TASHKENT UNIVERSITY OF
INFORMATION TECHNOLOGIES
NAMED AFTER MUHAMMAD AL-KHWARIZMI

MUHAMMAD AL-XORAZMIY NOMIDAGI
TOSHKENT AXBOROT TEXNOLOGIYALARI
UNIVERSITETI

BULLETIN OF TUIT:

MANAGEMENT AND COMMUNICATION TECHNOLOGIES



ISSN:2181-1083 DOI:
Amirsaidov Ulugbek № 1(5)2024

Model for transmitting URLLC packets in 5G networks

Amirsaidov Ulugbek

Tashkent University of Information Technologies named after Muhammad al-Khwarizmi, Tashkent, Uzbekistan

amirsaidov.ulugbek@gmail.com

Abstract— **5G New Radio (NR) will support a new Ultra Reliable Low Latency Communications (URLLC) service designed to support small packets transmission with very strict latency and reliability requirements. Grant-free (GF) scheduling has been proposed for URLLC instead of the traditional high-latency grant-based (GB) scheduling adopted in 4G Long Term Evolution (LTE) networks. Although GF scheduling on shared resources provides lower latency, the ability to achieve the URLLC reliability requirement may be defaced due to the increased probability of collisions. In this paper, the optimal configuration of the modulation-code scheme and the number of retransmissions of Uplink Grant-Free URLLC packets are determined. Analytical expressions have been developed for calculating the service characteristics of URLLC traffic depending on the quality of the communication channel, modulation code scheme (MCS) parameters and the number of resource blocks required to transmit a packet after encoding it.**

Keywords— **5G New Radio; Ultra Reliable Low Latency Communication (URLLC); grant-free (GF) access; collision; modulation code scheme; signal-to-noise ratio (SINR).**

1. INTRODUCTION

5G networks are being developed to support a wide range of industries such as manufacturing, transportation, healthcare and energy. 5G enables three new types of communication services: Enhanced Mobile Broadband (eMBB), Massive Machine Type Communication (mMTC) and Ultra-Reliable Low Latency Communication (URLLC) [1,2].

URLLC support is especially relevant for many Industry 4.0 manufacturing applications, such as factory automation [3,4], automated vehicle control [5,6], and remote control [7,8]. Such services require very high reliability and often short latencies to the millisecond level. For a small packet of 32 bytes, the packet error rate should not exceed 10^{-6}, and the maximum acceptable radio delay, including possible retransmissions, is 1 ms. [1].

5G brings significant changes to support URLLC. Some of these changes are focused on the radio access network (5G New Radio) layer, as media access mechanisms account for an important portion of the overall end-to-end delay. For URLLC traffic, Grant-Free (GF) scheduling is proposed instead of the traditional high-latency Grant-Based (GB) scheduling adopted in 4G Long Term Evolution (LTE) [9]. GF-based sharing of dedicated resources by a group of UEs is intended to serve aperiodic traffic. In this case, the user equipment (UE) has to compete for its usage and collisions are possible. 5G NR provides the ability to transmit K replicas of the same packet in consecutive slots to avoid potential collisions. However, using K replica transmissions to achieve the reliability target may introduce additional delays.

To reduce latency, the UE can transmit uplink traffic with no contention-based granting and waiting for a message of resource granting or allocation. In contention-based access, two or more UEs may attempt to simultaneously transmit on a common channel and collisions may occur. ALOHA is a well-known example of a contention-based protocol [10,11].

2. RELATED WORKS

Paper [12] presents in-depth analysis of the reliability and latency levels that can be achieved with existing GF scheduling solutions depending on the number of UEs, the number of reserved radio resources and the number of replicas K. The ability to transmit K replicas of the same packet in consecutive slots for dealing with collisions is considered in [10-13]. The authors suggest that

transmission collisions that overlap in time and frequency lead to packet loss. However, in real systems, the collision and packet loss probabilities depend on the MCS and SINR at the receiver.

Various options for retransmitting packets in dedicated and shared resources were studied in [14-16], depending on the parameters of URLLC traffic.

In paper [17] authors provide analysis of three GF access schemes with Hybrid Automatic Request (HARQ) retransmissions and analytical model is developed to elaborate GF access and transmission (HARQ).

Issues of optimizing the transmission parameters of URLCC traffic packets are considered in [10, 18-21]. In [10], in order to reduce the probability of collisions in ALOHA multiple transmissions of the same packet is considered. The optimal number of sequential multiple transmissions is determined to reduce collisions and achieve required reliability within the delay window.

In [18] it is proposed to adaptively adjust the number of retransmissions and MCS parameters depending on the quality of the communication channel. In [19], the authors propose to adaptively select the MCS for each UE using a set of received signal power thresholds. In particular, for a UE with lower power, the gNB selects a more reliable MCS. However, the use of MCS with low spectral efficiency and a large number of transmission attempts increases the consumption of channel resources, which in turn reduces network throughput.

In [20], algorithms for adaptive selection of MCS and the number of packet retransmissions are considered in two scenarios: with periodic traffic, when each UE is allocated certain channel resources, and with sporadic traffic, when the base station distributes common channel resources between groups of UEs.

Authors in [21] show that adaptive selection of the number of transmission attempts reduces the probability of collisions relative to a fixed number of transmission attempts. However, the authors do not consider MCS parameters.

The research papers mentioned above assume that the packet length is constant and a certain number of resource blocks are required to transmit the packet. This does not take into account the modulation code scheme (MCS) for packet transmission. Depending on the channel quality, different MCS are implemented. In this case, the length of the packet after the MCS mechanism increases. As a result, the number of required resource blocks for packet transmission also increases. In this case, resource blocks are not fully used. The purpose of this work is to determine the optimal configuration of MCS - K (where K is the number of retransmissions) depending on the quality of the channel and the number of required resource blocks when scheduling GF.

3. PROBLEM STATEMENT WORK

The process of transmitting packets over the uplink of a single-cell network with one base station (BS) and N_{UE} users (UE) is considered. Depending on the network numerology, there are N_{RB} resource blocks (RB). Users access shared RBs based on the grant-free (GF) scheduling method with K-repetitions.

Each UE alternates between active and inactive states. The UE remains in the inactive state until it generates a packet and then transitions to the active state. In the active state, the UE transmits the same data packet in K consecutive transmission slots with a duration of T_{slot}, i.e. packet delay time is $Ts=KT_{slot}$.

The number of resource blocks n_{rb} required to transmit a packet of length L_p bits after implementing the modulation code scheme (MCS) is equal to

$$n_{rb} = \left\lceil \frac{L_p[1+(1-r)]}{12\times\phi_{sym}\times Q_m} \right\rceil \quad (1)$$

where r is the coding rate, defined as the ratio of information bits (L_p) to the total code length; ϕ_{sym} – number of symbols in the slot and Q_m – modulation order (number of bits per symbol).

Let us denote a resource unit (RU) as a frequency fragment consisting of n_{rb} RB. The total number of available resource units N_{RU} is defined as

$$N_{RU} = N_{RB}/n_{rb} \quad (2)$$

Given the ratio of average signal power to average noise power (SINR) in the communication channel and packet length, it is necessary to determine the optimal MCS-K configuration

$$opt\{MCS-K\} \quad (3)$$

at which the minimum packet delay is achieved

$$minT_s \quad (4)$$

Wherein specified restrictions on the delay time (T_s^*) and the probability of successful transmission (P_s^*) of the packet are provided.

4. MODELS FOR DETERMINING THE PROBABILISTIC-TIME CHARACTERISTICS OF PACKET TRANSMISSION

The process of generating packets by inactive users is modeled by Bernoulli's law with probability p. The probability distribution of the number of slots (k_{slot}) during which the user is in an inactive state is given by the geometric distribution

$$(k_{slot} = i) = p(1-p)^{i-1},\ i = 1,2,3\ldots \quad (5)$$

The average duration of a user's inactive state is

$$M[k_{slot}] = 1/p \quad (6)$$

In the active state, the user transmits a packet for K slot and transitions to the inactive state. The probability that a user will generate a new packet during a slot is given by restrictions

$$p_{slot} = \frac{K}{M[k_{slot}]+K} \quad (7)$$

The probability distribution of the number of packets generated by inactive users during a slot is given by

$$P(k_p = i) = C_N^i (p_{slot})^i (1-p_{slot})^{N-i}, \quad i = \overline{0,N} \quad (8)$$

An active user has an equal probability $(1/N_{RU})$ of choosing one of the shared RUs to transmit each repetition of its packet. The probability of packet collision is determined by the formula [15]

$$P_c = 1 - \sum_{i=1}^{N} \left(1 - \frac{1}{N_{RU}}\right)^{i-1} \frac{P(k_p=i)}{1-P(k_p=0)} \quad (9)$$

Then the packet error probability is given by

$$P_p = \sum_{i=t+1}^{Lc} C_{L_c}^i {P_b}^i (1-P_b)^{L_c-1} \quad (10)$$

where P_b is the bit error probability [22], t is the correction capability of the code and L_c is the length of the packet after encoding

$$L_c = L_p[1 + (1-r)] \quad (11)$$

The correction ability of LDPC code implemented in 5G networks is determined by the formula [23]

$$t \approx \lfloor L_c(30 - 30 * r) \rfloor \quad (12)$$

A packet retry once will succeed unless a collision or packet error occurs. The packet transmission will be successful if at least one transmission out of K repetitions is successful. Then the probability of successful packet transmission is given by the expression

$$P_s = 1 - [1 - (1-P_c)(1-P_p)]^K \quad (13)$$

5. NUMERICAL RESULTS

The initial data for numerical analysis is given in Table 1.

TABLE 1.INITIAL DATA FOR CALCULATION

Parameter	**Designation**	**Meaning**
Number of users	N	100
Packet length, bytes	L_p	32
Channel bandwidth, MHz	ΔF	50
Network Numerology	μ	1
Subcarrier difference, kHz	Δf	30
Total number of resource blocks	RB	273
Number of OFDM symbols in mine slot	ϕ_sym	7
Duration of one symbol, μs	t_sym	33,3

In [24] the recommended MCS for transmitting URLLC traffic packets is given.

MCSs with maximum spectral efficiency are determined for various SINR values from (given in Fig.1), providing an error probability of $\leq 10^{-6}$. In addition, for different values of SINR and MCS, the length of the packet after encoding L_c (13), the number of resource blocks n_{rb} for transmitting a packet with length L_c and the proportion of unused part in the last resource block are determined. The results obtained are summarized in Table 2.

TABLE 2. DATA PACKET TRANSMISSION PARAMETERS

SINR range, dB	**MCS**	**Packet length after MCS, L_c, bits $L_p = 256$ bits**	**Number of resource blocks (n_{rb}) for transmitting L_c bits**	**Share of unused portion in last RB**
-3.3 ÷ -2.7	MCS9	1045	7	0.78
-2.7 ÷ -1.8	MCS10	852	6	0.93
-1.8 ÷ -0.46	MCS11	692	5	0.89

-0.46 ÷ -0.18	MCS12	584	4	0.53
-0.18 ÷ 0.7	MCS13	499	3	0.03
0.7 ÷ 0.9	MCS14	436	3	0.41
0.9 ÷ 0.98	MCS15	772	3	0.71
0.98 ÷ 2.3	MCS16	694	3	0.94
2.3 ÷ 2.7	MCS17	605	2	0.2
2.7 ÷ 3.3	MCS18	535	2	0.41
3.3÷ 3.9	MCS21	599	2	0.82
3.9 ÷ 4.5	MCS22	563	2	0.89
4.5 ÷ 5.5	MCS23	508	2	0.99
5.5 ÷ 6.1	MCS24	463	1	0.08
6.1 ÷ 6.8	MCS25	426	1	0.16
6.8 ÷ 7.7	MCS26	394	1	0.22
7.7 ÷ 8.3	MCS27	365	1	0.28
> 8.3	MCS28	340	1	0.33

For very low SINR values < -3.3, MCS0 – MCS8 are used.

In accordance with Table 2, dependency graph is obtained for the probability of a packet error and the SINR values (Fig. 1)

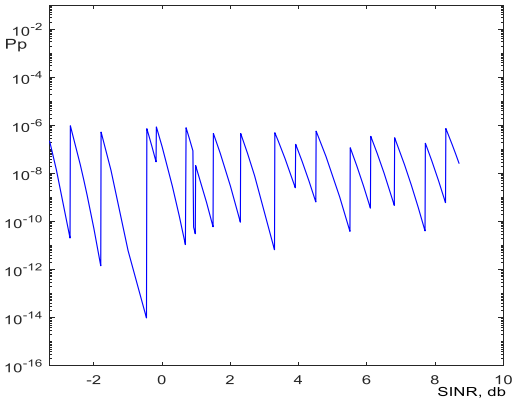


Figure 1. Dependency graph of the probability of packet error and SINR when choosing MCS in accordance with Table 2

In Table 2, using formula (1), the number of resource blocks for transmitting a packet after encoding is determined. In this case, the last resource block is not fully used because in formula (1) the resulting number is rounded up. In addition, several SINR–MCS variants use the same number of resource blocks to transmit packets. With such SINR – MCS options, it is advisable to use the option that provides the lowest probability of packet error. Then the graph of the packet error probability versus SINR has the following form (Fig. 2)

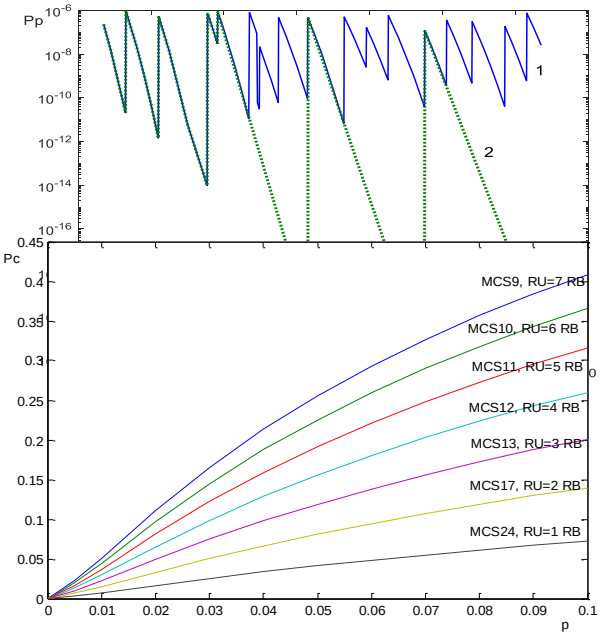


Figure 2. Dependency graph of packet error probability and SINR when selecting MCS in accordance with Tables 2 (curve 1) and the proposed variant (curve 2)

Based on the number of resource blocks for transmitting a packet for various SINR options given in Table 3 and formula (2), the total number of available resource units N_{RU} is determined. Next, for various packet generation probabilities p, the packet collision probabilities are determined using formula (9) (given in Fig. 3).

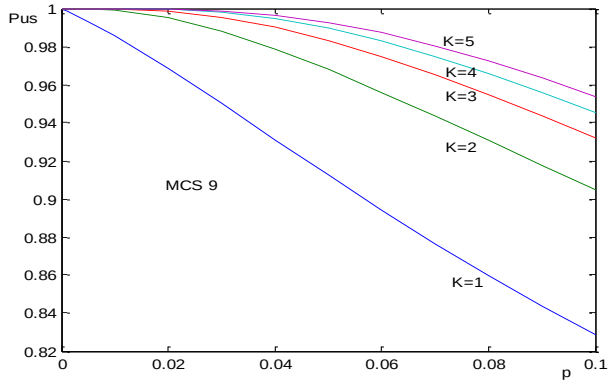


Figure 3. Dependence of the probability of packet collision on the probability of packet generation for different MCS

It follows from Figure 3 that by increasing MCS index the number of resource blocks for packet transmission increases (see Table 2). This leads to a decrease in the total number of available N_{RU} resource units and an increase in the probability of packet collisions. At the same time, with an increase in the probability of packet generation, the probability of packet collision also increases, since the duration of the user's inactive state decreases (6) and the probability of accessing a slot increases.

If the probabilities of collision and packet error are determined, then using formula (13) the probability of successful packet transmission is determined for various numbers of retransmissions and packet generation probabilities (Fig. 4)

Figure 4. Dependency graph of successful packet transmission probability on probability of generating packets for MCS9 and various numbers of repetitions

From Figure 4 it follows that as the number of retransmissions (K) increases, the probability of successful packet transmission increases. This in turn increases the packet delay time. In order to minimize the packet delay time (4) taking into account the given constraints, it is necessary to determine the optimal *MCS-K* design (3) for different packet generation probabilities (p). For the given restrictions $T_s^* = 1$ ms and $P_s^* = 0.999$ the optimal *MCS-K* designs are determined, which are shown in Table 3.

TABLE 3. OPTIMAL *MCS-K* DESIGNS

p	**Optimal number of packet retransmissions (K)**

	MCS 9	**MCS 10**	**MCS 11**	**MCS 12**	**MCS 13-16**	**MCS 17-23**	**MCS 24-28**
0.001	1	1	1	1	1	1	1
0.005	2	2	2	2	2	2	1
0.01	2	2	2	2	2	2	2
0.015	3	3	3	2	2	2	2
0.018	3	3	3	3	2	2	2
0.02	4	3	3	3	2	2	2
0.025	x	4	3	3	3	2	2
0.028	x	4	4	3	3	2	2
0.03	x	x	4	3	3	2	2
0.033	x	x	4	4	3	3	2
0.035	x	x	x	4	3	3	2
0.038	x	x	x	4	3	3	2
0.04	x	x	x	4	3	3	2
0.043	x	x	x	4	3	3	2
0.045	x	x	x	x	4	3	2
0.05	x	x	x	x	4	3	2
0.053	x	x	x	x	4	3	2
0.06	x	x	x	x	4	3	2
0.07	x	x	x	x	x	4	3
0.08	x	x	x	x	x	4	3
0.1	x	x	x	x	x	4	3
0.15	x	x	x	x	x	x	3
0.18	x	x	x	x	x	x	4
0.2	x	x	x	x	x	x	4
0.3	x	x	x	x	x	x	4
0.4	x	x	x	x	x	x	4
0.5	x	x	x	x	x	x	x

Note: x – the specified restrictions are not met.

6. CONCLUSIONS

In this paper the transmission processes of URLLC traffic packets on the uplink of 5G network based on the grant-free (GF) scheduling method with K-retransmissions have been studied. For different intensities of the packet flow, the optimal designs of ‘MCS - number of retransmissions’ are determined while satisfying the specified restrictions on the probability of successful delivery and packet delay. This takes into account the number of allocated resource blocks for transmitting a packet after its encoding and the share of the unused portion of the allocated resource blocks. Analytical expressions are obtained for calculating the probabilities of collision and packet error, taking into account the parameters of the packet flow, communication channel and the ‘MCS - number of retransmissions’ design.

The future scope of research will consider the issues of transmitting packets of heterogeneous URLLC traffic, taking into account various requirements for the probability of successful delivery and packet delay. The tasks related to optimal distribution of common resource block between heterogeneous URLLC traffic and selection of the ‘MCS - number of retransmissions’ configuration will be elaborated.

REFERENCES

[1] Study on Scenarios and Requirements for Next Generation Access Technologies, document 3GPP, TS 38.913 v15.2.0, Jun. 2018.

[2] IMT Vision-Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond, document M.2083-0, Recommendation ITU-R, Sep. 2015, p. 2083.

[3] Klessig, H.; Ashraf, S.A.; Almeroth, B.; Riedel, I.; Puschmann, A.; Elste, T.; Simsek, M.; Schulz, P.; Matthe, M.; Fettweis, G.; et al. Latency Critical IoT Applications in 5G: Perspective on the Design of Radio Interface and Network Architecture. IEEE Commun.

Mag. 2017, 55, 70–78. doi: 10.1109/MCOM.2017.1600435CM

[4] B. Holfeld et al., "Wireless communication for factory automation: An opportunity for LTE and 5G systems" IEEE Commun. Mag., vol. 54, no. 6, pp. 36–43, Jun. 2016. doi:10.1109/MCOM.2016.7497764

[5] 3GPP. Technical Specification Group Radio Access Network; Study on Physical Layer Enhancements for NR Ultra-Reliable and Low Latency Case (URLLC); 3GPP: Sophia Antipolis, France, 2018; Release 16, 3GPP TR 38.824 V1.0.0.

[6] C. Campolo, A. Molinaro, A. Iera, and F. Menichella, "5G network slicing for vehicle-to-everything services," IEEE Wireless Commun., vol. 24, no. 6, pp. 38–45, Dec. 2017. doi:10.1109/MWC.2017.1600408

[7] A. Azari, M. Ozger, and C. Cavdar, "Risk-aware resource allocation for URLLC: Challenges and strategies with machine learning," IEEE Commun. Mag., vol. 57, no. 3, pp. 42–48, Mar. 2019. doi: 10.1109/MCOM.2019.1800610.

[8] 3GPP. Technical Specification Group Services and System Aspects; Study on Communication for Automation in Vertical Domains; 3GPP: Sophia Antipolis, France, 2018; Release 16, 3GPP TR 22.804 V16.2.0.

[9] U.Amirsaidov, A.Qodirov A Packet Delay Assessment Model in the Data Link Layer of the LTE. – JOIV: Int. J. Inform. Visualization, 5(4) – December 2021, 402-408. DOI:10.30630/joiv.5.4.601.

[10] Singh, B, Tirkkonen, O, Li, Z & Uusitalo, M 2018, 'Contention-Based Access for Ultra-Reliable Low Latency Uplink Transmissions', IEEE WIRELESS COMMUNICATIONS LETTERS, vol. 7, no. 2, pp. 182 - 185 . doi:10.1109/LWC.2017.2763594.

[11] Casini E., Gaudenzi R.D., Herrero O.D.R. Contention Resolution Diversity Slotted ALOHA (CRDSA): An Enhanced Random Access Scheme for Satellite Access Packet Networks. *IEEE Trans. Wirel. Commun.* 2007;**6**:1408–1417. doi: 10.1109/TWC.2007.348337.

[12] M. C. Lucas-Estan, J. Gozalvez, and M. Sepulcre, "On the Capacity of 5G NR Grant-Free Scheduling with Shared Radio Resources to Support Ultra-Reliable and Low-Latency Communications," in Sensors, vol. 19, no. 16, p. 3575, 2019. doi:10. 3390/s19163575.

[13] Wu, Y.; Zhang, L.; Wang, C.; Chen, Y. Performance Evaluation of Grant-Free Transmission for Uplink URLLC Services. In Proceedings of the 2017 IEEE 85th Vehicular Technology Conference (VTC Spring), Sydney, Australia, 4–7 June 2017; pp. 1–6. doi:10.1109/VTCSpring.2017.8108593

[14] Abreu, R.; Mogensen, P., Pedersen, K.I. Pre-Scheduled Resources for Retransmissions in Ultra-Reliable and Low Latency Communications. In Proceedings of the 2017 IEEE Wireless Communications and Networking Conference (WCNC), San Francisco, CA, USA, 19–22 March 2017; pp. 1–5. doi:10.1109/WCNC.2017.7925877.

[15] Mohamed Yacine Lezzar, Mustafa Mehmet-Ali. Optimization of ultra-reliable low-latency communication systems. Computer Networks , Volume197, 9 October 2021, 108332. doi:10.1016/j.comnet.2021.108332

[16] Kotaba, R.; Manchon, C.N.; Balercia, T.; Popovski, P. Uplink Transmissions in URLLC Systems with Shared Diversity Resources. IEEE Wirel. Commun. Lett. 2018, 7, 590–593. doi: 10.1109/LWC.2018.2799592.

[17] Liu Y., Deng Y., Elkashlan M., Nallanathan A., Karagiannidis G.K. Analyzing grant-free access for URLLC service. IEEE Journal on Selected Areas in Communications, Vol. 39, No3, March 2021, pp. 741-755. doi:10.1109/JSAC.2020.3018822.

[18] Jacobsen, T.; Abreu, R.; Berardinelli, G.; Pedersen, K.; Mogensen, P.; Kovacs, I.Z.; Madsen, T.K. System Level Analysis of Uplink Grant-Free Transmission for URLLC. In Proceedings of the 2017 IEEE Globecom Workshops (GC Wkshps), Singapore, 4–8 December 2017; pp. 1–6. doi: 10.1109/GLOCOMW.2017.8269137.

[19] T. Jacobsen, R. Abreu, G. Berardinelli, K. Pedersen, I.Z. Kovacs, P. Mogensen, Joint resource configuration and MCS selection scheme for uplink grant-free URLLC, in: 2018 IEEE Globecom Workshops, GC Wkshps, 2018, pp. 1–6, doi:10.1109/GLOCOMW.2018.8644377.

[20] Aleksei Shashin, Andrey Belogaev, Artem Krasilov, Evgeny Khorov. Adaptive parametrs selection for uplonk grant-free

URLLC transmission in 5G systems. Computer Networks, Volume 222, February 2023. doi:10.1016/j.comnet.2022.109527.

[21] Ozaku, Y. Shimbo, H. Suganuma, F. Maehara, Adaptive repetition control using terminal mobility for uplink grant-free URLLC, in: Proceedings of the IEEE 91st Vehicular Technology Conference, VTC Spring, IEEE, 2020, pp. 1–5, doi:10.1109/VTC2020-Spring48590.2020.912840323.

[22] Sklyar B. Digital communication. Theoretical foundations and practical application. Second Edition. – M.: Williams Publishing House, 2003.-1104 p.

[23] Amirsaidov U.B., Qodirov A.A. Evaluation of Correcting Ability of LDPC Code in 5G Networks.- International Journal of Advanced Research in Science, Engineering and Technology. Vol. 7, Issue 1, January 2020. pp. 12454-1258. http://www.ijarset.com/upload/2020/january/19-azamattuit2013-29-revised.pdf

[24] 3GPP TS 38.214 v 15.2.0, “Physical layer procedures for data,” Jul. 2018.