AN OPTIMIZATION APPROACH OF BLOCK LENGTH FOR URLLC-5G

MỘT GIẢI PHÁP TỐI ƯU ĐỘ DÀI GÓI TIN CHO DỊCH VỤ 5G URLLC

Pham Thi Quynh Trang[1,*], Duong Thi Hang[1],
Tong Van Luyen[1], Nguyen Viet Tuyen[2]

DOI: https://doi.org/10.57001/huih5804.2023.218

ABSTRACT

Fifth Generation wireless networks (5G) have been one of the priority areas studied by scientists in recent years because of their benefits in many fields of life. The requirements in modern communication systems are to increase performance in the process of transmitting and receiving information. Extremely reliable low-latency communication (URLLC) is one of the three main tasks in 5G. According to 3GPP, URLLC has 99.999% transmission accuracy with a latency of less than 1ms which is the goal of many current studies. In this article, we analyze and evaluate some of the factors that affect the latency and probability of errors that can be achieved in the uplink and downlink of Massive MIMO in the finite block in URLLC. In addition, this study presents a solution that offers a suitable length in the packet design of large MIMO systems that support the high-reliability targets required in URLLC.

Keywords: *5G, URLLC, Massive MIMO, finite block length.*

TÓM TẮT

Mạng không dây thế hệ thứ năm (5G) là một trong những lĩnh vực được các nhà khoa học ưu tiên nghiên cứu trong những năm gần đây vì những lợi ích của nó mang lại trong nhiều lĩnh vực của đời sống. Các yêu cầu trong giao tiếp hiện đại là tăng hiệu suất trong quá trình truyền nhận thông tin. Truyền thông có độ trễ thấp cực kỳ đáng tin cậy (URLLC) là một trong ba nhiệm vụ chính trong 5G. Theo 3GPP, URLLC có chính xác truyền 99,999% với độ trễ dưới 1ms đang là mục tiêu hướng tới của nhiều nghiên cứu hiện nay. Trong bài báo này, chúng tôi phân tích và đánh giá một số yếu tố ảnh hưởng đến độ trễ và xác suất lỗi có thể đạt được trong đường lên và đường xuống của Massive MIMO ở khối hữu hạn trong URLLC. Ngoài ra, trong nghiên cứu này còn trình bày một giải pháp đưa ra block length phù hợp trong thiết kế gói tin của các hệ thống MIMO lớn hỗ trợ các mục tiêu độ tin cậy cao được yêu cầu trong URLLC.

Từ khóa: *5G, URLLC, Massive MIMO, độ dài khối hữu hạn.*

---

[1]Faculty of Electronic Engineering, Hanoi University of Industry, Vietnam
[2]Department of Academic Affairs, Hanoi University of Industry, Vietnam
[*]Email: phạm.trang@haui.edu.vn
Received: 10/3/2023
Revised: 30/6/2023
Accepted: 25/11/2023

1. INTRODUCTION

The fifth generation (5G) of wireless networks, which is the latest and newest wireless standard, has just begun in recent years. However, this network promises to support a variety of applications such as industrial automation, cloud robotics, and intelligent traffic. In a recent GSA report, 5G networks have been implemented in 72 countries since August 2021. There have been many discussions about Fifth Generation (5G) mobile communication since the 2012s. In September 2015, ITU-R agreed to three main services for 5G including Enhanced Mobile Broadband (eMBB); Ultra-Reliable and Low-Latency Communication (URLLC); and Massive Machine Type Communication (mMTC) [1, 2]. The classification of service in 5G is presented as follows:

Enhanced mobile broadband (eMBB) is the first 5G category to bring the benefits of 5G to the general public. 5G eMBB delivers high-quality internet access even under harsh environmental conditions. 5G eMBB guarantees a gigabit range of mobile broadband speeds and higher data bandwidth. 5G eMBB possibly makes good indoor connectivity among many devices in densely populated areas, wide network coverage, and real-time communication and connectivity even when mobile broadband services are accessed from moving vehicles [2].

The second service namely massive machine-type communication (mMTC) supports massive device connectivity in IoT applications. mMTC uses non-human-type communication models that prioritize low-rate, uplink-centric transmission. The applications that use mMTC don't have collisions because the schemes differ from those used in traditional human-type communication and use small packet data transmission techniques. In addition, mMTC also combines random access and scheduling strategies when there are thousands of IoT devices waiting for access [2].

The service category called Ultra-reliable low-latency communication (URLLC) is envisioned to require very low latency and extremely high reliability. This service is applicated to here of traffic safety, automatic control, and intelligent surgery [3].

The Release-15 standard of 3GPP was issued in March 2017 and completed the Release-17 Stage-2 freeze in June 2021. According to Release-17, the requirements for three main services in 5G are shown in table 1 [4].

Table 1. The requirements for three main services in 5G [4]

SERVICES	DATA RATE	LATENCY	RELIABILITY
EMBB	0.5 - 1.5Gb/s	< 20ms	BER ≤ 10^{-6}
MMTC	40Mb/s	< 20ms	BER ≤ 10^{-6}
URLLC	40Mb/s	< 1ms	BER ≤ 10^{-9}

The new wireless requires a much lower latency and error probability than current wireless systems, especially with URLLC service. The main challenge in fulfilling these requirements is the development of packet transmission. In theory, if using a long data packet structure for reducing error probability then delay time increases, in contrast, if using a sort data packet for reducing latency then error probability can grow up. In this paper, we consider and analyze the packet length influence on the transmission. We also present a way to find packet length, which balances both factors including latency and reliability.

2. RELATED WORKS

Because the URLLC's standard has not been worked out, many different solutions for the design of URLLC have been put forward by researchers. In transmission, for achieving high reliability, diversity in time, frequency diversity, and spatial diversity should be exploited. The spatial diversity offered by multiple antennas becomes critical to achieve the desired reliability. The latest mock-up of spatial diversity is multiple antenna technologies called Massive MIMO (multiple-input multiple-output), which is a wireless network where base stations (BS), equipped with a very large number M of antennas, serve a multitude of UEs via linear spatial signal processing [5].

In fact, the number of antennas and the length of transmission data is finite, so spatial correlation to obtain realistic estimates of the error probability is important. Besides this, performance is impacted extremely by pilot contamination. To assess the error probability achievable in the uplink and downlink of Massive MIMO at finite blocklength the [6] provides a framework for the characterization and numerical evaluation using the saddlepoint approximation method. According to the authors in [6] the infinite blocklength assumption may give incorrect error probability estimates. They prove that as the number M of antennas grows to infinity the error probability at finite blocklength goes to zero even under pilot contamination if using minimum mean-square error (MMSE) processing and spatially correlated channels. In [6] also show that with a base station with M = 100 antennas and used MMSE processing a target error probability of 10^{-5} can be achieved only if the orthogonal pilot sequences are assigned to all the users in the network.

The researchers in [7] proposed the general formula to allocate pilot signals to guarantee delivery alarm traffic, while also minimizing the number of pilots reserved for alarms, thus maximizing the channel resources available for other traffic in URLLC. They presented a collision trees algorithm, which allows for sharing the pilot are triggered at the same time, and therefore it is beneficial for lower probability alarms to share pilots more than higher probability alarms.

The URLLC service standards require much lower latency and higher accuracy than what current wireless systems can guarantee. The main challenge in responding to these requirements is the development of short packet transmission, which is the opposite of the current standards, which use a long data packet structure. There are many papers that analyze the performance of short-packet communication, including the maximal achievable rate at finite packet length and finite packet error probability. The authors of [8] find out the maximal channel coding rate achievable at a given block length and error probability. A review of recent advances in the theory of short-packet communications was provided by the authors of [9]. They gave three examples of how this theory can help design efficient communication protocols that are suited to short-packet transmissions. Their analysis indicates the insight is that, when short packets are transmitted, it is crucial to take into account the communication resources that are invested in the transmission of metadata. This proclaims that these are not well understood yet and that further research is needed, both on theoretical and the applied.

3. SYSTEM MODELS AND PROBLEM FORMULATION

3.1. System models

The system model of uplink transmission in 5G systems utilizing URLLC can be briefly shown in Figure 1. In this study, we investigate the effect of the block size on the error probability based on the normal approximation. We start by considering the simple case in which the received signal is the superposition of a scaled version of the desired signal and additive Gaussian noise. This simple channel model is used for the analysis of the length of the packet based on the error probability achievable in massive MIMO networks. In the simulation scenario, we assume that SNR = -20dB, and the number of antennas =100 with perfect CSI. We survey the relationship between the length of the block and the average error probability in the uplink of a single-UE multiantenna system.

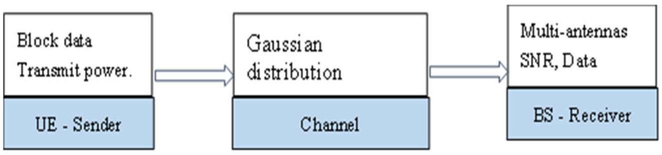


Figure 1. The diagram of the communication system

To survey the block length in the URLLC we present the block length structure in Figure 2. A packet consists of 3 components that are pilot, ECC Redundancy and Information. Where N is the packet length of the Massive MIMO system. There are many studies that give the right ratio between Pilot and Information to achieve the highest information transmission performance. In this study we surveyed and gave a suitable N length to achieve a probability of a goal error of 10^{-9}.

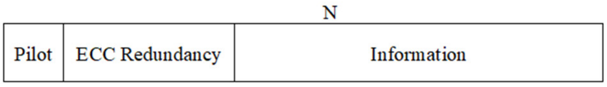


Figure 2. Block structure

3.2. Problem formulation

Shanon's information theory applies for long block-length wireless communications so that in URLLC it will not be accurate and will lead to non-optimal radio resource allocations. Thus, a new theory must be proposed and studied to satisfy the new standards in 5G. During the last decades, the information theory community has made significant progress to resolve the problem of transmitting short packets. The author Polyanskiy provided a formula called Normal approximation for finite block-length information theory.

The authors showed that in various channels with positive capacity C(p), the maximal achievable rate for short block-length transmission can be approximated following [8].

$$R^*(n,\epsilon) = C(p) - \sqrt{\frac{V(p)}{n}}Q^{-1}(\epsilon) + O(\frac{\log(n)}{n}) \qquad (1)$$

Where: V(ρ) is channel dispersion with:

$$V = (1 - \frac{1}{(1+\rho)^2}(\log_2 e)^2 \qquad (2)$$

Q(x) is Q - function or error function with:

$$Q(x) = \epsilon = \int_x^\infty e^{-z^2}dz \qquad (3)$$

N: block size

ϵ: error probability.

The normal approximation formula has made a breakthrough in short packet communication research applied to URLLC [10]. It provides accurate results for medium block length with n ≥ 200, but the results are inaccurate for very short block length when n ≪ 200. The other proposal approximation is called saddlepoint approximation, and the authors proved that this approximation outperforms the normal approximation, specifically in the case of a very short block length. Another, saddlepoint approximation is an accurate performance metric for URLLs over the entire range of the system parameters [10, 11]. The saddlepoint approximation leads to the following expansion [12]:

$$R(\tau,s) = \frac{1}{T}(I_s(\rho) - \Psi_{\rho,s})\tau)) \qquad (4)$$

$$\epsilon^*(\tau,s) \le e^{L[\psi_{\rho,s}(\tau) - r\psi_{\rho,s}(\tau)]}\Big[\Psi_{\rho,s}(\tau,\tau) + \Psi_{\rho,s}(1-\tau,\tau) + \frac{\hat{K}_{\rho,s}(\tau)}{\sqrt{n}} + O(\frac{1}{\sqrt{n}})\Big] \qquad (5)$$

Where: $O(\frac{1}{\sqrt{n}})$ is uniform in τ, s, and ρ.

$$\Psi_\theta(u,\tau) \triangleq e^{n\frac{u^2}{2}\psi''_\theta(\tau)Q(u\sqrt{n\psi''_\theta(\tau)})} \qquad (6)$$

$$\hat{K}_\theta(\tau) \triangleq \frac{1}{\sqrt{2\pi}}\frac{\psi'''_\theta(\tau)}{\psi''_\theta(\tau)^{3/2}} \qquad (7)$$

$$\psi_\theta(\tau) \triangleq \log m_\theta(\tau) \qquad (8)$$

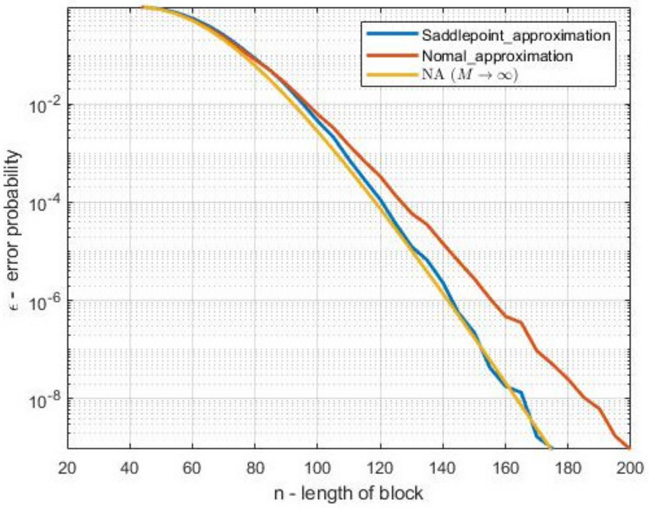
With $\sup_{\theta\in S} m_\theta^k(\tau) < \infty$ (9)

4. PROPOSED APPROACH

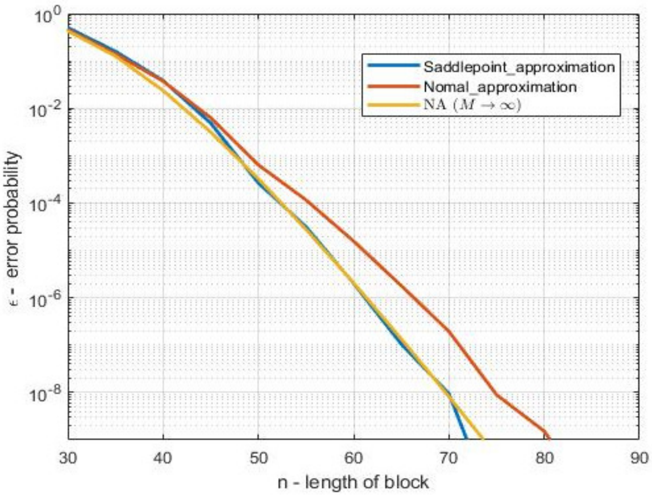
The proposed approach for optimizing the length of blocks is developed based on normal approximation and saddlepoint approximation theory. The proposal is inspired from finding the trade-off points between the latency and the reliability of the system. The algorithm of this proposed approach is presented as:

The algorithm for block length survey is shown following:

```
Algorithm
Input:
        M: number of antennas.
        SNR: signal to noise ratio.
        B: information bit.
Output:
        N: length of block.
        Esp: error probability.
1.      Set parameters M, SRN, B.
2.      Set N =30.
3.      Initialization channel information (Calculate capacity Gaussian channel, Dispersion Gaussian channel).
4.      While N<200:
            Generate channel.
            Estimate channel.
            Evaluate error probability for perfect CSI base on normal approximation and saddlepoint approximation.
            Update N = N +5
            Repeat step 4.
```



a) SNR = -20dB



b) SNR = -15dB

Figure 3. Relationship between the block length and error probability

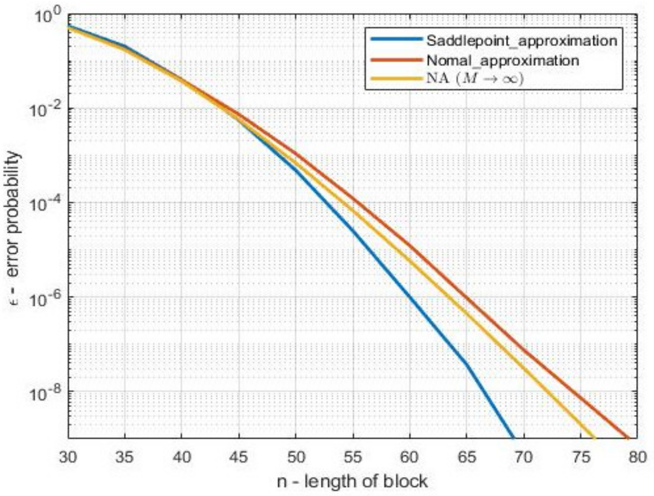


Figure 4. Block length and error probability when BS' antennas =300

Figures 3 and 4 show the relationship between block length and error probabilities in the UL of a single-UE multi-antenna system. In this, the number of antennas is 100, SRN = -20 dB, and the MR method is used for estimating channel. According to the Figure 3a simulation results, the block length should be around 175 bits if saddle point approximation is used, or 180 bits if normal approximation is used, to achieve error probabilities less than 10^{-9}. The block size can be reduced when SNR increases, as shown in Figure 3b.

In the same scenario, if the number of antennas at BS increases to 300, as shown in the results in Figure 4, there will be a significant reduction in block length.

5. CONCLUSION

In this paper, we presented the new information theory based on transmitting short packets, which can support the high reliability targets demanded in URLLC. Specifically, we find the block size in the uplink of a single-UE with a BS equipped with multi-antennas. The result of finding the length of the block based on recent results using the normal approximation and saddle point approximation method. This research applies to a realistic Massive MIMO network with imperfect channel state information, spatially correlated channels, arbitrary linear spatial processing, and randomly positioned UEs.

REFERENCES

[1]. *5G market update: Executive summary - August 2021* [Online]. Available: https://gsacom.com/paper/5g-market-update-executive-summary-august-2021/

[2]. Erik Dahlman, Stefan Parkvall, Johan Sko ̇ld, 2021. *5G NR: the next generation wireless access technology*. Academic Press, Elsevier Ltd.

[3]. Arti Sharma, Mohammad Salim, 2019. *Polar Code Appropriateness for Ultra-Reliable and Low-Latency Use Cases of 5G Systems*. International Journal of Networked and Distributed Computing Vol. 7(3); July, pp. 93–99

[4]. Trung-Kien Le, Umer salim, Florian kaltenberger, 2020. *An Overview of Physical Layer Design for Ultra-Reliable Low-Latency Communications in 3GPP Releases 15, 16, and 17*. Digital Object Identifier 10.1109/ACCESS.2020.3046773.

[5]. H. Q. Ngo, E. G. Larsson, T. L. Marzetta, 2013. *Energy and spectral efficiency of very large multiuser MIMO systems*. IEEE Trans. Commun., vol. 61, no. 4, pp. 1436–1449, Apr. 2013

[6]. Johan Ostman, Alejandro Lancho, Giuseppe Durisi, Luca Sanguinetti, 2021. *URLLC with Massive MIMO: Analysis and Design at Finite Blocklength*. IEEE Transactions on Wireless Communications, DOI 10.1109/TWC.2021.3073741.

[7]. Min Dong, Lang Tong, 2002. *Optimal Design and Placement of Pilot Symbols for Channel Estimation*. IEEE Transactions on signal processing, Vol. 50, No. 12.

[8]. Yury Polyanskiy, H. Vincent Poor, Sergio Verdú, 2010. *Channel Coding Rate in the Finite Blocklength Regime*. IEEE Transactions on Information Theory, Volume 56, Issue 5.

[9]. Giuseppe Durisi, Tobias Koch, Petar Popovski, 2016. *Towards Massive, Ultra-Reliable, and Low-Latency Wireless Communication with Short Packets*. Proceedings of the IEEE, Volume 104, Issue 9.

[10]. Najib Odhah, Eckhard Grass, Rolf Kraemer, 2022. *Effective Rate of URLLC with Short Block-Length Information Theory*. Würzburg Workshop on Next-Generation Communication Networks (WueWoWas'22), https://doi.org/10.25972/OPUS-28085

[11]. Johan Ostman, Alejandro Lancho, Giuseppe Durisi, Luca Sanguinetti, 2021. *URLLC with Massive MIMO: Analysis and Design at Finite Blocklength*. IEEE Transactions on Wireless Communications, DOI 10.1109/TWC.2021.3073741.

[12]. Alejandro Lancho, Johan Ostman, Giuseppe Durisi, Tobias Koch, Gonzalo Vazquez-Vilar, 2020. *Saddlepoint Approximations for Short-Packet Wireless Communications*. IEEE Trans. Wireless Commun. 19, 7, 4831 – 4846, https://doi.org/10.1109/TWC.2020.2987573.

THÔNG TIN TÁC GIẢ

Phạm Thị Quỳnh Trang[1], Dương Thị Hằng[1], Tống Văn Luyên[1], Nguyễn Viết Tuyến[2]

[1]Khoa Điện tử, Trường Đại học Công nghiệp Hà Nội

[2]Phòng Đào tạo, Trường Đại học Công nghiệp Hà Nội