Mathematical Model of MCCA-based Streaming Process in Mesh Networks in the Presence of Noise

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Abstract—One of the today challenges for the mesh networks researches is reliable transmission of multimedia traffic. This traffic demands high quality of service (QoS), to provide which it is suitable to use Mesh Coordinated Channel Access (MCCA) – the novel medium access method described in IEEE 802.11s. According to MCCA, mesh stations (STAs) set up periodic reservations; if all STAs in the network support MCCA, every STA gets access to the medium with no contention during the reservations it has scheduled. Most papers devoted to MCCA are written under the assumption of ideal channel conditions. However, in order to satisfy QoS demands, it is necessary to take random noise into account. In this paper we propose an analytical model of the multihop MCCA-based streaming process in the presence of noise. The model predicts the Packet Loss Ratio (PLR) over the transmission route and can be efficiently utilized to analyze and optimize the process of traffic transmission.

I. INTRODUCTION

Wireless Mesh Networks (WMNs), the target of research of IEEE 802.11 “S” Task Group, grow in popularity every year, and the range of their application is rapidly increasing. Today WMN developers face a challenge of enabling high quality transmission of stream traffic. To organize a WMN work, two types of medium access may be utilized: random and deterministic. Several works, e.g. [1], [2], have shown that between medium access methods described by IEEE 802.11s (random Enhanced Distributed Channel Access and deterministic MCCA [3]), MCCA (also referred to as MDA in early drafts) provides better capacity in WMNs. Furthermore, since MCCA provides periodical reservations guarded from the collisions, it is much more suitable when transmitting multimedia traffic with high QoS demands. Thus, we consider MCCA in this work.

To schedule medium usage and reserve time for the transmission in advance, every STA supporting MCCA relies on periodic Delivery Traffic Indication Message (DTIM) beaconing specified by IEEE 802.11 [4] and IEEE 802.11s [3] standards; time between consecutive DTIM beacon frames is called Mesh DTIM interval. Established reservations are regular and characterized by (i) the number $N$ of reservations placed within a DTIM interval (that is, the reservation period is $t_c = \frac{DTIM}{N}$), (ii) the reservation duration $T$, and (iii) the time interval $Offset$ between a DTIM beacon and the following reservation: see Fig. 1. Beacons generated by a STA contain the information about reservations established by the STA and its neighbors. Thus, every STA in the two-hop neighborhood is aware of upcoming reservations and refrains from transmission during them.

However, several papers have shown that MCCA does not guarantee collision-free transmissions within reservations. Papers [5], [6] address the degrading impact of MCCA-incapable STAs on the MCCA performance. Papers [7], [8] address the problem of interference coming from outside the two-hop neighborhood. In our work, the interference from outside the two-hop neighborhood is considered as one of random noise sources and it is supposed that all STAs in the network support MCCA.

Fig. 1. MCCA reservation timing

In all existing studies of MCCA, the channel is assumed to be ideal, that is, random noise is absent. This assumption leads to exactly one reservation being scheduled for every packet to be transmitted. Unfortunately, random noise inherent to wireless medium may often affect transmissions within MCCA reservations, causing frequent packet losses, which are unacceptable when providing high QoS. The common solution for the packet loss phenomenon is to retransmit lost packets. However, with only one reservation scheduled for each packet, repeated transmissions are not possible. Thus, it is necessary to take packet losses into account when planning reservations.

When a QoS-sensitive data flow is transmitted, the delay of each delivered packet shall not exceed the maximum delay $D_{QoS}$ and the PLR of the flow shall not exceed the PLR threshold $PLR_{QoS}$. The transmission over a one-hop route may be organized as follows: a packet is retransmitted either until it is successfully transmitted or until the time it has spent in the queue of the transmitting STA exceeds $D_{QoS}$. To transmit a packet flow over a multihop route, QoS demands should be distributed among the hops of the route.

The main task of this paper is to develop an analytical method of finding the optimal set of reservation periods at every hop of the route over which the multimedia stream is transmitted in the 802.11s MCCA-based mesh network, taking into account packet retransmissions necessary in the presence of noise. With the optimal periods, QoS requirements
are met and the consumed channel resource is minimal. We solve the task in our previous paper [9] for the case of the transmission of a Constant Bit Rate (CBR) flow over one hop route. However, the single-hop model developed in [9] cannot be directly used as a building block to analyze the multihop case, because the CBR flow transmitted by the source STA becomes a non-CBR one when it is relayed by other STAs on the route.

So, in the next section we extend the model [9] to describe a non-CBR flow transmission. In section III, we use the model to find out how to distribute end-to-end QoS requirements among the hops of a multihop route and to determine the optimal reservation periods for a given distribution of QoS requirements. Section IV concludes this work.

II. Mathematical Model

The analysis of multihop streaming is a complicated task. The approach that we adopt in this work is to investigate the flow transmission sequentially over each of the hops in the route. The end-to-end QoS delay boundary \( D^{QoS} \) is distributed among the hops, that is, each hop \( k \) is assigned with delay boundary \( D_k^{QoS} \) so that \( \sum_k D_k^{QoS} = D^{QoS} \). The input packet flow at each hop is assumed to be Markovian. More specifically, we assume that packet interarrival time \( t^* \) is chosen from a finite increasing set \( T^* = \{t^*_0, i = 1, ..., max\} \) with probabilities \( \{p_i, i = 1, ..., max\} \): \( Pr(t^* = t^*_i) = p_i \).

For each hop \( k \) with a known input flow characterized by interarrival time distribution and with a known delay boundary \( D_k^{QoS} \), we find PLR\(_k\) and the output flow, which is the input flow for the next hop \( k+1 \). End-to-end PLR can be easily found:

\[
PLR = 1 - \prod_k (1 - PLR_k). \tag{1}
\]

Further in this section, we consider a flow transmission over one hop and omit the subscript \( k \) indicating the hop number. All transmissions of the flow packets happen within MCCA reservations established with period \( t^*_c \) and are acknowledged by the receiving STA. Packets are assumed to be of the same size. The reservation duration \( T \) is equal to the packet plus acknowledgement transmission time.

To model the non-ideal channel, we introduce the probability \( q \) of a packet transmission failure, assuming the failures non-correlated. We neglect acknowledgment transmission failures due to relatively small size of the acknowledgement.

All values \( t^*_k \) and \( t^*_c \) are represented as integer numbers of some time units (for example, microseconds). Let \( \tau \) be the greatest common denominator of the set \( \{t^*_0, t^*_1, ..., t^*_c, t^*_c\} \). So,

\[
t_j = t^*_j/\tau, \quad j = 1, ..., max, \quad t_c = t^*_c/\tau, \tag{2}
\]

are integer values. We divide the continuous time scale into time slots of size \( \tau \) so that each reservation begins at a slot border. It is possible since \( t^*_c \) contains \( \tau \).

Let us introduce a one-dimensional Markov chain with discrete time, which instances \( t \) and \( t + 1 \) correspond to the beginnings of consecutive reservations. At any time \( t \), the state of the system is described by an integer number \( h(t) \) in the following way. If \( h(t) \geq 0 \), the queue of the transmitting STA is not empty and \( h(t) \) is the number of whole slots that the Head-Of-Line (HOL) packet has spent in the queue. If \( h(t) < 0 \), the queue is empty and \( |h(t)| \) equals the time before the next packet arrival, expressed in \( \tau \) and rounded down.

Let us determine the maximum allowed state \( d \) of the system. First, we prove that the time \( \xi \) between a packet arrival and the beginning of the next time slot is equal for all packets. Consider arrivals of any two packets into the queue. Let \( \xi_i : 0 \leq \xi_i < \tau, \quad i = 1, 2 \), be the time intervals between arrivals of the first and the second packets and the beginnings of time slots following the arrivals. Then the time interval between the packet arrivals is \( t_{int} = \xi_1 + n \cdot \tau - \xi_2, n \in \mathbb{N} \). If \( \xi_1 \neq \xi_2 \), then \( t_{int} \) does not contain \( \tau \), which contradicts (2).

Hence, at the beginning of any reservation corresponding to time instance \( t \), time that the HOL packet has spent in the queue equals \( \xi + h(t) \cdot \tau \); this time cannot exceed \( D = D^{QoS} - T \), otherwise, the packet is expired and should be discarded. So, we can assume that the packet is discarded right before the reservation if \( \xi + h(t) \cdot \tau > D \). Hence, maximum allowed \( h(t) \) equals

\[
d = \left\lfloor \frac{D - \xi}{\tau} \right\rfloor. \tag{3}
\]

The minimal allowed state of the system is \( -t_{max} + t_c \). It is achieved when a successful packet transmission starts within a time slot after the packet arrives to the empty queue, and the time before the next packet arrival takes the maximum value.

To find \( \xi \), the delay \( T^{off} \) between the first packet arrival and the following reservation can be used. The beginning of the latter reservation coincides with the beginning of a time slot, therefore \( T^{off} = k \cdot \tau + \xi, k \in \mathbb{N} \). Then

\[
\xi = T^{off} \mod \tau. \tag{4}
\]

In the particular case when the beginning of first reservation coincides with a packet arrival, \( \xi = 0 \).

Let us find the probabilities of transitions between the system states. We distinguish the following transition types (see Table I, where Next In The Flow (NIF) packet is the packet following the current HOL packet in the flow), depending on events which happen in the interval \( [t; \ t + 1] \) between the beginnings of the current and the next reservations:

1) A transition from state \( k < 0 \): no packet is transmitted.
2) A transition from state \( 0 \leq k \leq d - t_c \): when a packet transmission fails.
3) A transition from state \( d - t_c < k \leq d \) when a packet transmission fails and only one packet leaves the queue (because of its expiration).
4) A transition from state \( 0 \leq k \leq d \): when a packet transmission succeeds and only this packet leaves the queue.
5) A transition from state \( d - t_c < k \leq d \): when a packet transmission fails and two or more packets leave the queue (two or more packets are expired).
6) A transition from state $0 \leq k \leq d$ when a packet transmission succeeds and two or packets leave the queue.

Let us find the probabilities $b_{kl}^{(n)}$ that the system transits from state $h(t) = k$ to state $h(t+1) = l$ and the transition is of type $n \in \{1,...,6\}$.

**Type 1.** The queue is empty, so no packet is transmitted and the system transits to the state $k + t_c$.

$$b_{kl}^{(1)} = \begin{cases} 1, & l = k + t_c, \; k < 0; \\ 0, & \text{otherwise.} \end{cases}$$

**Type 2.** The transmission fails, but the HOL packet does not expire before the next reservation, so the system transits to the state $k + t_c$.

$$b_{kl}^{(2)} = \begin{cases} q, & l = k + t_c, \; 0 \leq k \leq d - t_c; \\ 0, & \text{otherwise.} \end{cases}$$

**Type 3.** The transmission fails, and the HOL packets expires before the next reservation. The NIF packet does not expire before the next reservation, and the time it has spent in the queue by time instance $t + 1$ equals $k + t_c - t_{last}$, where $t_{last} = t_{last} \cdot \tau$ is the time between the arrivals of the HOL and the NIF packets. That is,

$$b_{kl}^{(3)} = \begin{cases} qp_i, & t_i = k + t_c - l, \; t_i \tau \in T^*, \\ (1 - q)p_i, & d - t_c < k \leq d; \\ 0, & \text{otherwise.} \end{cases}$$

**Type 4.** The HOL packet is successfully transmitted; the NIF packet does not expire before the next reservation. This case is similar to the previous one:

$$b_{kl}^{(4)} = \begin{cases} (1 - q)p_i, & t_i = k + t_c - l, \; t_i \tau \in T^*; \\ 0, & \text{otherwise.} \end{cases}$$

With transitions of types 5 and 6, two or more packets leave the queue within reservation period $[t+1]$. The model presented in this paper is built for analyzing flow transmission under strict QoS requirements, when packet loss ratio should be small. In such a case, it is a rare phenomenon that more than one packet is discarded within a reservation period. We take the phenomenon into account, however, we assume that no more than two packets may leave the queue during a reservation period. So, we consider only cases when exactly two packets leave the queue with the transitions of types 5 and 6. The probabilities of these transitions must therefore be normalized.

**Type 5.** The transmission fails, and both the HOL and the NIF packets expire before the next reservation, thus $d - t_c < k \leq d$ and $k + t_c - t_{last} > d$. We need also to consider the next interarrival time $t_{last2}$ between the NIF packet and the packet following it. According to the assumption above, the packet following the NIF one does not expire: $k + t_c - t_{last} - t_{last2} = l \leq d$. So,

$$b_{kl}^{(5)} = \begin{cases} C_k q \sum_{(j_1,j_2) \in R_{kl}} p_{j_1} p_{j_2}, & d - t_c < k \leq d; \\ 0, & \text{otherwise,} \end{cases}$$

where $R_{kl} = \{(j_1,j_2) : t_{j_1} \tau \in T^*, t_{j_2} \tau \in T^*, l = k + t_c - t_{j_1} - t_{j_2} \text{ and } k + t_c - t_{j_1} > d\}$. The normalizing multiplier can be found as follows:

$$C_k = \frac{\sum_{l} \sum_{(j_1,j_2) \in R_{kl}} p_{j_1} p_{j_2}}{\sum_{l} \sum_{(j_1,j_2) \in R_{kl}} p_{j_1} p_{j_2}}.$$

**Type 6.** The HOL packet leaves the queue due to the successful transmission. The NIF packet expires before the next reservation. The case is similar to the previous one. So,

$$b_{kl}^{(6)} = \begin{cases} C_k \sum_{(j_1,j_2) \in R_{kl}} p_{j_1} p_{j_2}, & 0 \leq k \leq d; \\ 0, & \text{otherwise.} \end{cases}$$

Obviously, the transition probability $b_{kl}$ from state $k$ to state $l$ can be found as $b_{kl} = \sum_{n=1}^{6} b_{kl}^{(n)}$. Solving the system of equations

$$\pi_i = \sum_{k=-t_{max}+t_c}^{d} b_{kl} \pi_k, \; l \in \{-t_{max} + t_c, ..., d\},$$

supplemented with the normalization requirement $\sum_i \pi_i = 1$, we find stationary probabilities $\{\pi_i\}$ of the Markov chain states.

In order to estimate PLR, let us first find how many packets are discarded on the average during one reservation period. As previously stated, we operate under the assumption that no more than two packets leave the queue within a reservation period. So, the number of discarded packets is equal to 0 if the transition is of types 1, 2 or 4, 1 if the transition is of type 3 or 6, and 2 if the transition is of type 5. Thus, if the system transits from state $k$, $\sum_{l}[b_{kl}^{(3)} + 2b_{kl}^{(5)} + b_{kl}^{(6)}]$ packets are discarded on the average.

The average number of packets arriving during a reservation period equals $\frac{t_c}{\sum_{j_1} p_{j_1} t_{j_1}}$. Thus, the packet loss ratio equals:

$$PLR = \frac{\sum_k \sum_{l} (t_{kl}^{(3)} + 2t_{kl}^{(5)} + t_{kl}^{(6)}) \pi_k}{\sum_{j_1} p_{j_1} t_{j_1}}. \tag{5}$$

Let us find the distribution $\{p_i^t\}$ of times $\{t_i^k\}$ between packets in the output flow, that is, the distribution of time intervals between successful transmissions. Since packets can be transmitted only within a reservation, and the reservation period equals $t_i^k$, we have: $\forall t_i^k, i \in N: t_i^k = i \cdot t_c$.

Assume that the system is in state $k$ before the reservation at time $t$. Let us find the probabilities $b_{kl}^t$ that the next successful transmission happens at time $t + r$. 


<table>
<thead>
<tr>
<th>Type</th>
<th>HOL packet</th>
<th>NIF packet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>not arrived</td>
<td>not expired</td>
</tr>
<tr>
<td>2</td>
<td>failed,not expired</td>
<td>expired</td>
</tr>
<tr>
<td>3</td>
<td>failed, expired</td>
<td>not expired</td>
</tr>
<tr>
<td>4</td>
<td>succeeded</td>
<td>succeeded</td>
</tr>
<tr>
<td>5</td>
<td>failed, expired</td>
<td>expired</td>
</tr>
<tr>
<td>6</td>
<td>succeeded</td>
<td>expired</td>
</tr>
</tbody>
</table>
When \( r = 0 \), \( \theta^k_r \) equals the probability of the successful transmission happening within the first reservation, that is, \( 1 - q \) if there is a packet in the queue and \( 0 \) if the queue is empty:

\[
\begin{cases}
\theta^k_0 = 0, & k < 0, \\
\theta^0_0 = 1 - q, & k \geq 0.
\end{cases}
\] (6)

By induction on \( r \) we find \( \{\theta^k_r\} \). Assume that sets \( \{\theta^k_r\} \) are known for all \( r \leq r_0 \). Let us express an element of set \( \{\theta^k_{r_0+1}\} \) in terms of \( \{\theta^k_{r_0}\} \). To find \( \theta^k_{r_0+1} \), we consider the following three cases:

1) \( k < 0 \). There are no packets in the queue and a packet transmission does not happen. So, after the first reservation the system transits to the state \( k + t_c \) and:

\[ \theta^k_{r_0+1} = \theta^k_0 \cdot t_c, \quad k < 0. \] (7)

2) \( 0 \leq k \leq d - t_c \). There is a packet in the queue, but, in order for the next successful transmission to happen after \( r_0 + 1 \) reservation periods, it is necessary that the transmission fails within the first reservation. Then the next state of the system is \( k + t_c \):

\[ \theta^k_{r_0+1} = q \theta^{k+t_c}_0, \quad 0 \leq k \leq d - t_c. \] (8)

3) \( k > d - t_c \). There is a packet in the queue, and, as in the previous case, its transmission should fail within the first reservation. After this failed transmission, the HOL packet expires and is discarded. We have:

\[
\theta^k_{r_0+1} = q \cdot \sum_{j=k+t_c-t}^{d} p_j \theta^{j+t_c-t}_0 + q \cdot \sum_{l} \sum_{(j_1,j_2) \in R_{kl}} p_{j_1} p_{j_2} \theta^{j_2}_{r_0}, \quad k > d - t_c,
\] (9)

where the first sum accounts for the case when the NIF packet remains in the queue and the second sum accounts for the case when the NIF packet is expired and therefore leaves the queue.

Any \( \theta^k_r \) can be found recursively with the help of (6)–(9).

The probability that after a successful transmission the system appears in state \( j \) is equal to

\[
\rho_j = \frac{\sum_{i=0}^{d} (b_{ij}^{(4)} + b_{ij}^{(6)}) \pi_i}{(1-q) \sum_{i=0}^{d} \pi_i},
\]

where \( \sum_{i=0}^{d} \pi_i \) is the normalization multiplier, indicating that the transmission can only happen from state \( i \geq 0 \).

So, the probability \( \rho_i' \) that consecutive successful transmissions are separated by \( i \) reservation periods can be found as follows:

\[
\rho_i' = \sum_{j=-t_{max}+t_c}^{d} \rho_j \cdot \theta^i_{j-1}.
\] (10)

The presented model describes the process of flow transmission over one hop. Using the model, we find the PLR and the output flow for the given hop. To analyze the multihop transmission, we assume that the delay requirement \( D^{QoS} \) is distributed among the hops in some way. We then apply the model to each of the hops sequentially. The flow generated by an application is the input flow of the first hop. The output flow of each hop, except for the last one, serves as the input flow for the next hop. Notice that the distribution (10) of times between packets in an output flow is not limited, while the model of transmission over one hop operates with flows with finite interarrival time sets. So, in order to apply this model to multihop transmission analysis, we limit the distribution \( \{p'_i\} \) by choosing \( i_{lim} \in N \) and postulating \( \forall i > i_{lim} : \hat{p}'_i = 0 \). New distribution \( \{p'_i\} \) must be normalized: \( \sum_i p'_i = 1 \). So, we define \( p'_i \) as follows:

\[
\begin{cases}
p'_i = \frac{\hat{p}'_i}{\sum_{i \leq i_{lim}} \hat{p}'_i}, \quad i \leq i_{lim}, \\
p'_i = 0, \quad i > i_{lim}.
\end{cases}
\]

and use the normalized distribution \( \{p'_i\} \) to describe the output flow of each hop.

To find PLR over the whole multihop route, we use (1), where \( PLR_k \) for hop \( k \) is found by (5).

### III. Numerical Results

In this section, we consider different scenarios of a multimedia flow transmission over a multihop route, using MCCP reservations at every hop to access the medium. Also, for simplicity, we assume that each STA on the route sets up its reservations in a way that the delay \( T^{QoS} \) between the first packet arrival to the STA’s queue and the beginning of the first reservation established by the STA equals zero. The case when \( T^{QoS} \neq 0 \) for some hops can be analyzed similarly, with regard to (3) and (4).

First, we consider a simple scenario, when CBR voice traffic with packet interarrival time \( t_v = 20 \) ms is transmitted over 3-hop route; packet transmission failure probability equals to 0.2, 0.4 and 0.3 for 1st, 2nd and 3rd hops, respectively. The end-to-end delay boundary \( D^{QoS} = 150 \) ms is distributed evenly between the steps, that is, \( D^1_{QoS} = D^2_{QoS} = D^3_{QoS} = 50 \) ms, and the reservation period equals \( t_c^* \) for all hops. We assume that the reservation duration \( T \) equals 0.2 ms, which is enough to transmit a voice packet and to receive the acknowledgement frame. This \( T \) value is used for all scenarios in this section.

The PLR over the route depends on \( t_c^* \) only. Reservations with longer periods consume less network capacity, so, to minimize the consumed channel resource, we find the maximum \( t_c^* \) such that \( PLR(t_c^*) \leq PLR^{QoS} \). The process is described by the PLR vs. \( t_c^* \) curve shown in Fig.2. Using the curve, we find the optimal \( t_c^* \) corresponding to a specific \( PLR^{QoS} \); for example, as shown in Fig.2, the maximum reservation period that provides \( PLR \leq 5\% \) equals 9.9 ms. To show that the PLR estimation is accurate enough, we present results obtained by our analytical method and through simulation in GPSS World [10] environment.

Fig.2 features significant spurt growths of PLR at \( t_c^* = 8.4 \) ms and \( t_c^* = 10 \) ms. This is not a peculiarity of the given scenario, but rather a common effect in \( PLR(t_c^*) \) dependency. Roughly speaking, this happens because a slight increase in \( t_c^* \) may decrease the number of transmission opportunities for
some packets in the flow. For example, consider a packet which arrives to the queue right before a reservation. For the considered scenario, when $t^*_c = 9.9$ ms, six reservations happen while the packet stays in the queue (immediately after its arrival, and 9.9, 19.8, ..., 49.5 ms after). The last reservation ends 49.7 ms after the packet arrival, and therefore can be used for the packet transmission. However, with $t^*_c = 10$ ms, the sixth reservation ends after the packet expiration and cannot be used for its transmission. So, the number of reservations the packet can use to be transmitted is decreased with the increase in $t^*_c$ from 9.9 ms to 10 ms. This leads to jump in PLR.

Let us estimate the accuracy of our method, depending on the number of hops in the route. Consider a transmission of the same voice flow as in the previous scenario over a route containing several hops with transmission failure probability $q = 0.3$ equal for all hops. The QoS delay boundary $D_{QoS} = 150$ ms is distributed evenly between the hops. Fig.3 plots the optimum reservation period versus the number of hops.

The error in PLR estimation with our model increases with the number of hops. However, the error in estimating the optimum reservation period remains low at least up to 5 hops, as shown in the Fig.3.

We have considered the case when the reservations set up by STAs on the route have equal periods and the delay boundary is distributed evenly between the hops. This is convenient when showing some features of the model and describing how to apply it. However, when hops of the transmission route are affected by noise of different intensity, it seems much more reasonable to give a bigger portion of the delay boundary $D_{QoS}$ to the the “noisy” hops as well as to establish more frequent reservations on such hops. Let us use our model to find out how to distribute the delay boundary between the hops properly.

To determine which $D_{QoS}$ distribution is optimal for the given scenario, we consider different distributions of $D_{QoS}$ between the hops and find the optimum reservation periods $t^*_c$ for each $D_{QoS}$ distribution, using exhaustive search. As a criterion to compare $D_{QoS}$ distributions, we introduce the channel load parameter $\psi = \sum_k 1/t^*_c$, which is proportional to the time the channel is occupied by the flow transmission. Obviously, the optimum $D_{QoS}$ distribution corresponds to the least channel load.

Our research revealed that in a wide area of $D_{QoS}$ distributions the channel load is only slightly (up to 5%) higher than the channel load corresponding to the optimum $D_{QoS}$ distribution. One major regularity was discovered: when transmission failure probability falls into the range from 0.1 to 0.5 on every hop, the even distribution of delay boundary between hops leads to the channel load within 5% range from the minimal load achieved with the optimal distribution. That is, when distributing the delay boundary, it is almost never a bad idea to distribute it evenly between hops. Fig.4 illustrates these facts. To obtain this figure, we consider a transmission of a multimedia flow with packet interarrival time $t^*_\lambda = 20$ ms, delay boundary $D_{QoS} = 150$ ms and the PLR boundary $PLR_{QoS} = 5\%$ over a 3-hop route with $q_1 = 0.2, q_2 = 0.5, q_3 = 0.3$. We find optimum reservation periods for every $D_{QoS}$ distribution and choose the distribution leading to minimal channel resource consumed. As we consider the transmission over 3 hops, the $D_{QoS}$ distribution can be characterized by delay boundaries assigned to the first and the second hops. As one can see in Fig.4, the area of $D_{QoS}$ distributions where the channel load is within 5% range from the minimal one is indeed wide, and the even distribution of the delay boundary falls into this area.

Let us discuss optimum reservation periods obtained with the even delay boundary distribution, which is almost optimal in almost any scenario, as we have shown. Some results, presented in Table II and obtained for the 3-hop route scenario with different transmission error probabilities on the hops of the route, prove our intuitive assumption that reservations should be established with shorter periods on “noisy” hops.

The other thing to be noticed is that optimum reservation periods depend not only on the set of transmission failure probabilities $\{q_1, q_2, q_3\}$, but also on the way these probabil-
Fig. 4. 5% optimum area for different delay boundary distributions

<table>
<thead>
<tr>
<th>$q_1$</th>
<th>$q_2$</th>
<th>$q_3$</th>
<th>$t^*_{1}, \text{ms}$</th>
<th>$t^*_{2}, \text{ms}$</th>
<th>$t^*_{3}, \text{ms}$</th>
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</thead>
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<tr>
<td>0.5</td>
<td>0.3</td>
<td>0.2</td>
<td>75</td>
<td>140</td>
<td>115</td>
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<tr>
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<td>0.5</td>
<td>0.3</td>
<td>140</td>
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</tr>
<tr>
<td>0.3</td>
<td>0.2</td>
<td>0.5</td>
<td>115</td>
<td>115</td>
<td>70</td>
</tr>
</tbody>
</table>

TABLE II
OPTIMAL RESERVATION PERIODS

For that, we built an analytical model of multimedia flow one-hop transmission using MCCCA reservations, which allows to estimate PLR and interarrival time distribution for the output flow with a given delay boundary, reservation period and packet transmission failure probability for the hop. Using the model sequentially for each hop of the route, we estimate the end-to-end PLR for a specific distribution of the end-to-end delay boundary among the hops and given reservation periods on every hop. Thus, the model can be efficiently exploited to analyze and optimize the process of multimedia traffic transmission over a multihop route in the presence of noise. Specifically, we suggested an analytical method allowing to minimize the consumed channel resource while providing the necessary QoS. After validating our model by simulation, we conducted the vast analysis of different scenarios of multimedia flow transmission with MCCCA reservations and made the following unobvious conclusion regarding the delay boundary distribution: the even distribution of delay boundary among the route hops is an almost optimal solution if the reservations are scheduled properly. This feature may be exploited to significantly simplify the search of the optimal reservation scheme.

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REFERENCES


