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A Packet Delay Assessment Model in the Data Link Layer of the LTE

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Abstract*— The issues of modeling and evaluating the characteristics of the LTE data link layer functioning are considered. Transmitting packets in the data link layer are represented by a probabilistic-temporal graph consisting of two subgraphs. The first subgraph describes the operation of the HARQ protocol, and the second subgraph describes the operation of the ARQ protocol. The first subgraph is nested within the second subgraph. The probabilities of correct reception, non-error detection, and retransmission of packets in the MAC and RLC layers and generating functions of the packet service time based on the HARQ and ARQ protocols are determined. With the help of generating functions, the average value, variance, and coefficient of variation of the packet service time are determined. To calculate the average packet delay time in the LTE data link layer, the type of queuing system is selected, taking into account the coefficient of variation of the packet service time. The analysis of packets' delay time in the network's data link layer is carried out for different values of the intensity of packet arrival and the probabilities of a bit error in the physical layer of the network. For the sustainable functioning of the data link layer of the network, the limit values of the intensity of the arrival of packets are determined for a given probability of a bit error in the physical layer of the network.

***Keywords*— LTE networks; HARQ protocol; ARQ protocol; HARQ-ARQ interaction; HARQ and ARQ probabilistic-temporal graphs; generating packet service time functions; queuing system; average packet delay time.**

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I. INTRODUCTION

Currently, wireless information transmission networks are one of the main directions of the development of info-communications. LTE (Long-Term Evolution) is a standard of universal city networks in which wireless broadband access is used by a very wide range of applications - from traditional voice transmission to modern multimedia applications.

The LTE network provides users with access to all kinds of services and the Internet through the IP protocol. All nodes of the LTE network are usually divided into two categories. The nodes are related to the radio access network, and the nodes are the core network. The key element that determines the effectiveness of any radio network is the algorithms and mechanisms used to transfer data between the base station (eNB) and mobile user terminals (UE). LTE architecture is considered in Cox [1].

OFDM (Orthogonal Frequency-Division Multiple Access) technology is used at the physical layer of LTE with 4FM, 16QAM, and 64QAM modulation. Each UE is assigned a specific range of channel resources in the time-frequency domain (Resource Grid). The number of resource blocks in the resource grid depends on the channel bandwidth and ranges from 6 (1.4 MHz) to 110 (20 MHz). In the time domain, the length of the radio frame is 10 ms, which is divided into ten subframes, each 1 ms long. In LTE, the transmission time interval (TTI) is 1 ms, so every 1 ms, the scheduler must multiplex users in the resource grid.

Packet transmission at the MAC (Media Access Control) layer is based on the HARQ (Hybrid Automatic Repeat Request) protocol, which is a combination of (Hybrid) error detection methods with packet retransmission and noise-immunity coding. Upon receiving a packet containing errors not corrected by the channel decoder, the receiver discards the received packet and requests its retransmission (HARQ retransmission). In the presence of significant radio interference or a high level of interference, the number of retransmissions of data packets may be unacceptably large. To limit the resulting time delays, HARQ is usually configured to limit the maximum number of retransmissions, after which the packet is recognized as irreparably damaged and discarded. At the same time, at a higher layer of the receiver protocol stack (RLC- Radio Link Control layer), a problem can be detected, and a lost packet is re-requested through the basic scheme of the ARQ (Automatic Repeat Request) protocol.

II. Material and Method

A. Existing work

There are numerous works on modeling and evaluating quality-of-service indicators in LTE networks. Some of these works close to the proposed work are discussed below. In Sassioui *et al.* [2], the efficiency of data transmission using AMC-HARQ schemes over a radio channel with slow and fast fading is evaluated. Recommendations for improving the efficiency of AMC-HARQ interaction are given.

To reduce the processing time by Early Hybrid Automatic Repeat Query (E-HARQ) has been proposed to the receiver and fast feedback [3]. The results showed that the new class of retransmission protocols significantly improved the performance of ultra-reliable low latency communications (URLLC) systems. Whereas, in Makki *et al.* [4], the throughput of a hybrid automatic repeat request (HARQ) communication system for coding words with variable length has been evaluated. It is shown that the adaptive choice of the word length can increase the system's throughput.

A comparative analysis of the performance of encoded and non-encoded ARQ has been carried out [5]. It has been shown that coded ARQ provides up to 40% performance gain. The performance evaluation of an incremental reservation (IR) hybrid automatic re-query (HARQ) over dual Rayleigh channels has been carried out [6]. Analytical expressions for calculating the average waiting time for a packet in the queue, average power consumption, and energy efficiency are determined. The trade-off between energy efficiency and spectral efficiency is investigated. The performance evaluation of LTE with IR-HARQ has been carried out [7]. A method of variable bandwidth distribution among network users is proposed. The advantage of the proposed method in comparison with a fixed channel bandwidth distribution is shown.

In Bruno *et al.* [8], Downlink simulation at MAC level in LTE is performed considering the combination of channel adaptation and error correction schemes. It is shown that the efficiency of the IR-HARQ scheme depends on the choice of modulation and coding methods. In Mahjabeen *et al.* [9], potential network quality analysis approaches based on mobility are researched. In Amali and Ramachandran [10], a broad survey on 5G cellular network architecture and some of the promising key technologies such as cloud RAN (Radio Access Network), Software-Defined Networking (SDN), Network Function Virtualization (NFV), and modulation formats are given.

Coding and modulation issues are considered in Singh *et al.* [11]. Whereas, in Temitope *et al.* [12], modeling and evaluation of the efficiency of the LTE physical layer in the LTE System Toolbox environment are performed. Some previous studies have considered the issues of assessing the influence of the modulation method and information coding rate on the adaptive LTE bandwidth control process in the presence of interference in the information exchange channel [13], [14]. The performance of LTE control channels with fixed receivers and an ideal estimation channel was studied in Milo and Hanus [15].

In Woltering *et al.* [16], in order to increase the system throughput, a multi-level ACK/NACK transmission scheme is proposed. In Milo and Hanus [17], the influence of the HARQ scheme on the probabilistic-temporal characteristics of the system is analyzed. In Chuag and Lin [18], an analytical model is proposed for the functioning of HARQ-ARQ and the research of time parameters (timers) of feedback protocols. In Ikuno *et al.* [19], the HARQ characteristics are determined taking into account the parameters of the signal-code structure and the level of interference in the radio channel. In [20], HARQ bandwidth analysis and packet transmission delay on the Raleigh radio channel is performed. The optimization problems for the HARQ scheme are considered in Shariatmadari *et al.* [21] and Malak *et al.* [22]. Optimization of the transmission of control information in LTE was discussed in Chen *et al.* [23].

B. Suggested work

The aim of the work is to develop a model for estimating the average delay (stay) time of a packet in the system, taking into account the HARQ and ARQ mechanisms. Distinctive features of the work are:

- the average packet service time at the ARQ level, which includes the HARQ level, is determined based on a probabilistic-temporal graph and generating functions.
- to calculate the average packet delay time, the model type of queuing systems is selected, taking into account the coefficient of variation of packet service time.
- when calculating the probabilistic-temporal characteristics of packet service, the probability of a bit error achieved after implementing the signal-code construction is taken into account.

The work consists of an introduction, four parts, and a conclusion. In the first part, a generalized model of the functioning of the LTE data link layer and a methodology for solving the assigned task are provided. In the second part, models for determining the average packet service time at the HARQ and ARQ levels and a model for determining the average packet delay time in the system are developed. In the third part, the results of numerical calculations are given. In conclusion, the main results obtained and ways to expand the developed models are presented.

C. Models for Researching the Characteristics of the LTE Data Link Layer

1) Generalized Model: A generalized model of packet transmission from the RLC layer of the UE to the RLC layer of the eNB is shown in Figure 1. To describe packet transmission processes, the theory of probabilistic-temporal graphs and the method of generating functions are used. The process of transmitting packets from the MAC layer of the UE to the MAC layer of the eNB is described by the generating function $\boldsymbol{F_1(z)}$. The process of transmitting packets from the RLC layer of the UE to the RLC layer of the eNB is described by the generating function $\boldsymbol{F_2(z)}$. Obviously, $\boldsymbol{F_1(z)}$ is embedded in $\boldsymbol{F_2(z)}$.

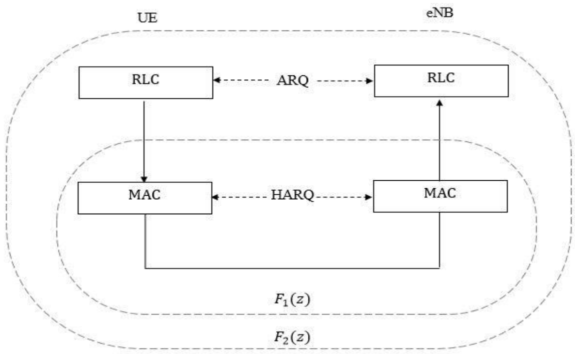

Fig. 1 Generalized model of the packet transmission process in the LTE data link layer

2) Estimation model of packet service time in the MAC layer: In accordance with the HARQ mechanisms, the probabilistic-temporal packet transmission graph for determining $F_1(z)$ is shown in Figure 2.

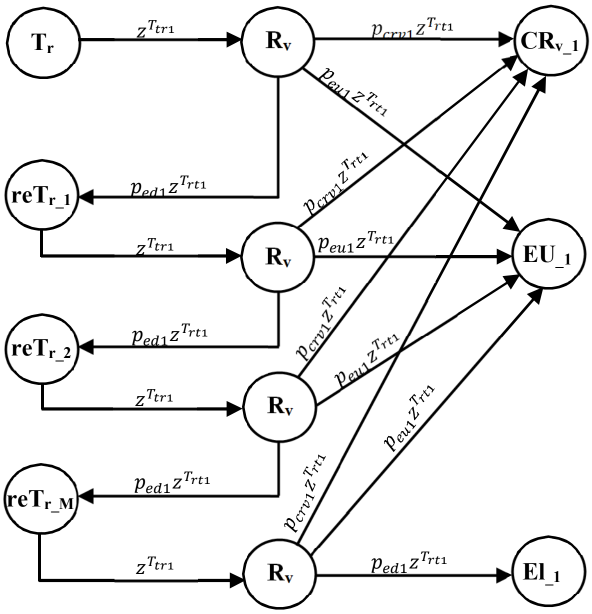

Fig. 2 Probabilistic-temporal graph of HARQ packet transmission

The characteristics of the probabilistic-temporal graph are shown in table 1.

TABLE I
CHARACTERISTICS OF PROBABILISTIC-TEMPORAL GRAPH OF HARQ PACKET TRANSMISSION

No	Generating functions of graph branches	Function parameters
1	$z^{T_{tr1}}$	T_{tr1} - HARQ packet transmission time T_{rt1} - the latency time of HARQ receipt
2	$p_{crv1}z^{T_{rt1}}$	p_{crv1} - the probability of receiving the HARQ packet correctly
3	$p_{ed1}z^{T_{rt1}}$	p_{ed1} - the probability of detecting an error in the HARQ packet
4	$p_{eu1}z^{T_{rt1}}$	p_{eu1} - the probability of an undetected error in the HARQ packet

Note: Index 1 shows that the parameters relate to MAC layer.

The probability of receiving the HARQ packet correctly is equal to

$$p_{crv1} = [1 - p_1]^{n_1} \quad (1)$$

where, p_1 is the probability of bit error after the implementation of the signal-code construction, consisting of modulation and turbo coding methods; n_1 is the length of the HARQ packet. The probability of an undetected error in packet n_1 is defined as

$$P_{eu1} = \frac{1}{2^{r_{k1}}}\sum_{i=d_o}^{n_1} C_{n_1}^{i}\, p_1{}^{i}(1 - p_1)^{n_1 - i} \quad (2)$$

where, r_{k1} is the number of bits of the checksum (CRC) of the packet n_1; d_o is Hamming's minimum code distance. The probability of detecting an error in packet n_1 is equal to

$$p_{ed1} = 1 - (p_{crv1} + p_{eu1}) \quad (3)$$

After an error is detected, the HARQ packet retransmission procedure begins. The HARQ process can be completed with the following outcomes:

- correct reception of the packet $(P_{crv}, f_{crv1}(z))$;
- undetected errors in the packet $(P_{eu1}, f_{eu1}(z))$;
- elimination of the packet, after the maximum number (M) of repetitions $(P_{el1}, f_{el1}(z))$.

The generating functions $f_{crv1}(z)$, $f_{eu1}(z)$ and $f_{el1}(z)$ are determined by summing up the options for obtaining the considered outcomes in a probabilistic-temporal graph (figure 2):

$$f_{crv1}(z) = p_{crv1}z^{T_t}\sum_{k=0}^{M}[p_{ed1}z^{T_t}]^k \quad (4)$$

$$f_{eu1}(z) = p_{eu1}z^{T_t}\sum_{k=0}^{M}[p_{ed1}z^{T_t}]^k \quad (5)$$

$$f_{el1}(z) = [p_{ed1}z^{T_t}]^{M+1} \quad (6)$$

where, $T_t = T_{tr1} + T_{rt1}$.

The probabilities of outcomes are defined as follows.

$$P_{crv1} = f_{crv1}(z = 1) = p_{crv1}\frac{1 - p_{ed1}{}^{M}}{1 - p_{ed1}} \quad (7)$$

$$P_{eu1} = f_{eu1}(z = 1) = p_{eu1}\frac{1 - p_{ed1}{}^{M}}{1 - p_{ed1}} \quad (8)$$

$$P_{el1} = f_{el1}(z = 1) = p_{ed1}{}^{M+1} \quad (9)$$

It can be shown that the sum of the probabilities (4-6) is equal to one

$$P_{crv1} + P_{eu1} + P_{el1} = 1 \quad (10)$$

The generating function of the HARQ level $F_1(z)$ is determined by summing the generating functions (4-5)

$$F_1(z) = f_{crv1}(z) + f_{eu1}(z) + f_{el1}(z) \quad (11)$$

The average HARQ service time is defined as

$$\bar{T}_{s1} = \frac{dF_1(z)}{dz}, \quad \text{at } z = 1 \quad (12)$$

Taking the derivative of (11) taking into account formulas (4-6) and substituting z = 1, we find

$$\bar{T}_{s1} = \Big[(p_{crv1} + p_{eu1})\frac{1-p_{ed1}{}^{M+1}-(M+1)p_{ed1}{}^{M}(1-p_{ed1})}{(1-p_{ed1})^2} + +(M+1)p_{ed1}\Big]T_t \quad (13)$$

3) Packet service time evaluation model in the RLC layer: The probabilistic-temporal graph of the packet transmission from the ARQ of the sender to the ARQ of the receiver is shown in Figure 3.

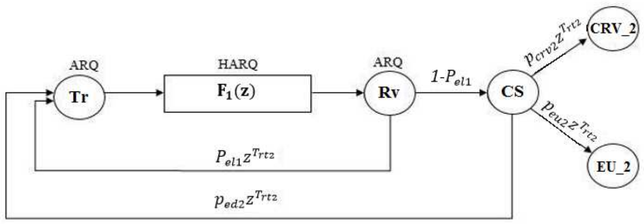

Fig. 3 Probabilistic-temporal graph of ARQ packet transmission

The characteristics of the probabilistic-temporal graph are shown in table 2.

TABLE II
CHARACTERISTICS OF PROBABILISTIC-TEMPORAL GRAPH OF ARQ PACKET TRANSMISSION

No.	Generating functions of graph branches	Function parameters
1	$F_1(z)$	A generating function of HARQ process (see formula 11)
2	$P_{el1}z^{T_{rt2}}$	T_{rt2} - the time of delivery of the ARQ receipt. P_{el1} - the probability of eliminating the HARQ data block (see formula 9)
3	$p_{ed2}z^{T_{rt2}}$	p_{ed2} - probability of error detection in the ARQ data block
4	$p_{crv2}z^{T_{rt2}}$	p_{crv2} - the probability of the correct reception of the ARQ data block
5	$p_{eu2}z^{T_{rt2}}$	p_{eu2} - the probability of an undetected error in the ARQ data block

The probability of bit error at the ARQ level after implementing HARQ is equal to

$$p_2 \approx \frac{P_{eu1}}{n_2} \quad (14)$$

where, n_2 is the length of the ARQ packet; P_{eu1} is the probability of an undetected error in the HARQ packet (see formula 8).

The probabilities of correct reception CRv_2 (p_{crv2}), undetected error EU_2 (p_{eu2}) and detection of an error ED_2 (p_{ed2}) in the ARQ packet are determined by the formulas:

$$p_{crv2} = (1-p_2)^{n_2} \quad (15)$$

$$p_{eu2} = \frac{1}{2^{r_{k2}}}\sum_{i=d_o}^{n_2} C_{n_2}^{i}\, p_2{}^{i}(1-p_2)^{n_2-i} \quad (16)$$

$$p_{ed2} = 1-(p_{crv2}+p_{eu2}) \quad (17)$$

where r_{k2} is the number of bits of the checksum (CS) of the data block n_2. At the receive side of ARQ, the following events may occur:

ARQ packet missing due to HARQ level elimination:

- An error was detected in the ARQ packet.
- ARQ packet correctly received.
- An error was not detected in the ARQ packet.

A packet retransmission receipt is sent in the first two cases, and in the last two cases, the ARQ process ends. Based on the probabilistic-temporal graph, we determine the generating function of the transmission time of the data block ($F_2(z)$) from the sender of ARQ to the receiver. In the probabilistic-temporal graph, there are two loops associated with the transmission of receipts for retransmission of the ARQ packet. To eliminate these loops, we use the well-known graph transformation rules. For the first loop, the equivalent generating function is written as

$$f_{1e}(z) = \frac{F_1(Z)}{1-P_{el1}Z^{T_{rt2}}} \quad (18)$$

For the second loop, the equivalent generating function has the form

$$f_{2e}(z) = \frac{f_{1e}(z)}{1-p_{ed2}Z^{T_{rt2}}} \quad (19)$$

The generating functions of the ARQ packet transmission time with the outcomes of the correct reception and the undetected error are of the form.

$$f_{crv2}(z) = f_{2e}(z)p_{crv2}z^{T_{rt2}} \quad (20)$$

$$f_{eu2}(z) = f_{2e}(z)p_{eu2}z^{T_{rt2}} \quad (21)$$

The generating function of the packet transmission time ($F_2(z)$) from the sender of ARQ to the receiver is defined as the sum of (20) and (21).

$$F_2(z) = f_{crv2}(z) + f_{eu2}(z) \quad (22)$$

The average value and variance of the service time of the ARQ packet are defined as.

$$\bar{T}_{s2} = \frac{dF_2(z)}{dz}, \quad \text{at } z=1 \quad (23)$$

$$D_{s2} = \frac{d^2F_2(z)}{dz^2} + \frac{dF_2(z)}{dz} + \left(\frac{dF_2(z)}{dz}\right)^2, \text{ at } z=1 \quad (24)$$

The standard deviation (σ_{s2}) and the coefficient of variation of the service time (v_{s2}) of the ARQ packet are determined by the formulas:

$$\sigma_{s2} = \sqrt{D_{s2}} \quad (25)$$

$$v_{s2} = \frac{\sigma_{s2}}{\bar{T}_{s2}} \quad (26)$$

Taking the derivative of $F_2(z)$ and substituting z = 1, we find the average service time of the ARQ packet

$$\bar{T}_{s2} = \frac{[\bar{T}_{s1}(1-P_{el1})+P_{el1}T_{rt2}](1-P_{el1})(1-P_{ed2})+P_{ed2}T_{rt2}}{(1-P_{el1})(1-P_{ed2})^2} \quad (27)$$

4) Estimation model of packet delay-time (stay) in the RLC layer: Suppose the incoming ARQ packet stream is Poisson with an intensity of λ (packet/TTI) and an unlimited queue for packets. Then, the queuing system (QS) model of type M/G/1 can be used to estimate the packet delay time. The Pollaczek-Khinchine formula determines the average waiting time for a packet in a queue.

$$W_2 = \frac{\lambda\bar{T}_{s2}{}^2(1+v_2{}^2)}{2(1-\rho)} \quad (28)$$

where, $\rho = \lambda/\mu_{s2} < 1$ is the system utilization.

$\mu_{s2} = n_{HARQ}/\bar{T}_{s2}$ is service intensity of the ARQ packets and n_{HARQ} is the number of parallel HARQ processes. The average packet delay-time (stay) in the RLC layer is defined as.

$$\bar{T}_d = W_2 + \bar{T}_{s2} = \frac{\lambda \bar{T}_{s2}^2(1+v_2^2)}{2(1-\rho)} + \bar{T}_{s2} \quad (29)$$

III. Results and Discussion

A. Generalized Model

The initial data for numerical analysis are given in table 3. [1], [13], [14].

TABLE III
THE INITIAL DATA FOR NUMERICAL ANALYSIS

Parameters	Values
p_1	$10^{-6} - 10^{-2}$
n_1, bit	1024
n_2, bit	1000
M	3
n_{HARQ}	3
T_{tr1}, ms	2TTI
T_{rt1}, ms	1TTI
T_{rt2}, ms	2TTI
λ, packet/TTI	0.1-0.5

B. Average Packet Service Time in the MAC Layer

The dependency graph of the probabilities of outcomes of the HARQ process on the probability of bit error is shown in Figure 4.

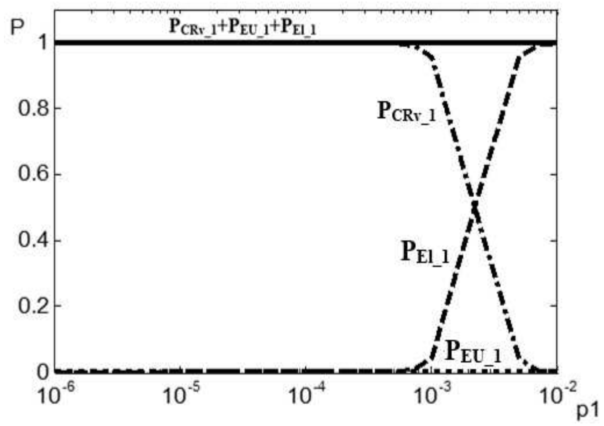

Fig. 4 The dependency graph of the probabilities of outcomes of the HARQ process on the probability of bit error

It can be seen from Figure 4, that for $p_1 > 10^{-3}$, the probability of the correct reception of the HARQ packet sharply decreases, and the probability of eliminating the packet increases. The sum of the probabilities of outcomes is equal to one. The dependency graph of the average service time of the HARQ packet on the probability of a bit error of the maximum number of retries M = 4 and M = 3 is shown in Figure 5.

It can be seen from Figure 5 that for $p_1 > 10^{-4}$, an average packet service time begins to increase due to an increase in the number of retransmissions. When $p_1 > 7 * 10^{-3}$, the number of retries reaches the maximum value (M), and the packet is eliminated. It can be seen from Figure 2 that for $p_1 > 7 * 10^{-3}$, the probability of eliminating the packet is equal to one.

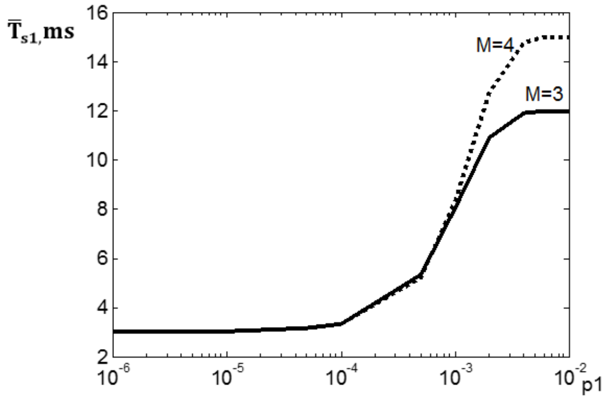

Fig.5 The dependency graph of the average service time of the HARQ packet on the probability of a bit error

C. The Average Packet Service Time in the RLC Layer

The dependency graph of the average service time of the ARQ packet on the probability of a bit error is shown in Figure 6.

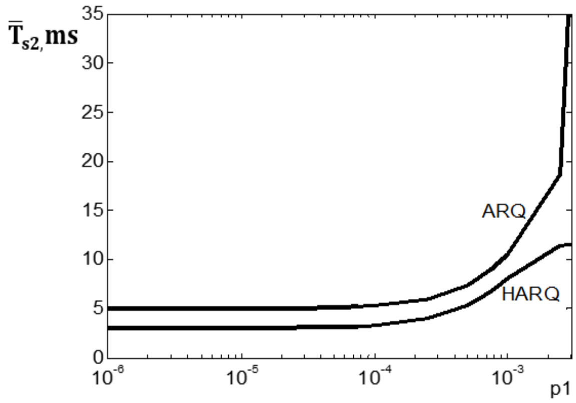

Fig. 6 The dependency graph of the average service time of the ARQ packet on the probability of a bit error

It can be seen from Figure 6 that the average service time at low values of p_1 increases sharply due to an increase in the probability of packet elimination at the HARQ level (see Figure 2). The dependency graph of the coefficient of variation of the service time of the ARQ packet on p_1 is shown in Figure 7.

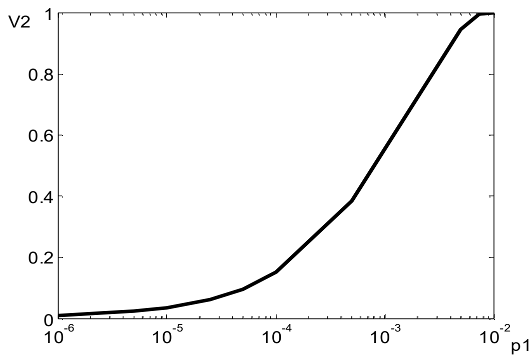

Fig. 7 The dependency graph of the coefficient of variation of the service time of the ARQ packet on the probability of bit error

It can be seen from Figure 7 that the coefficient of variation v_2 for $p_1 < 10^{-6}$ tends to zero, and with increasing p_1 it starts to increase and tends to one. Thus, the service time of the ARQ packet has an arbitrary distribution.

D. Average packet delay-time

Since the service time of the ARQ packet has an arbitrary distribution, the choice of the M/G/1 model of the QS is reliable. The dependency graph of $\overline{T}_d$ on the probability of a bit error for the AWGN radio channel model (AWGN-Additive White Gaussian Noise) and different values of λ is shown in Figure 8.

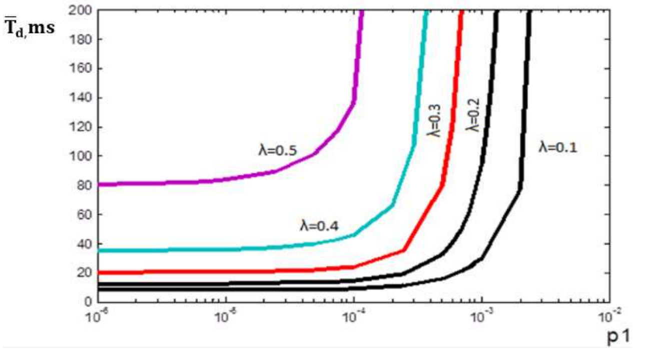

Fig. 8 The dependency graph of the average delay-time of the ARQ frame on the probability of bit error

It can be seen from Figure 8 that with an increase in packet arrival rate, the average delay-time increases. For each value of λ, there is a certain value p_1^*, after which the average packet delay-time sharply increases. This is explained by the fact that at these points of p_1, the utilization of the system approaches one. Therefore, the probability of bit error, determined depending on the implemented signal code construction (SCC) and the signal-to-noise ratio in the communication channel, should be less than p_1^*.

The dependency graph of the average delay time of ARQ frames on the probability of a bit error for $\lambda = 0.1$ and various models of the radio channel is shown in Figure 9.

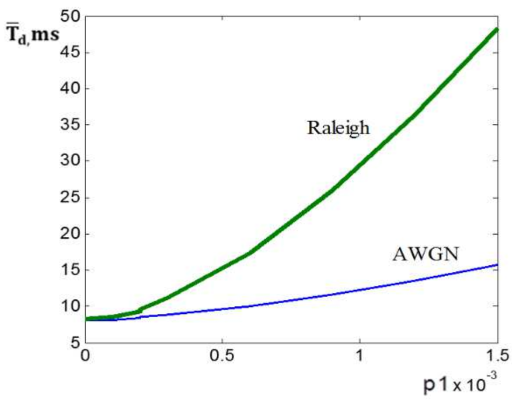

Fig. 9 The Dependence of the average frame delay time on the probability of a bit error in AWGN and Raleigh channels

Signal fading in a wireless environment leads to an increase in the delay time of data frames in the transmission link of the LTE network since the probability of data frame error and retransmission in the Raleigh fading channel is greater than in the AWGN channel.

IV. CONCLUSIONS

The conducted research allows us to do the following conclusions: When analyzing the characteristics of the LTE data link layer, it is necessary to take into account the interconnection of the HARQ, ARQ, and SCC mechanisms. The quality of packet service substantially depends on the probability of a bit error achieved using the SCC. A QS model for packet delay must be chosen after determining the type of distribution of packet service time. The developed models allow us to determine the probabilistic temporal characteristics of HARQ-ARQ processes taking into account the quality of the radio channel.

In the upcoming research, including the SCC parameters in the developed models is recommended. This will allow us to select the SCC parameters to ensure the specified indicators of the quality of service of packets.

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