = 2$ and $M = 3$

Figure 3.3 examines the impact of T on the end-to-end Block Error Rate (e2e BLER) of the system using the FDF scheme, where $N = 2$, $M = 3$ and

$\bar{\gamma} = 10, 15, 20$ dB. By analyzing the figure, it is evident that the e2e BLER decreases as $\bar{\gamma}$ càng tăng increases and remains constant when $T \geq 2$. Therefore, setting, $T = 2$ is an efficient choice to enhance system performance and reduce setup costs.

Figure 3.4 demonstrates that the e2e BLER depends on the number of relays N and the number of antennas M at the destination in a three-dimensional space. Specifically, system performance improves as $\bar{\gamma}$, N and M increase. his highlights the importance of accurately designing the number of relays N and antennas M to enhance performance as expected while minimizing installation costs. For instance, when $\bar{\gamma} = 15$ dB và $T = 2$, the e2e BLER approaches 10^{-5}, and the number of relays and antennas can be optimally selected as $M = 3$ and $N = 4$. Therefore, the values $M = 3$ and $N = 4$ are adopted for the simulations presented from Figure 3.5 onward.

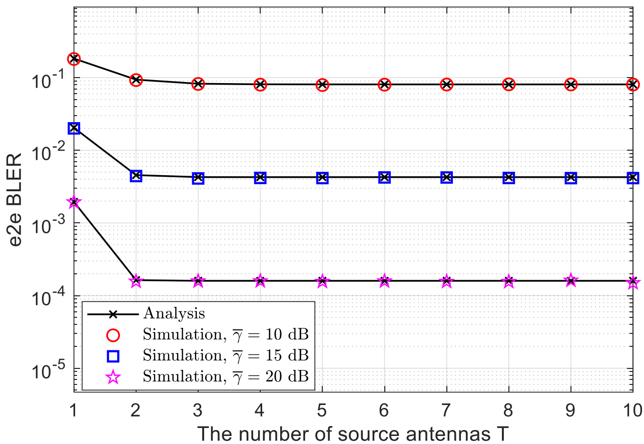

Figure 3.3: The impact of e2e BLER on the number of source antennas T with $N = 2$ and $M = 3$

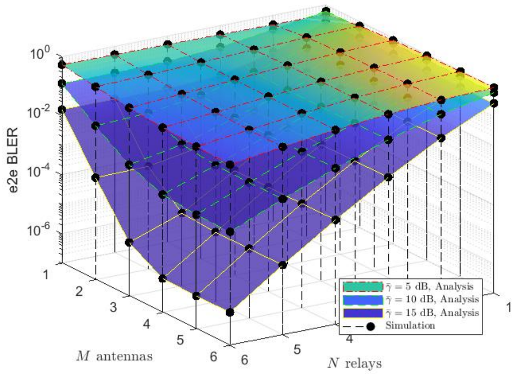

Figure 3.4: e2e BLER based on the number of relays N and antennas M under three cases of $\bar{\gamma} = 10, 15$ dB, and 20 dB

In Figure 3.5, the system performance is improved by increasing $\bar{\gamma}$ and the block length k. However, larger block lengths also result in higher end-to-end latency, as described in Figure 3.7.

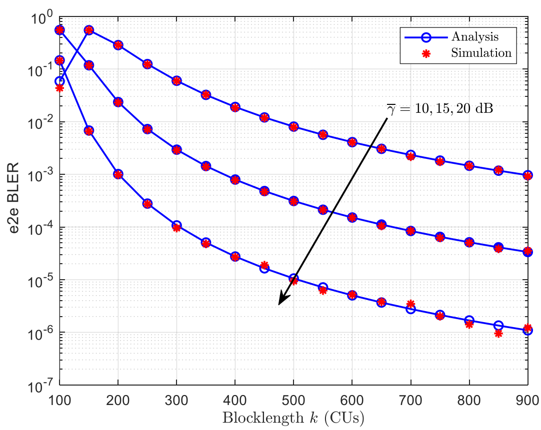

Figure 3.5: e2e BLER as a function of block length k under three cases $\bar{\gamma} = 10, 15$ dB, and 20 dB

Therefore, when improving performance by increasing the $\bar{\gamma}$ or extending the block length, careful consideration is required. For instance, at $\bar{\gamma} = 20$ dB, to ensure the reliability requirement of $BLER \approx 10^{-5}$, a block length of 450 CUs can be selected. Figure 3.6 confirms that the theoretical result curves and simulation curves converge with the asymptotic curves in the high-SNR region. Furthermore, the second asymptotic curve (based on Riemann integration) perfectly aligns with the first asymptotic curve (based on infinitesimal equivalence). Thus, the second approximation method is considered an effective evaluation of the first approximation method. Additionally, this method can be utilized to simplify the computational complexity when calculating the e2e BLER for SPC systems.

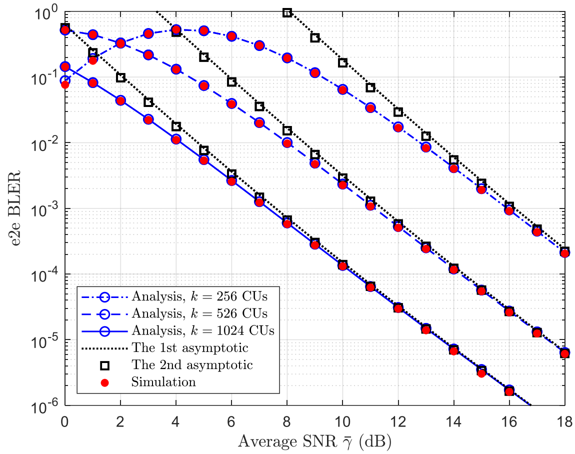

Figure 3.6: The dependency of approximate and asymptotic e2e BLER on $\bar{\gamma}$ in cases $k = 256, 512$ CUs and 1024 CUs.

Performance optimization: We configure the parameters for a non-optimized power allocation (PA) with $P_{\mathcal{S}} = P_{\mathcal{R}_b} = 0.5P_0$ and a non-optimized relay location (RL) where the distances $d_1 = d_2 = 0.5D$. These configurations are applied to general cases with $T = 2$, $N = 3$, and $M = 4$ as well as to the specific case with $T = 1$, $N = M = 2$. Figure 3.8 demonstrates that the performance of the optimized PA significantly outperforms the non-optimized case at all values of $\bar{\gamma}$ for both general and specific scenarios. Notably, with $BLER \approx 10^{-5}$ the array gains (SNR gap between the optimized and non-optimized curves) are approximately $2.5\,\text{dB}$.

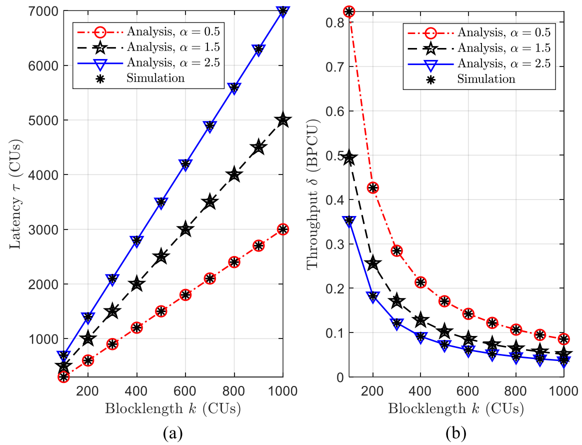

Figure 3.7: End-to-end latency and throughput as functions of block length k at $\bar{\gamma} = 20\,\text{dB}$ for cases $\alpha = 0.5$, 1.5, and 2.5.

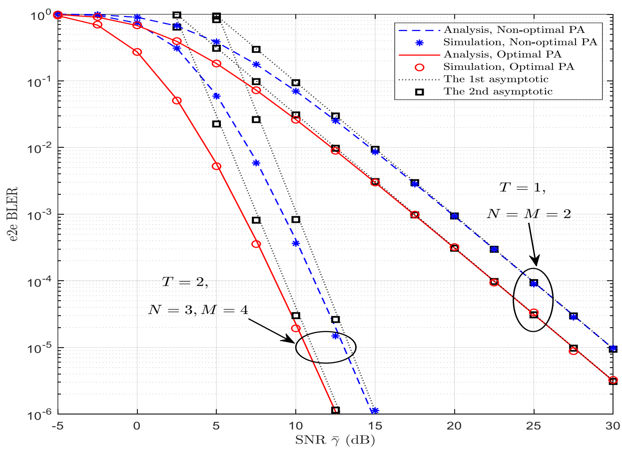

Figure 3.8: e2e BLER as a function of average SNR for optimized and non-optimized power allocations.

In Figure 3.9, the performance in the case of optimized relay location significantly outperforms the non-optimized case. For $BLER \approx 10^{-5}$, the array gains achieved are $6.25\,\text{dB}$ and $9.5\,\text{dB}$, respectively.

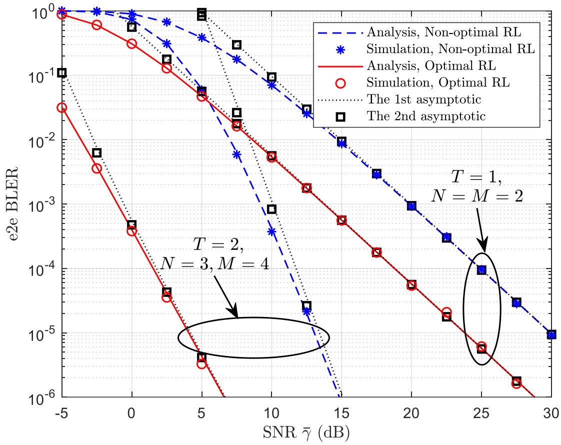

Figure 3.9: e2e BLER as a function of average SNR for optimized and non-optimized relay locations.

The results presented in Chapter 3 highlight the impact of system performance on SNR, the number of relay nodes, the number of destination antennas, and the block length. Specifically, system performance improves with increased SNR (i.e., higher source power), more relay nodes, additional destination antennas, and longer block lengths. However, the following considerations should be taken into account during system design: (1) Excessive increases in source power may cause interference to other users in the network; (2) The number of relay nodes and destination antennas should be chosen appropriately based on the system's diversity gain; (3) Extending block length may lead to higher latency.

Moreover, configuring the system in an optimized mode significantly enhances network performance. The findings in Chapter 3 are supported by the published results in [A-1] by the Ph.D. candidate.

CHAPTER 4: PERFORMANCE ANALYSIS OF SHORT-PACKET COMMUNICATION SYSTEMS IN RELAY NETWORKS WITH INTELLIGENT REFLECTING SURFACES

Chapter 4 proposes an SPC system model utilizing IRS, as illustrated in Figure 4.1.

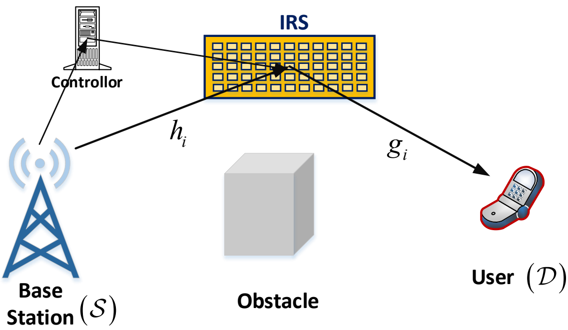

Figure 4.1: SPC model assisted by IRS.

In this system, the source node $(\mathcal{S})$, acting as the base station, employs a single antenna to transmit signals to the destination node $(\mathcal{D})$, which functions as a user, with the assistance of an IRS. The direct link between $\mathcal{S}$ and $\mathcal{D}$ is not considered due to environmental obstructions such as buildings and trees. The channel between $\mathcal{S}$ and $\mathcal{D}$ follows a quasi-static flat Rayleigh fading model. Moreover, the IRS is capable of coordinating and exchanging channel state information CSI from both $\mathcal{S}$ and $\mathcal{D}$ through a wireless controller.

The performance of the SPC system via IRS is analyzed and evaluated based on BLER and the system's diversity gain. Additionally, the proposed system's performance is compared with that of an SPC system utilizing a relay $\mathcal{R}$.

The simulation results were conducted using identical simulation parameters for both the SPC systems via IRS and $\mathcal{R}$ as follows: the transmitted data size $\beta = 256$ bits; the block length $k = 200$ CUs ; the normalized transmission distance $D = 1$; the transmission distances $d_1 = d_2$ (where IRS and $\mathcal{R}$ are placed equidistantly between $\mathcal{S}$ and $\mathcal{D}$) ; the transmission power is identical for both systems. The simplified path loss model between the transmitter and the receiver is defined as: $PL = PL_0 \left(d / d_0 \right)^{-\eta}$, where $PL_0 = -30\,\text{dB}$ represents the power loss at the reference distance $d_0 = 1\,\text{m}$, and và $\eta = 3$ is the path loss exponent.

Figure 4.3 illustrates that the BLER of the system with IRS improves significantly (decreases more rapidly) compared to the FDF and AF systems when considering $L = 6$ and $L = 10$. In particular, as the value of L increases, the BLER decreases further, indicating improved system performance.

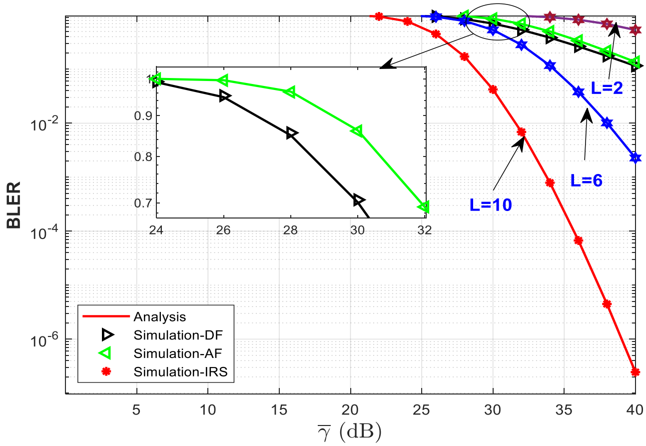

Figure 4.3: BLER comparison between SPC systems via IRS and $\mathcal{R}$ with $L = 2$, $L = 6$ and $L = 10$, respectively.

Observing Figure 4.4, it is evident that as both L and $\bar{\gamma}$ increase, the BLER significantly decreases. However, as $\bar{\gamma}$ increases, the transmission power of the source also rises, leading to potential interference with other users. Therefore, to enhance the system's performance while maintaining a fixed source power, increasing the number of reflective elements L of the IRS could achieve the desired BLER levels.

Finally, Figure 4.5 analyzes the impact of block length k on BLER and latency (τ) in SPC systems utilizing IRS , for increasing values of $\bar{\gamma}$ at $20\,\text{dB}$, $25\,\text{dB}$, and $30\,\text{dB}$. The latency τ is defined as the time required for the source to successfully transmit the signal to the receiver: $\frac{k}{1 - \bar{\varepsilon}_{e2e}^{\text{IRS}}}$. Observing the figure, a clear trade-off between reliability and latency is evident in SPC systems utilizing IRS. Specifically, both k and $\bar{\gamma}$ positively contribute to improving reliability, as reflected in a significant reduction in BLER. However, as k increases, the latency τ also grows proportionally to the block length, resulting in longer transmission times. At $\bar{\gamma} = 30\,\text{dB}$, , the BLER drops to extremely low values, below 10^{-10}, when $k \geq 300$. This demonstrates that the system can achieve very high reliability with high signal power and long block lengths. However, the increase in latency caused by larger k must be carefully considered during system design to meet the specific requirements of different applications.

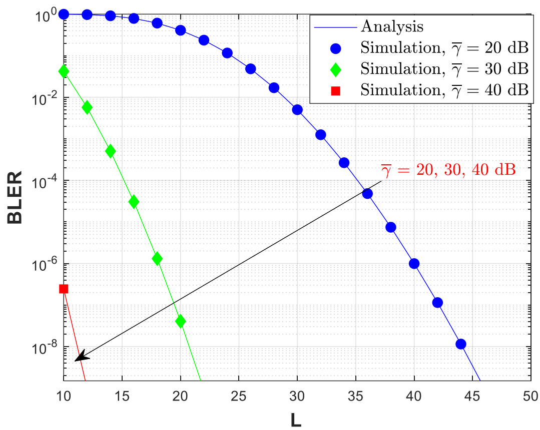

Figure 4.4: BLER as a function of the number of reflective elements L in SPC systems via IRS.

The results presented in Chapter 4 demonstrate that the performance of spc systems supported by irs has significantly improved, achieving higher diversity gains compared to DF systems utilizing relay nodes. Furthermore, it is observed that increasing the number of reflective elements in the irs during the design process is an effective measure to enhance the performance of the proposed system. The content of chapter 4 is based on research articles published in the journal of science and technology of information and communication (JSTIC) ([B-1], [B-2]).

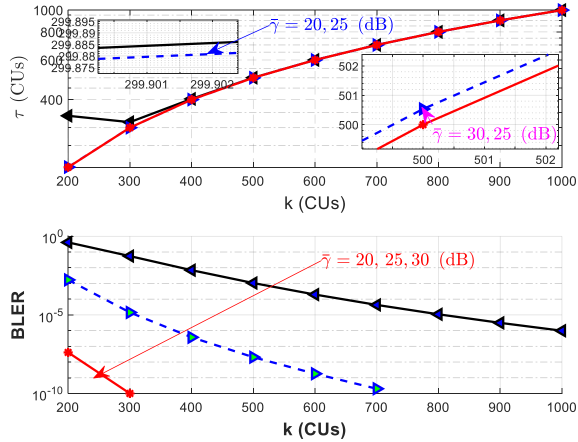

Figure 4.5: The impact of BLER and latency on block length k in SPC systems via IRS.

CHAPTER 5. DESIGN OF A SHORT-PACKET COMMUNICATION SYSTEM IN NON-ORTHOGONAL MULTIPLE ACCESS NETWORKS USING INTELLIGENT REFLECTING SURFACES

Chapter 5 proposes an SPC model supported by an IRS in a non-orthogonal multiple access (NOMA) network, In this model, a base station (BS) equipped with N antennas employs NOMA to simultaneously transmit signals to two single-antenna users: a nearby user ($\mathcal{U}_1$) and a distant user ($\mathcal{U}_2$), as illustrated in Figure 5.1. An IRS with L passive reflecting elements is utilized to enhance the signal quality for the distant user $\mathcal{U}_2$. The BS leverages beamforming techniques to optimize signal transmission to $\mathcal{U}_1$. The direct path from the BS to $\mathcal{U}_1$ is obstructed by obstacles such as trees or buildings. The system operates under independent and identically distributed Rayleigh fading channels with uniform signal attenuation.

The performance of users in the network of the proposed model is evaluated based on parameters such as BLER, latency, and reliability. Additionally, Chapter 5 introduces a Deep Neural Network (DNN) model to predict BLER and power allocation for the system, which is detailed in Figures 5.2 and 5.4.

The DNN model is composed of an input layer, $\mathbb{Z}-1$ hidden layers, and an output layer, as shown in Figure 5.2. The input layer contains 14 neurons, where each neuron corresponds to an input parameter provided to the system. Each of the $\mathbb{Z}-1$ hidden layers consist of $Q^{(z)}$ neurons ($z=1,...,\mathbb{Z}-1$) and employs the Sigmoid function as the activation function.

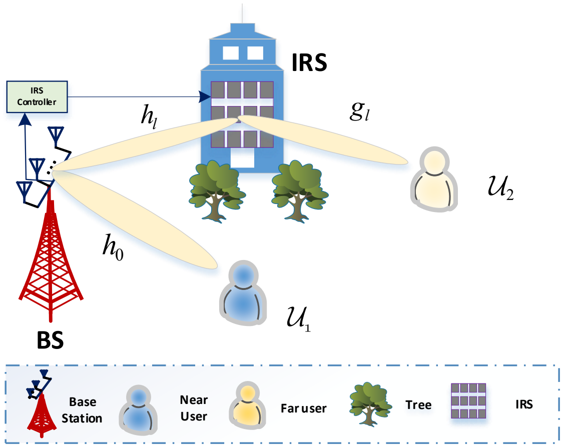

Figure 5.1: The model of IRS-assisted beamforming-NOMA networks for SPC.

Similarly, the DNN model for power prediction, illustrated in Figure 5.4, includes an input layer (containing a single neuron for $\bar{\varepsilon}_i$), $\mathbb{Z}^*-1$ hidden layers with $Q^{(z^*)}$ neurons per layer ($z^*=1,...,\mathbb{Z}^*-1$) and an output layer (containing a single neuron for the output $\hat{P}_i$), the model undergoes a training and testing process.

The DNN network operates in two phases: training and prediction, as illustrated in Figure 5.3. The training phase utilizes the Levenberg–Marquardt algorithm to optimize model parameters through offline learning from a dataset. After training, the DNN is ready for the online prediction phase using new data.

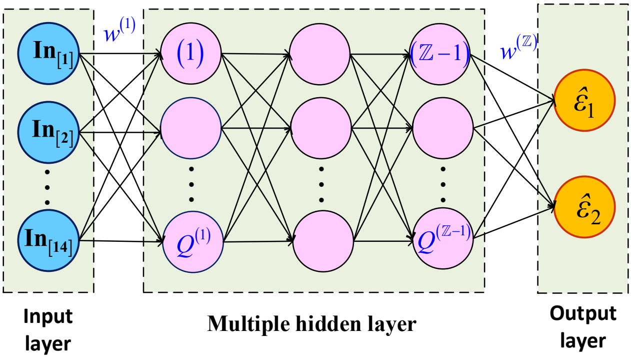

Figure 5.2: The proposed DNN model for BLER prediction at $\mathcal{U}_i$, $i = \{1,2\}$.

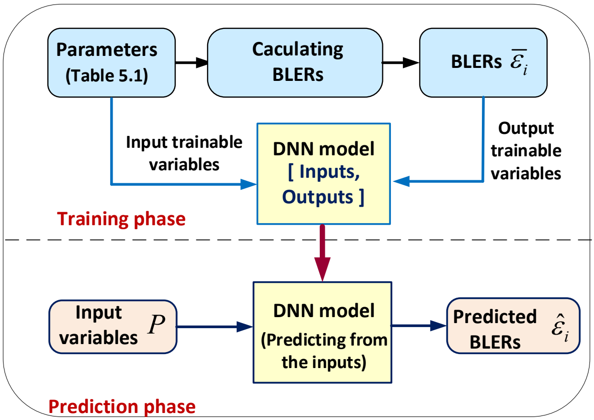

Figure 5.3: The DNN framework of training and prediction phase.

First, Figure 5.5 shows that the BLER of $\mathcal{U}_1$ and $\mathcal{U}_2$ decreases over the range of $\overline{\gamma}$ at medium and high levels according to the power allocation coefficients α_1 and α_2 for $\mathcal{U}_1$ and $\mathcal{U}_2$, respectively. Specifically, the BLER at $\mathcal{U}_2$ is always lower than that at $\mathcal{U}_1$, tindicating that the performance at $\mathcal{U}_2$ is better, even with lower power allocation.

From Figure 5.5, it can be observed that the DNN-predicted results (represented by dashed lines) align closely with the analytical results and simulation outcomes for all $\bar{\gamma}$ values at $\mathcal{U}_1$ and $\mathcal{U}_2$. This serves as initial evidence of the advantages of using DNN over simulation-based methods and demonstrates the improvements offered by DNN, as clearly illustrated in Figure 5.9 and Table 5.3. The optimal power allocation coefficients, $\alpha_1 = 0.6$ and $\alpha_2 = 0.4$, are chosen for all subsequent simulations shown in Figure 5.6.

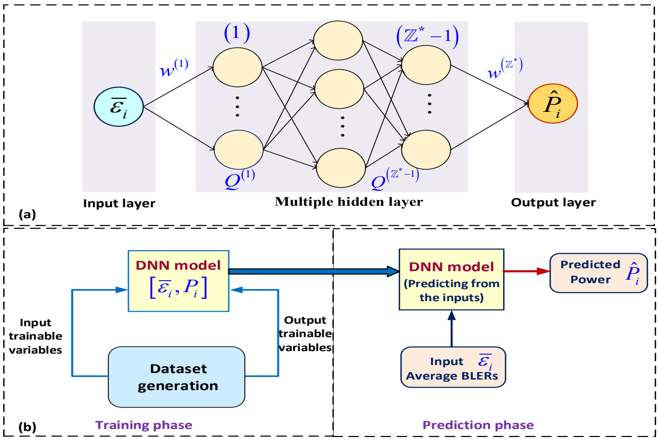

Figure 5.4: Design of DNN model for the transmit power prediction at $\mathcal{U}_i$, $i = \{1, 2\}$.

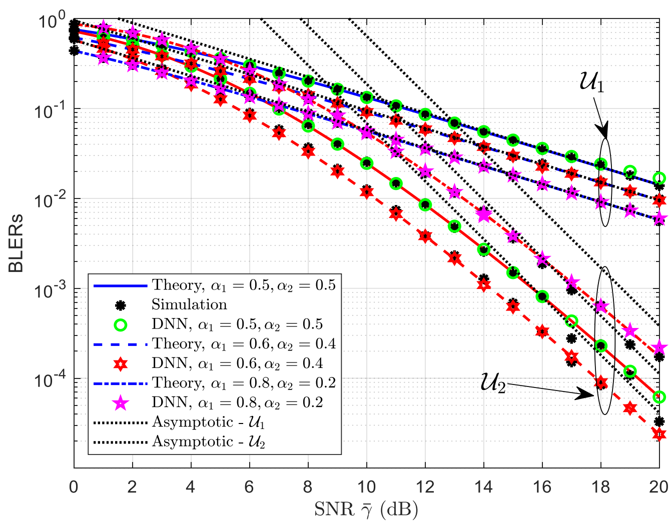

Figure 5.5: The Impact of SNR on the BLER of $\mathcal{U}_1$ and $\mathcal{U}_2$ under three scenarios of power allocation coefficients: $\alpha_1 = \alpha_2 = 0.5$, $\alpha_1 = 0.6$, $\alpha_2 = 0.4$, and $\alpha_1 = 0.8$, $\alpha_2 = 0.2$.

Figure 5.6 demonstrates that the BLER of both $\mathcal{U}_1$ and $\mathcal{U}_2$ decreases as k and $\bar{\gamma}$ increase. Notably, the performance of $\mathcal{U}_2$ improves compared to $\mathcal{U}_1$, despite the lower power allocation for $\mathcal{U}_2$. This highlights the effectiveness of the IRS, as a higher reflection factor results in a smaller BLER for $\mathcal{U}_2$ as shown in Figure 5.7.

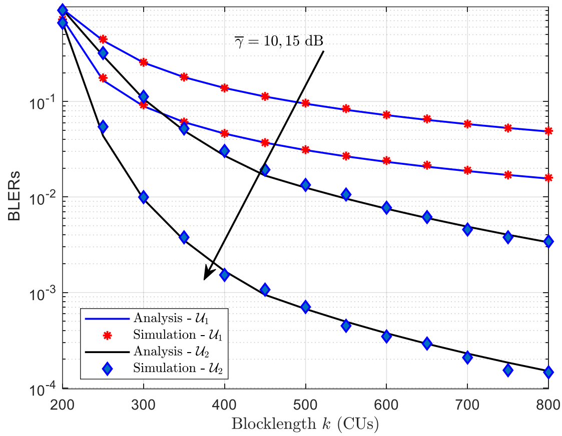

Figure 5.6: The impact of k on the BLER of $\mathcal{U}_1$ and $\mathcal{U}_2$ with $\alpha_1 = 0.6$ and $\alpha_2 = 0.4$.

However, we must also consider the trade-off between large k and high latency, as shown in Figure 5.8. For instance, to meet the uRLLC service requirement of $\mathcal{U}_2$ with a BLER $\leq 10^{-5}$ at $\bar{\gamma} = 20$ dB, the block length k được should be set to 600 CUs.

Figure 5.8: The impact of latency and reliability for $\mathcal{U}_2$ improve compared to $\mathcal{U}_1$ across all scenarios of $\bar{\gamma}$. It is noteworthy that as k increases, latency also grows proportionally for both $\mathcal{U}_1$ and $\mathcal{U}_2$. Specifically, at $k = 300$ CUs, the latency for both users achieves an optimal value and approaches saturation $k = 400$ CUs. For instance, at $\bar{\gamma} = 20$ dB, the latency of $\mathcal{U}_2$ is $\tau = 300$ CUs.

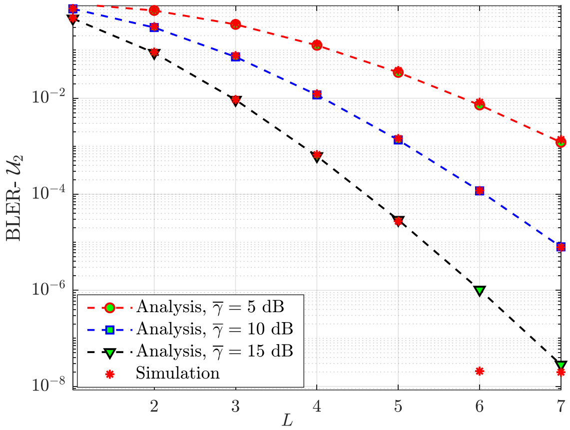

Figure 5.7: The impact of L on the BLER of $\mathcal{U}_2$ under three scenarios of $\bar{\gamma} = 5\text{dB}$, $\bar{\gamma} = 10\text{dB}$, and $\bar{\gamma} = 15\text{dB}$.

Figure 5.9 illustrates the effectiveness of the DNN model based on the number of test samples. As the number of samples increases, the results become more accurate. Compared to traditional analytical methods and Monte Carlo simulations, the prediction time using the DNN model is significantly shorter. The prediction time for $\mathcal{U}_1$ and $\mathcal{U}_2$ is 0.002797 seconds and 0.002962 seconds, respectively. Figure 5.10 demonstrates that increasing the number of hidden layers beyond two results in less accurate predictions. This leads to lower RMSE and MAPE errors, as shown in Figure 5.11, in power prediction results P.

Moreover, careful consideration is required when increasing the number of hidden layers, as it may lead to higher system execution time.

To ensure real-time implementation in the short-packet communication system, a four-layer configuration is selected as the optimal hidden layer setup for the DNN model.

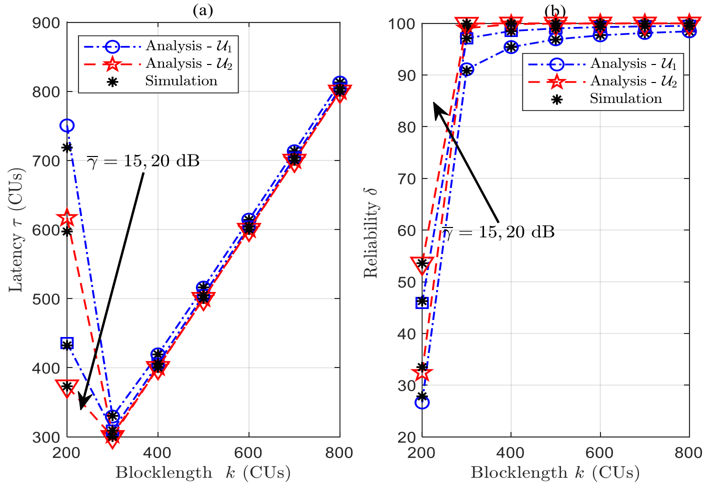

Figure 5.8: The impact of latency and reliability on k for $\mathcal{U}_1$ và $\mathcal{U}_2$ under $\overline{\gamma} = 15\,\text{dB}$ và $\overline{\gamma} = 20\,\text{dB}$.

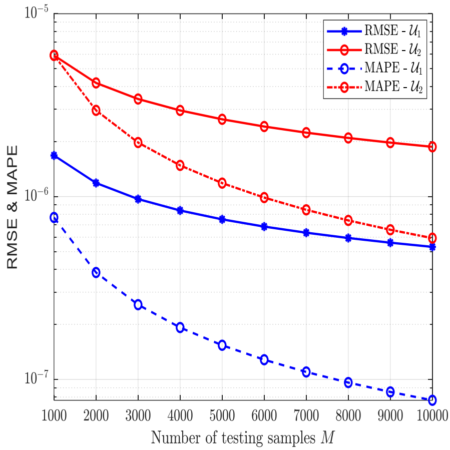

Figure 5.9: RMSE and MAPE vs. number of test samples.

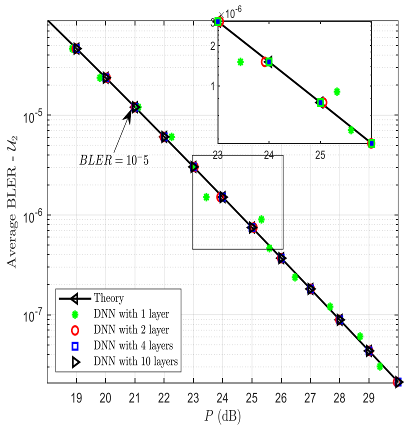

Figure 5.10: BLER vs. allocated power at $\mathcal{U}_2$ for different layers.

From Figure 5.10, it can be observed that at $BLER \approx 10^{-5}$, the allocated power is approximately 21 dB. This implies that the transmitted power for 21dB . This implies that the transmitted power for $\mathcal{U}_2$ and $\mathcal{U}_1$ lis 8.4 dB and 12.6 dB, respectively. The results presented in Chapter 5 demonstrate that the BLER of the distant user (supported by IRS) is significantly reduced compared to that of the nearby user, despite receiving a larger power allocation. Furthermore, simulation results highlight the effectiveness of the DNN model in prediction tasks, both in terms of reliability and execution time, compared to numerical analysis and Monte Carlo simulation methods.

Notably, the DNN-based deep learning approach proves its capability to address two challenges: predicting BLER (the forward problem) and optimizing BLER to determine the transmit power of the system efficiently (the inverse problem). The findings of Chapter 5 have been recognized through a paper published in the IET Communications journal, indexed in SCIE (Q2) ([A-2]).

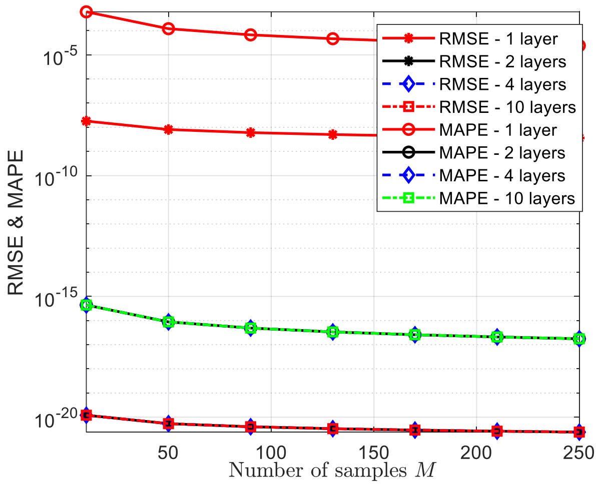

Figure 5.11: The impact of RMSE and MAPE on the number of hidden layers and sample size in the DNN model.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions of the thesis

This thesis has achieved the scientific objectives set out in the proposal, with the main contributions outlined as follows:

- The thesis proposes an SPC model in a two-hop DF network over a Rayleigh fading channel, with the following novel contributions: (1) The FDF system improves performance compared to SDF with all values of power allocation at the source; (2) The performance of the FDF system improves as the number of antennas at both the source and destination, the number of relay nodes, the block length, and the transmission power are increased; (3) The spatial diversity gain of the system is calculated by the minimum value between the product of antennas at the source and the number of relay nodes, and the number of antennas at the destination. This is important for system design, enhancing reliability and reducing deployment costs; (4) The spatial diversity gain of the system is calculated by the minimum value between the product of antennas at the source and the number of relay nodes, and the number of antennas at the destination. This is important for system design, enhancing reliability and reducing deployment costs.
- The thesis also introduces an SPC model in relay networks with IRS support. The results of this system model demonstrate that, compared to FDF, the SPC system via IRS achieves better diversity and performance. This is significant for the design and deployment of new networks, allowing for the replacement of relay nodes with IRS to improve QoS and extend coverage with lower costs.
- The thesis has designed an SPC system in NOMA networks with IRS support. The innovation in this model's design is that the transmitter uses beamforming techniques to optimize signal transmission performance to the intended users. Additionally, the system proposes new methods for calculating BLER, latency, and reliability. Notably, the system suggests a DNN-based network using DL to predict performance and transmission power allocation accurately, quickly, and more simply compared to existing methods. In other words, with DL, we can

predict parameters such as power, latency, or throughput of the system, while complying with BLER constraints required by uRLLCs, thus minimizing costs when designing and deploying real-world networks.

6.2 Recommendations for future research

In the coming period, we will continue to propose improvements for the network to meet uRLLC standards and enhance the quality of future network systems. The following research directions are outlined:

- Expansion of SPC in NOMA networks to serve multiple users with random distribution.
- Study of a combined reflection and transmission approach using STAR-IRS as a replacement for IRS, aimed at improving coverage and maximizing multi-user service capacity in network systems. The result of this research direction is the work [C-1], which is included in the publication list.
- Examine SPC systems through other generalized fading channels, such as Nakagami-m and Rician fading channels.
- Investigate reinforcement learning methods to solve optimization problems for system performance, enabling enhanced uRLLC services in future network systems like 6G. The result of this research direction is the work [C-2], which is included in the publication list.
- Design of SPC systems supported by multiple IRS panels to aid signal transmission in challenging terrain areas, such as large urban environments.
- Additionally, research SPC systems using millimeter-wave (mmWave) frequencies to improve latency and increase data transmission speed for future network systems.
- Furthermore, we are exploring the Rate-Splitting Multiple Access (RSMA) method within SPC to optimize transmission speeds, support multi-connectivity, reduce latency, and, in particular, implement a network system that is less complex than the NOMA approach.

PUBLICATIONS

A. International Journal

[A-1]. **N. T. Y. Linh**, T. Ngo Hoang, P. N. Son, and V. N. Q. Bao, "Dual-hop Relaying Networks for Short-Packet URLLCs: Performance analysis and Optimization," Journal of Communications and Networks, vol. 24, no. 4, pp. 408-418, Aug. 2022, doi: 10.23919/JCN.2022.000020. **(SCIE-Q1)**

[A-2]. **N. T. Y. Linh**, P. N. Son, and V. N. Q. Bao, "Intelligent reflecting surface-assisted beamforming-NOMA networks for short-packet communications: Performance analysis and deep learning approach," IET Communications, vol. 17, no. 16, pp. 1940-1954, Aug. 2023, doi: 10.1049/cmu2.12667. **(SCIE-Q2)**

B. National Journal

[B-1] N. T. Y. Linh, N. H. Tu, and V. N. Q. Bảo, "Đánh Giá Hiệu Năng Mạng Chuyển Tiếp Từng Phần Với Đa An ten Thu Trong Truyền Thông Gói Tin Ngắn," Journal of Science and Technology on Information and Communications, vol. 1, no. 4A, pp. 53-61, Dec. 2020.

[B-2]. N. T. Y. Linh, V. N. Q. Bao, Pham Ngoc Son, "Phân Tích Độ Lợi Phân Tập Cho Mạng Chuyển Tiếp Qua Mặt Phản Xạ Thông Minh Và Nút Chuyển Tiếp Trong Truyền Thông Gói Tin Ngắn," Journal of Science and Technology on Information and Communications (JSTIC), vol. 1, no. 4B, pp. 56-64, Dec. 2021.

[B-3] N. T. Y. Linh, V. N. Q. Bao, Pham Ngoc Son, "Dự Đoán Công Suất Tối Ưu Nguồn Phát Của Hệ Thống Truyền Gói Tin Ngắn Qua Mặt Phản Xạ Thông Minh Bằng Kỹ Thuật Học Sâu," Journal of Science and Technology on Information and Communications, vol. 1, no. 1A, pp. 11-18, Apr. 2023.

C. Proceedings of the International Conference

[C-1] N. T. Y. Linh, P. N. Son, and V. N. Q. Bao, "Performance Evaluation of Simul taneously Transmitting and Reflecting Intelligent Reflecting Surface -

Assisted NOMA Networks for Short-Packet Communications," in 2023 RIVF International Conference on Computing and Communication Technologies (RIVF), 2023, pp. 194-199, doi: 10.1109/RIVF60135.2023.10471771.

[C-2] N. T. Y. Linh, P. N. Son, and V. N. Q. Bao, "Power allocation for the STAR-RIS-NOMA Short Packet communication system using Deep Reinforcement Learning," in 2024 International Conference on Advanced Technologies for Communications (ATC), 2024, pp. 215-220, IEEE.