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ADAPTIVE CONTROL AT THE LINK LAYER OF THE PACKET RADIO NETWORKS

A mathematical model for calculating the optimal effective transmission rate at the link level of radio networks using a flexible adaptive multiple access protocol with carrier signal control and variable data frame length is proposed. This model is a tool for calculation of both the radio bandwidth network capacity and the optimal deviation of the data packet length at adaptive control of competitive access to a radio channel with a fixed strategy in conditions of significant fluctuation in traffic intensity and changes in interference intensity in the radio channel.

Keywords: *radio networks, interference, contention, mathematical model, adaptive control, packet.*

Introduction

Radio networks with packet switching are an integral part of modern telecommunication systems. Their architecture, principles of construction, and operation, have two main differences due to the use of a radio channel. First of all, they are more vulnerable to interference of various origins at the physical level, which imposes restrictions on the length of data packets. The second difference is due to the fact that, by its very nature, a radio channel is a mono-channel structure that requires certain rules for subscribers, according to which they should coordinate their transmissions. These rules are regulated by radio channel access control protocols [1], the task of which is to ensure the maximum effective transmission speed in conditions of unpredictable variability in the local concentration of subscribers, and therefore the traffic intensity. A feature of the channel layer of packet radio networks is its structure, which includes a logical link control protocol (LLC — Logical Link Control), and a radio channel access control protocol (MAC — Medium Access Control).

Optimizing the effective transmission speed of packet radio networks is carried out by adaptive management methods at different levels of their architecture [1–5]. But at the same time, models are used for each protocol separately, without taking into account the influence or limitations of other protocols. For example, [6] proposed an adaptive MAC protocol with variable packet length. In this protocol, subscribers must distinguish three states of the radio channel:

(*i*) busy (when a carrier signal is detected);

(*ii*) transmission permission state (the carrier signal is absent for a time no longer than the time of propagation of the radio signal in the network);

(*iii*) free state (the carrier signal is absent for more than the maximum time of propagation of the radio signal in the network).

In the transmission permission state (*ii*), the subscriber has the right to transmit a packet of the set size. In the free state (*iii*), the transmission of a longer packet is allowed. If the radio channel is busy (*i*), then the subscriber acts according to a flexible strategy, postponing the transmission to a later time determined by a delay chosen randomly from a certain interval. After the specified time, the subscriber again checks the presence of the carrier signal. Such a transmission organization makes it possible to transmit packets of a standard (fixed) length during heavy traffic, and when the intensity decreases, when there are pauses in traffic, to transmit one packet of a longer length after its completion. It has been provenby our methodology that by changing the length of packets transmitted in the free state of the radio channel depending on the traffic intensity, it is possible to ensure the maximum level of bandwidth of the radio channel. But it is seen that such a change in the length of data packets will lead to a change in the effectiveness of their transmission at the physical level (the probability of successful transmission of a packet at a given interference resistance in the radio channel will change), and in the LLC protocol (the ratio of the size of the data field and service information in the format of packets will change).

Formulation of the problem

The problem of adaptive control of the effective transmission rate for a hard MAC protocol is solved in [7].The purpose of this work is to determine the effective transmission speed of the channel layer of packet radio networks when using the flexible adaptive MAC protocol with variable packet length [6], taking into account the limitations of the physical layer and the LLC protocol.The effective transmission speed in a packet radio network at a given physical V bit/sec transmission speed is defined as a function:

$$C = VC_M(P_M, C_{PLr}), \tag{1}$$

where C_M is the efficiency coefficient of the CSMA (multiple access with media control) protocol, taking into account the complex effect of the probability of successful packet transmission P_M, which is determined by the procedures of the CSMA protocol, and the joint efficiency coefficient of the physical layer and the LLC protocol C_{PLr} .The latter in turn depends on the probability of successful packet transmission at the physical level of the radio network,and from the factor of increasing the length of the packets and the efficiency factor of the adopted frame format.

Mathematical model

When defining P_P and C_L, we use the results of [7]. With a given probability p of a mistake per one bit in the radio channel, the probability of error-free packet transmission is determined by its length (the number of bits) $L = n + c$, where n is the length of the information part of the packet,and c is the length of the service part of the packet (protocol redundancy): $P_p = (1-p)^{(n+c)}$. The coefficient of the effective transmission speed of the LLC protocol is determined by the ratio of the length of the information part of the packet to the total length of the packet: $C_L = \frac{n}{L}$. The joint transmission efficiency coefficient of the physical layer and the LLC layer is then determined by the equation:

$$C_{PL} = P_P C_L = \frac{n\left(1-p\right)^{(n+c)}}{L}.$$

Obviously, with a fixed value of the length of the service part of the packet, the effective transmission speed increases with an increase in its information length. At the same time, when the length of the packet increases, the probability P_P of it ssuccessful transmission decreases.That is, the task of increasing the effective transmission speed must be solved on the basis of a compromise in meeting the conflicting requirements of the physical layer and the LLC protocol.

For each error probability value in the radio channel, there is an optimal length of the information part of the packet n_o, which is easy to obtain from the condition $\frac{dC_{PL}}{dn} = 0$:

$$n_o = \frac{-c\ln(1-p) - \sqrt{(c\ln(1-p)^2 - 4c\ln(1-p)}}{2\ln(1-p)}.$$

Then the optimal length of the package $L_o = n_o + c$.

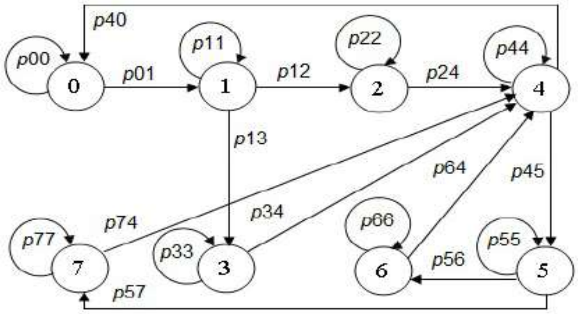

Fig. 1. Diagram of radio channel states

For a given channel level protocol, the length of the service part of the packet is fixed, and the variation r of the L packet length relative to the optimal one, when $n = n_o$, is carried out by changing the value n: $\frac{n+c}{n_o+c} = r$. Hence, the change in "r"(length of the packet) in times can be achieved at $n = rn_o + (r-1)c$. Then for the variable we can write:

$$C_{PLr} = \frac{[rn_o + (r-1)c](1-p)^{r(n_o+c)}}{r(n_o+c)}. \qquad (2)$$

We obtain the equation of the probability of P_M conflict-free transmission for the CSMA protocol with a variable length of data packets rL_o. To simplify the analysis, it is usually assumed that packets arriving for transmission, and packets whose transmission is delayed due to the presence of a carrier signal or the need for retransmission, form a single source of incoming packets with intensity λ [8].The process of changing the states of the radio channel is described by a single-digit Markov chain with continuous time [9].

According to the above procedures of the CSMA protocol, the radio channel can be in one of eight states:

$(k=0)$ — free;

$(k=1)$ — vulnerability when transmitting a packet of length rL_o;

$(k=2)$ — conflict-free transmission of a packet of length rL_o;

$(k=3)$ — conflict when transmitting packets of length rL_o;

$(k=4)$ — transfer permission;

$(k=5)$ — vulnerability when transmitting a packet of length L_o;

$(k=6)$ — conflict-free transmission of a packet of length L_o;

$(k=7)$ — conflict when transmitting packets with a length of L_o.

We consider the probabilities of transitions between theabove states of the radio channel from an arbitrary time t for an infinitesimally small interval Δt:

1. If the radio channel is in the state {0}, that is, the radio channel is free, then:

– with the probability $p01 = \lambda\Delta t$, a new packet will arrive from the input stream during the time Δt interval, which will immediately occupy the radio channel, which will lead to its transition to state {1} at the $t + \Delta t$ moment of time;

– with probability $p00 = 1 - \lambda\Delta t$, the state of the radio channel will not change.

2. If the radio channel is in state {1}, that is, in the vulnerability interval, then:

– with the probability $p12 = \frac{\Delta t}{a}$ that the vulnerability interval will end before at least one more packet arrives, and the radio channel will go into the state of conflict-free transmission of the packet {2}, where a is the propagation time of the radio signal in the network, during which all subscribers will register the presence of the carrier signal;

– with probability $p13 = \lambda\Delta t$, a new packet arrives from the input stream, a collision occurs, and both packets go into the number of pending transmissions. Therefore, at the moment of time the radio channel will be in the state {3};

– with probability $p11 = 1 - \left(\frac{1}{a} + \lambda\right)\Delta t$ the state of the radio channel will not change.

3. If the radio channel is in state {2}, that is, conflict-free packet transmission is carried out, then:

– with the probability $p24 = \frac{\Delta t}{T}$ that the packet transmission will be completed, where $T = \frac{rL_o}{V}$, and the radio channel will transition to the transmission permission state {4};

– with the probability $p22 = 1 - \frac{\Delta t}{T}$ that the state of the radio channel will not change.New incoming packets, if there is a carrier signal, will delay transmission and will not change the state of the radio channel.

4. If the radio channel is in state {3}, i.e. conflicting packets are being transmitted, then:

– with probability $p34 = \frac{\Delta t}{T}$, the parallel (conflicting) transmission of packets will end, and the radio channel will enter the state of transmission permission {4};

– with the probability $p33 = 1 - \frac{\Delta t}{T}$ the state of the radio channel will not change.New packets in the presence of a carrier signal will delay transmission and will not change the state of the radio channel.

5. If the radio channel is in the transmission permission state {4} then:

– with the probability $p40 = \frac{\Delta t}{a}$ the vulnerability interval will end and the radio channel will go into the free state {0};

– with a probability of $p45 = \lambda \Delta t$, during the time interval Δt, a new packet will arrive from the input stream, which will immediately occupy the radio channel, which will lead to its transition at the moment of time $t + \Delta t$ to the state of vulnerability {5};

– with the probability $p44 = 1 - \left(\frac{1}{a} + \lambda\right)\Delta t$ the state of the radio channel will not change.

6. If the radio channel is in a state of vulnerability {5} then:

– with the probability $p56 = \frac{\Delta t}{a}$ the vulnerability interval will end before at least one more packet arrives, and the radio channel will switch to the state of conflict-free packet transmission {6};

– with the probability $p57 = \lambda \Delta t$, a new packet will arrive from the incoming stream, a conflict will occur, and both packets will go to the number of delayed transmissions. So, at the instant of time $t + \Delta t$, the radio channel will be in state {7};

– with the probability $p55 = 1 - \left(\frac{1}{a} + \lambda\right)\Delta t$ the state of the radio channel will not change.

7. If the radio channel is in a state of conflict-free transmission {6}, then:

– with the probability $p64 = \frac{\Delta t}{T_o}$ the packet transmission will end, where $T_o = \frac{L_o}{V}$ and the radio channel will go into the transmission permission state {4};

– with the probability $p66 = 1 - \frac{\Delta t}{T_o}$ the state of the radio channel will not change.New incoming packets, if there is a carrier signal, will delay transmission and will not change the state of the radio channel.

8. If the radio channel is in state {7}, that is, conflicting packets are being transmitted, then:

– with the probability $p74 = \frac{\Delta t}{T_o}$ the conflicting transmission of packets will end, and the radio channel will change to the transmission permission state {4};

– with the probability $p77 = 1 - \frac{\Delta t}{T_o}$ the state of the radio channel will not change. New packets in the presence of a carrier signal will delay transmission and will not change the state of the radio channel. Figure 1 shows a diagram ofthe above analysuis of radio channel states and the probability of transitions between them for a given CSMA protocol.

From this diagram, you can write down a system of finite-difference equations for the probability of radio channel states:

$$P_0(t + \Delta t) = (1 - \lambda \Delta t) P_0(t) + \frac{1}{a} \Delta \mathrm{t}\, P_4(t),$$

$$P_1(t + \Delta t) = \left(1 - \left(\frac{1}{a} + \lambda\right)\Delta t\right) P_1(t) + \lambda \Delta \mathrm{t} \mathrm{P}_0(t),$$

$$P_2(t + \Delta t) = \left(1 - \frac{\Delta t}{T}\right) P_2(t) + \frac{1}{a} \Delta \mathrm{t} P_1(t),$$

$$P_3(t + \Delta t) = \left(1 - \frac{\Delta t}{T}\right) P_3(t) + \lambda \Delta t P_1(t),$$

$$P_4(t + \Delta t) = \left(1 - \left(\frac{1}{a} + \lambda\right)\Delta t\right) P_4(t) + \frac{\Delta t}{T} P_2(t) + \\ + \frac{\Delta t}{T} P_3(t) + \frac{\Delta t}{T_o} P_6(t) + \frac{\Delta t}{T_o} P_7(t),$$

$$P_5(t + \Delta t) = \left(1 - \left(\frac{1}{a} + \lambda\right)\Delta t\right) P_5(t) + \lambda \Delta t P_4(t),$$

$$P_6(t + \Delta t) = \left(1 - \frac{\Delta t}{T_o}\right) P_6(t) + \frac{\Delta t}{a} P_5(t),$$

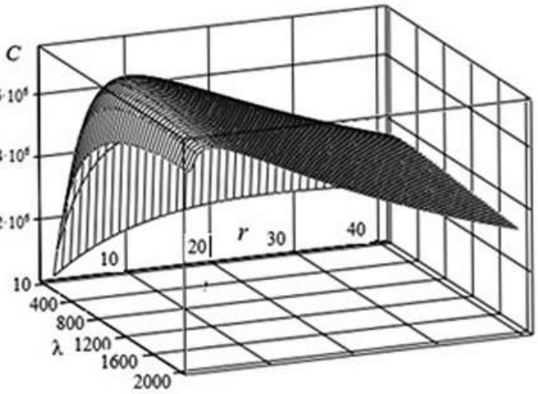

Fig.2. Effective transmission speed

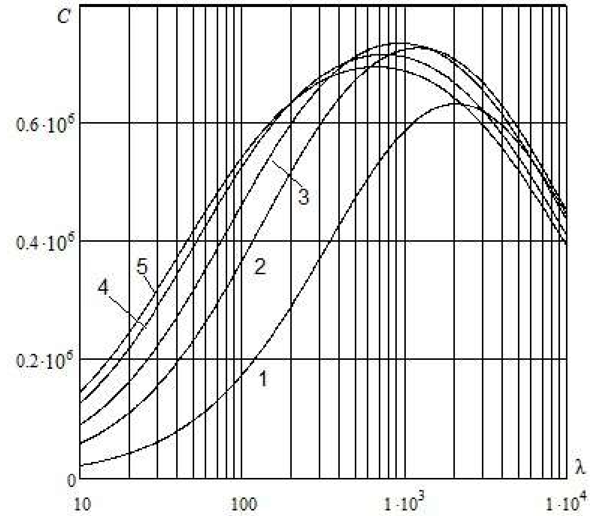

Fig.3. Dependence of effective transmission speed on traffic intensity for a number of r values *r*: 1 — *r*=1; 2 — *r*=3; 3 — *r*=5; 4 — *r*=8; 5 — *r*=10

$$P_7(t+\Delta t)=\left(1-\frac{\Delta t}{T_o}\right)P_7(t)+\lambda\Delta t P_5(t)\cdot$$

Taking $\Delta t \to 0$, we obtain a system of linear differential equations that satisfies the probability distribution of radio channel states:

$$\frac{\partial P_0(t)}{\partial t}=-\lambda P_0(t)+\frac{1}{a}P_4(t),$$

$$\frac{\partial P_1(t)}{\partial t}=-\left(\frac{1}{a}+\lambda\right)P_1(t)+\lambda P_0(t),$$

$$\frac{\partial P_2(t)}{\partial t}=-\frac{1}{T}P_2(t)+\frac{1}{a}P_1(t),$$

$$\frac{\partial P_3(t)}{\partial t}=-\frac{1}{T}P_3(t)+\lambda P_1(t),$$

$$\frac{\partial P_4(t)}{\partial t}=-\left(\frac{1}{a}+\lambda\right)P_4(t)+\frac{1}{T}P_2(t)+$$
$$+\frac{1}{T}P_3(t)+\frac{1}{T_o}P_6(t)+\frac{1}{T_o}P_7(t),$$

$$\frac{\partial P_5(t)}{\partial t}=-\left(\frac{1}{a}+\lambda\right)P_5(t)+\lambda P_4(t),$$

$$\frac{\partial P_6(t)}{\partial t}=-\frac{1}{T_o}P_6(t)+\frac{1}{a}P_5(t),$$

$$\frac{\partial P_7(t)}{\partial t}=-\frac{1}{T_o}P_7(t)+\lambda P_5(t).$$

From the condition of stationarity, it is easy to obtain a system of linear algebraic equations from this system of equations that connects the probabilities of the states of the radio channel:

$$\lambda P_0(t)=\frac{1}{a}P_4(t),$$

$$\left(\frac{1}{a}+\lambda\right)P_1(t)=\lambda P_0(t),$$

$$\frac{1}{T}P_2(t)=\frac{1}{a}P_1(t),$$

$$\frac{1}{T}P_3(t)=\lambda P_1(t),$$

$$\left(\frac{1}{a}+\lambda\right)P_4(t)=\frac{1}{T}P_2(t)+\frac{1}{T}P_3(t)+\frac{1}{T_o}P_6(t)+\frac{1}{T_o}P_7(t),$$

$$\left(\frac{1}{a}+\lambda\right)P_5(t)=\lambda P_4(t),$$

$$\frac{1}{T_o}P_6(t)=\frac{1}{a}P_5(t),$$

$$\frac{1}{T_o}P_7(t)=\lambda P_5(t).$$

This system of equations allows us to find the probabilities of the states of the radio channel $P_1=\frac{a\lambda P_0}{1+a\lambda}$, $P_2=\frac{T\lambda P_0}{1+a\lambda}$, $P_3=\frac{aT\lambda^2 P_0}{1+a\lambda}$, $P_4=a\lambda P_0$, $P_5=\frac{(a\lambda)^2 P_0}{1+a\lambda}$, $P_6=\frac{aT_o\lambda^2 P_0}{1+a\lambda}$, $P_7=\frac{a^2T_o\lambda^3 P_0}{1+a\lambda}$. Here

$P_0 = \dfrac{1 + a\lambda}{(1 + a\lambda)(1 + a\lambda + \lambda T + aT_o\lambda^2) + a\lambda}$, taking into account the normalization of $\sum_{i=0}^{i=7} P_i(t) = 1$.

According to the procedures of the CSMA protocol, conflict-free packet transmission is carried out in states 2 and 6 of the radio channel; in state 2, a packet of r times increased length is transmitted, and in state 6, a packet of optimal length is transmitted.Therefore, the efficiency coefficient of the CSMA protocol, taking into account the complex influence of the physical layer and the *LLC* protocol, will be determined by the equation:

$$C_M = P_2 C_{PLr} + C_{PLo} P_6, \qquad (3)$$

where $C_{PLo} = \dfrac{n_o(1-p)^{(n_o+c)}}{n_o + c}$ is the coefficient of joint efficiency of the physical layer and *LLC* protocol for the optimal length of packets (r=1). Then, taking into account (1)–(3), we obtain our equation of the effective transmission rate:

$$C = \frac{VT_o\lambda(rC_{PL} + a\lambda C_{PLo})}{(1 + a\lambda)(1 + a\lambda + \lambda T + aT_o\lambda^2) + a\lambda}\ .$$

The results

Fig.2 shows the dependence of the effective transmission speed on the traffic intensity and the coefficient of increase in the length of the packets that are transmitted in the free state of the radio channel.

Fig.3 shows sections of the graph plane $C(\lambda, r)$ for a number of values of the coefficient of increase in the length of data packets *r* for clarity. Calculations were made with $p - 10^{-5}$ and size of the network equal to 30 km, which gives the value $a = 10^{-5}$ of the physical transmission speed $V = 10^6$ bit/sec and the length of the service part of the packet c=50 .

It can be seen that up to a certain increase in the length of the data packets, the effective speed of transmission also increases, but when $r > 5$ the effective speed begins to decrease due to the strengthening of the influence of the probability of damage to the data packet by interference in the radio channel.That is, there is an optimal packet size $L = rL_o$ that provides the maximum effective transmission speed.

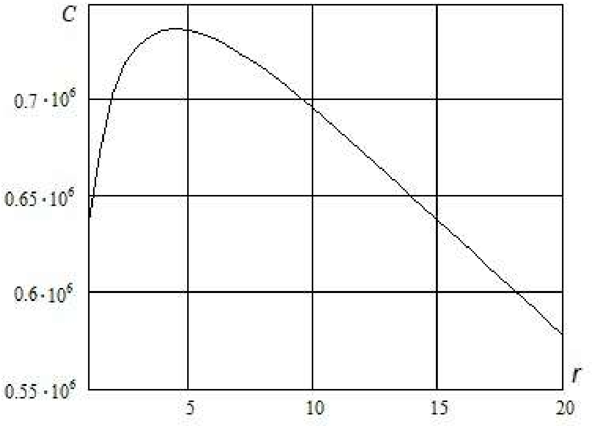

Fig.4. Dependence of the effective transmission speed on the change in the length of data packets

Fig.4 shows the dependence of the effective transmission rate on the change in the length of packets, which illustrates the existence of an optimal value *L*. It can be seen from the graphs that the optimal size *L* for a given set of system parameter values makes it possible to increase the effective transmission speed to 0,736·10^6 bit/s, i.e., by 16% compared to 0,634·10^6 bit/s at L_o.

Conclusions

The proposed mathematical model can be used in adaptive LLC and MAC protocols of packet radio networks to calculate the optimal value of the length of data packets, taking into account the complex influence of the physical and channel levels of the network during competitive access to the radio channel, as well as to calculate the effective data transmission rate for each set of values system parameters.

The control strategy for the considered flexible adaptive MAC protocol with an increase in the length of the packets allows to increase the effective transmission speed by 16%. At the same time, there is (and can beefficiently calculated) according to this model an optimal increase in the number of data packets for each set of system parameters, such as the transmission speed, the probability of damaging one bit of information due to interference in the radio channel, as well as the structure of the LLC protocol packet. Increasing the length of packets beyond this optimal value leads to a decrease in the effective transmission speed.

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АДАПТИВНЕ УПРАВЛІННЯ НА КАНАЛЬНОМУ РІВНІ ПАКЕТНИХ РАДІОМЕРЕЖ

Вступ. Радіоканал є обмеженим природним ресурсом, тому його ефективне використання є актуальним науково-технічним завданням. Один із шляхів його вирішення – використання адаптивного управління пропускною здатністю радіомереж з конкурентним доступом до радіоканалу.

Мета статті. Визначення впливу довжини пакета на ефективну швидкість передачі радіомереж з урахуванням параметрів, форматів і процедур фізичного та канального рівнів при використанні протоколу *MAC* з гнучкою стратегією конкурентного доступу до радіоканалу.

Методи. Поставлена мета досягається створенням та аналізом математичної моделі ефективної швидкості передачі в радіомережах. Модель описується рівнянням для ефективної швидкості передачі, яка є функцією як ймовірності безконфліктної передачі протоколу *MAC*, так і коефіцієнта відхилення розміру пакета даних від оптимального для протоколу *LLC* з урахуванням ймовірністі пошкодження пакетів у радіоканалі.

Результати. Доведено, що стратегія керування для розглянутого гнучкого адаптивного протоколу *MAC* забезпечує збільшення ефективної швидкості передачі на 16%. У цьому випадку існує і може бути розраховано оптимальне збільшення довжини пакетів даних для кожного набору параметрів мережі, таких як фізична швидкість передачі, ймовірність пошкодження одного біта інформації перешкодами в радіоканалі, структура пакета протоколів *LLC*. Збільшення довжини пакетів понад оптимальну призводить до зниження ефективної швидкості передачі.

Висновки. Запропонована математична модель є інструментом для розрахунку як пропускної здатності радіомережі, так і оптимального відхилення довжини пакета даних при адаптивному управлінні конкурентним доступом до радіоканалу з гнучкою стратегією в умовах значних коливань інтенсивності трафіку та змін в інтенсивності перешкод у радіоканалі.

Ключові слова: *радіомережі, перешкоди, конкурентний доступ, математична модель, адаптивне керування, пакет.*