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Articles

Analyzing and stabilizing multichannel ALOHA with the use of the preamble-based exploration phase

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Introduction: *Internet of Things devices are actively used within the framework of Massive Machine-Type Communication scenarios. The interaction of devices is carried out by random multiple-access algorithms with limited throughput. To improve throughput one can use orthogonal preambles in the ALOHA-type class of algorithms.* ***Purpose:*** *To analyze ALOHA-based algorithms using the exploration phase and to calculate the characteristics for the algorithm with and without losses with a finite number of channels.* ***Results:*** *We have described a system model that employs random access for data transmission over a common communication channel with the use of orthogonal preambles and exploration phase. We have obtained a formula for numerical calculation of the throughput of an algorithm channel with losses with an infinite number of preambles and a given finite number of channels. The calculation results for several values of the number of independent channels are presented. A modification of the algorithm using the exploration phase and repeated transmissions is proposed and described. The system in question can work without losses. For this system, we have given the analysis of the maximum input throughput up to which the system operates stably. Also, the average delay values for the algorithm that were obtained by simulation modeling are shown. By reducing the number of available preambles, the results obtained can be used as an upper bound on the system throughput.* ***Practical relevance:*** *The results obtained allow to assess the potential for improving the throughput of random multiple-access systems in 6G networks through the application of the exploration phase.*

Keywords *— multichannel ALOHA, maximum throughput, random multiple access, stability, Massive Machine-Type Communications, Internet of Things.*

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Introduction

Currently, there is an active development of wireless communication technologies, caused by a large increase in the requirements for the number of operating devices and the amount of transmitted data. A prime example is the Internet of Things (IoT) technology. Support for this technology in cellular networks is being studied in both the standard (5G) and emerging standards (6G). IoT systems are expected to work within the framework of the Massive Machine-Type Communications scenario. The possibility of operation of a potentially infinite number of devices and a high load on the network [1–3] are considered. Since the number of users is potentially infinite, random access algorithms are assumed [4, 5]. As a rule, varieties of algorithms such as ALOHA and its modifications are considered. The existing algorithms have restrictions on the limiting input arrival rate (throughput), which become few with the existing increase in the number of users. There are various approaches to increase the throughput of algorithms. Thus, approaches based on the use of non-orthogonal multiple access (NOMA), sequential interference cancellation (SIC) and orthogonal preambles are proposed [6–12]. However, NOMA and SIC methods are computationally intensive. Therefore, in this article we will consider an approach using orthogonal preambles. The work [12] considers a system with independent channels and a multichannel ALOHA algorithm that uses orthogonal preambles to implement work with two phases. The exploration phase is the phase of evaluating possible collisions using preambles. Users then transmit messages in the Data Transmission Phase based on the results of the EP. In this paper, we will take as a basis the model of such a system. In contrast to [12], we will analyze the throughput for a finite number of independent channels. It also proposes a modification of the algorithm using repeated transmissions, which allows the system to work without losses. This algorithm can be used to organize data transmission in high reliability systems [13–15]. For such a model, the limiting input arrival rate is sought, up to which the system is stable for a given number of channels.

Analysis of a system with losses

Let us introduce a system of assumptions for the system under consideration.

Assumption 1. The entire time of the channel operation is divided into frames of the same length. A frame consists of two phases: an exploration phase (EP) and a data transmission phase (DTP). Each phase is followed by a response from the base station (BS). In the exploration phase, orthogonal preambles are transmitted, and in the data transmission phase, user messages are transmitted. Users know exactly the boundaries of the division into frames and phases and can transmit data only at the beginning of the corresponding phase at the beginning of a new frame.

Assumption 2. There is a set of K independent channels. All users have unique preambles. A preamble is a sequence of bits of a certain length, which is much less than the length of the message. The preamble transmission rate is the same. The BS can reliably determine the number of preambles on each channel.

Assumption 3. In each channel, during each phase of the frame, one of the following events can occur:

— "Success" — if the data was transmitted by one user;

— "Empty" — none of the users transmitted data;

— "Conflict" — simultaneously, two or more users were transmitting data. If a conflict occurs during the EP, then the BS will successfully determine the number of preambles. If a conflict occurs during the DTP, then the users' messages overlap and cannot be processed on the receiving side.

At the end of each phase, all users will reliably know what event happened in the channel.

Assumption 4. The system has a potentially unlimited number of users. The number of messages appearing in the system in one frame is distributed according to the Poisson law with the parameter $K\lambda$.

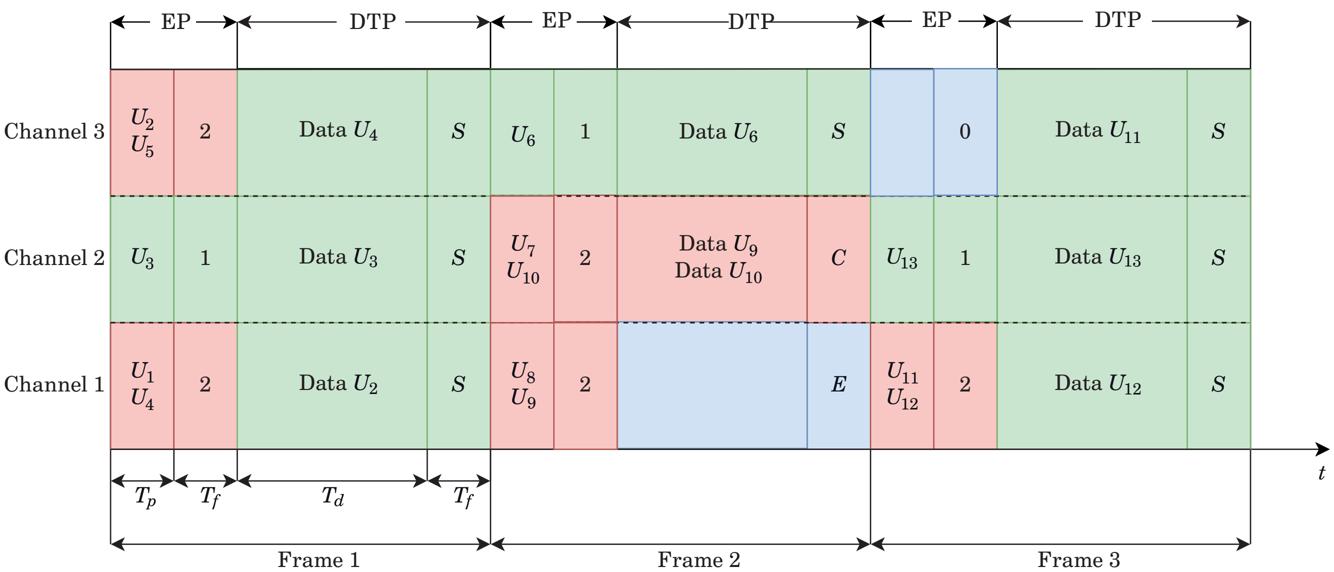
Assumption 5. The time of the data transmission phase will be taken as a unit of time, and the time of the exploration phase will be taken as 0.

Let us describe the considered algorithm. According to *Assumption 1*, each frame consists of two phases: EP and DTP. In EP, users randomly select one of the K channels and send a preamble over it. The BS then estimates the number of preambles in each channel and broadcasts this information to all users. After that, users are divided into two groups. The first group (G_S) includes users in whose channels one preamble was transmitted. All other users fall into the second group (G_C). Channels selected by users in G_S are assigned to them, and all other channels belong to the second group.

Then comes DTP phase. G_S users transmit data with a probability of one. Users of the G_C decide whether to transmit data to them with a probability equal to $p_{DTP} = \min\left\{1, \dfrac{K - |G_S|}{|G_C|}\right\}$. Users of the G_C group who decide to transmit data randomly select one of the channels of the second group and transmit their data. The base station then informs all users about the events that have occurred in each channel via the feedback channel.

Consider an example of the algorithm shown in Fig. 1.

The system has three data channels. *Consider the first frame*. In the first channel in the exploration



■ ***Fig. 1.*** Example of the algorithm's lossy work phase users U_1 and U_4 decided to send their preambles, in the second channel user U_3 decided to send a preamble, in the third channel users U_2 and U_5 decided to send preambles. After evaluating the preambles in each channel, the base station will return to all users the next set of data {2, 1, 2}. Thus, channels one and three belong to group two, hence users U_1, U_2, U_4 and U_5 also belong to the G_C. Channel two belongs to group one and also user U_3 belongs to G_S.

This is followed by the data transmission phase, in which the user from the first group remains in the same channel and transmits with probability equal to one. Users of the second group randomly decide whether or not to send data to them. In this case, the transmission probability will be equal to $p_{DTP} = \min\left\{1,\ \frac{2}{4}\right\} = 0.5$. Assume that users U_1 and U_5 decide not to transmit, but users U_2 and U_4 decide to transmit and randomly reselect one of the channels of group two. Let user U_2 reselect the first channel, and user U_4 reselect the third channel. Thus, as a result, the "Success" event will occur in all channels.

Consider the next frame. Suppose that in the exploration phase, users U_8 and U_9 decide to transmit their preambles on the first channel, users U_7 and U_{10} on the second channel, and user U_6 on the third channel. Then, the base station, having estimated the number of received preambles in each channel, returned the following data set to all users {2, 2, 1}. Thus, channels one and two belong to group two, hence users U_7, U_8, U_9 and U_{10} also belong to the G_C. Channel three belongs to group one, and user U_6 belongs to G_S.

This is followed by the data transmission phase, in which the user from the first group remains in the same channel and transmits with probability equal to one. Users of the second group randomly decide whether or not to send data to them. In this case, the probability of transmission will be equal to $p_{DTP} = \min\left\{1,\ \frac{2}{4}\right\} = 0.5$. Assume that users U_7 and U_8 decide not to transmit, users U_9 and U_{10} decide to transmit and randomly reselect one of the channels of group two. Let both users U_9 and U_{10} reselect the second channel. Thus, the event "Empty" occurred in the first channel, the event "Conflict" occurred in the second channel, and the event "Success" occurred in the third channel.

Consider the third frame. Assume that in the exploration phase, users U_{11} and U_{12} decide to transmit preambles on the first channel, user U_{13} transmits the preamble on the second channel. Then, the base station, having estimated the number of received preambles in each channel, returned to all users the following data set {2, 1, 0}. Thus, channels one and three belong to group two, hence users U_{11} and U_{12} belong to the G_C. Channel two belongs to group one and also user U_{13} belongs to G_S.

This is followed by the data transmission phase, in which the user from the first group remains in the same channel and transmits with probability equal to one. The users of group two randomly decide to send data to them or not. In this case, the probability of transmission will be equal to $p_{DTP} = \min\left\{1,\ \frac{2}{2}\right\} = 1$. Assume that user U_{11} decides to transmit and randomly reselects the third channel. User U_{12} decided to transmit and randomly reselected the first channel. Thus, the "Success" event occurred in all channels.

Let us analyze for the algorithm with a finite number of channels. By analogy with [12], we will consider the normalized throughput (per channel) and denote it as $T(\lambda, K)$.

Throughput per channel is calculated as

$$T(\lambda,\ K) = \frac{E\left[N_t\right]}{K}, \tag{1}$$

where N_t is the number of users who logged out of the system at time t, $N_t \in \{0,\ 1,\ 2,\ \ldots,\ K\}$; K is the number of channels in the system; λ is the intensity of the input arrival rate in the system, which affects the distribution of the random variable N_t.

Denote by N_t^i the number of users leaving channel I at time t, then $N_t = N_t^{(1)} + N_t^{(2)} + \ldots + N_t^{(K)}$. Then from (1) it follows:

$$T(\lambda) = \frac{E\left[N_t^{(1)} + N_t^{(2)} + \ldots + N_t^{(K)}\right]}{K} = \frac{\sum_{i=1}^{K} E\left[N_t^{(i)}\right]}{K}.$$

It might be noted that $E\left[N_t^{(1)}\right] = E\left[N_t^{(2)}\right] = \ldots = E\left[N_t^{(K)}\right]$. Then:

$$T(\lambda) = E\left[N_t^{(1)}\right].$$

Taking into account the fact that only message one user can be successfully transmitted in one channel, then $E\left[N_t^{(1)}\right] = \Pr\left\{N_t^{(1)} = 1\right\}$. Thus, we get that:

$$T(\lambda) = \Pr\left\{N_t^{(1)} = 1\right\}.$$

Next, we will show how to calculate this probability for channel number 1. For a channel with other numbers, the probability is calculated similarly. Note the following:

$$\Pr\left\{N_t^{(1)}=1\right\}=\Pr\left\{N_t^{(1)}=1,\ S_{EP}\right\}+\Pr\left\{N_t^{(1)}=1,\ S_{DTP}\right\},$$

where S_{EP} is success in the first phase (EP); S_{DTP} is success in the second phase (DTP).

Success in the first phase occurs only if the channel in question has been selected by one user. Given *Assumption 4*, the value of this probability can be calculated as

$$\Pr\left\{N_t^{(1)}=1,\ S_{EP}\right\}=\lambda e^{-\lambda}.$$

If there was no success in a given channel in the first phase, then success in the second phase depends on the number of channels in which there was no success, let's denote the number of such channels as L, then:

$$\Pr\left\{N_t^{(1)}=1,\ S_{DTP}\right\}=\sum_{l=1}^{K}\Pr\left\{N_t^{(1)}=1,\ S_{DTP},\ L=l\right\}. \tag{2}$$

Next, we will show how to calculate the terms from the sum in expression (2), for each l. Denote by $\Pr\{S_{EP},\ W = K - l\}$ the probability that the event "Success" occurred in $K - l$ channels during the exploration phase.

If $l = 1$, then in all other channels except the current one there should be a "Success" event, therefore

$$\Pr\left\{S_{EP},\ W=K-1\right\}=\left(\lambda e^{-\lambda}\right)^{K-1}.$$

Let i_1 users arrive at the input of the current channel. We write the probability of such an event as: $\Pr\left\{entered\ i_1\ users\right\}=\frac{\lambda^{i_1}}{i_1!}e^{-\lambda}$. During the data transmission phase, the current channel can have a "Success" event if two events occur:

— at the exploration phase of the current channel there was an event "Conflict" ($i_1 \geq 2$);

— during the data transmission phase, only one of the users participating in the "Conflict" event during the exploration phase will make a decision to transmit in the current channel. Since in this case, the users make a decision to transmission with the probability $\frac{1}{i_1}$. So, the probability of such an event is $\Pr\left\{S_{DTP}\mid i_1\right\}=C_{i_1}^{1}\frac{1}{i_1}\left(1-\frac{1}{i_1}\right)^{i_1-1}=\left(1-\frac{1}{i_1}\right)^{i_1-1}$.

Taking into account the introduced notation, we obtain:

$$\Pr\left\{N=1,\ S_{DTP},\ L=1\right\}=\Pr\left\{S_{EP},\ W=K-1\right\}\sum_{i_1=2}^{\infty}\Pr\left\{S_{DTP}\mid i_1\right\}\Pr\left\{entered\ i_1\ users\right\}=$$

$$=\lambda^{K-1}e^{-\lambda K}\sum_{i_1=2}^{\infty}\left(1-\frac{1}{i_1}\right)^{i_1-1}\frac{\lambda^{i_1}}{i_1!}.$$

If $l = 2$, then in all channels, except for the current and one more, there should be a "Success" event, therefore

$$\Pr\left\{S_{EP},\ W=K-2\right\}=C_{K-1}^{K-2}\left(\lambda e^{-\lambda}\right)^{K-2}.$$

Let i_1 users arrive at the input of the current channel, and i_2 users at the input of another. We write the probability of such an event as:

$$\Pr\left\{entered\ i_1\ users\right\}\Pr\left\{entered\ i_2\ users\right\}=\frac{\lambda^{i_1}}{i_1!}e^{-\lambda}\frac{\lambda^{i_2}}{i_2!}e^{-\lambda}.$$

During the data transmission phase, the current channel can have a "Success" event if two events occur:

— $i_1 \neq 1$ and $i_2 \neq 1$ and $i_1 + i_2 \geq 2$;

— during the data transmission phase, only one of the users participating in the "Conflict" event during the exploration phase will make a decision to transmit in the current channel. Since in this case the users decide to transmit in the current channel with the probability $\frac{1}{2}\cdot\frac{2}{i_1+i_2}$. Then, the probability of the event "Success" in the current channel is equal to $\Pr\{S_{DTP} \mid i_1, i_2\} = C^1_{i_1+i_2}\frac{1}{i_1+i_2}\left(1-\frac{1}{i_1+i_2}\right)^{i_1+i_2-1} = \left(1-\frac{1}{i_1+i_2}\right)^{i_1+i_2-1}$.

Taking into account the introduced notation, we obtain:

$$\Pr\{N=1,\ S_{DTP},\ L=2\} = C^{K-2}_{K-1}(\lambda e^{-\lambda})^{K-2}\sum_{\substack{i_1=0\\ i_1\neq 1\\ i_1+i_2\neq 0}}^{\infty}\sum_{\substack{i_2=0\\ i_2\neq 1\\ i_1+i_2\neq 0}}^{\infty}\left(1-\frac{1}{i_1+i_2}\right)^{i_1+i_2-1}\frac{\lambda^{i_1}}{i_1!}e^{-\lambda}\frac{\lambda^{i_2}}{i_2!}e^{-\lambda} =$$

$$= C^{1}_{K-1}(\lambda e^{-\lambda})^{K-2}\sum_{\substack{i_1=0\\ i_1\neq 1\\ i_1+i_2\neq 0}}^{\infty}\sum_{\substack{i_2=0\\ i_2\neq 1\\ i_1+i_2\neq 0}}^{\infty}\left(1-\frac{1}{i_1+i_2}\right)^{i_1+i_2-1}\frac{\lambda^{i_1}}{i_1!}e^{-\lambda}\frac{\lambda^{i_2}}{i_2!}e^{-\lambda} =$$

$$= C^{1}_{K-1}\lambda^{K-2}e^{-\lambda K}\sum_{\substack{i_1=0\\ i_1\neq 1\\ i_1+i_2\neq 0}}^{\infty}\sum_{\substack{i_2=0\\ i_2\neq 1\\ i_1+i_2\neq 0}}^{\infty}\left(1-\frac{1}{i_1+i_2}\right)^{i_1+i_2-1}\frac{\lambda^{i_1+i_2}}{i_1!i_2!}.$$

If $l = 3$, then in all channels, except for the current one and two more, there should be a "Success" event, therefore

$$\Pr\{S_{EP},\ W=K-3\} = C^{K-3}_{K-1}\left(\lambda e^{-\lambda}\right)^{K-3}.$$

Let i_1 users arrive at the input of the current channel, and i_2 and i_3 users, respectively, at the input of the other two channels. We write the probability of such an event as:

$$\Pr\{entered\ i_1\ users\}\Pr\{entered\ i_2\ users\}\Pr\{entered\ i_3\ users\} = \frac{\lambda^{i_1}}{i_1!}e^{-\lambda}\frac{\lambda^{i_2}}{i_2!}e^{-\lambda}\frac{\lambda^{i_3}}{i_3!}e^{-\lambda}.$$

During the data transmission phase, the current channel can have a "Success" event if two events occur:

— $i_1 \neq 1$ and $i_2 \neq 1$ and $i_3 \neq 1$ and $i_1 + i_2 + i_3 \geq 2$;

— during the data transmission phase, only one of the users participating in the "Conflict" event during the exploration phase will make a decision to transmit in the current channel. Since in this case the users decide to transmit in the current channel, the probability depends on the sum of the number of users in the channels under consideration. If $2 \leq i_1 + i_2 + i_3 \leq 3$, then the probability of the "Success" event in the current channel is $\Pr\{S_{DTP} \mid i_1, i_2, i_3, L=3\} = (i_1+i_2+i_3)\frac{1}{3}\left(1-\frac{1}{3}\right)^{i_1+i_2+i_3-1}$. If $i_1 + i_2 + i_3 > 3$, then the probability of the "Success" event in the current channel is $\Pr\{S_{DTP} \mid i_1, i_2, i_3, L=3\} = \left(1-\frac{1}{i_1+i_2+i_3}\right)^{i_1+i_2+i_3-1}$.

We introduce the following indicator function $I\{statement\} = \begin{cases}1, & true\\ 0, & false\end{cases}$.

Taking into account the introduced notation, we obtain:

$$\Pr\{N=1,\ S_{DTP},\ L=3\} =$$

$$= C^{K-2}_{K-1}(\lambda e^{-\lambda})^{K-3}\sum_{\substack{i_1=0\\ i_1\neq 1\\ i_1+i_2+i_3\neq 0}}^{\infty}\sum_{\substack{i_2=0\\ i_2\neq 1\\ i_1+i_2+i_3\neq 0}}^{\infty}\sum_{\substack{i_3=0\\ i_3\neq 1\\ i_1+i_2+i_3\neq 0}}^{\infty}\Pr\{S_{DTP} \mid i_1, i_2, i_3, L=3\}\frac{\lambda^{i_1}}{i_1!}e^{-\lambda}\frac{\lambda^{i_2}}{i_2!}e^{-\lambda}\frac{\lambda^{i_3}}{i_3!}e^{-\lambda} =$$

$$= C_{K-1}^{2}(\lambda e^{-\lambda})^{K-3} \sum_{\substack{i_1=0\\ i_1\neq 1\\ i_1+i_2+i_3\neq 0}}^{\infty} \sum_{\substack{i_2=0\\ i_2\neq 1\\ i_1+i_2+i_3\neq 0}}^{\infty} \sum_{\substack{i_3=0\\ i_3\neq 1\\ i_1+i_2+i_3\neq 0}}^{\infty} \Pr\{S_{DTP} \mid i_1, i_2, i_3, L=3\} \frac{\lambda^{i_1}}{i_1!}e^{-\lambda}\frac{\lambda^{i_2}}{i_2!}e^{-\lambda}\frac{\lambda^{i_3}}{i_3!}e^{-\lambda} =$$

$$= C_{K-1}^{2}\lambda^{K-3}e^{-\lambda K} \sum_{\substack{i_1=0\\ i_1\neq 1\\ i_1+i_2+i_3\neq 0}}^{\infty} \sum_{\substack{i_2=0\\ i_2\neq 1\\ i_1+i_2+i_3\neq 0}}^{\infty} \sum_{\substack{i_3=0\\ i_3\neq 1\\ i_1+i_2+i_3\neq 0}}^{\infty} \Pr\{S_{DTP} \mid i_1, i_2, i_3, L=3\} \frac{\lambda^{i_1+i_2+i_3}}{i_1!i_2!i_3!} =$$

$$= C_{K-1}^{2}\lambda^{K-3}e^{-\lambda K} \sum_{\substack{i_1=0\\ i_1\neq 1\\ i_1+i_2+i_3\neq 0}}^{\infty} \sum_{\substack{i_2=0\\ i_2\neq 1\\ i_1+i_2+i_3\neq 0}}^{\infty} \sum_{\substack{i_3=0\\ i_3\neq 1\\ i_1+i_2+i_3\neq 0}}^{\infty} \left(I\{i_1+i_2+i_3 \le 3\}\left((i_1+i_2+i_3)\frac{1}{3}\left(1-\frac{1}{3}\right)^{i_1+i_2+i_3-1}\right)+\right.$$

$$\left. + I\{i_1+i_2+i_3 > 3\}\left(\left(1-\frac{1}{i_1+i_2+i_3}\right)^{i_1+i_2+i_3-1}\right)\right)\frac{\lambda^{i_1+i_2+i_3}}{i_1!i_2!i_3!}.$$

Then we can write in general:

$$T(\lambda) = \lambda e^{-\lambda} + \sum_{l=1}^{K} C_{K-1}^{l-1}\lambda^{K-l}e^{-\lambda K} \sum_{\substack{i_1=0\\ i_1\neq 1\\ \sum_{j=1}^{l} i_j\neq 0}}^{\infty} \cdots \sum_{\substack{i_l=0\\ i_l\neq 1\\ \sum_{j=1}^{l} i_j\neq 0}}^{\infty} \left(I\left\{\sum_{j=1}^{l} i_j \le l\right\} \sum_{j=1}^{l} i_j \frac{1}{l}\left(1-\frac{1}{l}\right)^{\sum_{j=1}^{l} i_j} + \right.$$

$$\left. + I\left\{\sum_{j=1}^{l} i_j > l\right\}\left(1-\frac{1}{\sum_{j=1}^{l} i_j}\right)^{\sum_{j=1}^{l} i_j - 1}\right)\frac{\lambda^{\sum_{j=1}^{l} i_j}}{\prod_{j=1}^{l} i_j!}, \qquad (3)$$

where $I\{statement\} = \begin{cases} 1, \; true \\ 0, \; false \end{cases}$.

Formula (3) can be used to calculate for any number of channels.

Figure (2) shows the results obtained by (3) for a different number of channels depending on the throughput per channel.

From Fig. 2, it can be seen that the throughput limit is reached when the input arrival rate is greater than 1. The values of the maximum throughput and the corresponding input arrival rate are presented in Table 1.

The values presented in this table will be used as a parameter for the lossless algorithm.

Analysis of a system without losses

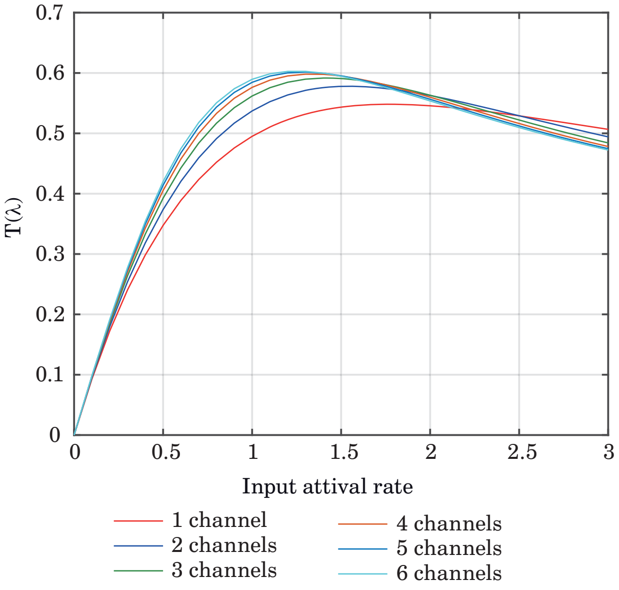
Let us describe a modification of the algorithm [12], in which users remain in the system until they successfully transmit a message (system without losses).

To do this, we add one more assumption to the system.

Assumption 6. The number of active users (having a message ready for transmission) is known to M.

According to *Assumption 1*, each frame consists of two phases: EP and DTP. This algorithm repeats the description structure of the phases of the previous algorithm, but the transmission probability in the EP phase is $p_{EP} = \min\left\{1, \frac{KG}{M}\right\}$, where G is the algorithm parameter. The user tries to send his message until he receives confirmation of successful transmission.

Consider an example of the algorithm shown in Fig. 3.



■ ***Fig. 2.*** Throughput per channel on the input arrival rate

Consider the first frame. Suppose that by the beginning of this frame there are messages from users U_1, U_2, U_3, U_4, U_5 and everyone decided to transmit. Let in the EP users U_4 and U_5 decide to transmit in the first channel, users U_3 in the second channel, users U_1 and U_2 in the third channel. BS, having estimated the number of preambles in each channel, will return the following information to all users

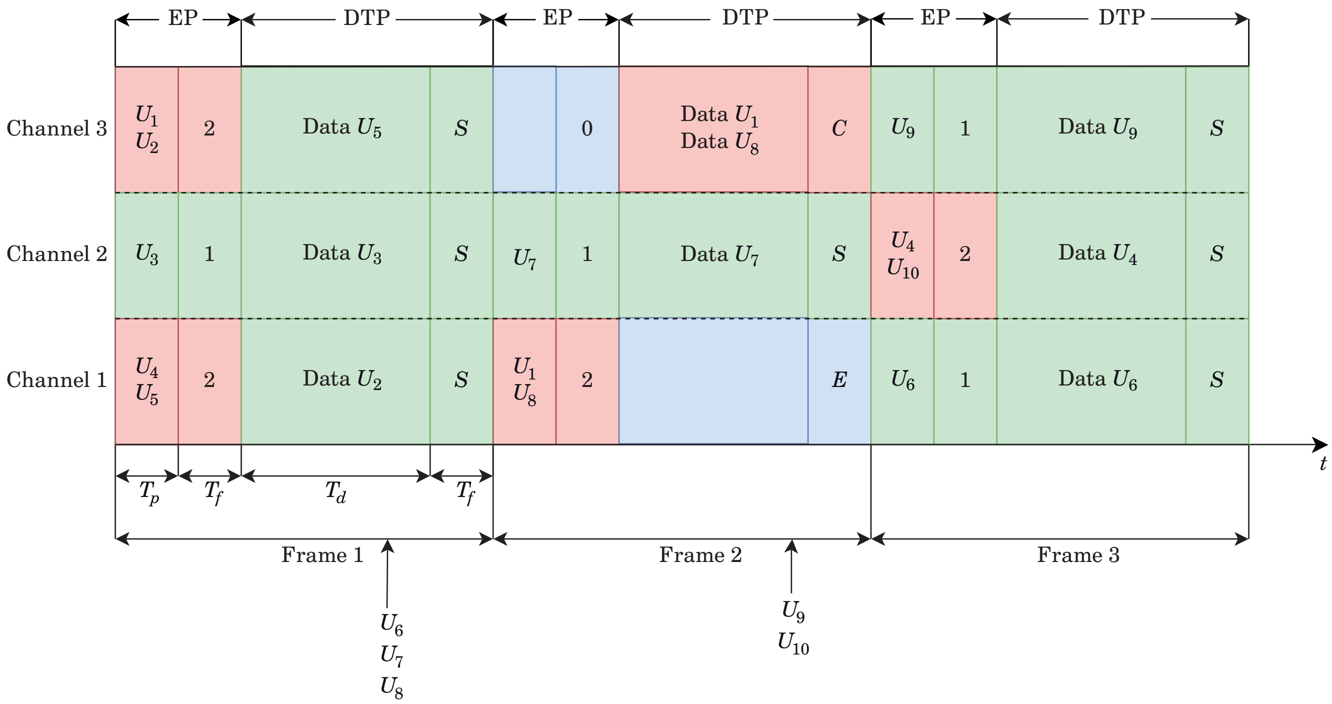
■ ***Table 1.*** *Maximum throughput*

Number channel	max $T(\lambda)$	λ
1	0.5482	1.775
2	0.578	1.55
3	0.5917	1.415
4	0.5983	1.34
5	0.6015	1.285
6	0.6031	1.25

{2, 1, 2}. Thus, user U_3 belongs to the G_S, and users U_1, U_2, U_4, U_5 belong to the G_C.

Then the DTP follows, in which the U_3 user transmits with probability one in the second channel. Users of the G_C with a probability of $p_{DTP} = \min\left\{1, \dfrac{2}{4}\right\} = 0.5$ decide to send them data in this frame or not. Suppose that users U_1 and U_4 decided not to transmit, and users U_2 and U_5 decided to transmit and reselected channels 1 and 3, respectively. As a result, the “Success” event will occur in all three channels.

Consider the second frame. At the beginning of this frame, there are messages from users U_1 and U_4 from the previous frame, as well as new ones from users U_6, U_7 and U_8. In the EP, users decide to transmit preambles or not with a probability equal



■ ***Fig. 3.*** Example of the lossless algorithm’s work to $p_{EP} = \min\left\{1, \frac{3}{5}\right\} = 0.6$. Suppose that users U_4 and U_6 decided not to transmit, and users U_1, U_7 and U_8 decided to transmit. User U_7 chose the second channel, and users U_1 and U_8 chose the first channel. The BS, having estimated the number of preambles in each channel, will return the following information to all users {2, 1, 0}. Thus, user U_7 belongs to the G_S, and users U_1, U_8 to the G_C.

Then the DTP follows, in which the user U_7 transmits with probability one in the second channel. In this case, users of G_C transmit data with a probability of $p_{DTP} = \min\left\{1, \frac{2}{2}\right\} = 1$. Let's assume that users U_1 and U_8 have both re-selected the third channel. As a result, the "Empty" event will occur in the first channel, the "Success" event in the second channel, and the "Conflict" event in the third channel.

Consider the third frame. At the beginning of this frame there are messages from users U_1, U_4, U_6, U_8 from the previous frames, as well as new ones from users U_9 and U_{10}. Suppose that users U_4, U_6, U_9 and U_{10} decide to transmit in EP. User U_6 chose the first channel, users U_4 and U_{10} chose the second channel, and U_9 chose the third channel. BS, having estimated the number of preambles in each channel, will return the following information to all users {1, 2, 1}. Thus, users U_6 and U_9 belong to the G_S, and users U_4, U_{10} to the G_C.

This is followed by the DTP. Suppose that user U_{10} decided not to transmit, and user U_4 decided to transmit and re-selected the second channel. As a result, the "Success" event will occur in all three channels.

For a system with repeated transmissions, we introduce two characteristics [16]:

— the dependence of the average delay on input arrival rate $d(\lambda)$;

— the limiting input arrival rate at which the system works stably $\lambda_{cr} \triangleq \sup\{\lambda : d(\lambda) < \infty\}$.

Let us show how, for a system described by a set of assumptions, λ_{cr} can be calculated.

The number of active users during system operation can be described by the following recursive equation:

$$M_{t+1} = M_t - N_t + V_t,$$

where M_t and M_{t+1} are the number of users in the system at time t and $t+1$, respectively; N_t is the number of users who logged out of the system at time t, $N_t \in \{0, 1, 2, \ldots, K\}$, K is the number of channels in the system; V_t is the number of users who arrived at time t, distributed according to the Poisson law with the parameter λ.

It follows from this description that the sequence of random variables M_t defines a homogeneous irreducible aperiodic Markov chain.

To analyze stability, we calculate the mathematical expectation $E[N_t|M_t = m]$. It follows from the Foster criterion (see, for example, [17]) that λ_{cr} can be defined as the following limit:

$$\lambda_{cr} = \frac{\lim_{m\to\infty} E\left[N_t \mid M_t = m\right]}{K}. \tag{4}$$

Denote by $N_t^{(i)}$ the number of users leaving channel i at time t, then $N_t = N_t^{(1)} + N_t^{(2)} + \ldots + N_t^{(K)}$. Then from (4) it follows:

$$\lambda_{cr} = \lim_{m\to\infty} \frac{E\left[N_t^{(1)} + N_t^{(2)} + \ldots + N_t^{(K)} \mid M_t = m\right]}{K} = \frac{\lim_{m\to\infty} \sum_{i=1}^{K} E\left[N_t^{(i)} \mid M_t = m\right]}{K} = \frac{\sum_{i=1}^{K} \lim_{m\to\infty} E\left[N_t^{(i)} \mid M_t = m\right]}{K}.$$

It can be noted that for any value of m

$$E\left[N_t^{(1)} \mid M_t = m\right] = E\left[N_t^{(2)} \mid M_t = m\right] = \ldots = E\left[N_t^{(K)} \mid M_t = m\right].$$

Then:

$$\lambda_{cr} = \lim_{m\to\infty} E\left[N_t^{(1)} \mid M_t = m\right].$$

Taking into account the fact that only message one user's can be successfully transmitted in one channel, then $E\left[N_t^{(1)} \mid M_t = m\right] = \Pr\left\{N_t^{(1)} = 1 \mid M_t = m\right\}$.

Then:

$$\lambda_{cr} = \lim_{m\to\infty} \Pr\left\{N_t^{(1)} = 1 \mid M_t = m\right\}. \tag{5}$$

To calculate (5), we formulate and prove the following assertion.

Statement 1. Let there be m active users in some frame with number t. Then, as $m \to \infty$, each channel independently receives a Poisson input flow with intensity 1.

Proof: Let's consider the channel number i. Let $M_t = m$ and $m \ge K$, $m \ge G$, then all users decide to transmit with probability $p_{EP} = \frac{KG}{m}$ and those users who decide to transmit will choose the i-th channel with probability $p = \frac{1}{K}$. Denote by $Z_t^{(i)}$ the number of such users. The random variable $Z_t^{(i)}$ is distributed according to the Binomial distribution with parameters $\frac{G}{m}$ and m, then $E\left[Z_t^{(i)}\right] = \frac{G}{m} m = G$. If $m \to \infty$, then the Binomial distribution becomes a Poisson distribution with the same expectation.

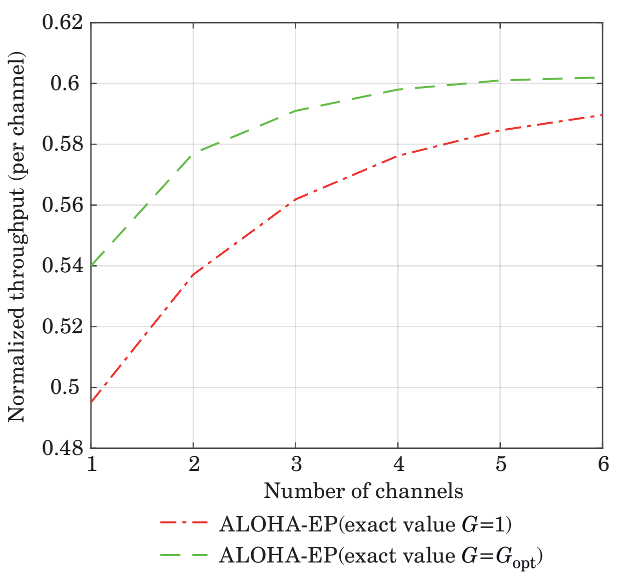
It follows from the statement that the value of the limit (5) can be calculated by substituting the value $\lambda = G$ into (3). Thus, using (3), we can calculate the value of λ_{cr}. The optimal value of G that maximizes the value of λ_{cr} is defined as

$$G_{\text{opt}} = \arg\max_{\lambda} T(\lambda).$$

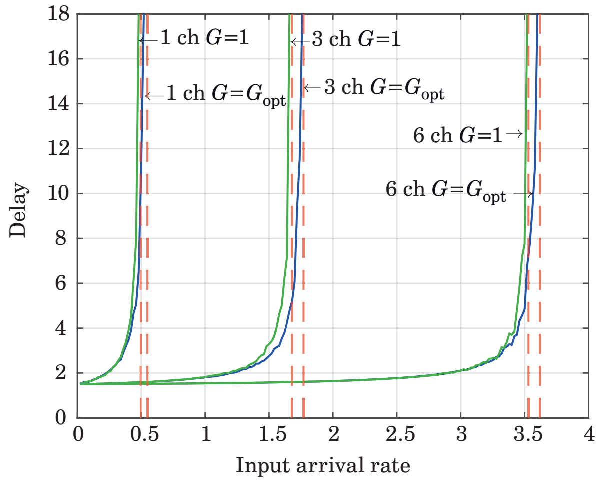
Figure 3 shows that the maximum limiting intensity with a small number of channels is achieved at the parameter $G_{\text{opt}} > 1$.

On Fig. 4 shows the results of calculating the critical input intensity up to which the system is stable according to formula (3) for the values of the number of channels 1, 2, 3, 4, 5 and 6. It is also shown that the optimal choice of the G parameter makes it possible to increase the throughput with a small number of channels. With an increase in the number of channels, this gain decreases, and with a large number of channels, the optimal value is $G = 1$.

To numerically calculate the average delay in the system, it is necessary to find the stationary distribution of the Markov chain with a countable number of states and cumbersome expressions for calculating the transition probabilities. Therefore, to illustrate the effect of the parameter G on the delay, a Java program was developed and implemented that simulates the operation of the system, taking into account the assumptions described earlier. The results obtained by simulation modeling are presented in Fig. 5. The number of experiments was chosen such that the value of the confidence interval coincides with the thickness of the graph. As the throughput is approached, the delay increases and then tends to infinity, in which case the system is not stable.



■ ***Fig. 4.*** Throughput on the number of channels



■ ***Fig. 5.*** Delay in system without losses at $G = 1$ and G = opt from input arrival rate per channel

Conclusion

The paper considers a model of a random multiple access system based on ALOHA with exploration phase from [12], where the calculation of the throughput per channel for an infinite number of channels was proposed. A method for analyzing the characteristics of the algorithm is proposed, which, in contrast to [12], makes it possible to calculate the throughput per channel for a given number of channels. It is shown that the maximum throughput with a finite number of channels is achieved at the input intensity $\lambda > 1$.

A modification of the algorithm for lossless operation is proposed by using repeated transmissions and changing the operation of the exploration phase to stabilize the operation of the algorithm. It is shown that the system provides stable operation when the input arrival rate does not exceed the maximum throughput. The dependence of delays in the system, obtained using simulation modeling, is also given.

The model considered in the paper and its modification is based on 3 unrealistic assumptions: an infinite number of preambles, the availability of information on the number of active users, and no time is spent on the exploration phase. These assumptions can be consistently discarded in further studies. Can use the method of estimating the number of active users (see, for example, [18–20]). If the number of preambles is limited, then the results of the above analysis will be an upper bound on the throughput. Also in the future, it is necessary to take into account the duration of the exploration phase and the response of the base station.

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Анализ и стабилизация многоканального алгоритма ALOHA с использованием фазы исследования на основе преамбул

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Введение: в настоящее время активно используются устройства интернета вещей, функционирующие в рамках сценариев массивных машинных коммуникаций. Взаимодействие устройств осуществляется алгоритмами случайного множественного доступа, имеющими ограниченную пропускную способность. Для увеличения пропускной способности можно использовать ортогональные преамбулы в классе алгоритмов ALOHA. **Цель:** провести анализ алгоритмов на базе ALOHA, использующих фазу исследования, и вычислить характеристики для алгоритма с потерями и без потерь при конечном числе каналов. **Результаты:** описана модель системы случайного доступа для передачи данных по общему каналу связи с использованием ортогональных преамбул и фазы исследования. Получена формула для численного расчета пропускной способности на канал алгоритма с потерями при бесконечном числе преамбул и заданном конечном числе каналов. Представлены результаты расчета для нескольких значений числа независимых каналов. Предложена и описана модификация алгоритма, использующая фазу исследования и повторные передачи. Данная система может работать без потерь. Для этой системы приведен анализ предельной пропускной способности, до которой система работает стабильно. Также показаны значения средней задержки для алгоритма, полученные имитационным моделированием. При уменьшении числа доступных преамбул данные результаты можно использовать в качестве верхней границы пропускной способности системы. **Практическая значимость:** полученные результаты позволяют оценить потенциальные возможности увеличения пропускной способности систем случайного множественного доступа в сетях 6G за счет применения фазы исследования.

Ключевые слова — многоканальная ALOHA, предельная интенсивность выходного потока, случайный множественный доступ, стабильность, массовая межмашинная связь, интернет вещей.

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