Distributed Queue Random Multiple Access Algorithm for Centralized Data Networks

Vladimir A. Kobliakov, Andrey M. Turlikov and Alexey V. Vinel

Abstract — *The development of efficient media access control protocols for new generation networks, such as IEEE 802.16 metropolitan wireless system, is a challenging task nowadays. The problem of designing an efficient random multiple access algorithm for centralized data network, where subscriber stations transmit bandwidth requests to the base station in an uplink channel, is a focus of the paper. For this purpose special model for a centralized network is considered and new random multiple access algorithm is developed and analyzed. This algorithm, further referred to as distributed queue algorithm (Multi-FS-ALOHA), is shown to provide higher tenacity and lower mean delay for the request transmission in comparison to binary exponential backoff, standardized in IEEE 802.16, as well as FS-ALOHA it is based on. Optimization of parameters for the developed algorithm is fulfilled; impact of the noise on its performance is investigated. The analysis is conducted by means of both analytical techniques and simulations*[1].

Index Terms — random access algorithm, centralized data network, IEEE 802.16.

I. INTRODUCTION

Random multiple access (RMA) is a well-known method used in communication systems where very large number of stations occasionally transmits packets by means of a single channel [1]. In centralized data networks, transmissions in the uplink direction – from subscriber stations to the base station may be handled by means of this method providing the above condition is valid. Special periods of time called *contention intervals* are allocated by the base station for the random access purposes. Informally RMA algorithm is a rule subscriber stations use to perform the first transmission attempt and further retransmissions in case of *collisions* occurred during contention intervals. Collision is a situation, when several stations transmit at the same time, which makes the reception of the packet impossible and conceptually similar is the situation of packet distortion by noise.

The purpose of this paper is development and analysis of new RMA algorithm, which outperforms existing ones in terms of two main performance metrics: tenacity and mean delay, which are explained further. Due to great interest to new generation wireless networks nowadays, we focus on the IEEE 802.16 [2] media access control (MAC) sublayer operation as an example for possible application of our analysis. Although the considerations presented are general enough to be used in any similar data network.

In IEEE 802.16 *binary exponential backoff* (*BEB*) algorithm is standardized for collision resolution. In spite of its obvious advantage – simplicity, BEB has serious disadvantage. As it is proven in [3], for infinite number of stations modified BEB (where geometrical distribution instead of uniform one is used for setting waiting interval) is unstable for any non-zero packets arrival rate. From the practical point of view, this means, that when there are thousands of stations in the system (like in IEEE 802.16e), queues of packets will grow up till the buffers overflow, finally resulting in the whole system collapse. Though BEB as it is defined in IEEE 802.16 has not been shown to be unstable for any positive arrival rate value, it is very likely, that it inherits this property of its modified version.

FIFO-by-sets-ALOHA is introduced and analysed in [4] and [5]. It uses more sophisticated procedure for collision resolution, replacing independent retransmissions of all stations, as it is done in BEB, by specially organized distributed queue, consisting of packets, which once has been involved in the collisions. It is shown in [4], that FS-ALOHA is inefficient for long contention interval durations. FS-ALOHA++ from [5], which has been supposed to solve this problem, does not improve the situation significantly.

In this paper, we introduce so-called *distributed queue algorithm* (or *Multi-FS-ALOHA*) which extends the ideas of mentioned above algorithms. Applying the queuing theory methods and simulations we evaluate Multi-FS-ALOHA performance metrics. The analysis is conducted in the assumption of an error-prone communication channel. The proposed algorithm is shown to be noise-resistant and efficient for different system parameters. Moreover, it shows excellent performance for large contention intervals.

The rest of the paper is organized as follows. Section II briefly explains centralized data network structure as well as model developed for its analysis. Operation of BEB, FS-ALOHA and Multi-FS-ALOHA is described in Section III, while in Section IV mathematical analysis and simulation results for the Multi-FS-ALOHA are presented. Conclusion remarks are contained in Section V.

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II. MODEL FOR CENTRALIZED DATA NETWORK

A. *Basics of IEEE 802.16 MAC operation*

Throughout of this paper we consider a network with a point-to-multipoint (PMP) architecture, which consists of one base station (BS) managing several subscriber stations (SSs). Transmissions between the BS and SSs are realized in fixed frames by means of time division multiple access (TDMA) / time division duplexing (TDD) mode of operation. The frame structure consists of a downlink sub-frame for transmission from the BS to SSs and an uplink sub-frame for transmissions in the reverse direction. The Tx/Rx transition gap (TTG) and Rx/Tx transition gap (RTG) shall be inserted between the sub-frames to allow terminals to turn around from reception to transmission and vice versa. In the downlink sub-frame the Downlink MAP (DL-MAP) and Uplink MAP (UL-MAP) messages are transmitted, which comprise the bandwidth allocations for data transmission in downlink and uplink direction, respectively (Fig. 1).

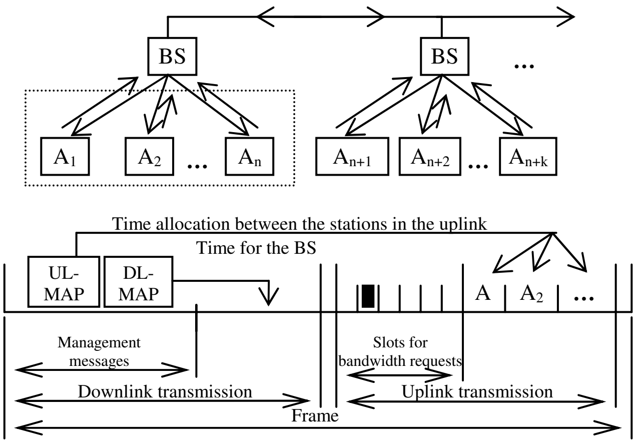

Fig. 1. Centralized data network architecture. Frame structure represents main features of IEEE 802.16 MAC.

The uplink sub-frame contains of transmission opportunities scheduled for bandwidth requests purposes, in which Bandwidth Request (BW-REQ) message can be transmitted, which serves for SSs to indicate to the BS that they need UL bandwidth allocation. The BS manages the number of transmission opportunities through the UL-MAP message.

B. *Model for Random Access*

Let us consider infinite number of subscriber stations. The time axis is divided into the frames. Each frame comprises K equal slots for the random access. The duration of a slot corresponds to the time needed for the bandwidth request transmission. The BS chooses K in order to make a trade-off between the duration of contention period and the duration of payload transmission within the whole frame duration, which is fixed. Therefore, in the following discussion, K is assumed to be a fixed value.

We define arrival rate λ as the mean number of the requests, arriving into the system, for the frame duration. It is assumed, that requests arrive into the system according to Poisson law with parameter λ. New request is put in the buffer and transmitted in the next frame.

Three situations should be distinguished in any slot, namely: "empty" (E) – nobody transmitted in the slot, "success" (S) – exactly one station transmitted in the slot and "collision" (C) – at least two or more stations transmitted in the slot. We assume error-prone channel conditions. Let noise influence the base station ability to detect the situation in a slot. Following classical model from [7] we assume, that two types of errors are possible. In the first case noisy signal, which happened during the empty slot is considered a collision ("false" collision). In the second case the fact of request distortion by noise leads to the BS's decision about the collision. Denote the probabilities of these events q_0 and q_1 respectively. Let by the beginning of each frame BS transmit to all stations ternary vector of length K, indicating the situations in each of the slots as they have been seen in the previous frame.

III. RANDOM ACCESS ALGORITHMS FOR CENTRALIZED DATA NETWORKS

A. *Binary Exponential Backoff Description*

In IEEE 802.16 for collision resolution, a binary exponential backoff algorithm is introduced. Here we use the formalized description from [7]. Before each transmission attempt, a station uniformly chooses an integer number from the interval [0, W_i–1], where W_i is the current value of its backoff window. Chosen value, referred to as a backoff counter, indicates the number of slots the station has to wait before the transmission of a request (Fig. 2).

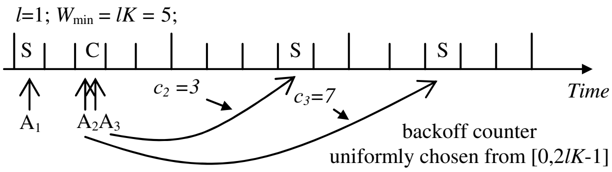

Fig. 2. Example of BEB operation.

For first transmission attempt, the backoff window W_0 is set to $W_{\min}$. In the case of a collision a station doubles its backoff window value, and so the backoff window after i collisions, W_i, becomes $2^i W_{\min}$. The window is not doubled if it reaches the maximum value $W_{\max} = 2^m W_{\min}$, where m is referred to the maximum backoff stage. In the case of the successful transmission the backoff window is set to the minimum value $W_{\min}$. The standard IEEE 802.16 does not define any relationship between the parameters $W_{\min}$, $W_{\max}$ and K. Let us notice, that if $W_{\min}$<K, then some time slots will never been used during the first transmission attempt. Furthermore, we set $W_{\min} = lK$, where l is a natural number, in order to uniformly distribute the transmission attempts over the available random access slots.

B. FIFO-by-sets-ALOHA description

Note that in BEB collided stations perform retransmissions independently. FS-ALOHA operates in more complicated way. For the algorithm operation all available K slots are divided into two non-intersecting subsets. Namely, first S slots are used to transmit new packets, while other $N = K - S$ are used for collision resolution. First S slots are referred to as *access slots* and rest N of them – as *collision resolution slots*.

A station willing to transmit new request waits till the beginning of a frame and then uniformly chooses one of S slots for the transmission. All stations, which has been involved in the collisions on S slots of a frame form so-called *collision set*. These sets are served in the order of their appearance and represent a distributed queue. Each station from the collision set in the head of the queue uniformly chooses one of N slots to transmit (Fig. 3).

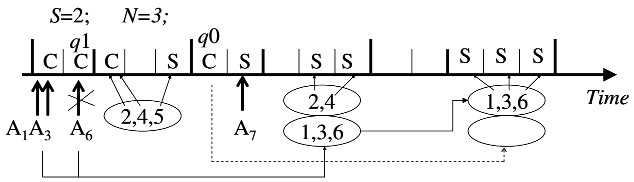

Fig. 3. Example of FS-ALOHA operation. Ovals represent collision sets, numbers identify stations. Note, that empty collision set is a result of a noise in the first slot of second frame, which has been considered a collision.

A set is considered to be successfully transmitted in case BS understands that all subscribers in it have successfully transmitted. Absence of collisions during N slots for collision resolution indicates that the set has been served. Each station stores current length of the distributed queue and its own position in this queue. We refer reader to [4] for more implementation details.

C. Multi-FIFO-by-sets-ALOHA description

We propose to enhance FS-ALOHA in the following way. First of all, let us assume that the number of *access slots* and number of *collision resolution slots* may vary from frame to frame (Fig. 4).

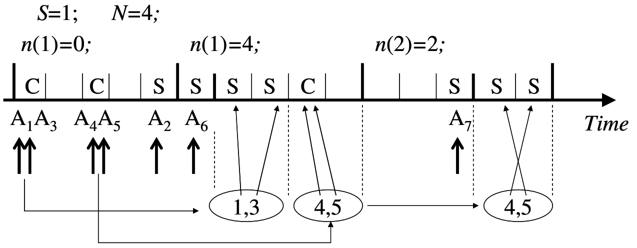

Fig. 4. Example of Multi-FS-ALOHA operation. Note, that in the first frame all S slots are assigned for new requests. Then the number of slots for collision resolution is proportional to the number of collision sets in the distributed queue.

Denote $s(t)$ and $n(t)$ values for number of access slots and collision resolution slots respectively in frame number t. Then $n(t) = \min(2x(t), N)$, and $s(t) = K - n(t)$, where $x(t)$ – number of collision sets by the beginning of frame t. Secondly, let collision set be formed from the stations, which have collided in one slot (and not on first S slots of a frame like in FS-ALOHA). Thirdly, collision sets are served in parallel using $n(t)$ slots of frame, which are divided into pairs. Thus, maximum number of collision sets, which may be served in parallel in one frame equals to $N/2$ (assuming that N is always even).

IV. DISTRIBUTED QUEUE ALGORITHM ANALYSIS

A. Tenacity Derivation

Transmission rate (tenacity) R is defined as a maximal packet arrival rate λ, under which, finite mean delay D for request transmission is still provided: $R = \sup\{\lambda\text{: } D<\infty\}$ [8]. Consider the way to compute the tenacity of Multi-FS-ALOHA introduced in this paper. For simplicity let us first consider Multi-FS-ALOHA operation for the following values of the parameters: $S = 1$ and $N = 2$.

Describe algorithm operation in terms of queuing theory. Note, that we have infinite queue of collision sets and one serving device. The system is synchronized and frame is considered a unit of time. Time intervals between sets arrival are independent identically distributed random variables. This statement is valid for time needed to serve one collision set as well. Thus, considered system may be modelled as a queue *GI/GI/*1. According to [9] this queue is stable if the following condition holds

$$\Lambda < \mu, \tag{1}$$

where Λ is the mean number of collision sets arriving into the system for frame duration and $1/\mu$ is the mean time needed to serve one set.

Transmission rate (tenacity) of the algorithm may be calculated by means of determining $\lambda_{\max}$ maximal value of λ under which inequity (1) holds. Applying reasoning from [11] (“saturation rule”) it can be shown, that arrival rate $\lambda < \lambda_{\max}$ exists, under which queue is always non-empty and at the same time system is stable (i.e. arrival rate equals to outgoing rate). Thus, contention interval is divided into S and N slots during the operation of system.

During the frame either one or none sets may arrive into the distributed queue, thus

$$\Lambda = \Pr\{arrival\ of\ one\ set\} = 1 - e^{-\lambda} - \lambda e^{-\lambda} + q_0 e^{-\lambda} + q_1 \lambda e^{-\lambda}. \tag{2}$$

Let

$$T(x) = \sum_{k=2}^{\infty} T_k \frac{x^k}{k!} e^{-x} + T_0 e^{-x} q_0 + T_1 x e^{-x} q_1, \tag{3}$$

where T_k is the mean number of frames needed to serve collision set consisting of k ($k \geq 0$) requests (the expressions for T_k are included into Appendix).

It can be shown, that $\Psi = 1/\mu$ can be computed in the following way

$$\Psi = \frac{T(\lambda)}{1 - e^{-\lambda} - \lambda e^{-\lambda} + q_0 e^{-\lambda} + q_1 \lambda e^{-\lambda}}. \quad (4)$$

From (1) – (4) we conclude, that considered queuing system is stable for such values of λ, under which the following inequity holds

$$T(\lambda) < 1. \quad (5)$$

Let's extend our considerations for the case of an arbitrary S and N. Then collision sets arrival rate is S times larger than for the simplest case, while number of serving devices equals to $N/2$, so we can modify (1)

$$S\Lambda < \frac{N}{2}\mu. \quad (6)$$

Taking into account equations (1) – (5), transmission rate R may be computed as $R(S, N) = \lambda_{\max} / (S + N)$, where $\lambda_{\max}$ is the maximal λ under which the following holds

$$T(\lambda / S) < N/(2S). \quad (7)$$

B. Parameters optimization

Now let us show, how to choose S and N to maximize the transmission rate providing, that total number of available slots K is fixed. Let us choose arrival rate according to "saturation rule" (see Section IV.A). Thus, contention interval is divided into S and N slots during the operation of system. Consider operation of a system having this arrival rate during the infinite time interval. Denote $\alpha = \lambda / (S + N)$ – arrival rate computed for one slot. For system in stable mode, mean number of the arrived requests for slot duration, equals to mean number of successfully transmitted requests in one slot. Then arrival rate α may be expressed as a ratio between the number of transmission attempts for new requests and total number of slots. Let us number all *access slots* using natural numbers from 1 to n. Denote k_i number of requests, which have been transmitted in slot number i, and t_i – total number of slots (both *access* and *collision resolution slots*) needed to successfully transmit all these k_i requests.

Taking into account the above notation, arrival rate may be computed as

$$\alpha = \lim_{n \to \infty} \frac{k_1 + k_2 + \ldots + k_n}{t_1 + t_2 + \ldots + t_n}. \quad (8)$$

Applying Theorem 1 from [12] we conclude that

$$\alpha = \frac{M[k_i]}{M[t_i]}. \quad (9)$$

Denote x – mean number of the requests being transmitted in one of *access slots* of a frame, then $M[k_i] = x$ and $M[t_i] = 1 + 2T(x)$. Thus from (8) and (9) we obtain, that α turns out to be

$$\alpha = \frac{x}{1 + 2T(x)}. \quad (10)$$

In order to compute maximal transmission rate of the algorithm, it is necessary to maximize the ratio $M[k_i]/M[t_i]$. Denote x^* – value for x, which maximizes this ratio. On the other hand to provide the stability, inequity (7) must be hold:

$$T(x^*) < N/(2S). \quad (11)$$

From (11) it results, that in order to achieve maximal transmission rate the following relationship between S and N is to be satisfied:

$$\begin{cases} N = 2T(x^*)S \\ K = S + N \end{cases}. \quad (12)$$

As K, S and N are natural numbers and due to algorithm operation N should be even, then first equation from (12) can not be satisfied in general case. Thus, the solution of system (12) should be approximated to the nearest integer, what leads to transmission rate degradation in comparison with the optimal value.

For instance, applying (10) and (12) for the ideal channel conditions, we obtain $x^* \approx 1.0191$ and $T(x^*) \approx 0.712$. In the case of sufficiently large values for K, algorithm transmission rate equals to

$$R = \frac{x^*}{1 + 2T(x^*)} \approx 0.4204.$$

If $K = 4$, then optimal values are $S = N = 2$. Solving equation $T(R/S) = N/(2S)$ with R as unknown, transmission rate may be obtained and approximately equals to 0.4148.

C. Numerical results

In this section, we show numerical results for Multi-FS-ALOHA, FS-ALOHA and BEB. Results for Multi-FS-ALOHA are obtained using explained above method. Analogous method has been applied for FS-ALOHA analysis. BEB has been investigated by means of simulations. Important detail is that for BEB simulation we use finite number of stations assumption [8] and Poisson arrival process is replaced by Bernoulli one. However, as number of modelled stations is large enough, namely 1000, we believe, that results obtained for BEB may be comparable with those obtained for Multi-FS-ALOHA. As for the BEB parameters, we use realistic values l = 1 and m = 10, which are close to optimal ones for $K > 20$ [8].

Let us investigate how the length of contention interval influences the transmission rate for the case of ideal channel conditions (fig. 5).

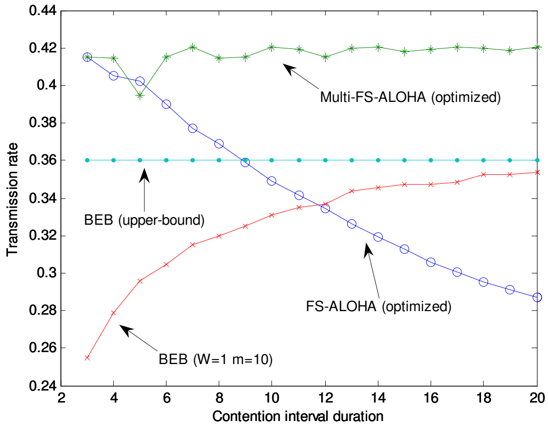

Fig. 5. Transmission rate for error-free channel. Multi-FS-ALOHA provides high tenacity for any contention interval duration.

For Multi-FS-ALOHA as well as FS-ALOHA S and N been chosen for each value of K to maximize the tenacity (so actually upper bound for tenacity is plotted). Upper bound for BEB transmission rate is shown to be approximately 0.36 in [8]. Note that for K = 5 algorithm FS-ALOHA behaves better than Multi-FS-ALOHA. The reason for it is that at this point the ratio between S and N differs from optimal one, which has been found in previous section. For this point it is better to set S = 3 instead of S = 1. Anyway, Multi-FS-ALOHA provides highest transmission rate among all the algorithms considered for any contention interval length.

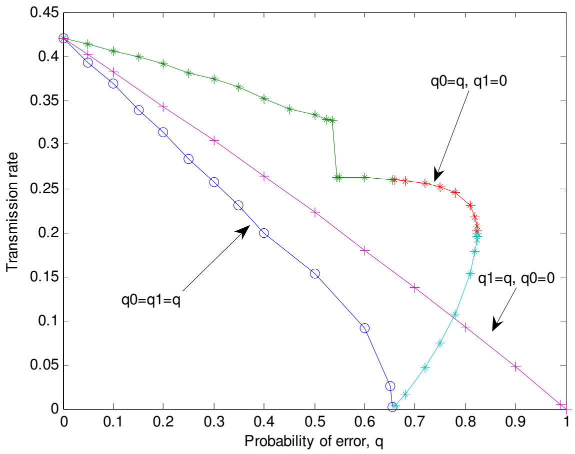

Fig. 6. Transmission rate of Multi-FS-ALOHA for error-prone channel. In the legend we show, what kind of errors (modelled by q_0, q_1 or both types) influence the performance on the corresponding curves.

The relationship between the noise signals probabilities and transmission rate of Multi-FS-ALOHA is depicted in Fig. 6 for contention interval duration K = 24 and optimal S and N ratio.

An interesting effect can be seen for the curve, when $q_1 = 0$. When there is a non-zero error probability of only one type, namely noise during an empty slot is considered a collision, then system is stable for some interval of λ for $0.655 < q_0 < 0.823$. On the one hand, there are such λ values in this interval, which are so large, that they reduce the number of empty slots (and consequently probability of "false" collisions on an empty slot). On the other hand, arrival rate λ is not so large to cause system collapse.

Finally, we give simulation results for the mean request delay provided by all considered algorithms in Fig. 7 and Fig. 8. Delay is the time from the moment of request arrival till the moment when subscriber station understands, that it has been successfully transmitted.

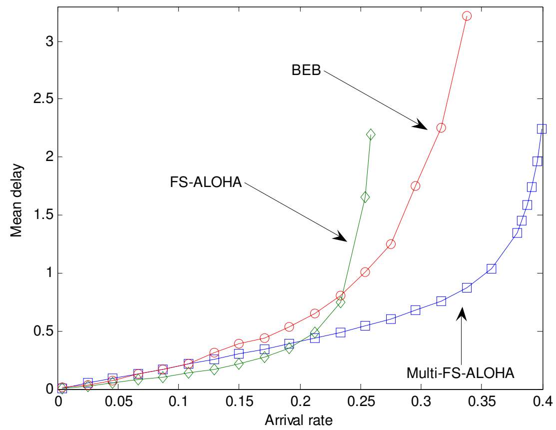

Fig. 7. Mean request delay for varying arrival rate (ideal channel). Parameters: K=24, FS-ALOHA S=16, Multi-FS-ALOHA S=10. We do not display constant average addition to mean delay (1/2) caused by waiting of a subscriber till the beginning of frame. Moreover, duration of a frame, where request is successfully transmitted, also is not added to displayed delay. Thus, in case request is successfully transmitted at the first transmission attempt, delay on the plot equals to zero.

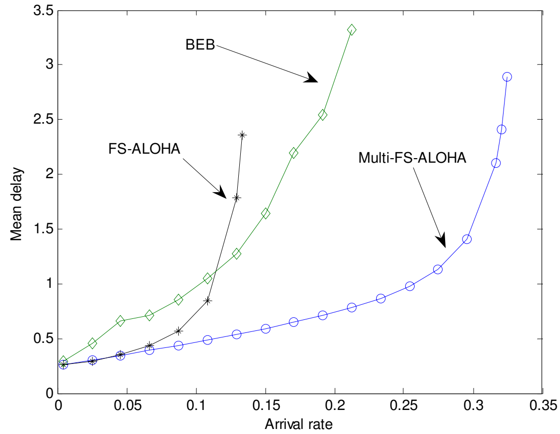

Fig. 8. Mean request delay for varying arrival rate (error-prone channel). Assume, that error probabilities are q_0 = 0 and q_1 = 0.2.

V. CONCLUSION

New random multiple access algorithm Multi-FS-ALOHA for centralized data network has been introduced and analyzed. Under the assumption of infinite number of stations it provides high transmission rate (approximately 0.42) independently of contention interval duration. However, in contrast to most widely used binary exponential backoff, Multi-FS-ALOHA requires ternary (and not binary) channel feedback for its operation. For future research we suppose to investigate other random access algorithms which are based on the distributed queue management.

APPENDIX

Here expressions for T_k are written out. According to the algorithm description, noise influences the system operation. Particularly, collision sets including zero or one requests may be formed.

In case when no transmission takes place during a slot, but BS makes a decision about the collision due to noise in communication channel ("false" collision), collision set containing no request is formed. Mean time needed to serve it is

$$T_0 = \frac{1}{(1-q_0)^2}.$$

In case when one station transmits a request in some slot, but BS does not receive it, because of distortion by noise, collision set containing one request is formed. Mean time needed to serve such kind of a set is

$$T_1 = \frac{1+(1-q_1)q_0 T_0}{(1-q_1)}.$$

For collision set consisting of larger number of requests the following equation holds

$$T_k = \frac{1+\sum_{i=1}^{2}\pi(i,k)\sum_{m=0}^{i-1}\binom{i}{m} q_1^m (1-q_1)^{i-m} T'_{k-i+m}}{1-\sum_{i=0}^{2}\pi(i,k)q_1^i}, \quad T'_k = \begin{cases} 1 & k=0 \\ T_k & k \geq 1 \end{cases},$$

$\pi(i, k)$ – probability, that i from k requests from the set will be successfully transmitted using two allocated slots. For $k = 2$ it is easy to obtain $\pi(2,2) = 0.5$, $\pi(1,2) = 0$ and $\pi(0,2) = 0.5$, while for $k \geq 3$ the following holds $\pi(2,k) = 0$, $\pi(1,k) = k2^{1-k}$ and $\pi(0,k) = 1 - \pi(1,k)$.

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