


Analytical Model of Information Exchange in the Low-Orbit Segment of Heterogeneous Networks Using Discrete Beam Hopping Technology

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ABSTRACT

Low-orbit satellite communication systems are an important element of geographically distributed heterogeneous networks (HetNets) and enable global fixed and personal mobile communications across the entire surface of the Earth. The article is devoted to the study of the average delay of information exchange in “down” communication line between repeater satellite with phased array antenna with discrete beam hopping (DBH) on board and user terminals. A mathematical model as a queuing system (QS) has been developed to calculate the average delay time of information transmission in “down” communication line. Analytical expressions have been obtained that relate the value of the average delay time to the main system parameters: channel bandwidth, number of scanning beams and of time slots in the scan frame, etc. for two beam scanning algorithms: a static and a dynamic one. The dependencies illustrating the advantages of using the technology of discretely scanning beams are given, including estimate of the gain in the presence of several beams. Estimates of the number of beams of phased array antenna depending on the limitations on its size, antenna pattern and the size of the scanning sector are given, and an estimate of the throughput of the communication line is obtained depending on the number of beams.

Keywords: Heterogeneous networks; Low-orbit satellite communication systems; Phased array antenna; Multibeam antenna systems; Discrete beam hopping; Average delay time.

INTRODUCTION

The current stage of development of society is characterized by global digital transformation (Cioca *et al.* 2024; Maheshwari 2019; Norton and Shroff 2018). In turn, the introduction and use of digital technologies is possible only in the presence of developed information systemsones, one of the main elements of which is telecommunications infrastructure. Such infrastructure should provide users with various services, ensuring minimal signal delays, high data transfer rates, and reliable delivery of information to consumers. To ensure these indicators, it is necessary to combine various communication networks into a single telecommunication network, i.e., to create an integrated communication network that can provide a full range of telecommunications services (Arnold and Hugo 2018; Jia *et al.* 2024; Zang *et al.* 2022). Such a heterogeneous network (HetNet), consisting of various networks

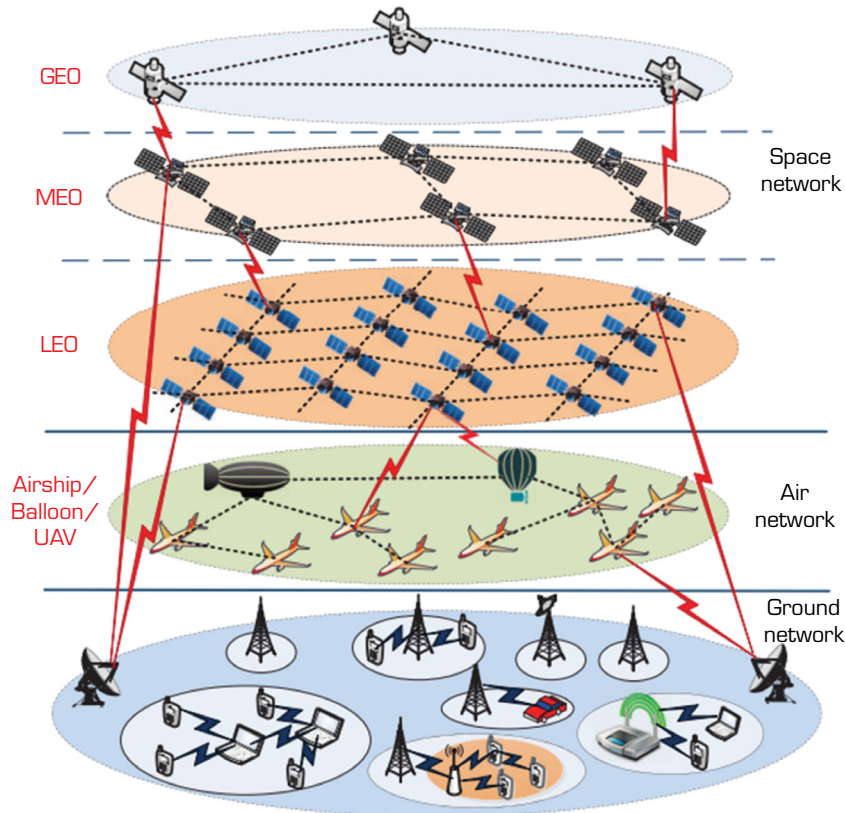
Received: Aug. 18, 2025 | **Accepted:** Oct. 29, 2025

Peer Review History: Single Blind Peer Review.

Section editor: Luiz Martins-Filho 



operating on different technologies and standards, should function as a single system, ensuring a seamless transition from one network to another (Bosch *et al.* 2018; Cespedes, Shen 2015; Zia *et al.* 2009). Geographically distributed HetNets are of particular interest in the context of global digitalization, which provide global coverage of territories and the ability to provide a wide range of communication services for various subscribers. An example of such a HetNet is Space-Air-Ground Integrated Networks (SAGIN), the emergence of which became possible due to the development of telecommunications, space, and aviation technologies (Chen *et al.* 2023; Liu *et al.* 2018; Sheng *et al.* 2022). As follows from Fig. 1, SAGIN is based on three segments: satellite, air, and ground, which can operate jointly and independently of each other.



Source: Retrieved from Liu *et al.* (2018).

Figure 1. SAGIN network architecture.

The upper level of SAGIN (Space Network) consists of communication satellites in different orbits: geostationary earth orbit (GEO), medium earth orbit (MEO) and Low-orbit satellite communication systems (LEO), which can be all-electric (Abbasrezaee and Saraaeb 2021).

The middle level (Air Network) is air mobile systems (aircrafts, balloons, airships, and unmanned aerial vehicles). Air Network, the basic elements of which are high and low altitude platforms, has a lower cost than the Space Network and allow for regional wireless access (Arum *et al.* 2020; Chechin *et al.* 2022).

The ground segment (Ground Network) consists of terrestrial communication systems: cellular, mobile, and ad hoc networks.

LEO satellite communication systems are the only communication networks that can provide global fixed and personal mobile communications across the entire surface of the Earth. This quality, combined with low latency of information transmission, due to the success of the development of modern technologies for the production of communications satellites (CS), on-board radio engineering systems (OBRES), and user terminals (UTs), is a great advantage in the construction of communication networks to provide integrated services for commercial and special use.

The requirements for improving the quality and range of communication services provided have set the task for design companies to develop LEO that would ensure the speed of information exchange with UT of about $100 \text{ Mbit}\cdot\text{s}^{-1}$ with the provision of a wide range of services dictated by the modern communication services market, at an acceptable cost of ground UTs and communication services. As a result, such new LEO as Starlink, O3b (O3b mPOWER), and OneWeb have already been put into commercial operation, and a number of systems are in the process of design and testing: Kuiper, Thousand Sails Constellation (Qianfan), “Guowang” (formerly Hongyun) (Kulu 2024; Neinaiaie and Kassas 2022; Nystrom *et al.* 2025; Osoro and Oughton 2021). The common solution implemented in all these projects is the use of one or more onboard multibeam antenna systems (MASs) based on active phased array antennas (PAAs), with each PAA forming several independent beams to service UT in the service area. The existing LOSCS Iridium and Globalstar use fixed antenna beams. However, such a design of UT information exchange system does not allow achieving high throughput due to the fact that the power of CS transmitters is used inefficiently to irradiate the borrowed surface of those areas where there are no active subscribers. An increase in the throughput of the satellite communication channel can be achieved by using discrete beam hopping (DBH) technology, in which the power of CS transmitters is concentrated precisely in those areas where there are active subscribers. When using DBH, the main task is to ensure a given level of service for each segment (cell) of the service area by rationally distributing CS capacity in accordance with the information exchange protocol. The solution to this problem is associated with calculating the average delay time when transmitting information from CS to UT depending on the number of DBH, scanning through the ground cells of the service coverage, taking into account the specified restrictions on the time of information delivery.

There are many works in the scientific and technical literature devoted to the assessment of the throughput of CS with PAA, which consider such aspects as signal modulation, coding, multiple access methods, calculation of the energy characteristics of satellite channels, etc. (Elbert 2004; Kamnev *et al.* 2010; Kodheli *et al.* 2021; Minoli 2015; Richharia 1995, 2014; Roddy 2001; Mailloux 2009; Visser 2005). Separately, it is worth mentioning the work of Kodheli *et al.* (2021), which provides an overview of modern trends in the construction of satellite communication systems, including integration with 5G networks, on-board signal processing, communication protocols, antenna systems, etc. The issues of assessing the efficiency of using MAS on board CS for communication with UT are considered in sufficient detail in Anzalchi *et al.* (2010); Christopoulos *et al.* (2012); Greda *et al.* (2010); Kamnev *et al.* (2010); Richharia (2014); Wang *et al.* (2021); Wei *et al.* (2022); and Ye *et al.* (2020). The authors propose various solutions for adapting CS to traffic changes by appropriately adjusting the antenna beams. In particular, Anzalchi *et al.* (2010) analyzed the possibility of using DBH to ensure system flexibility to traffic changes and compared it with the case where such switching is absent. It is also worth noting the article by Feng *et al.* (2023), who analyzed the information exchange in communication lines “up” from subscribers to the repeater satellite. But when providing the “Internet Access” service, the volume of traffic to subscribers in the “down” line is about 75%, and in the “up” line about 25%. That is why Starlink uses three PAAs on the “down” line, and only one PAA on the “up” line.

Despite the practical value of the results obtained either as a result of iterative procedures or using simulation models, these works do not explicitly present the models and results that determine the technical appearance of OBRES CS: the optimal number of beams to achieve a given information transmission delay, taking into account the overhead costs and restrictions on the mass-dimensional characteristics of PAA.

In addition, since the study of information exchange using multi-beam antennas on CS is a fairly complex task, the vast majority of studies on the effectiveness of using MAS on board CS have been performed using simulation models. Although simulation modeling is one of the tools for analyzing and designing communication networks, it has a number of shortcomings that limit their practical application (Pegden *et al.* 1995; Shannon 1975). Therefore, an urgent task is to develop a mathematical model of information exchange in LOSCS using multi-beam PAA, including DBH, which would allow to obtain the dependence of the throughput and probabilistic-temporal characteristics of information exchange on the main system parameters in an analytical (explicit) form.

The purposes of this work are:

- Development of a mathematical model of the information exchange process in LOSCS in the “down” line CS-UT communication line using DBH technology on board in the form of a QS;

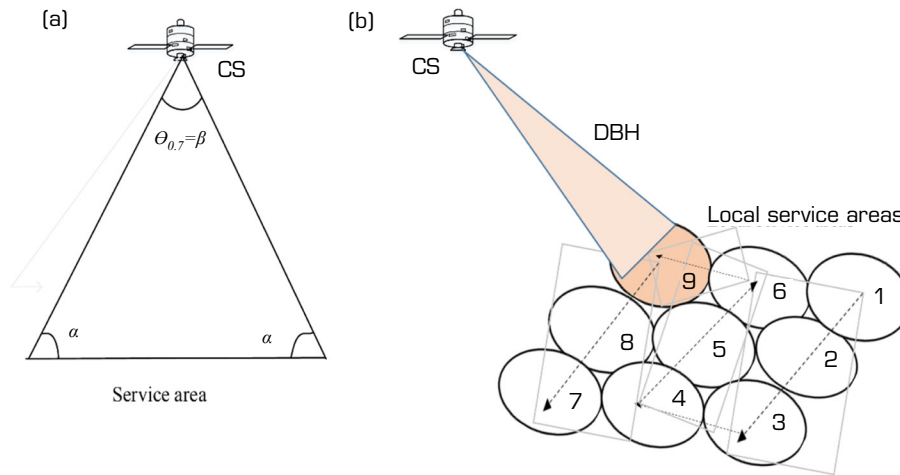


- Analysis of the characteristics of information exchange, primarily the average delay time of information transmission for different variants of DBH scanning over the service area and different numbers of DBH on CS;
- Evaluation of the gain when using DBH technology compared to an antenna with one global beam at a given viewing angle with a fixed CS transmitter power for the compared variants with different service costs of bandwidth for synchronization and the time of switching DBH from one cell to another.

The approach to the evaluation of the characteristics of information exchange proposed by the authors and the results obtained in the work with minimal changes can be used to analyze time delays in the communication channels of MEO-UTs and Air Mobile Systems-UTs.

THEORETICAL BASIS

Since the majority of communication services, for example, “Internet Access”, are dominated by traffic towards the subscriber, it is necessary to evaluate possible ways to increase the bandwidth of the CS-UTs communication channel. In general, the width $\Theta_{0.7}$ of antenna pattern CS should be equal to the angular size β of the service area visible from CS (Fig. 2a). For example, at an orbital altitude of 550 km, the diameter of the radio visibility zone on the Earth’s surface is 1,900 km, provided that the elevation angle α of UT antennas is not less than 250. The efficient operation of UT antennas with a flat phased array is possible at an elevation angle α of not less than 30°–40°.



Source: Elaborated by the authors.

Figure 2. Service area (a) and DBH usage pattern (b).

The throughput of CS-UT communication line is defined as Eq. 1 (Kamnev *et al.* 2010).

$$C = \frac{P_s}{h_n^2 k T} = \frac{P_t G_t S_r}{4\pi h_n^2 r^2 L k T} = \frac{P_t G_t G_r}{16\pi^2 h_n^2 r^2 L k T} = \frac{EIRP * Q}{k h_n^2 L_C L} = 2220.7 \frac{P_t D_r^2 K_i^*}{h_n^2 r^2 L k T \beta^2} \quad (1)$$

where P_s is the received signal power, $EIRP$ (Equivalent Isotropically Radiated Power) = $P_t G_t$, h_n^2 is the threshold signal-to-noise ratio, r is the length of radio line, S_r is the effective area of the receiving antenna, $Q = G_r / T$ is the quality factor of the receiving system, k is the Boltzmann constant, $T = T_a + T_e$ is the equivalent noise temperature of the receiving system, T_a is the total antenna losses and sky noise, $T_e = T_0 (F_{sys} - 1)$ is the receiver noise temperature, $T_0 = 290^\circ\text{K}$, $F_{sys} = 10^{NF/10}$ is the receiver noise ratio, and B_n is the noise bandwidth, which can be estimated as $(1.002 \div 1.57)B$, where B is the receiver bandwidth, P_t is the transmitter power, G_t

and G_r are the gain factors of transmitting and receiving antennas, respectively, L_c is the signal energy loss along the propagation path, and L is the additional losses in the communication line.

Analysis of the relation (1) shows that the most significant for increasing the capacity of CS-UT communication channel is the use of MAS and DBH (Kamnev *et al.* 2010). In this case, DBH scans the service area, divided into individual cells (Fig. 2b). The rationale for using DBH in CS-UT channel can be done quite simply by comparing it with an on-board antenna with one global beam covering the entire service area. When using one global transmitting beam on CS, each UT analyzes the group information flow and selects information according to its assigned individual frequency, time or code feature. If the information for each of the m for uniformly distributed over the service area UT, or, what is the same, the number of cells in the service area, is transmitted at a rate of C , then the capacity of the global beam will be mC . When using an m -beam transmitting antenna, the gain of each zonal beam will increase by m times compared to the global one, but in this case the transmitter power of the CS is divided between m beams, so the *EIRP* and, accordingly, the throughput of each zonal beam will be the same as that of the global one.

When transmitting address information intended for one or more closely located UTs, the following situation arises. If the group information flow is divided between the transmitting beams in such a way that only information intended for the UT of the zone it serves is sent to each zonal beam, then the multibeam transmitting antenna provides a gain in throughput of m times compared to a single-beam antenna. However, this gain can only be realized by using on-board packet switching. In what follows, when describing and analyzing the characteristics of information exchange in CS-UT communication channel, we will assume that PAA generally forms m beams, in which case the entire power of the CS transmitter is fully utilized and its throughput will be equal to m^2C , and the average speed of information transfer in each of the zones mC , which results in a gain in throughput of m times compared to a single global beam (Kamnev *et al.* 2010). When using DBH as a receiving beam, there is no gain in throughput (Kamnev *et al.* 2010).

The main advantage of DBH is the simplicity of redistributing CS capacity among service areas, achieved by distributing the exposure time for each area in the exposure frame proportionally to the required capacity. However, it should be noted that there are also serious disadvantages when using DBH:

- There is no possibility of multiple use of the frequency, since the areas are served sequentially in time by a single beam, so it is impossible to implement spatial frequency division;
- A single transceiver with a bandwidth equal to the network capacity is required to serve the entire area. With the required high capacity, the lack of sufficiently wideband transceivers may be an obstacle to using one DBH;
- With a high capacity of the CS-UT channel, the costs associated with the time of switching the beam from one spatial position to another become noticeable, as a result of which the efficiency of channel use decreases.

The above reasons lead to the fact that in CS-UT communication channel DBH technology with one scanning beam can be used only in networks with a relatively low throughput: no more than 150-200 Mbit·s⁻¹. On the other hand, MAS is largely free from the listed DBH disadvantages, but in this case the problem of redistribution of the repeater's communication resources between the transmitting beams operating in parallel is significantly complicated. Therefore, the disadvantages of DBH can be largely compensated for by using several beams operating in parallel in CS-UT communication channel, which is confirmed by the results of the analysis conducted by the authors.

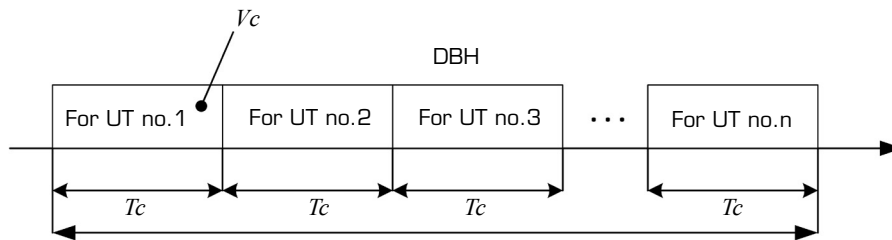
METHODOLOGY

Communications satellites receives internet traffic from gateway either via direct communication channels from gateway or via intersatellite communication lines upon request from subscribers (outgoing traffic). A queue of incoming traffic to subscribers is formed on CS. This traffic is transmitted to multiple geographically distributed subscribers using discrete scanning beams. Each beam in the presented model is a service device in terms of queuing theory. Scanning takes place during a cycle (frame). Depending on the type of traffic in the scan (exposure) frame, each subscriber is allocated one or more time slots in this scan picture. The proposed article does not set the task of finding the optimal (according to the selected criterion) UTs scanning algorithm, depending on their priorities and other parameters.



Information exchange in the “down” CS-UT communication channel using DBH actually corresponds to time division multiplexing of CS-UT communication channel. The process of beam exposure during information exchange can be represented as the transmission of information in frames of duration T_k , equal duration of DBH exposure in n zones. Each frame is divided into slots (time windows) intended for transmitting information to each UT. In general, the number of slots in a frame exceeds the number of the UTs and is distributed among them in accordance with the requests transmitted by the UTs. In particular, if there are several UTs in the DBH zone, then the exposure of this zone (the number of slots provided to subscribers in this zone) will be equal to the number of active UTs. As a mathematical apparatus for studying the probabilistic-temporal characteristics of information exchange in CS-UT communication channel, it is proposed to use the queuing theory, which takes into account the random nature of information flows.

Let's assume that there are n UTs with the same information activity in the CS service area. Then the frame, consisting of n slots, is divided equally between UT, and its structure has the form shown in the Fig. 3.



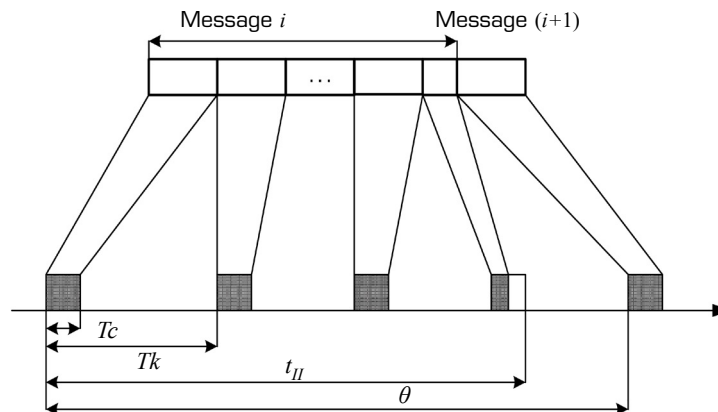
Source: Elaborated by the authors.

Figure 3. Frame structure when exposing DBH by service area.

It is advisable to first consider a static scanning algorithm in which DBH scans along a pre-fixed route across the service area, retargeting each cell with a diameter equal to the beam diameter at the -3 dB level on the Earth's surface, regardless of whether there are active UT in this cell or not. Let us call this DBH scanning control algorithm static.

Let the message flows coming to all subscribers have the same statistical characteristics. These messages, in accordance with the UT request for the required service, arrive at random moments in time. The probability that over a time interval of duration y , k messages come in, denote it as $\mu_k(y)$. The message volumes are independent random variables. The probability that the message volume UT equal to r bit we denote as q_r ($r = 1, 2, 3, \dots$).

The mechanism for transmitting a message over the CS-UT communication channel using DBH is shown in Fig. 4 (Kamnev *et al.* 2010). Transmission is carried out in the form of a sequence of slots equally spaced over a time interval equal to the frame duration T_k . The volume of each slot, except perhaps the last one, is equal to Eq. 2.



Source: Retrieved from Kamnev *et al.* 2010.

Figure 4. Mechanism for transmitting messages in DBH exposure frame across the service area.

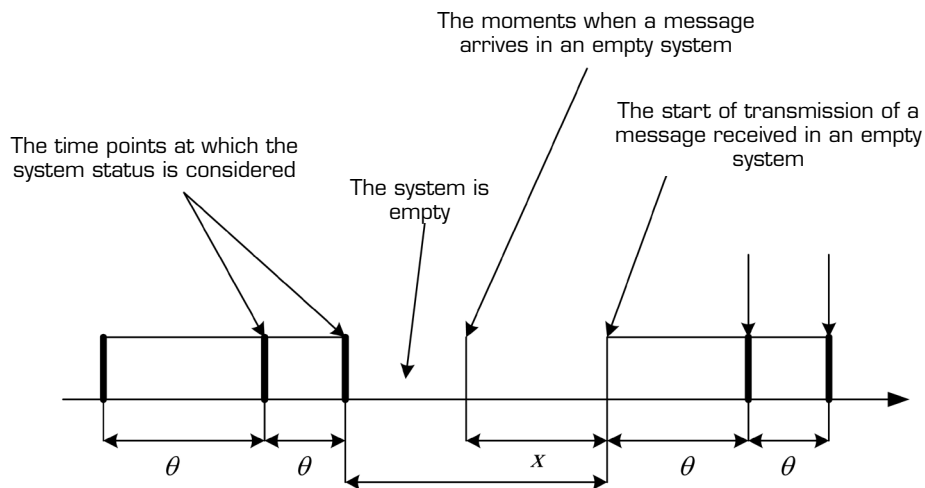
$$V_c = mCT_k/n \quad (2)$$

where C is the throughput (capacity) of CS-UT communication line according to Eq. 1, m is the number of beams using DBH technology, n is the number of slots in a frame.

To simplify further analysis, it is necessary to use the concept of virtual message transmission time θ , equal to the number of frames in which the message in question was transmitted in the corresponding slots. The distribution of the virtual transmission time is uniquely related to the distribution of the volume of the transmitted message and the slot volumes. The probability that the virtual transmission time is iT_k will be equal to Eq. 3.

$$u_i = P(\theta = iT_k) = \sum_{r=(i-1)V_c+1}^{r=V_c} q_r, \quad i=1,2,\dots \quad (3)$$

Using the concept of virtual data transfer time makes it possible to present a batch service to a conventional single-line QS with continuous service. To determine the average message delay time, it is necessary to determine the average number of messages in the system that are in the queue plus in the channel. At the moment of receipt of the next message, the number of messages in the system increases by one, and at the moment of completion of the message transmission, it decreases by one. The frame structure at the time points immediately following the end of message transmission is shown in Fig. 5. If there are messages in QS, they are output to the channel sequentially without interruptions, and each message occupies the channel for a random period of time θ , distributed in accordance with Eq. 3. If QS is free at some point in time, a new message arriving in an empty system waits for a random period of time for the nearest slot assigned to it and only then does its transmission begin.



Source: Elaborated by the authors.

Figure 5. Structure of message output to CS-UT communication channel.

Under the assumptions made regarding the properties of UT information flow, the number of messages in the system at successively considered moments of completion of transmissions forms a first-order Markov chain. An exhaustive characteristic of a first-order Markov chain is the matrix of one-step transition probabilities, the elements of which are p_{ij} which are equal to the probabilities of the chain transition from the state j in a state i for one step (Kleinrock 1975; Saaty 1961). The probability that there are messages in QS in steady state (the corresponding Markov chain is in the i -th state) - can be found using the total probability (Eq. 4)

$$P_i = \sum_j P_j p_j \quad (4)$$

Let $(i=0,1,2,...)$ be the unconditional probability that new messages were received during the waiting time for the slot and the transmission of the message to QS, and $(i=0,1,2,...)$ be the unconditional probability that new messages were received during the transmission of the message.

To switch from a non-zero state i to a state in one step it is necessary that new messages arrive in the system during the transmission of the message (taking into account one message leaving the system at the end of the transmission). Transition from state i to the state $j \leq i-1$ is impossible, since no more than one message leaves the system at a time. For the system to transition from the zero state to any other state, j requires that over time $(x+\theta)$ the j new messages are received.

In accordance with Eq. 4 and taking into account the structure of the transition probability matrix, the system of linear equations for the probabilities of finding the system at the end of the transmission of messages (packets) in the i -th state will be written as shown in Eq. 5 (Kamnev *et al.* 2010):

$$\begin{cases} P_0 = a_0 P_0 + b_0 P_1 \\ P_1 = a_1 P_0 + b_1 P_1 + b_0 P_2 \\ P_2 = a_2 P_0 + b_2 P_1 + b_1 P_2 + b_0 P_3 \\ P_3 = a_3 P_0 + b_3 P_1 + b_2 P_2 + b_1 P_3 + b_0 P_4 \\ \dots \end{cases} \quad (5)$$

The technique used to connect the distribution of the number of messages with a system of linear algebraic equations is called the nested Markov chain method (Kleinrock 1975).

To solve the resulting system of Eq. 5, the method of generating functions is used (Saaty 1961). Let the generating function of the desired probability distribution as in Eq. 6.

$$F(s) = \sum_{i=0}^{\infty} P_i s^i \quad (6)$$

Then, multiplying each row of the system of Eq. 5 by s^i and summing up all the rows, Eq.6 is converted to Eq. 7:

$$\begin{aligned} F(s) = & P_0(a_0 s^0 + a_1 s^1 + a_2 s^2 + \dots) + P_1(b_0 s^0 + b_1 s^1 + b_2 s^2 + \dots) \\ & + P_2 s(b_0 s^0 + b_1 s^1 + b_2 s^2 + \dots) + \dots \end{aligned} \quad (7)$$

Let's introduce two functions:

$A(s) = \sum_{i=0}^{\infty} a_i s^i$ is the generating function of the distribution of the number of messages arriving in the system during time $(x+\theta)$, $B(s) = \sum_{i=0}^{\infty} b_i s^i$ is the generating function of the number of messages entering the system during time θ So:

$$F(s) = P_0 A(s) + B(s)(P_1 + P_2 s + P_3 s^2 + \dots) = P_0 A(s) + \frac{B(s)}{s} [F(s) - P_0] \quad (8)$$

The solution of the obtained Eq.8 with respect to $F(s)$ is Eq.9 $F(s)$, :

$$F(s) = P_0 \frac{B(s) - sA(s)}{B(s) - s} \quad (9)$$

The generating function of the desired distribution is found to within a constant factor P_0 . The value of P_0 is determined from the normalization condition $F(1) = 1$. Substituting $s = 1$ in Eq. 9 and revealing the uncertainty according to L'Hôpital's rule, it turns out Eq. 10:

$$P_0 = \frac{1 - B'(1)}{1 + A'(1) - B'(1)} \quad (10)$$

and $F(s)$ takes the following final form (Eq. 11):

$$F(s) = \frac{1 - B'(1)}{1 + A'(1) - B'(1)} \cdot \frac{B(s) - sA(s)}{B(s) - s} \quad (11)$$

The average number of packets in the system at the end of message transmission is: Eq. 12.

$$\bar{i} = \sum_{i=0}^{\infty} P_i = F'(1) \quad (12)$$

Differentiating Eq. 11 with respect to s and expanding the uncertainty twice, we obtain Eq. 13:

$$\bar{i} = \frac{A'(1)[2 + B'(1) - 2B'(1)] + A''(1)[1 - B'(1)]}{2[1 + A'(1) - B'(1)][1 - B'(1)]} \quad (13)$$

The necessary derivatives are calculated as: (Eqs. 14–15):

$$b_i = \int_0^{\infty} \mu_i(\theta) f(\theta) d\theta \quad (14)$$

$$B(s) = \sum_{s=0}^{\infty} b_i s^i = \sum_{s=0}^{\infty} \int_0^{\infty} \mu_i(\theta) s^i f(\theta) d\theta \quad (15)$$

For example, it is rational to consider the Poisson message flow, the model of which is traditionally used in the analysis of the probabilistic-temporal characteristics of QS. In this case, a random number of messages i , generated by the source over a time interval of duration T_0 , has a distribution (Eq. 16) (Kleinrock 1975; Saaty 1961).

$$P_i(T_0) = \frac{(\lambda T_0)^i}{i!} e^{-\lambda T_0}, \quad i = 0, 1, 2, \dots \quad (16)$$

And time intervals X between adjacent events of the flow are subject to an exponential probability distribution $\omega(x) = \lambda * e^{-\lambda x}$.

$$\text{So, } \mu_i(\theta) = \frac{(\lambda\theta)^i}{i!} e^{-\lambda\theta} \quad (17)$$

and therefore (18):

$$\begin{aligned} B(s) &= \sum_{s=0}^{\infty} b_i s^i = \sum_{s=0}^{\infty} \int_0^{\infty} \frac{(\lambda\theta)^i}{i!} e^{-\lambda\theta} s^i f(\theta) d\theta = \int_0^{\infty} e^{-\lambda\theta(1-s)} f(\theta) d\theta \\ B(s) &= \int_0^{\infty} \lambda\theta e^{-\lambda\theta(1-s)} f(\theta) d\theta \\ B'(s) &= \int_0^{\infty} (\lambda\theta)^2 e^{-\lambda\theta(1-s)} f(\theta) d\theta \quad (18) \\ B(1) &= \int_0^{\infty} \lambda\theta f(\theta) d\theta = \lambda\bar{\theta} \\ B'(1) &= \int_0^{\infty} (\lambda\theta)^2 f(\theta) d\theta = \lambda^2 \bar{\theta}^2 \end{aligned}$$

Function $A(s)$ is the generating function of the distribution of the sum of two independent random variables: the number of messages received over a time interval of duration θ , and the number of messages received during the time interval x , separating the moment of receipt of a message in an empty system from the moment of the beginning of the nearest slot. Therefore $A(s) = C(s)B(s)$, where $C(s)$ is the generating function of the distribution of the number of messages (packets) arriving in a time interval x , and therefore (Eqs. 19–20):

$$A'(s) = C'(s)B(s) + C(s)B'(s) \quad (19)$$

$$A''(s) = C''(s)B(s) + 2C'(s)B'(s) + C(s)B''(s) \quad (20)$$

Since the moments of generating messages to subscribers are not synchronized with the time structure of the frame, there is no reason to consider any part of the frame preferable for the occurrence of messages. Consequently, the distribution of the value can be considered equally probable (Eq. 21).

$$f(x) = \begin{cases} \frac{1}{T_k} & \text{at } 0 \leq x \leq T_k \\ 0 & \text{at } x < 0, x > T_k \end{cases} \quad (21)$$

And the desired values of the derivatives will be as shown in Eq. 22.

$$\begin{aligned} C'(1) &= \frac{\lambda}{T_k} \int_0^{T_k} x dx = \frac{\lambda T_k}{2} \\ C''(1) &= \frac{\lambda^2}{T_k} \int_0^{T_k} x^2 dx = \frac{(\lambda T_k)^2}{3} \quad (22) \\ A'(1) &= B(1) + C'(1) = \lambda\bar{\theta} + \frac{\lambda T_k}{2} \\ A''(1) &= B''(1) + 2C'(1)B'(1) + C''(1) = \frac{(\lambda T_k)^2}{3} + \lambda^2 \bar{\theta}^2 + \lambda^2 T_k \bar{\theta} \end{aligned}$$

And the average message delay time when using DBH is shown in Eq. 23.

$$\bar{\tau} = \frac{\bar{t}}{\lambda} - \frac{(n-1)}{mn} T_k \quad (23)$$

The second term in Eq. 23 reflects the fact that the virtual transmission time θ determines the duration of a message in terms of messages in a queue and affects the length of that queue. Real message transmission time t_p less by the amount $\frac{(n-1)}{mn}$, because the transmission ends at the end of the slot allocated to UT in question, and the remaining part of the frame until the beginning of the next slot assigned to it, DBH communication channel in question is not loaded (Fig. 3).

Using Eqs. 13, 18, and 22, after algebraic transformations, we finally obtain Eq. 24.

$$\bar{\tau} = \frac{T_k \left(1 + \frac{\lambda T_k}{3}\right) + \bar{\theta} \left[2(1 - \lambda \bar{\theta}) - \lambda^2 T_k \left(\bar{\theta} + \frac{T_k}{3}\right)\right] + \lambda \bar{\theta}^2 \left(1 + \frac{\lambda T_k}{2}\right)}{(2 + \lambda T_k)(1 - \lambda \bar{\theta})} - \frac{n-1}{nm} T_k \quad (24)$$

where $\bar{\theta} = T_k \sum_{i=1}^{\infty} \dot{u}_i$, $\bar{\theta}^2 = T_k^2 \sum_{i=1}^{\infty} i^2 u_i$, and u_i is determined by Eq. 3.

Let, for example, multipacket messages for UTs have a fixed volume V , multiple of slot volume $V = lV_c$, where l is the number of frames required to transmit a message, and V_c is determined by the relation in Eq. 2, then it is true: $\bar{\theta} = \frac{nV}{mC}$, $\lambda \bar{\theta} = \frac{\lambda nV}{mC} = \rho$, $\bar{\theta} = \frac{nV}{mC}$, $\lambda \bar{\theta} = \frac{\lambda nV}{mC} = \rho$, where ρ is the loading. Therefore, Eq. 24 is transformed into a more compact form (Eq. 25).

$$\bar{\tau} = \frac{nV}{mC} \left[\frac{2 - \rho + \frac{1}{l} \left(1 - \frac{\rho^2}{2} + \frac{\rho(1-\rho)}{3l}\right)}{\left(2 + \frac{\rho}{l}\right)(1-\rho)} - \frac{n-1}{mnl} \right] \quad (25)$$

Equation 25 is valid for the static DBH scanning algorithm. However, with low information activity of UTs, the channel throughput will be low due to DBH scanning of “empty” (inactive) cells. Therefore, a more efficient option is to scan DBH only for active cells in which currently active UTs are located, as implemented, for example, in Starlink (Pehterev *et al.* 2022). This DBH scan control algorithm is called dynamic. “Empty” cells at the current moment in time correspond to zero states in the mathematical model presented above, the probability of which is P_0 (Eq. 26).

$$P_0 = \frac{1 - B(1)}{1 + A'(1) - B(1)} \quad (26)$$

where: $A'(1) = \lambda \bar{\theta} + \frac{\lambda T_k}{2}$, $B'(1) = \lambda \bar{\theta}$.

For this case, it is necessary to reduce the delay in Eq. 25 by the value of the weighted average time the system spends in the zero state. In such a dynamic DBH scanning control algorithm, the average time spent in the zero state will be by the value $P_0 \bar{\tau}$ less than when implementing a static algorithm. In this case, the average delay $\bar{\tau}_d$ will be equal Eq. 27.

$$P_0 = \frac{1 - B(1)}{1 + A'(1) - B(1)} \quad (27)$$

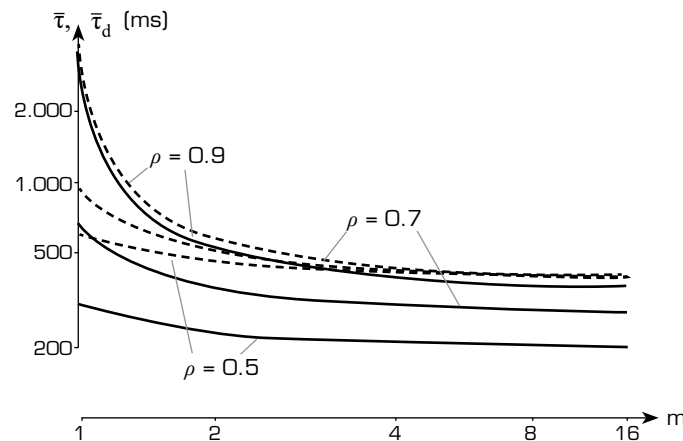


RESULTS

When calculating the average delay time and comparatively evaluating DBH options, the following initial data were adopted, which correspond to the parameters of existing CS, including Starlink:

- In the compared variants the powers of CS transmitters are the same;
- The total throughput of the communication channel is $C = 100 \text{ Mbit}\cdot\text{s}^{-1}$;
- The frame length is $T_k = 40 \text{ ms}$;
- The number of time slots in a frame is $n = 80$;
- The m number of DBH beams varies from 1 to 16;
- The average message length is 64 kB;
- The specific costs of establishing synchronization and the time of DBH switching between cells are 5%, which is equivalent to a 5% reduction in the time-slot duration;
- The change in the total load ρ in the service area is from 0.5 to 0.9.

Figure 6 shows the dependences of the average delay time for static (dashed lines) and dynamic (solid lines) scanning algorithms, calculated according to Eqs. 25 and 27.



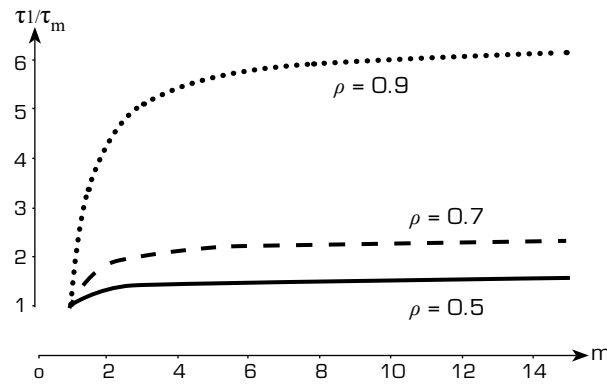
Source: Elaborated by the authors.

Figure 6. Dependence of the average delay time on m number of DBH rays under static τ and dynamic τ_d scanning algorithms.

As follows from the analysis of the given dependencies, the implementation of the dynamic scanning algorithm provides a gain compared to the static algorithm from 1.1 (at high loads) to 2.0 times at low loads. This is explained by the fact that at low loads, when implementing the static algorithm, most of the slots are empty, and DBH wastes time scanning cells in which there are no active UTs. As the load increases, the number of such empty cells decreases, and as a result, the gain value also decreases. Figure 7 illustrates the dependence of the gain on the delay time when using DBH technology with a dynamic scanning algorithm (τ_m), compared to a single global beam antenna (τ_1) for different values of m . The results show that the gain in delay when implementing information exchange with several DBH compared to a single-beam antenna is from 1.2 (at low load) to 2 (at $\rho = 0.7$) and 6 times (at $\rho = 0.9$), and a significant part of this gain is already ensured when the DBH number is equal to $m = 6$.

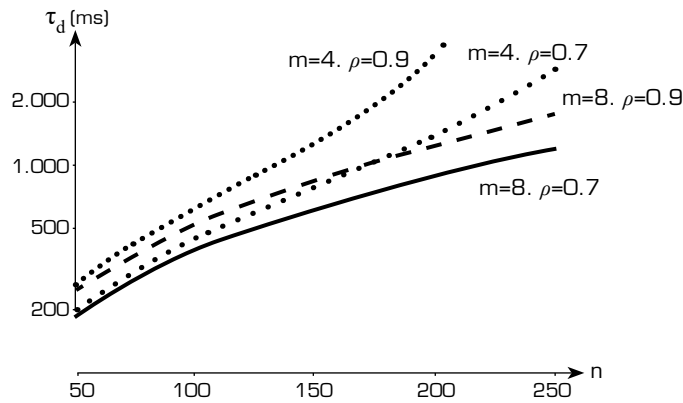
Figure 8 shows the dependence of the average delay time $\bar{\tau}_d$ from the number of slots n from 50 to 250 in a frame of duration $T_k = 40 \text{ ms}$ with different number of DBH with dynamic scanning algorithm and loading ρ . As follows from this graph, when the number of slots changes from 50 to 100, the average delay time also increases approximately twofold, and the growth is almost linear. As the number of slots increases further, a nonlinear increase in the average delay time is observed, and this trend is more pronounced the higher the load.

The presented dependencies are obtained when, with an increase in the number of DBH rays, the width of the radiation pattern of each DBH rays decreases proportionally. In accordance with Eq. 1, the bandwidth of each communication line C increases linearly.



Source: Elaborated by the authors.

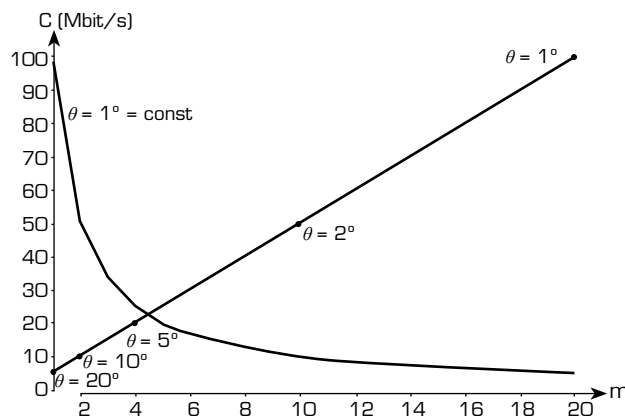
Figure 7. Comparative evaluation of the gain in delay time when using DBH technology with a dynamic scanning algorithm.



Source: Elaborated by the authors.

Figure 8. Dependence of the average delay time on n number of slots in a frame.

If, as the number of beams increases, the width of the radiation pattern of each beam is fixed, then, obviously, the bandwidth of each communication line will decrease, and the average delay in transmitting information will increase. The dependences of the bandwidth of communication lines on the number of beams are shown for these two cases in Fig. 9.



Source: Elaborated by the authors.

Figure 9. Dependence of the bandwidth of each communication line with an increase in the number of beams for cases of proportional decrease in the width of the radiation pattern Θ =variable ($20^\circ \div 1^\circ$) DBH in the service area and fixed $\Theta=1^\circ$ =const.



DISCUSSION

The above graphic dependencies clearly demonstrate the efficiency of using DBH in LOSCS; however, the question of practical application of the obtained results remains open. A number of requirements are imposed on CS design, one of which is the limitation on the weight and size characteristics of PAA. Therefore, it is important to evaluate the dependence of the PAA, antenna pattern (AP) sizes of one DBH – $\Theta_{0.7}$ and the value of the scanning angle – β from the number of DBH in the PAA. This estimate can be obtained based on the results obtained and well-known study on the analysis and development of PAA (Voskresensky 1994, Bhattacharyya 2006, Bosch *et al.* 2018).

As it is shown in these works, PAA radiation pattern depends on AP of one emitter $F_1(\varphi)$ and the lattice multiplier $F_2(\varphi)$, and is determined by the ratio $F(\varphi) = F_1(\varphi) \cdot F_2(\varphi)$. As an example, it is advisable to consider the square PAA construction, in which AP coincides in both planes. To simplify the calculations, it is rational to consider the dependence only on $\Theta_{0.7}$, and also assume that AP is completely determined by the multiplier $F_2(\varphi)$.

Hella Power Beam Width $F_2(\varphi)$ is defined as follows (Eq. 28).

$$\Theta_{0.7} = \frac{49\lambda}{D \cos(\beta)} \text{ (degrees)} \quad (28)$$

Where λ is the wavelength and D is the linear size of PAA. D can be expressed in terms of n , the total number of emitters, and d , the distance between the phase centers of the emitters (grating pitch), which is kept below λ to avoid the appearance of side radiation maxima.

It is rational to consider several frequency ranges on the communication line “down”. If the CS-UT communication line operates in the *Ka*-band at a frequency $f = 18$ GHz, then the optimal dimensions of PAA are 1×1 m, the value of the scanning sector will be taken as β from -50° to 50° , and the AP value of one DBH is $\theta = 5^\circ$. Since the distance between elements is 0.95λ , then the linear length of the lattice will be $D = 0.2692$ m. In this case, it is possible to obtain 9 DBH by dividing the antenna into 9 sectors (3 rows of 3 segments). The number of emitters in each segment will be 18×18 . When loading, for example, $\rho = 0.7$ under the conditions specified above, the average message transmission time when using the DBH dynamic scanning algorithm will be 286 ms (Fig. 6).

If the CS-UT communication line operates in the *Ku* band on the frequency $f = 12$ GHz, then the linear size of PAA is 0.4 m. In this case, it becomes possible to form four independent beams and provide an average delay of 305 millisecond (Fig. 6).

Thus, based on the above estimates, the authors formulated the following thesis as a discussion: When operating LOSCS, in order to reduce the cost of onboard and subscriber PAAs, it seems advisable to increase the number of CSs in the orbital group while simultaneously reducing the size of the service area of each CS (DBH scanning area) β within $\pm 20^\circ$. In this case, PAA sizes for 18 and 12 GHz frequencies will be 0.174 and 0.26 m, respectively. With the accepted initial data, it is possible to implement 25 and 9 DBHs, respectively.

Only an approximate estimate of the DBH number is given here, which may change slightly once other factors are taken into account, such as the influence of diffraction maxima, etc. These issues require additional research, which, according to the terms of the grant, should be carried out by the authors in the future.

The following main issues are supposed to be considered as areas of promising research:

- Evaluation of the efficiency of modulation methods and noise-correcting coding as applied to CS-UT communication channel;
- Evaluation of the influence of intrasystem interference (side lobes of the antenna pattern) on the quality of communication in CS-UT communication channel;
- Conducting research on the characteristics of information exchange with other DBH exposure algorithms over the service area.

CONCLUSION

A mathematical model in the form of QS is presented to calculate the average delay time for transmitting information in the CS-UTs downlink when using DBH transmitting PAA to CS.

Analytical expressions are obtained for calculating the average delay time depending on the general system characteristics for static and dynamic DBH scanning algorithms across service areas.

It is shown that the dynamic DBH scanning algorithm provides a gain in relation to the static algorithm from 1.2 to 6 times depending on the load and the number of DBHs.

The use of several DBHs leads to a decrease in delay by several times, and a significant part of this gain is already provided with a number of DBHs used equal to 6.

Estimates are given for the possible number of DBHs depending on the restrictions on PAA size, the width of DBH radiation pattern and the size of DBH scanning sector.

CONFLICT OF INTEREST

Nothing to declare.


AUTHORS' CONTRIBUTIONS

Conceptualization: Chechin G, Kolesnichenko V, Mikhailov Yu, Zhuchkov I; **Methodology:** Chechin G, Zhuchkov I; **Research:** Chechin G, Kolesnichenko V, Zhuchkov I; **Software:** Chechin G, Kolesnichenko V, Mikhailov Yu, Zhuchkov I; **Data curation:** Chechin G, Kolesnichenko V, Mikhailov Yu, Zhuchkov I; **Formal analysis:** Chechin G, Kolesnichenko V, Mikhailov Yu, Zhuchkov I; **Validation:** Chechin G, Kolesnichenko V, Mikhailov Yu, Zhuchkov I; **Visualization:** Chechin G, Kolesnichenko V, Mikhailov Yu, Zhuchkov I; **Resources:** Chechin G, Kolesnichenko V, Mikhailov Yu, Zhuchkov I; **Acquisition of funding:** Chechin G, Kolesnichenko V, Mikhailov Yu, Zhuchkov I; **Project administration:** Chechin G, Kolesnichenko V, Mikhailov Yu, Zhuchkov I; **Supervision:** Chechin G, Kolesnichenko V, Mikhailov Yu, Zhuchkov I; **Writing - Preparation of original draft:** Chechin G, Kolesnichenko V, Mikhailov Yu, Zhuchkov I; **Writing - Proofreading and editing:** Chechin G, Kolesnichenko V, Mikhailov Yu, Zhuchkov I; **Final approval:** Kolesnichenko V.

DATA AVAILABILITY STATEMENT

All data sets were generated or analyzed in the current study.

FUNDING

Russian Science Foundation 
Grant No: 23-69-10084

DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE TOOLS

When conducting research and preparing the text of the article, the authors did not use any AI tools/services and take on assumes full responsibility for the content of the publication.

ACKNOWLEDGEMENTS

Not applicable.



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