ISSN 0005-1179, Automation and Remote Control, 2013, Vol. 74, No. 9, pp. 1460–1473. © Pleiades Publishing, Ltd., 2013.
Original Russian Text © A.N. Krasilov, A.I. Lyakhov, D.M. Ostrovsky, E.M. Khorov, 2013, published in Avtomatika i Telemekhanika, 2013, No. 9, pp. 34–52.

A Dynamic Channel Reservation Method for Multimedia Streaming in Wi-Fi Mesh Networks

A. N. Krasilov, A. I. Lyakhov, D. M. Ostrovsky, and E. M. Khorov

Institute for Information Transmission Problems (Kharkevich Institute), Russian Academy of Sciences, Moscow, Russia

Received January 25, 2013

Abstract—To improve data transmission robustness in the Wi-Fi Mesh standard, a deterministic channel access method was added to the basic random access method, which enabled the stations to get a contention-free access in the previously reserved time intervals. This mechanism can be conveniently used for transmission of the real-time multimedia streams which require quality-of-service support. However, the packet transmission in the reserved time intervals is affected by random noise and interference, and the time-consuming reservation procedure does not allow one to change on-the-fly the amount of reserved channel resources. A method for dynamic channel reservation which takes into account these aspects of the deterministic channel access mechanism and meets the quality-of-service requirements was proposed.

DOI: 10.1134/S0005117913090038

1. INTRODUCTION

The impetuous growth in the amount of wireless devices and the ever-increasing volumes of the real-time multimedia traffic dispute the ability of the existing centralized wireless networks with a single basic station having a large coverage to manage the user load. That is why today we witness the development of wireless technologies for the networks consisting of many basic stations having each small coverage but capable of transmitting data at high rates [1]. The stations of a network consisting of more than one remote basic station are connected by the wired or wireless communication channels. The wired connections hinder development and servicing of the networks with multiple stations and, thereby, constrain their growth. The networks based exclusively on the wireless technologies are free of this disadvantage. Perhaps the multistep decentralized Wi-Fi Mesh networks described in the IEEE 802.11s standard [2] give here the most striking example. Efficiency of the wireless network depends essentially on the channel access mechanisms used. Being an extension of the Wi-Fi technology, by default the Wi-Fi Mesh makes use of the mechanism of enhanced distributed channel access (EDCA).

The contention access mechanism enables all stations to contend on equal conditions for the access to the channel using for that the carrier sense multiple access with collision avoidance (CSMA/CA). This method was developed for the case where all stations are within the mutual audibility zone. Yet in the multistep network it proved to be incapable to maintain high data transmission reliability between two neighboring stations because of the so-called hidden network effect [3, 4]. Also, the random nature of network access fails to guarantee the desired quality of service (QoS) which is critical for transmission of the real-time multimedia data. The IEEE 802.11s standard [2] solves these problems by adding to the existing contention access mechanism a new mechanism of mesh coordination function controlled channel access (MCCA).

In distinction of the mechanism of contention access allowing the stations to access the channel at a random time instant, the mechanism of deterministic access allows the stations to access the channel at the previously reserved time intervals. According to the standard [2], each reservation established between the transmitter and receiver represents a set of equal-sized time intervals situated at equal distances from each other. Within these intervals, only the transmitter and receiver get access to the medium,[1] and their one-step neighbors, that is, the stations within the immediate radio audibility of the transmitter and receiver, must refrain from transmission.

The stations perform the following procedure to establish a new reservation. The transmitter first determines the time intervals where a new reservation can be established. According to the standard, these intervals should not be occupied by the reservations of the one-step neighbors of both the transmitter and the receiver. Then, the transmitter and receiver agree about the reservation parameters by exchanging the service messages transmitted using the contention access mechanism. As soon as they agree about the parameters of the new reservation, the transmitter and receiver notify about it all their one-step neighbors, and only after that this reservation can be used for data transmission.

The neighbor stations are usually notified about opening of new reservations or closure of the existing ones by the so-called service messages transmitted in the beacon frames. Since the time of beacon transmission is longer than that of an individual data frame, the time from the instant of making decision about establishment of the reservation to its immediate use may be appreciable. Stated differently, the variation in the amount of the reserved channel resources occurs with a certain delay. Nevertheless, the deterministic access mechanism proved to be handy for the flow data transmission.

Let us see how the transmission of constant-intensity flow (voice flow, for example) between two stations can be established using the mechanism of deterministic access. Let the data frame size L at the channel level, the interval T between the arrivals of two successive frames to the transmitting station queue, and the QoS requirements on the maximum permissible portion of the lost frames PLR^{QoS} and the maximal permissible delivery frame D^{QoS} be known for the flow.

If one assumes that the frame transmissions within the reservation intervals are always successful, then it suffices to establish one reservation with the period of reservation repetition interval T and the duration of each interval sufficient for transmission of the data frame of size L. Therefore, precisely one attempt of transmission is made for each data frame. However, as many studies (see, for example, [5, 6]) show, transmission of frames even within the reserved intervals is susceptible to the noise due to the following causes. First, noise can be due to the random noise always existing in the wireless channel. Second, according to the standard [2], the stations lying outside the one-step neighborhood of the stations establishing reservation can transmit during this reservation with the use of the contention access or the deterministic access, that is, interfere with the transmission inside the reservation interval. As was shown in [6], in certain cases the interference can result in an appreciable reduction in the probability of data frame delivery and, as the result, in violation of the QoS requirements. Therefore, to satisfy the QoS requirements at the channel reservation, one must take into account the repeated transmissions whose number depends on the channel noise intensity. Importantly, since the noise can be caused by the interference from stations using the contention access mechanism, the characteristic time of variation of noise intensity may be smaller than the time required for channel reservation using the deterministic access mechanism.

The present paper considers the following scheme of resource reservation for organization of repeated transmissions. To transmit a flow, N identical reservations with the period T are established so that each packet has exactly N attempts of transmission (see Fig. 1). As was already noted, the number of reservations N must be selected dynamically so as to satisfy the requirement on the portion of the constant frames PLR^{QoS} under the current noise intensity. In turn, the requirement on delay is always satisfied, provided that the end of the reservation interval corresponding to the

[1] If the acknowledgement policy is used, the receiver can send the acknowledgement frame in response to the successfully received data frame.

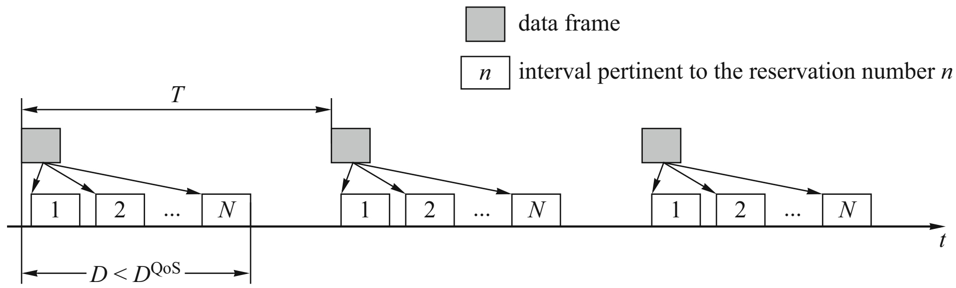

Fig. 1. Scheme of resource reservation for transmission of constant-intensity flow.

last attempt of equation lies not farther than D^{QoS} from the time of arrival of the data frame to the queue of the transmitting station.

Thus, to organize the data flow transmission with guaranteed servicing using the deterministic access mechanism, it is required to (i) estimate the intensity of channel noise and (ii) assign the number of reservations needed to satisfy the QoS requirements depending on the current noise intensity. It is obvious that the number of reservation N must be at that as small as possible, that is, such that the flow transmission uses the minimal amount of the channel resources.

To solve problems (i) and (ii), the present paper proposes a method of dynamic control of the amount of the reserved channel resources which relies on the statistics of frame transmission in the established reservations to estimate the channel noise intensity and varies the set of reservations, that is, closes the existing or establishes additional reservations, so that the QoS requirements be satisfied.

In Section 2 the problem is stated in formal terms, and the requirements on the method developed are formulated. Section 3 gives a brush treatment of the existing methods of dynamic control of the reserved channel resources. Section 4 describes the proposed method of control, and Section 5 presents the results of analyzing its efficiency in various scenarios. Section 6 formulates the conclusions and the lines of future research.

2. FORMAL STATEMENT OF THE PROBLEM

Let us formulate stricter requirements on the developed method.

Requirement 1 (basic) lies in satisfying the QoS requirements at flow transmission. Namely, the time of delivery of the data frames from the transmitter to the receiver must be at most D^{QoS}, and the portion of lost frames must be at most PLR^{QoS}. According to the scheme of resource reservation described in the last section, the delay requirement is satisfied if the end of the reservation interval where the last attempt of transmission is made lies at most at the distance D^{QoS} from the instant of queuing the frame (see Fig. 1). We assume that at any time instant the channel has a sufficient amount of free resources for satisfaction of this condition. The problem, therefore, comes to determining the number of reservations which must be established to satisfy the requirement on the portion of lost frames.

We define in formal terms the satisfaction of the requirement on the portion of lost frames. The entire time of flow transmission is divided into equal-sized intervals (for example, of one-second length). For each time interval I, the portion of lost frames is the ratio of the lost frames L_I to the total number of transmitted frames W_I. We notice that W_I is constant for a constant-intensity flow, $W_I \equiv W$. We establish that for the interval I the requirement on the portion of lost frames is satisfied if $\frac{L_I}{W} \leqslant PLR^{\mathrm{QoS}}$. Obviously, there exists no method satisfying this requirement for all intervals I because the noise intensity varies unpredictably in time. Therefore, we can assert that the method satisfies the requirement on the portion of lost frames with the reliability α if

$$\mathbb{P}\left\{\frac{L_I}{W} \leqslant PLR^{\mathrm{QoS}}\right\} \geqslant \alpha, \tag{1}$$

where $\mathbb{P}\{A\}$ is the probability of event A. At that, α must be close to one (for example, 0.95).

Requirement 2. As was already noted in the last section, if requirement (1) is satisfied, then the method must establish the minimal number of possible reservations. The free channel resources may be used in turn for transmission of other flows. Therefore, the total network capacity increases with reduction in the amount of the channel resources used to transmit each flow.

Requirement 3 lies in that the method must be *stable* in the sense that is should not too often establish or close the reservations if the level of channel noise does not vary. This requirement is due to the following facts. First, a reservation cannot be established or closed suddenly. As was indicated in the last section, this requires time t_{setup} equal approximately to one beacon-interval. Second, too frequent establishment or closure of reservations lead to a dramatic increase in the service traffic and also mistiming of the schedules of different stations. This requirement can be formulated in stricter terms as follows: at satisfaction of Requirements 1 and 2, the frequency of reservation establishment must be as small as possible.

3. REVIEW OF THE EXISTING DYNAMIC CONTROL METHODS

Even a simplest review shows that the considered problem of controlling the amount of reserved channel resources with the aim of providing the desired quality of servicing at transmission of the real-time multimedia flows is far from being new. At that, the majority of the approaches suggested recently, as well as in the present paper, is based on the mechanism of deterministic access. The diversity of reservation schemes used by different technologies can be dichotomized into the centralized-control and distributed-control schemes.

In the centralized-control schemes, the channel resources are distributed by one central unit. For example, in the infrastructure networks based on the standard IEEE 802.11 such device is called the access point, and in those based on the IEEE 802.16 or 3GPP LTE standards, the basic station. To reserve resources for flow transmission in the centralized-control networks, the clients send requests to the central station. The request informs about the flow parameters and the requirements on the quality of servicing. The central station in turn allocates the required amount of the channel resources in compliance with the current channel conditions.

In the case of distributed-control schemes, there is no predefined device in the network. In particular, in the multistep networks it is often impossible to specify a device related directly with the rest of them. Therefore, resources are reserved using a special procedure for coordination of the neighboring devices. For example, in this manner works the procedure described in the last section for establishment of reservation in the Wi-Fi Mesh networks. The WiMedia technology described by the ECMA 368 standard [7] is an another example of the technologies using the distributed-control resource reservation schemes.

A vast majority of works proposing control methods of the channel resources for the centralized-control networks were published for the time being. In particular, there are dozens of publications considering various methods of dynamic control of channel resource reservation for transmission of constant-intensity [8] and variable-intensity [9, 10] flows in the infrastructure networks IEEE 802.11. These methods, unfortunately, cannot be used directly in the multistep networks because they are based on the assumption that the resources can be allocated or released almost immediately. Although this assumption is true for the centralized-control networks where all resources are controlled by a single device, for the multistep networks it is not valid. Such networks can use only the distributed-control schemes assuming a nonzero delay of establishing reservation.

There are also works proposing methods of dynamic control of the amount of reserved channel resources for the networks with distributed control. In particular, [11, 12] presented methods for determination of the amount of resources reserved for transmission of flows of constant and variable intensities on the basis of the WiMedia technology. A disadvantage of these studies lies in the assumption that the transmissions within the reserved time intervals are always successful. However, as was already noted, this assumption needs not be always true because of the interference and random noise in the channel. An analytical model enabling one to determine the minimal amount of the channel resources to be reserved by the deterministic access mechanism to satisfy the QoS requirement at transmitting constant-intensity flow in the Wi-Fi Mesh network was proposed in [13]. It is assumed at that that the probability of losing a data frame is constant within the reservation intervals. Unfortunately, its authors do not describe how to estimate this probability and what to do if the channel conditions vary in time. The present paper considers a more general case where the noise intensity can vary in time. The following section suggests a method to estimate the channel noise intensity and rearrange dynamically reservation so as to satisfy the QoS requirements at flow transmission.

4. DESCRIPTION OF THE PROPOSED METHOD

4.1. Basic Points

As was already noted in Section 1, the amount of resources to be reserved for flow transmission with the aim of satisfying the QoS requirements depends on the channel noise intensity. At that, the noise intensity may vary substantially in time. Therefore, the main idea of the proposed method lies in the periodic activation of the procedure which (i) estimates the noise intensity on the basis of information about the transmissions in the established reservations, that is, constructs a function estimating the probabilities of successful frame transmission with the use of some reservation set, and then (ii) varies the set of reservations, that is, establishes additional reservations or closes the existing ones so as to satisfy the requirements described in Section 2 with the use of a minimal amount of the channel resources. This procedure consists of three steps described briefly below.

It is assumed at the *first step* that the channel characteristics do not vary during the time interval between two successive activations of the procedure. The function $P_X(R)$ estimating the probability of successful frame transmission with the use of the reservation set R is constructed on the basis of this assumption and with regard for the information $X = X(R^{cur})$ about successful and unsuccessful transmissions of the h last frames in each reservation from the current set R^{cur}. This function is determined for each set R which can be obtained from the current set R^{cur} only by adding new or only by removing some of the existing reservations. To predict quality of the new reservations, the model described in Section 4.2 is used.

At the *second step* of the procedure, the minimal set R^* of reservations, that is, the set consisting of the minimally possible number of elements for which the requirement on the portion of the delivered frames is satisfied, is determined using the constructed function $P_X(R)$. To verify whether this requirement is satisfied for the reservation set R, it is necessary to determine the probability that at most $\lfloor W \times PLR^{\mathrm{QoS}} \rfloor$ frames are lost at the transmission of W successive data frames. If we assume that the transmissions of different frames are statistically independent, then the probability that at transmission of W frames k ones are not delivered to the addressee is given by

$$F_{W,P_X(R)}(k) = \sum_{i=0}^{k} \frac{W!}{(W-i)!i!}(1 - P_X(R))^i P_X(R)^{W-i},$$

where $F_{W,P_X(R)}(k)$ is the *failure* distribution function in W Bernoulli tests with the success probability $P_X(R)$. We get that the requirement on the portion of lost frames is satisfied with the reliability α if

$$F_{W,P_X(R)}\left(\lfloor W \times PLR^{\text{QoS}} \rfloor\right) \geqslant \alpha. \tag{2}$$

Therefore, the reservation set R^* consisting of the minimal number of elements satisfying condition (2) is determined at the second step.

To enhance the method's stability, at the *third step* a new reservation set R^{new} is generated with regard for the recommended reservation sets R^* obtained both at the current and previous activations of the procedure, as well as for the current reservation set R^{cur}. The set R^{new} is used until the next activation of the procedure.

The aforementioned procedure is activated periodically, the time between two successive activations being dependent on the period T of frame arrival and the result of the previous activation of the procedure. If no new reservations were established by executing the procedure, that is, $R^{new} \subseteq R^{cur}$, then at the next time it is activated after transmitting τ frames. We note that τ and h are the method parameters, $\tau \leqslant h$. If new reservations must be established, then it is required, first, to have time t_{setup} for establishing new reservations and, second, to have time Th for acquiring information about successes/failures at transmission through the new reservations. Therefore, at adding new reservations, the procedure is activated after transmitting $\tau' = \lceil \frac{t_{setup}}{T} \rceil + h$ frames. We describe each step in more detail.

4.2. First Step of the Procedure

At this step of the procedure constructed is the function $P_X(R)$ enabling one to estimate the probability of successful transmission of the frame with the use of the reservation set R. To construct $P_X(R)$, we make use of the information about successful and faulty attempts to transmit the last h frames in the current reservation set R^{cur}. we consider for that the $r^{cur} \times h$ matrix X, where r^{cur} is the size of the set R^{cur}. In X, the element $X_{i,j}$ is 1 if transmission of the frame numbered j in the ith reservation was successful and 0, otherwise. We notice that the sample represented by this matrix enables one to estimate the value of $P_X(R)$ for any set $R \subseteq R^{cur}$. It is required to predict for $R \supset R^{cur}$ the quality of the new reservations. We consider both cases in more detail.

4.2.1. Case of $R \subseteq R^{cur}$. In the sample X we mark only the rows referring to the set R and consider $\delta_R(j) = 1 - \prod_{i \in R}(1 - X_{i,j})$ indicating that the packet was transmitted successfully at least in one reservation from R. Then, obviously, the probability $P_X(R)$ can be given by

$$P_X(R) = \frac{1}{h}\sum_{j=1}^{h} \delta_R(j), \qquad R \subseteq R^{cur}. \tag{3}$$

4.2.2. Case of $R \supset R^{cur}$. Let $P_X(R^{cur}) = 1$ according to (3). Then, obviously, $\forall R \supset R^{cur} \Rightarrow P_X(R) = 1$.

If $P_X(R^{cur}) < 1$, then at least one frame was not transmitted successfully in any reservation. In this case, the quality of new reservations must be estimated for estimation of $P_X(R)$. For that, the following model is used.

Let the set R consist of r reservations. We numerate them in the order of intervals, that is, so that the first transmission attempt was made for each transmitted frame in the first reservation, the second attempt, in the second reservation, and so on (see Fig. 1). Let us consider the random variable U_i equal to 1 if the attempt of transmitting the frame in the ith reservation is successful and 0, otherwise. Then, in terms of the above notation we obtain that the probability of faulty frame transmission in no reservation from R is $\mathbb{P}\{U_1 = 0, U_2 = 0, \ldots, U_r = 0\}$.

If the transmission errors in different reservations were independent, the desired $P_X(R)$ could be established from

$$P_X(R) = 1 - \mathbb{P}\{U_1 = 0, U_2 = 0, \ldots, U_r = 0\} = 1 - \prod_{i=1}^{r} q_i, \quad q_i \stackrel{def}{=} \mathbb{P}\{U_i = 0\}, \tag{4}$$

by taking q_i as the estimates:

$$\hat{q}_i = \begin{cases} 1 - \dfrac{1}{h}\displaystyle\sum_{j=1}^{h} X_{i,j}, & i \in R^{cur} \\ \dfrac{1}{r^{cur}}\displaystyle\sum_{j \in R^{cur}} \hat{q}_j, & i \notin R^{cur}, \end{cases} \tag{5}$$

that is, by assuming that for the new reservations the probability of faulty transmission is equal to the mean probability of faulty transmission for the existing reservations.

However, as will be shown in Section 5, in the wireless channel the errors can be correlated. To allow for correlation, we use the assumption that the probability of error at transmission in the reservation i depends only on occurrence of the error at transmission through the reservation $(i-1)$. In mathematical terms, this means that $\mathbb{P}\{U_i = 0 \mid U_{i-1} = 0, \ldots, U_1 = 0\} = \mathbb{P}\{U_i = 0 \mid U_{i-1} = 0\}$. By denoting $\pi_{i,i-1} = \mathbb{P}\{U_i = 0 \mid U_{i-1} = 0\}$, we get that the probability of successful frame transmission with the reservation set R is given by

$$P_X(R) = 1 - \mathbb{P}\{U_1 = 0, U_2 = 0, \ldots, U_r = 0\} = 1 - q_1 \prod_{i=2}^{r} \pi_{i,i-1}, \quad R \supset R^{cur}. \tag{6}$$

Therefore, the probabilities $\pi_{i,i-1}$ are required to determine $P_X(R)$.

If $i,\ i-1 \in R^{cur}$, then the following estimate obtained from the definition of the conditional probability can be used as $\pi_{i,i-1}$:

$$\hat{\pi}_{i,i-1} = \frac{\sum\limits_{j=1}^{h}(1 - X_{i,j})(1 - X_{i-1,j})}{\sum\limits_{j=1}^{h}(1 - X_{i-1,j})}. \tag{7}$$

The zero denominator is guaranteed by the fact that $P_X(R^{cur}) < 1$ and, consequently,

$$\exists j : \forall i = 1, 2, \ldots, r^{cur} \Rightarrow X_{i,j} = 0.$$

Otherwise, that is, if at least one of the reservations (i or $i-1$) does not belong to R^{cur}, then to estimate the probability $\pi_{i,i-1}$ we use the following fact confirmed in the course of the preliminary experiments: the value of $\pi_{i,i-1}$ depends on the distance $\rho_{i,i-1}$ between the reservations i and $i-1$, that is, on the time interval between the beginnings of the two corresponding reservation intervals. Indeed, for $\rho_{i,i-1} \to 0$ the reservations actually coincide. Therefore, $\pi_{i,i-1} \to 1$. On the other hand, for $\rho_{i,i-1} \to \infty$ the frame transmissions in the reservations are independent and, therefore, $\pi_{i,i-1} \to q_i$.

In particular, the function

$$\pi_{i,i-1} = f_\lambda(\rho_{i,i-1}, q_i) = q_i + (1 - q_i)e^{-\lambda\rho_{i,i-1}}, \lambda \geqslant 0 \tag{8}$$

satisfies these limit properties. We assume that the value of λ depending generally on the current channel conditions is the same for all pairs $(i, i-1)$ of reservations and estimate it using the method of least squares. Having considered only the pairs of reservations $(i, i-1)$ such that $i, i-1 \in R^{cur}$ and determining for them the estimate (7), one can then determine $\hat{\lambda}$ minimizing the sum of the squares of deviations (8) from $\hat{\pi}_{i,i-1}$, that is,

$$\hat{\lambda} = \arg\min_{\lambda} \sum_{i=2}^{r} (\hat{\pi}_{i,i-1} - f_{\lambda}(\rho_{i,i-1}, \hat{q}_i))^2. \tag{9}$$

We notice that, strictly speaking, the function (9) must be minimized over the domain $\lambda \in [0, +\infty)$. However, without loss of precision we can confine from above by $\lambda_{\max} = C/\rho_{\min}$ the set of permissible values of the parameter λ. Here, $\rho_{\min}$ is the minimal possible distance between the reservations (for example, the duration of the reservation interval) and C is a sufficiently great ($C \approx 20$) number for which the exponent is negligible. Therefore, the problem of optimization (9) can be solved over the limited set $\lambda \in [0, \lambda_{\max}]$. The minimum of function (9) is sought on the set $\lambda \in [0, \lambda_{\max}]$ in the roots of its first derivative and boundary points.

Thus, in the case where $R \supset R^{cur}$, the following actions are performed to estimate $P_X(R)$. First, the probabilities q_i and $\pi_{i,i-1}$ are estimated for all reservations from R^{cur} using formulas (5) and (7), and then the parameter λ is estimated using (9). For those pairs of reservations $(i, i-1)$ for which i or $i-1$ do not belong to the set R^{cur}, the probability $\pi_{i,i-1}$ is estimated from (8) with allowance for the determined estimates $\hat{\lambda}$ and $\hat{q}_i$. The desired probability $P_X(R)$ is determined from (6).

4.3. Second Step of the Procedure

At the second step of the procedure, determined is the minimal set R^* of reservations satisfying the requirement on the portion of the lost frames (2). For that, first satisfaction of the requirement (2) on the set R^{cur} is verified. For that, the estimate of the probability $P_X(R)$, obtained according to (3) is used. Two cases are possible as the result.

For the current set R^{cur}, requirement (2) is satisfied. In this case, we initialize $R^* = R^{cur}$ and try to remove from the set R^* the reservations one after another until requirement (2) is violated. At that, each time the reservation $\arg\max_i \{P_X(R^* \setminus \{i\})\}$ is taken as the candidate for removal from R^*

For the current set R^{cur}, requirement (2) is not satisfied. In this case one needs to establish additional reservations. They are added one at a time beginning from the set $R^* = R^{cur}$.

The set Υ of the time instants that can be used to establish a new reservation ($\Upsilon \subset [0, \min\{T, D^{\mathrm{QoS}}\})$) is determined proceeding from the current schedule. Namely, each time instant $t \in \Upsilon$ defines uniquely a point on the time axis where the beginning of a new reservation interval can be established $i(t)$.[2] Therefore, for each time instant t it is possible to determine the value of $P_X(R^* \cup \{i(t)\})$. Next, the time instant $t_{\min}$ minimizing $P_X(R^* \cup \{i(t)\})$ is determined from all possible $t \in \Upsilon$ and used to establish a new reservation.

The above algorithm is repeated until satisfying requirement (2) or encountering the inability to establish a new reservation because of the shortage of resources. However, if used is the routing metric of [14] which allows one to construct the route along the least loaded network connections, then the latter situation is unlikely.

4.4. Third Step of the Procedure

Since the success of frame transmission in the reservations is of random nature, the set R^* obtained using the above steps may differ at the subsequent activations of the procedure even if the

[2] In the simplest case, it is possible to assume that Υ consists of a discrete set of the points $\Upsilon = \{t_i\}$.

channel characteristics do not vary. As was noted in Section 2, this fluctuation reduces efficiency of the deterministic access mechanism. Therefore, the third step is directed to improving the method's stability.

For that purpose, at selecting the set R_s^{new} at the sth activation of the control procedure we guide ourselves by the sets $R_s^*, R_{s-1}^*, \ldots, R_{s-l+1}^*$ obtained, respectively, at the $s, s-1, \ldots, s-l+1$ activations of the procedure. Here l limits the accounted history. For example, if $l = 1$, then decision about R_s^{new} is made only on the basis of the current decision R_s^*, and the third step includes no actions.

The reservations are added and removed according to the following rules.

If $|R_s^*| < |R_s^{cur}|$, then at most $\min\limits_{k=0,1,\ldots l-1} |R_{s-k}^*| - |R^{cur}|$ reservations can be removed. The order of reservation removal was described in Section 4.3. Stated differently, the reservations are removed only if they were excessive during l activations of the given procedure.

If $|R_s^*| > |R_s^{cur}|$, then $R_s^{new} \leftarrow R_s^*$, which means that if new reservation must be added, they are added independently of the prehistory.

5. NUMERICAL RESULTS

5.1. Setting up Experiment

Efficiency of the proposed method was analyzed using a two-component simulation system. The first component is represented by the simulation medium ns-3 [15] enabling one to model in detail the Wi-Fi Mesh network and, in particular, data transmission with the use of the deterministic access mechanism. Experiments where a constant-intensity flow was transmitted between two specified stations of the Wi-Fi Mesh network by the deterministic access mechanism were carried out using ns-3. In each experiment, consideration was given to the transmission of a voice flow (frame generation interval $T = 20$ ms) for which a fixed number $N = 8$ of reservations was established during the entire experiment. The reservations were situated so that the beginning of the reservation interval corresponding to the first reservation coincided with the arrival of a data frame to the queue and the distances between any two neighbor reservations were 320 μs. Depending on the scenario (each scenario is described minutely in what follows), transmission of the data frames within the reservation intervals was susceptible to noise or interference from the other stations. Each experiment in the ns-3 medium provided two matrices. The first matrix $\tilde{P} = \{\rho_{i,j}\}$ is that of the distances between all pairs (i, j) of reservations. The second matrix is the binary $N \times T_{exp}$ matrix $\tilde{X}$ carrying the information about the successful and faulty transmissions in all N reservations during the time of experiment $T_{exp} = 10^6$. Here and below, all time intervals are measured in T-long intervals if not otherwise stated.

The second component is the method of dynamic control realized in the programming language R [16]. Its operation was modeled as follows. The matrices $\tilde{X}$ and $\tilde{P}$ obtained using ns-3 were used as the source data. One reservation, that is, $|R^{cur}| = 1$, was established before the first activation of the control procedure. Its number was selected randomly from the set $\{1, \ldots, N\}$. Then, the control procedure was activated successively and the actions described in Section 4 were executed. The corresponding row of the matrix $\tilde{X}$ was used as the information about transmission at reservation $i \in R^{cur}$, and the necessary distances were obtained from the matrix $\tilde{P}$.

The need for the two-component simulation system was due to the fact that for a great number of the transmitting stations and high traffic load of the network the experiment time in ns-3 turns out to be appreciable, which hinders execution of many experiments required for comprehensive study of the proposed method. Therefore, the model of the method under consideration was realized as an individual software component whose source data are determined in ns-3.

The following indices were measured in each experiment to estimate the proposed method.

(1) portion of time QVR where requirement (2) on the portion of delivered frames was violated;

(2) mean time MCR of the established reservations, that is, the mean size of the set R^{cur};

(3) mean number FA of the reservations added during the time interval t_{setup}.

We notice that these indices enable one to judge whether the requirements of Section 2 are satisfied.

The following parameters were used in the experiments described below: $PLR^{\mathrm{QoS}} = 0.05$, $\alpha = 0.95$, $W = 50$. It was also assumed that the time to establish a reservation was $t_{setup} = 50$.

5.2. Adjustment of the Method Parameters

The first run of the experiments considered the impact of various values of the parameters τ, h, and l on the method's efficiency. For that, consideration was given to a synthetic scenario where transmissions of frames within the reserved intervals were subject to random noise. The noise was modeled by dividing the entire time of the experiment T_{exp} into the intervals T_{change} of the same duration. At the beginning of each interval, the value of the noise parameter was selected randomly from the four possible values and remained unchanged until the end of the interval. These four values were selected so that for each particular value of the noise parameter it was necessary to establish 1, 2, 3, or 4 reservations, respectively, in order to satisfy the requirement on the portion of the lost frames. Therefore, in the scenario at hand T_{change} characterizes the mean time of variations of the channel conditions.

Experiments were carried out in a wide range of possible values of τ, h, l, and T_{change}. Their results demonstrated that for any fixed values of h, l, and T_{change} smaller values of the parameter τ leads to a reduction in QVR and MCR at an insignificant growth in FA. This result shows that the minimal possible value of τ must be used. On the other hand, τ cannot be smaller than t_{setup} because a time equal to t_{setup} is required to establish or close a reservation. That is why we use below $\tau = t_{setup} = 50$.

The parameter h defines the sample amount used to estimate the current channel conditions. Let us see how the value of h affects the accuracy of the determined estimates. We consider for simplicity the case where $l = 1$, that is, at the third step of the procedure given in Section 4 we assumed that $R^{new} = R^{*}$. Figure 2 depicts the graphs of QVR and FA vs. the parameter h under different values of T_{change}. We notice that for any values of h and T_{change} the values of MCR are close to 2.5. The results obtained indicate that one needs not to take too great or too small

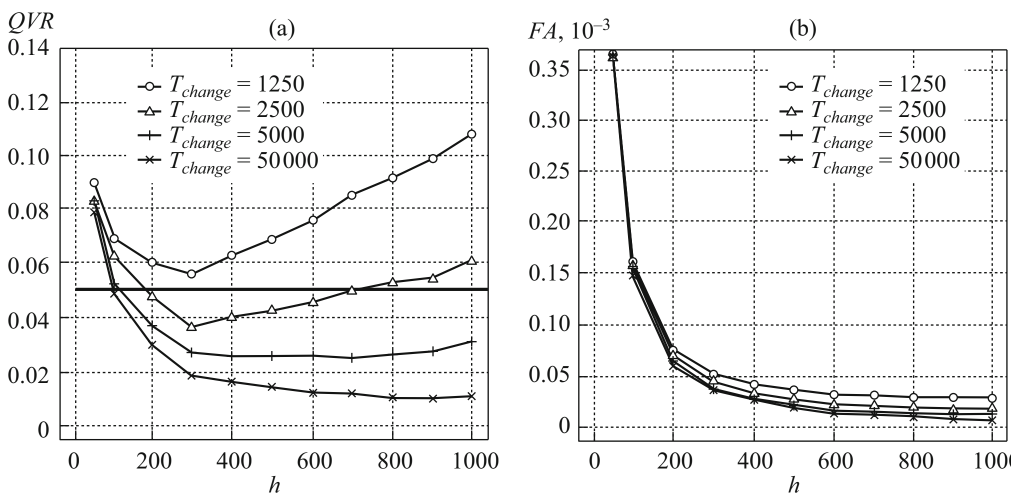

Fig. 2. Experimental results for various values of h and T_{change} for τ=50 and $l = 1$.

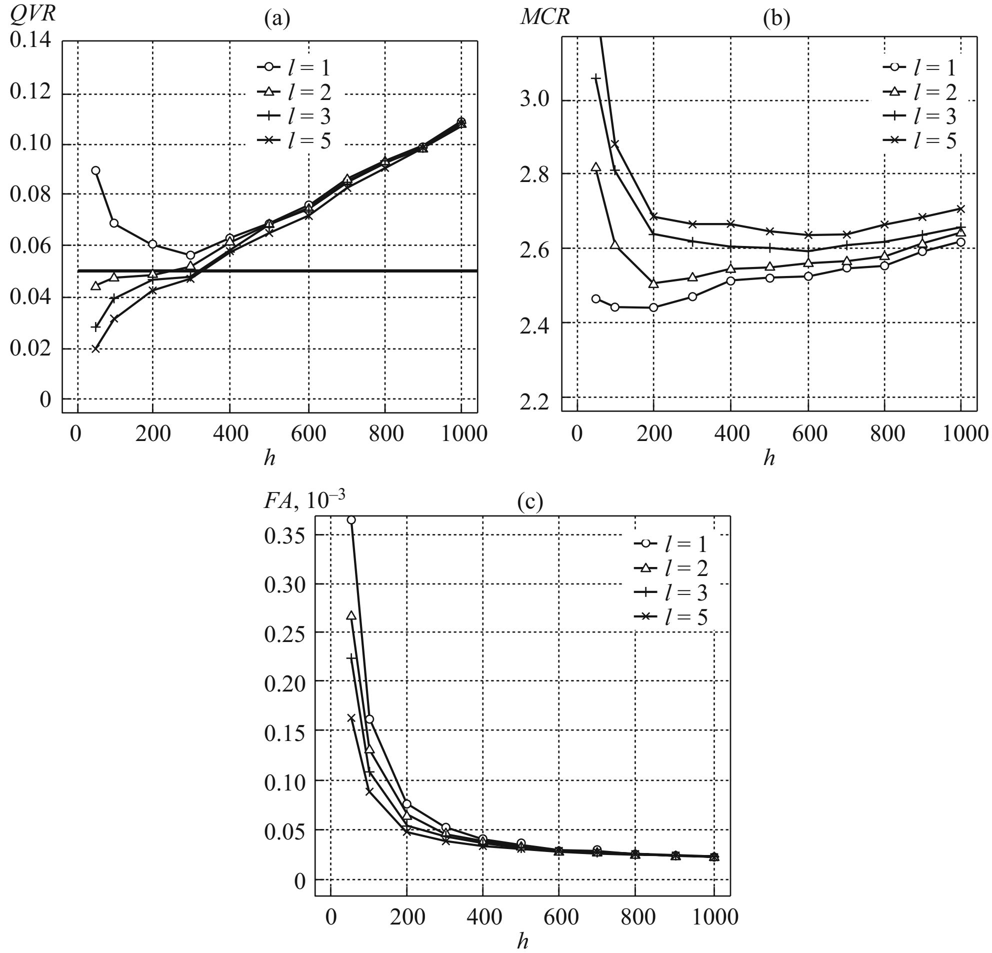

Fig. 3. Experimental results for various values of h and l for $\tau = 50$ and $T_{change} = 1250$.

values of the parameter h. Indeed, the too small values of h ($h < 100$) give rise to the errors in estimation of the probability $P_X(R)$ and, as the result, to failure to satisfy the requirement on the portion of the delivered frames and to high fluctuation, that is, frequent variation in the number of reservations used which is characterized by high FA. On the other hand, too high values of h ($h > 400$) reduce fluctuation, but prevent timely response to the varied channel conditions. In particular, this fact is observed for small values of T_{change}. Although the optimal value of h, that is, the value minimizing QVR, depends on the scenario, the results shown in Fig. 2 show that the values of h from $[200, 400]$ give a close-to-optimal solution within a wide range of scenarios.

Now we consider the impact of l on the method's efficiency. Figure 3 depicts the graphs of QVR, MCR, and FA for $T_{change} = 1250$ under various values of h and l. We notice that for $l = 1$ the requirement on the portion of lost frame is not satisfied under any h. This is due to the fact that for small values of T_{change} one has to use small values of h to respond timely to the changes in the channel conditions. At that, small values of h give rise to high fluctuation and violation of the QoS requirement. Fluctuation can be reduced and as the result the requirement on the portion of the lost frames can be satisfied by using the third procedure step and increasing l. However, the increased l leads to higher consumption of the channel resources. As can be seen from Fig. 3, for smaller values of h the increased l leads to a dramatic growth in MCR. This is due to the fact that at the third step of the procedure a new reservation is always added, if necessary, regardless of the value of l, and elimination of a reservation requires l repetitions of this recommendation.

For smaller h ($h < 100$), it is highly probable that a reservation is added erroneously despite the fact that the channel conditions do not change. In this case, the given reservation is eliminated only after l activations of the control procedure. Therefore, more reservation activations than is required by the channel conditions are used during l activations of the procedure because of the error occurring in estimation of the channel parameters. The results shown in Fig. 3 demonstrate that the values of $h \in [200, 300]$ and $l \in [3, 5]$ enable one to satisfy the requirement on the portion of the delivered frames at the expense of a slight increase in the channel load.

5.3. Scenario with Correlated Noise

In the above synthetic scenario, at transmission of frames the errors occurred independently in different reservations; therefore, the mean value of the parameter estimate λ was close to $\lambda_{\max}$. Let us consider a more general scenario characteristic of the Wi-Fi Mesh networks where the undesired signal is caused not only by the random noise, but also by the interference of the transmissions of other stations. In the given scenario, consideration is given to a multistep network with a mesh 6×5 topology. Two stations located at the network center transmit the voice flow using a fixed number $N = 8$ of reservations. At the same time, other stations transmit the background data (TCP protocol) using the mechanism of contention access. The amount of the generated background traffic is selected so as to make all stations operate in the saturated mode, that is,

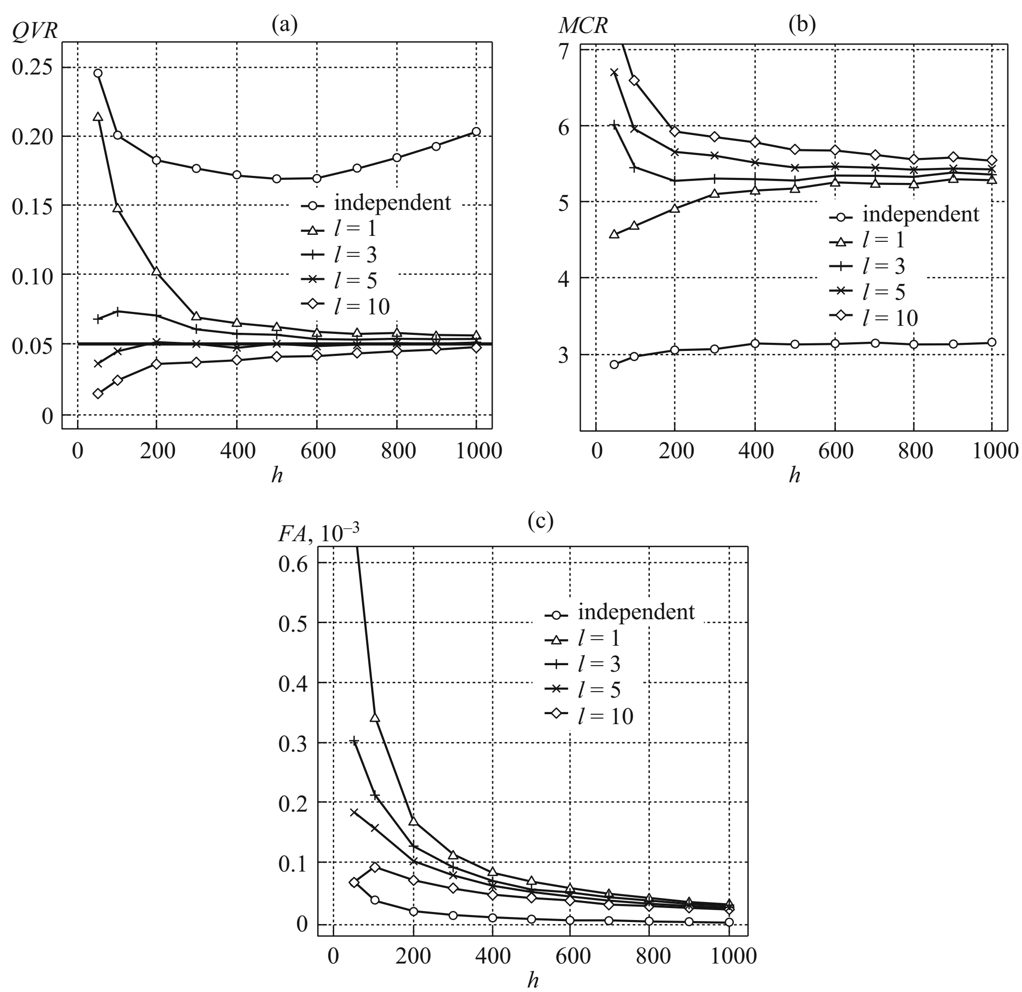

Fig. 4. Experimental results for different values of h and l, $\tau = 50$.

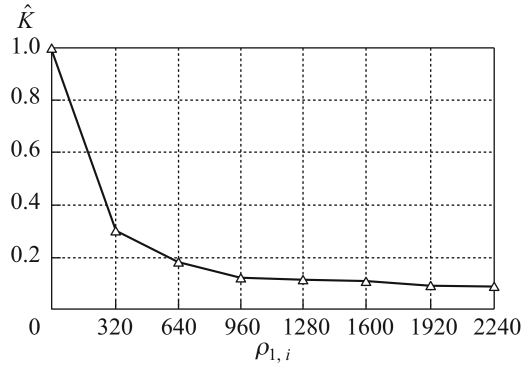

Fig. 5. The sampled correlation coefficient $\hat{K}$ vs. the distance between the reservations $\rho_{1,i}$.

always have queued a data frame for transmission. The size of the TCP-segment is 512 bytes. At the physical level, the IEEE 802.11a protocol is used [8], and all stations transmit at the basic rate of 6 Mb/s. The results of modeling the aforementioned scenario were obtained in the ns-3 medium and are used as the input data for estimation of the efficiency of the proposed method.

Figure 4 depicts the graphs of QVR, MCR, and FA for different values of h and l. It is seen that for the parameters $h \in [200, 300]$ and $l = 5$ recommended in the last section the proposed method satisfies the requirement on the portion of the lost frames, the amount of the reserved channel resources only slightly differing from the case of $l = 1$. We note that in contrast to the scenario where the undesired signal was cased by the random noise, in the present scenario the errors at transmissions in the neighbor reservations proved to be correlated. Figure 5 depicts the graph of the sampled correlation coefficient $\hat{K}$ (see [17, Ch. 9, § 1]) between reservations 1 and i ($i \in \{1 \ldots N\}$) depending on the distance $\rho_{1,i}$ between them. In the case at hand, $\rho_{1,i}$ is measured in microseconds, and, as was already noted, the distance between two neighbor reservations is 320 μs. We note that the correlation coefficient decreases exponentially with increased distance between reservations. This observation underlies generation of formula (8) in Section 4.2.

Figure 4 presents also for comparison the results (curve "independent") obtained under the assumption of independent errors in the neighbor reservations when $P_X(R)$ is calculated from (4). We see that this assumption provides an overestimated probability $P_X(R)$ and, correspondingly, reduces the number of reservations used. As the result, the requirement on the portion of the delivered frames is not satisfied. On the contrary, the approach to estimating the conditional probability $\pi_{i,i-1}$ as proposed in this paper enables one to take into account the correlation in the neighbor reservations which is characteristic of the WiFi Mesh networks and to satisfy the QoS requirement.

6. CONCLUSIONS

The paper proposed a method of dynamic control of the amount of reserved channel resources for the Wi-Fi Mesh stations. The method enables one to satisfy the QoS requirements at transmitting the real-time multimedia flows with the use of the minimal number of channel resources. The numerical results demonstrate that the proposed method reaches the aim in the environment of variable intensity of noise and correlated failures characteristic of the Wi-Fi Mesh networks. Despite the fact that this method is proposed for the Wi-Fi Mesh networks, the basic principles underlying it are applicable to other technologies using the mechanism of deterministic access with distributed resource control such as the WiMedia.

The proposed method was developed for the case of transmitting the constant-intensity flows. However, it can be extended to the transmission of variable-intensity flows such as the real-time video flows. For that, in addition to estimation of the current noise intensity in the channel, one has to estimate the incoming traffic and modify appropriately the amount of the reserved channel resources. Solution of this problem represents the line of out further studies.

ACKNOWLEDGMENTS

This work was supported by the Ministry of Education and Science of the Russian Federation (agreement no. 8731 of October 1, 2012).

REFERENCES

1. Dohler, M., 10 Times Beyond LTE-A—Business Case, Technologies, Challenges for Emerging 5G Networks, in *Keynote at Wireless Days*, 2012, Dublin, Ireland.
2. *IEEE 802.11s STANDARD for Information Technology—Telecommunications and Information Exchange Between Systems—Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. Amendment: Mesh Networking*, 2011.
3. Lyakhov, A., Pustogarov, I., and Gudilov, A., IEEE 802.11 Direct links: Interference Classification and Modeling, in *Proc. Int. Workshop Multiple Access Commun. (MACOM-2008)*, St. Petersburg, Russia, 2008, pp. 15–24.
4. Krasilov, A., Physical Model Based Interference Classification and Analysis, *Lecture Notes Comput. Sci.*, 2010, vol. 6235/2010, pp. 1–12.
5. Cicconetti, C., Lenzini, L., and Mingozzi, E., Scheduling and Dynamic Relocation for IEEE 802.11s Mesh Deterministic Access, in *Proc. 5th Annual IEEE Commun. Soc. Conf. Sensor, Mesh and Ad Hoc Commun. and Networks (SECON'08)*, 2008, pp. 19–27.
6. Krasilov, A., Lyakhov, A., and Safonov, A., Interference, Even with MCCA Channel Access Method in IEEE 802.11s Mesh Networks, in *Proc. IEEE Eighth Int. Conf. Mobile Ad-Hoc and Sensor Syst. (MASS'2011)*, 2011, pp. 752–757.
7. *ECMA: High Rate Ultra Wideband PHY and MAC Standard, ECMA-368*, December 2007.
8. *IEEE Standard for Information Technology—Telecommunications and Information Exchange Between Systems—Local and Metropolitan Area Networks – Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, 2007.
9. Rashid, M.M., Hossain, E., and Bhargava, V.K., Controlled Channel Access Scheduling for Guaranteed QoS in 802.11e-Based WLANs, *IEEE Trans. Wireless Commun.*, 2008, vol. 7, no. 4, pp. 1287–1297.
10. Skyrianoglou, D., Passas, N., and Salkintzis, A.K., ARROW: An Efficient Traffic Scheduling Algorithm for IEEE 802.11e HCCA, *IEEE Trans. Wireless Commun.*, 2006, vol. 5, no. 12, pp. 3558–3567.
11. Kuo, W.-K. and Wu, C.-Y., Supporting Real-Time VBR Video Transport on WiMedia-Based Wireless Personal Area Networks, *IEEE Trans. Vehicular Techn.*, 2009, vol. 58, no. 4, pp. 1965–1971.
12. Daneshi, M., Pan, J., and Ganti, S., Distributed Reservation Algorithms for Video Streaming Over UWB-Based Home Networks, in *Proc. Consumer Commun. Networking Conf. (CCNC'2010)*, 2010, pp. 1–6.
13. Shvets, E., Lyakhov, A., Safonov, A., and Khorov, E., Analytical Model of IEEE 802.11s MCCA-based Streaming in the Presence of Noise, *ACM Perform. Evaluat. Rev.*, 2011, vol. 39, no. 2, pp. 38–40.
14. Khorov, E., Lyakhov, A., and Safonov, A., Flexibility of Routing Framework Architecture in IEEE 802.11s Mesh Networks, in *Proc. IEEE 8 Int. Conf. Mobile Adhoc Sensor Syst. (MASS'2011)*, Valencia, Spain, 2011, pp. 777–782.
15. *The ns-3 Network Simulator* (http://www.nsnam.org/).
16. *The R Project for Statistical Computing* (http://www.r-project.org/).
17. Kovalenko, I.N. and Filippova, A.A., *Teoriya veroyatnostei i matematicheskaya statistika* (Probability Theory and Mathematical Statistics), Moscow: Vysshaya Shkola, 1973.

This paper was recommended for publication by A.V. Bernshtein, a member of the Editorial Board