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Data Transmission Model with Lost Fragments Recovery Based on Application Layer ARQ[1, 2]

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Wireless networks in difficult conditions of signal receiving are characterized by a high level of burst data losses, at which a large number of data fragments can be lost in a row. In this case, to recover the lost data, the use of forward error correction methods (FEC) in most cases does not give a sufficient effect. The use of standard data loss recovery methods based on automatic retransmission request (ARQ) at the data link and transport layers of the OSI model can lead to significant delays, which is often unacceptable for real-time streaming services. In such a case, it may be preferable to skip the piece of data rather than delay waiting for the piece to be delivered on retransmissions. The use of ARQ-based techniques on application layer of OSI model for data streaming allows for a more efficient recovery of lost data chunks in wireless networks with a high level of burst losses. The known models of a discrete channel for wireless networks allow for analytically assessing the probability of data loss, however, they do not take into account cases with retransmission of lost data. The study proposes a mathematical model of data transmission in a wireless communication channel based on the Gilbert model, which takes into account the loss recovery by the ARQ method and allows you to calculate the data loss ratio. To check the adequacy of the proposed model, a software was developed that ensures the transmission of data streaming in a wireless communication network with recovery of fragment losses at the application level, and a corresponding experimental study was carried out. It is shown that the mathematical model takes into account the burstiness of transmitted data losses and their recovery by the ARQ method.

Keywords: application layer, data fragment, ARQ, modelling, Data loss ratio.

Introduction

Data streaming in wireless LAN is now increasingly available in telecommunications and is used in multimedia services such as listening music, watching video, voice transmitting, multimedia conferences, real-time control, network games and other real-time applications. However, the quality of transmission in wireless networks is affected by factors such as signal attenuation, interchannel interference, multibeam propagation, etc. As a result, fragments of transmitted data can be lost, delayed, change the order. Thus, for example, when using video servers in these networks, distortions may appear on the played video on the client side or video content playback becomes impossible [1].

To improve the quality of data transmission in communication networks, the most widely used methods of data loss recovery are based on automatic requestand re-transmission ARQ and on the base of forward error correction FEC at various levels of the OSI model. Using the standard ARQ method in the TCP protocol, located at the transport layer of the OSI model, can cause significant latency in complex receive conditions, which is unacceptable for real-time streaming services. In this case, it is preferable to skip the data fragment than to wait for the fragment to be delivered during retransmissions. When bit errors are detected in the Data Link Layer frame, the corresponding fragment of application layer data is lost, as the frame is ignored. Since all fragments of the application layer data are numbered, this allows to detect the fact of their loss for a subsequent re-transfer request.

Wireless communication channels in difficult receiving conditions are characterized by a high level of grouping of data loss, that is, a large number of data fragments can be lost in a row. Therefore, the use of FEC methods, which include Reed-Solomon codes, turbocodes, convolutional codes and others, in wireless networks in most cases does not have a sufficient effect, since FEC codes are limited in their ability to recover lost data by the amount of redundant data in the transmitted blocks.

Various variants of adaptive FEC provide improvements in recovering ability in wireless com-

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munication, as confirmed in [2–7]. However, the use of methods based on the Application Layer ARQ of the OSI model for data streaming makes it possible to more efficiently recover lost fragments of data in a wireless communication environment with a high level of burst loss. Their effectiveness was studied in the works [8–12]. Such methods it is advisable to use in conjunction with Transport Layer UDP and RTP protocols for data streaming in wireless networks, provided that the timeout time is limited for re-transmitted fragments of data. This is necessary to take into account the numbering of the transmitted data fragments and provide real-time data streaming. In addition, the ARQ method can be used at the Data Link Layer, for example, in the HDLC protocol or at the Transport Layer (TCP protocol). However, these protocols do not provide sufficient flexibility in relation to video content, since they are difficult to upgrade due to the fact that they are standardized. The proposed data transmission model takes into account the recovery of lost fragments at the Application Layer of the OSI model based on ARQ methods used at the underlying levels.

The efficiency of data streaming in conditions of intense loss of data fragments during transmission over wireless communication channels can be assessed analytically, as well as by simulation and experimental studies. Known models of a discrete transmission channel for wireless networks [13–19] allow analytical assessment of the data loss probability but do not take into account those cases in which ARQ-based recovery methods are used. Consequently, the development of a mathematical model of data transmission in a wireless communication channel with the recovery of fragment losses based on ARQ is relevant.

The purpose of the study is to confirm the well-known hypothesis about the efficiency of data streaming with the recovery of lost fragments based on Application Layer ARQ in conditions of intense losses in the wireless communication network by mathematical modeling with confirmation of the results by experimental research. To achieve this goal, the problem of developing a mathematical model of data transmission in a wireless communication network with the restoration of frag losses is solved. To achieve this goal, the problem of developing a mathematical model of data transmission in a wireless communication network with the recovery of fragment losses based on the Application LayerARQ solved.

Simulation

At the physical, data-link, network and transport layers, the algorithms of various communication protocols use bits, frames, packets and segments per unit of information, respectively. The peculiarity of communication protocols at the application layer of the OSI model is that their development and implementation do not require hardware and software updating of low level protocols, which, as a rule, are standardized. Fragments of data are used as a unit of information at the Application Layer, which are encapsulated in Transport Layer segments when transmitted. Therefore, at the Application Level, a fragment is also taken as a unit of lost data. Streaming data at the Application Layer of the OSI model in a wireless LAN can be modeled using the Hilbert model (Fig. 1).

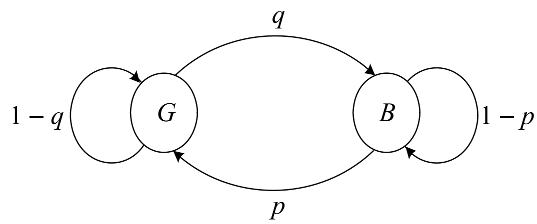

Fig. 1. Gilbert model

Using this model, the probability of fragment loss p_{data} and the average size of the burst lost $\overline{L}_{burst}$ are given. These values uniquely determine the probabilities of transitions p and q between lossless states G or loss B in accordance with the following formulas [20]:

$$p = \frac{1}{\overline{L}_{burst}}; \quad (1)$$

$$q = \frac{p_{data}}{\overline{L}_{burst}\left(1 - p_{data}\right)}. \quad (2)$$

Since the processing of one lost fragment burst along the communication line can occur during the processing of another lost fragment burst, it can be considered independently for calculations (Fig. 2).

The procedure for recovering fragment loss is based on the Selective Repeat scheme, in which a negative acknowledgement with the request the re-transmission of the lost data is sent after the loss of fragments is detected. There is no stop of transmission. Coding is not required to detect fragment integrity at the Application Level, since this occurs at the underlying levels. However, if errors are found, the data fragment is completely discarded. Thus, the starting point is to choose the calculation of characteristics for the case of loss of a certain burst of lost data.

Suppose that at some point in time t_0 the burst data loss with the length of N_0 is discovered. The distribution for this value can be found based on the following. If the data losses on the route of data transmission are described by the Gilbert model, then the probability that the length of the burst will be 1 fragment is p (probability of going back to good state), 2 fragments is $(1–p)p$, 3 fragments is $(1–p)^2p$, etc. (Fig. 3).

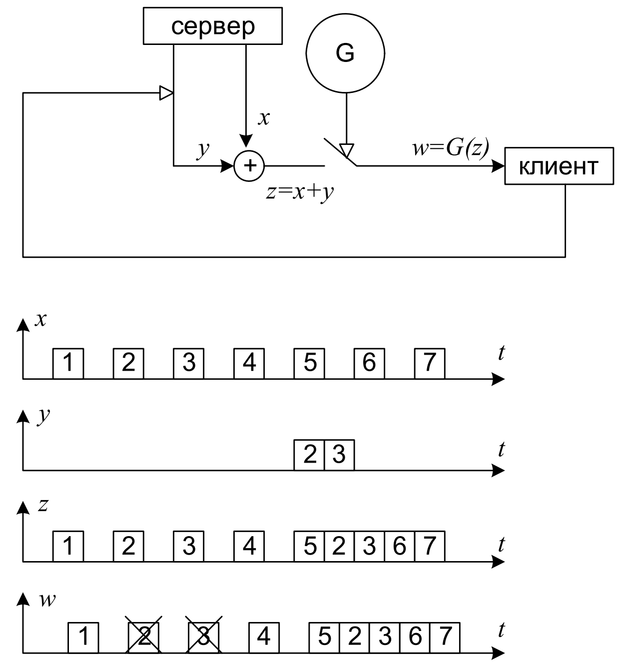

Fig. 2. Application Layer ARQ functioning model

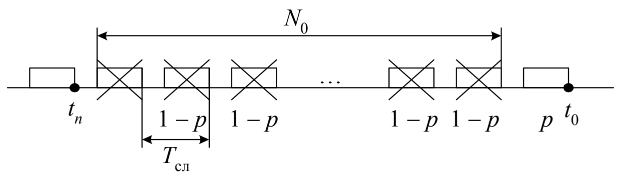

Fig. 3. Loss burst probability

The probability $P(N_0 = i)$ of the appearance of a burst of lost data fragments of length i is determined in accordance with the geometric distribution:

$$P\left(N_0 = i\right) = p\left(1-p\right)^{i-1}. \quad (3)$$

Thus, mathematical expectation

$$\sum_{i=1}^{\infty} p\left(1-p\right)^{i-1} i = \frac{1}{p} = \overline{L}_{burst} . \quad (4)$$

The moment of detection of a burst of lost fragments t_0 was preceded by the loss itself. Let suppose that t_n be the moment of transition to a bad state, and $Dt = t_0 – t_n$ is the time of detection of the fragment loss, which in accordance with Figure 3 can be found as

$$\Delta t = T_{TT} + N_0 T_{sl}, \quad (5)$$

where T_{TT} is the travel time of the data fragment from the sender to the recipient;T_{sl} – the period of the fragment transmission.

Next, at the same moment t_0, there is sending a negative acknowlegement. Let's find the probability of loss reception p_{NACK} based on the fact that if the length of the fragment is equal to L bits, then the probability of losing fragments of data p_{data} is associated with the probability of bit error p_{bit} by the following relation:

$$p_{data} = 1-\left(1-p_{bit}\right)^{L}. \quad (6)$$

Express p_{bit} via p_{data}:

$$1-p_{data} = \left(1-p_{bit}\right)^{L}, \quad (7)$$

$$p_{bit} = 1-\sqrt[L]{\left(1-p_{data}\right)}. \quad (8)$$

Thus

$$p_{NACK} = 1-\sqrt[L_D]{\left(1-p_{data}\right)^{L_N}}, \quad (9)$$

where L_D is the total length of the data fragment; L_N – the total length of the fragment of the negative acknowlegement.

In response to a negative acknowlegement comes $\left(1-p_{NACK}\right)\left(1-p_{data}\right)N_0$ fragments, while

$$\left(1-\left(1-p_{NACK}\right)\left(1-p_{data}\right)\right)N_0 = $$
$$= \left(p_{data} + p_{NACK} - p_{NACK}\,p_{data}\right)N_0$$

the required fragments will be lost again. Therefore, at time $t_{1,}$ another negative acknowledgement will be sent. The maximum time-out for lost fragments is $t_1 – t_0 = T_{RTO}$, etc. (Fig. 4).

This process will continue until all the required fragments are received or the total time-out T_w is exceeded. The maximum number of repeated K_R requests for the transfer of lost data fragments is determined according to the following formula:

$$K_R = \left\lfloor \frac{T_w - T_{TT} - N_0 T_{сл}}{T_{RTO}} \right\rfloor. \quad (10)$$

Thus, bursts of fragments of size N_0 will become groups of fragments of size

$$N_C = \left(p_{data} + p_{NACK} - p_{data}\,p_{NACK}\right)^{K_R} N_0 =$$
$$= N_0\left(p_{data} + p_{NACK} - p_{data}\,p_{NACK}\right)^{\left\lfloor \frac{T_w - T_{TT} - N_0 T_{sl}}{T_{RTO}} \right\rfloor}.$$

Taking into account the fact that N_0 is distributed from 1 to ∞ in accordance with the expression (3), we will find the mathematical expectation of the group of lost data fragments:

$$M\left[N_C\right]=\sum_{i=1}^{k-1}p\left(1-p\right)^{i-1}\left(p_{data}+p_{NACK}-\right.$$
$$\left.-p_{data}p_{NACK}\right)^{\left[\frac{T_w-T_{TT}-N_0T_{sl}}{T_{RTO}}\right]}i+\sum_{i=k}^{\infty}p\left(1-p\right)^{i-1}i,\quad(11)$$

where k is the value of i, starting from which the recovery of lost fragments is impossible. The appearance of the second term is due to the fact that with packs that last more than T_w, recovery is impossible, and the coefficient of loss in this case is equal to one. Then

$$T_w-T_{TT}-kT_{sl}=0,\qquad(12)$$

therefore

$$k=\left[\frac{T_w-T_{TT}}{T_{sl}}\right].\qquad(13)$$

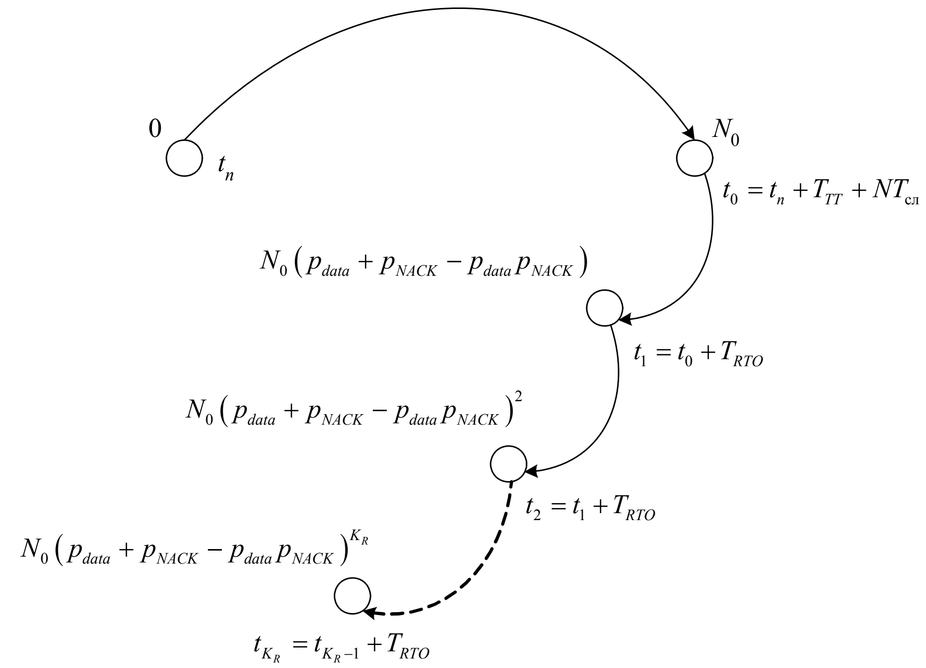

Fig. 4. Lost fragments request processing

The resulting sums of the second term in the expression (11) are sums of infinitely decreasing geometric progression, the first terms of which are equal to $p(1-p)^{k-1}$, $p(1-p)^k$,$p(1-p)^{k+1}$, …, and their steps are the same and equal to $1-p$. Then after the transformations the expression (11) will take the following form:

$$M\left[N_C\right]=\sum_{i=1}^{k-1}p\left(1-p\right)^{i-1}\left(p_{data}+p_{NACK}-\right.$$
$$\left.-p_{data}p_{NACK}\right)^{\left[\frac{T_w-T_{TT}-N_0T_{сл}}{T_{RTO}}\right]}i+\left(k-1+\frac{1}{p}\right)\left(1-p\right)^{k-1}.\quad(14)$$

For a simplified model, there is an expression

$$p_{data}=\frac{M\left[N_0\right]}{M\left[N_G\right]+M\left[N_0\right]}=\frac{\frac{1}{p}}{\frac{1}{q}+\frac{1}{p}}=\frac{q}{p+q},\qquad(15)$$

where N_G is the number of successively successfully incoming fragments. Since packets N_0 are reduced to groups of fragments N_C the loss coefficient of data fragments obtained using ARQ of the application layer, using formulas (14) and (15), can be found as

$$PLR_{ARQ}=\frac{M\left[N_C\right]}{M\left[N_G\right]+M\left[N_0\right]}=$$
$$=\frac{pq}{p+q}\left(p\sum_{i=1}^{k-1}p\left(1-p\right)^{i-1}\times\right.$$
$$\times\left(p_{data}+p_{NACK}-p_{data}p_{NACK}\right)^{\left[\frac{T_w-T_{TT}-N_0T_{сл}}{T_{RTO}}\right]}i+$$
$$\left.+\left(k-1+\frac{1}{p}\right)\left(1-p\right)^{k-1}\right).\qquad(16)$$

The obtained expression (16) allows to analytically assess the efficiency of data transmission using methods for recovering lost data fragments based on Application Layer ARQ in wireless networks characterized by a high level of burst loss.

Experimental study

For the experimental study of data streaming efficiency with the lost fragment recovery based on Application Layer ARQ a fragment of a wireless LAN was used, including a video stream server, a wireless access point and a client mobile computer (laptop). The laptop was connected to the server through a wireless router of the Linksys WRT54GL, as shown in Figure 5.

The VLC software video server broadcasted video to a laptop, in which the packet loss rate (PLR) and their burstness were measured using a software analyzer of streaming quality. This software measures PLR by counting the number of lost data fragments within a predetermined sample (1000 fragments). During the experiment, a test sequence videoframes "highway" was used, transmitted in a wireless LAN using the WiFi 802/11g standard at a frequency of 2.4 GHz.

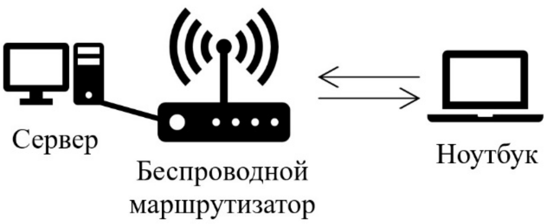

Fig. 5. Wireless LAN topology

To implement the functions of estimating the loss rate of data fragments, a developed software loss analyzer was used, the description of which is presented in [21]. It allows to obtain additional information about the data fragment, for example, its total length, and in real mode, visually to observe the transmitting process with the display of lost and successfully received fragments, as well as calculate the loss coefficient on a certain sample in time and the distribution of the probability of grouping the losses of data fragments. The software analyzer records information about all received and missed fragments of data of the Application Layer of the OSI model.

Results and discussion

Data transmission over a wireless LAN was modeled on the Gilbert model (see Fig. 1) taking into account the lost fragment recovery based on Application Layer ARQ. The transfer process was also implemented during the experimental study. Figure 6 presents the results of calculations of the probability of fragment loss for data streaming with the lost data recovery PLR_{ARQ} (curve "mod") according to the proposed mathematical model, as well as the results of the experiment in the form of dependence of the measured loss coefficient of PLR_{ARQ} fragments after recovery based on Application Level ARQ on the given probability of fragment loss p (curve "exp").

During the experiment, measurements of p and PLR_{ARQ} were made at five points located at different distances of the laptop from the wireless router. As the distance increased, the values of the measured parameters increased. Comparison of the calculation results and the experiment was carried out at points of experimental values.

For the purpose of comparative analysis of efficiency of data transmission with lost fragment recovery on the base of ARQ, let's introduce the concept of a "gain coefficient" on fragment losses (G_{PLR}). It determines how many times the loss coefficient of PLR fragments after loss recovery is less, which is the specified probability of fragment loss p:

$$G_{PLR} = \frac{p}{PLR}. \quad (17)$$

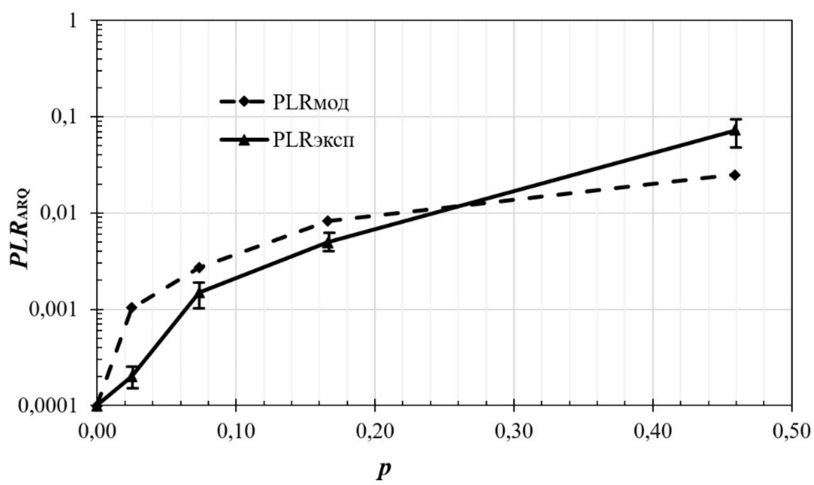

Fig. 6. Experimental and theoretical dependencies of$p$ and PLR_{ARQ}

For example, with the measured value *of PLR* = = 0.001 according to the result of the experiment, the gain coefficient was 60 for G_{PLR}. This means that in this case, if data is lost at p = 0.06, the video could not be played; however, as a result of ARQ-based recovery of lost data, the actual losses were

PLR = 0.001, which, according to ITU recommendations, provides an acceptable quality of video stream playback. A graph of the dependence of the loss rate of data fragments on *p* using the ARQ-based fragment recovery method is shown in Figure 7.

A comparison of the modelling results and the experiment shows that the mathematical model most corresponds to the practically obtained data in the range of *p* values of about 0.1-0.4. The maximum recovery capability of the experiment results showed at a value of $p \approx 0.02$. This is due to the fact that with a relatively small level of losses, accompanied by a low level of their grouping, the ARQ method manages to recover most of the lost data fragments. As *p* increases, the recovery capability decreases due to the fact that as the number of re-transmission requests increases, there is not enough specified recovery period, limited due to the need for real-time transmission. Discrepancies between the modelling and experiment results can be caused by several factors: the discrepancy between the time values of *T* in the model and the real physical values, random factors conducting an experiment, etc.

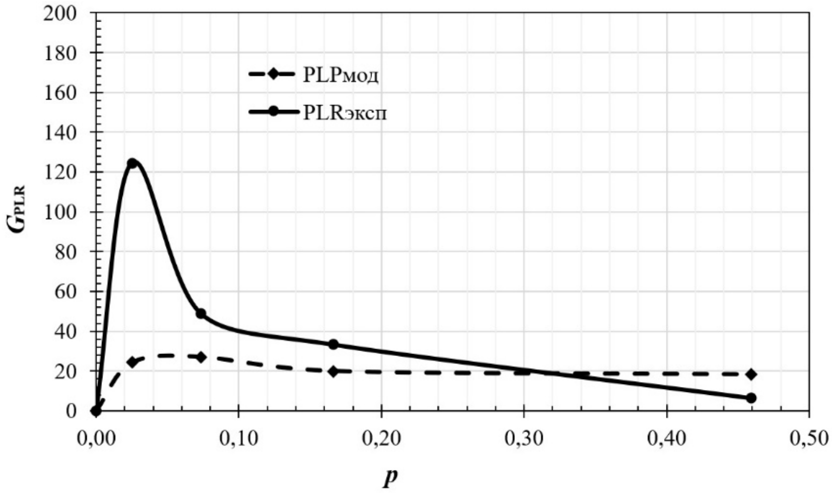

Fig. 7. Experimental and theoretical dependencies of G_{PLR} and *p*

Conclusion

The study substantiates the problem of mathematical modeling of data streaming in a wireless communication network with the fragment loss recovery based on Application Layer ARQ. On the basis of Gilbert's model, a mathematical model of data transmission was developed, taking into account the fragment loss recovery and allowing to assess the recovery ability of the ARQ method in conditions of high intensity of data fragment losses with their grouping in wireless networks communication. On the base of the developed software that provides the data streaming in a wireless communication network with the fragment loss recovery at the application level, experimental studies were conducted to measure the coefficient of data fragment loss. The dependences of the coefficient of data fragment loss after their recovery from data loss to recovery (experimentally) and on the given probability of loss of data fragments (analytically) are obtained. The results showed that the mathematical model most corresponds to the practically obtained data in the range of *p* values of about 0.1–0.4. The mathematical model takes into account the packet nature of the losses of the transmitted data and their recovery by the Application Layer ARQ method.

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Модель передачи данных с восстановлением потерянных фрагментов на основе ARQ прикладного уровня

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Для сетей беспроводной связи в сложных условиях приема характерен высокий уровень группирования потерь, при котором может теряться подряд большое количество фрагментов данных. В этом случае для восстановления потерянных данных применение методов прямой коррекции потерь FEC в большинстве случаев не дает достаточного эффекта.

Применение стандартных методов восстановления потерь данных на основе автоматического запроса повторной передачи ARQ на канальном и транспортном уровнях модели OSI может привести к появлению существенных задержек, что является неприемлемым для сервисов потоковой передачи в реальном режиме времени. В этом случае предпочтительнее пропустить фрагмент данных, чем вносить задержку на ожидание доставки фрагмента при повторных передачах. Применение методов, основанных на ARQ прикладного *уровня модели OSI для потоковой передачи данных, позволяет более эффективно восстанавливать потерянные фрагменты данных в сетях беспроводной связи с высоким уровнем группирования потерь. Известные модели дискретного канала передачи информации для беспроводных сетей позволяют аналитически оценить вероятность потерь данных, однако не учитывают случаи с повторной передачей потерянных данных.*

В исследовании предложена математическая модель передачи данных в канале беспроводной связи на основе модели Гильберта, которая учитывает восстановление потерь методом ARQ и позволяет рассчитывать коэффициент потерь фрагментов данных. Для проверки адекватности предложенной модели разработано программное обеспечение, обеспечивающее передачу потоковых данных в сети беспроводной связи с восстановлением потерь фрагментов на прикладном уровне, и проведено соответствующее экспериментальное исследование. Показано, что математическая модель учитывает группирование потерь передаваемых данных и их восстановление методом ARQ.

Ключевые слова: прикладной уровень, фрагмент данных, ARQ, моделирование, коэффициент потерь данных.

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