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ORIGINAL ARTICLE

Organization of Communication with the Unmanned Aerial Vehicle in a Combined Data Transmission Network

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ABSTRACT

Communication with UAV can be organized using terrestrial radio (high efficiency, but limited in terms of service area) and satellite (global coverage area, but large delay in propagation of radio signals) communication networks. Their integration will ensure high efficiency and reliability of information interaction with UAV. The task of dynamic control of information flows to ensure the specified characteristics is relevant. The article analyzes the algorithm for managing information flows when a communication session with UAV is performed through that segment of the network (terrestrial or satellite one), which at the moment will provide the maximum efficiency of information delivery. A mathematical model of information exchange in this integrated communication network as a queuing network with Poisson incoming traffic and exponential distribution of the volume of transmitted information has been developed. Ratios are obtained for calculating the average network delay depending on the ratio between throughputs of satellite and terrestrial segments of integration of the communication network. The proposed model allows selecting the required bandwidth of satellite and terrestrial segments of communication networks, where the specified requirements for the speed of information delivery are provided. The use of dynamic flow control can significantly increase the efficiency of information exchange with UAV.

Keywords: Ground receiving and transmitting node; Satellite communication systems; Dynamic flow control; Queuing system; Average delay time.

INTRODUCTION

Unmanned aerial technologies represent one of the dynamically developing areas in the robotics market, which is due to technical progress in the field of microprocessor computing, navigation, IT technologies and artificial intelligence technologies. Currently, UAVs are used in various areas of human activity, logistics, monitoring of the environment and industrial facilities, search and rescue operations, agriculture, remote sensing of the Earth, etc. (Arkin 2015; Kostin and Bogatov 2019; Scharre 2018; Sivakumar and Malleswari 2021; Sloggett 2014).

Some of the main trends in the development of unmanned aerial technologies are:

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- Introduction of big data technologies (Oussous *et al.* 2017) and further development of artificial intelligence algorithms, which can help to process and transmit the information received by UAVs to the ground control center or other UAVs faster, more accurately and easier;
- Introduction of technologies and systems of unmanned aircraft system traffic management (UTM) and remote identification (Remote ID) protected from external influences;
- Introduction of UAV swarm technologies (Campion *et al.* 2019; Ragab and Flores 2021): many self-organizing UAVs united in a group to perform a common task;
- Implementation of technologies for detecting obstacles and preventing UAVs from colliding with them and with each other.

The introduction of the technologies listed above determines the relevance of solving such problems as the operational control of UAVs, their interaction with other UAVs and the ability to communicate with UAVs and ground control points in real time. Therefore, the organization of operational and reliable communication between UAV and ground services is a priority task for the introduction of new unmanned technologies and can only be solved if there is a communication network that jointly uses telecommunication channels of the ground and satellite segments.

Communication with UAV can be organized using terrestrial radio communication networks and via satellite communication networks. Terrestrial radio networks provide high efficiency, but are limited in terms of service area. Conversely, satellite communication networks provide a global coverage area, but have a large delay in the propagation of radio signals. Various aspects of the organization of infocommunications between UAVs and ground centers were considered in a number of scientific and technical works, however, as a rule, they consider either the satellite one separately (as an option, the hybrid link "satellite-UAV-ground control center") or the ground segment. In particular, Hill (2016) considered the issues of organizing communication with UAVs using satellite channels, and Li *et al.* (2019; 2020a; b) proposed options for using UAVs (as alternatives to a network of low-earth satellite relays as a platform for organizing hybrid communications of the type "satellite-UAV-ground center". In Gupta *et al.* (2016) and Chen *et al.* (2020) an overview of the various architectures of the communication system for a swarm of UAVs, end-to-end data transmission in which is ensured by the choice of routing protocols, is considered. In Boev *et al.* (2014) the issues of organizing digital communication of UAV with a ground control complex when transmitting information over long distances are considered.

The integration of terrestrial and satellite communication networks allows for high efficiency and reliability of information interaction with UAV. The closest to the topic of this article is the work of Panteleimonov *et al.* (2020), which considers the creation of a universal communication and control network for UAVs, which ensures uninterrupted operation regardless of the location of UAV. To solve this problem, the authors proposed to use three digital data transmission networks (terrestrial, air based on UAV repeaters and satellite) using TCP/IP and SCADA protocol stack. The main focus of the authors is on the problems of reliability and survivability of the network, secrecy of communication and ensuring the cryptographic strength of information. At the same time, the article did not evaluate network delays and, accordingly, the efficiency of information exchange in such network, which is especially important to take into account at the stage of system design. Therefore, obtaining new knowledge on this problem is an urgent scientific and practical task.

The purpose of this work is to analyze the information exchange with UAV in a combined communication network based on the sharing of resources of terrestrial and satellite communication networks. A mathematical model of a combined communication network has been developed, which allows calculating the average network delay of information transmission and determining the main network parameters (throughput of communication channels) to ensure the specified indicators of information transmission efficiency. It is shown that the use of dynamic control of information flows can significantly increase the efficiency of information transmission, while the network delay depends significantly on the ratio of the bandwidths of terrestrial and satellite network segments.

THEORETICAL BASIS

Currently, to ensure the information interaction of UAVs with ground control points and with each other, ground receiving and transmitting node (GRTN) and satellite communication systems (SCS) are used based on geostationary (GEO), low orbit

(LEO) and medium orbit (MEO) relay satellites (Roddy 2001). In addition, a promising direction, but not yet widely used in practice, is the use of high altitude platform stations (HAPS) based on balloons and airships to organize communication with UAVs (Chechin *et al.* 2022; Liu *et al.* 2016; Xing *et al.* 2021).

The use of GRTN terrestrial network has a number of restrictions on the radio visibility zone from UAV, which usually does not exceed 30-100 km when using terrestrial antenna systems or placed on small masts. The creation of a full-fledged terrestrial communication network with the provision of service areas / radio visibility over large areas in most cases is not possible for economic and other reasons. The use of SCS allows significantly expanding the radio visibility zone with a set of UAVs, providing in some cases global coverage of near-Earth airspace, but has limitations on the energy characteristics of radio links, which does not allow to ensure the transmission speed in communication lines, for example, GEO - UAV with a wide radiation pattern of onboard antennas of more than 10 Mbps, and also leads to significant delays in information transmission due to the large (about 300 ms) propagation time of radio signals. However, along with the intellectualization of UAVs and the expansion of their areas of application, the requirements for increasing the speed of information delivery from or to UAVs are constantly growing, which necessitates the provision of information interaction between UAVs and control centers and among themselves in real time.

One of the options for increasing the efficiency of information exchange with UAVs is the integration of terrestrial and satellite data transmission networks, which will provide significant advantages over only satellite and/or only terrestrial information exchange networks. Such a network has a dynamically changing topology due to changes in radio visibility zones, signal propagation conditions in radio links, and changes in signal-to-noise ratio (SNR), which determines the throughput of communication channels. Along with a quantitative increase in frequency and time resources (increased in the zone of radio visibility from UAV), in such systems these connections are most efficiently used due to the emerging possibility of using dynamic control of information flows circulating in such communication networks. In particular, when GRTN terrestrial network is heavily congested or when UAV with GRTN is not radiovisible, it becomes possible to redirect information flows from UAV through the satellite network, bypassing these busy sections of GRTN network. In turn, when satellite communication channels are overloaded, it is advisable to use a set of GRTN to organize information exchange with UAVs, in the radio visibility zone of which UAVs are located.

As a theoretical prerequisite for such integration, there is a well-known fact from the queuing theory, which is traditionally used to calculate the main network parameters: the use of a combined resource (bandwidth, performance, etc.) with a common queue of requests for provision of communication services is preferable in almost all main indicators than the independent separate use of several communication systems of the same total bandwidth (Arjomandi *et al.* 2006).

METHODOLOGY

One of the urgent tasks in the construction of combined communication networks is the task of managing information flows and choosing the bandwidth of communication channels to ensure the specified indicators of the speed of information delivery from or to UAVs. To solve this problem, it is necessary to have a mathematical model that allows calculating the probabilistic-temporal characteristics (PTT) of information exchange, in particular, the network delay of information transmission.

In order to analyze the main PTT that determines the quality of information service for moving objects, we consider one of the variants of the combined system given below. Although this variant is a special case, a similar analysis technique can be applied to other applications.

We consider the following mathematical model. Let there be a set of UAVs, information interaction with which is organized using GRTN ground network and GEO communication channels. We will assume that communication between GRTN is carried out either through a wired terrestrial communication network or using radio communication channels via GEO, to the channels of which each GRTN or UAV has access. To simplify the task, we consider a satellite information transmission system with one GEO, shown in Fig. 1.

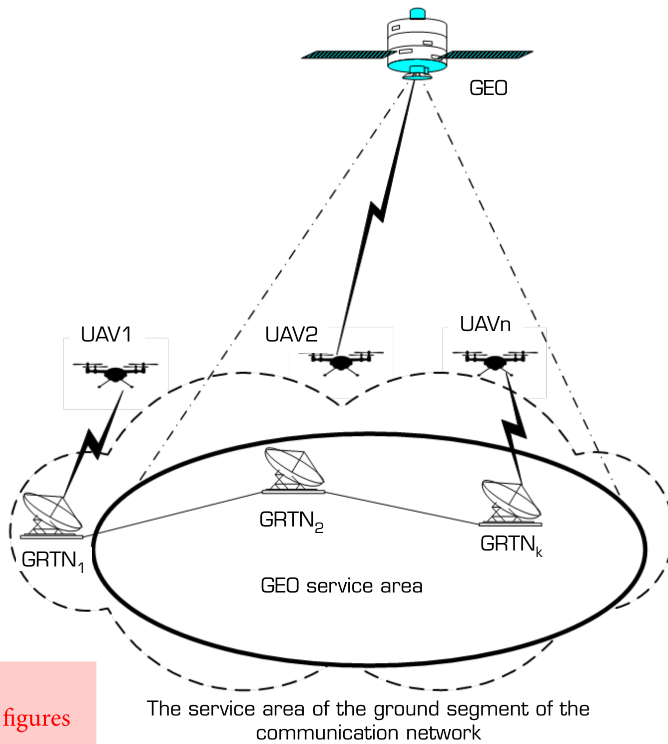

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Figure 1. Fragment of the combined communication network with UAV.

We consider the following information management approach flows in a combined communication network. If UAV has a certain amount of information intended for the transmission to GRTN, a request message is transmitted from UAV to provide a communication channel for UAV via GEO request communication channel to the communication network control center (with centralized network management). The control system, acting as a routing node, calculates the predicted time of message transmission along various routes of the integrated network. In particular, in the case under consideration, the delays in the transmission of information through the relay satellite and through GRTN terrestrial communication network are calculated. If the estimated time of transmission of information from UAV through GEO channels turns out to be longer than the time of establishing a connection and a communication session implemented through GRTN and the terrestrial communication network (the route starts at GRTN network node in which UAV is located), then the connection is established through the terrestrial network. Otherwise, information exchange with UAV is provided through GEO communication channels.

As a mathematical apparatus, we will use queuing theory, and as a mathematical model of a combined communication network, we will use a queuing network model in which the communication channels between GRTN and UAV and between UAV and GEO are serving devices. The first approximation, imitation of various trajectories of movement of mobile users through the radio visibility zones of GRTN network, can be random distribution of UAV in the service area of the combined network. We refer to each communication session as a service request, as is customary in queuing theory. As a model of input traffic to the communication network, we take the Poisson stream with the intensity λ of communication sessions, and the duration of communication sessions obeys the exponential law with the parameter μ, which is the intensity of service of applications equal to the inverse value of the average duration of information transmission from UAV: $\mu = \mu_s C$, where $\mu_s = 1/L$, L is the average value of the amount of information transmitted from UAV, C is the bandwidth of the communication channel equal to C_p, if the communication channel "UAV - satellite-repeater" is used, or C_h, if the communication channel "UAV - GRTN" is used. We will also assume that in the communication network, when implementing information exchange with the UAV, the communication network operates in a stationary mode. In this case, each node of the network can be represented as a single-channel queuing system of *M/M/1* type using the time division multiple access (TDMA) method or a multi-channel *M/M/n* queuing system (*n* is the number of channels) when using the frequency division multiple access (FDMA). These systems are quite fully explored in the fundamental works on the theory of queuing of Kleinrock (1976) and Saaty (1961), so in the future we will use the results given in these works, without unnecessary citation.

To obtain expressions for the average delay of information transmission in a communication network, it is necessary to obtain a system of algebraic equations that describe the states of the communication network under study. The number of tickets in the network and in the queuing systems (on service and in the queue) determines the state of this queuing system. For the communication network under study in the form of a queuing network, the jump intensity diagram looks like it is presented in Fig. 2.

The following designations are accepted in the figure: μh is the intensity of service of the application by GRTN communication channel, equal to $\mu_h = \mu_s C_h$; λ is the intensity of the occurrence of requests (communication sessions) with UAV, P_k^i is the probability that from the *i*-th GEO channel status request goes to the *k*-th route of ground network GRTN, starting in *k*-th GRTN (host), F_i is the probability that the residence time of the application when serviced through GEO communication channel, which is in the state *i*, turns out to be more than when serviced through the *j*-th GRTN node, in the radio visibility zone of which UAV is located.

We assume that the number of UAVs is sufficiently large, and the time interval for servicing an application through a ground communication network is an order of magnitude less than the average interval for the occurrence of applications. This is typical for cases when UAV moves from the radio visibility zone of one GRTN to the radio visibility zone of another GRTN. Thus, in this case, it is possible to use the model of an open queuing network.

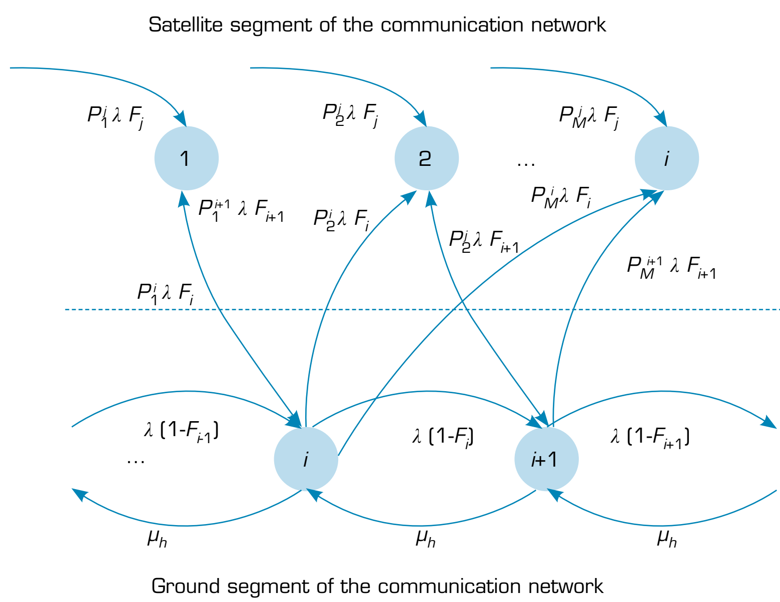

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Figure 2. Diagram of transition intensities in integrated communication networks.

In the stationary mode of operation of the communication network, the system of linear algebraic equations for the states of GEO communication channel looks like this (Eq. 1):

$$\{P_1\mu_p - P_0\lambda(1-F_0) = 0 \ldots P_{i+1}\mu_p + P_{i-1}\lambda(1-F_{i-1}) - P_i(\mu_p + \lambda(1-F_i)) = 0 \ldots \sum_{i=0}^{\infty} \quad P_i = 1 \tag{1}$$

Then, for the terrestrial communication network GRTN, the intensity of the input flow of requests (input traffic) through the *j*-th node will be determined as (Eq. 2):

$$\lambda_j = \lambda \sum_{k=0}^{\infty} p_j^k F_k \tag{2}$$

In order to determine the average delay in servicing a request through the j-th GRTN, it is necessary to have a mathematical model that would describe PTT of a given route. Each route is a serial connection of communication channels and transit nodes. To demonstrate the described methodology for calculating PTT, we will take the queuing system *M/M/1* as the mathematical model of the j-th. We introduce the notation $\mu_{hj} = \mu_j$, then the average delay of requests in the j-th GRTN will be (Eq. 3):

$$T_j = \left[\mu_j\left(1 - \frac{\lambda}{\mu_j} \sum_{k=0}^{\infty} p_j^k F_k\right)\right]^{-1} \tag{3}$$

Now we determine the probabilities F_k, included in Eq. 1. Since the input flow of customers is Poisson and the service time has an exponential distribution, the following expression is true (Saaty 1961):

$$F_k = \sum_{i=0}^{k} \frac{(\mu_p t)^i}{i!} e^{-\mu_p t} \tag{4}$$

Then, replacing in Eq. 4 t with T_i from Eq. 3, we get Eq. 5:

$$F_k = \sum_{l=0}^{k} \left(\frac{p_j^k \mu_p}{\mu_j\left(1 - \frac{\lambda}{\mu_p} \sum_{n=0}^{\infty} p_j^n F_n\right)}\right)^l \frac{}{l\,!} \quad exp\, exp \left\{\frac{p_j^k \mu_p}{\mu_j\left(1 - \frac{\lambda}{\mu_p} \sum_{n=0}^{\infty} p_j^n F_n\right)}\right\} \tag{5}$$

When $P_j^k = 1/M$, where M is the number of GRTN terrestrial network nodes, i.e. with an equiprobable distribution of the flow of applications from UAV over the nodes of the ground network, the last expression is simplified (Eq. 6 and 7):

$$F_k = \sum_{l=0}^{k} \left(\frac{\mu_p}{M\mu_j - \lambda \sum_{n=0}^{\infty} F_n}\right)^l \frac{}{l\,!} \quad exp\, exp \left\{\frac{\mu_p}{M\mu_j - \lambda \sum_{n=0}^{\infty} F_n}\right\} \tag{6}$$

$$\sum_{n=0}^{\infty} F_n < M\mu_j / \lambda \tag{7}$$

We assume that the performance (capacity) of the communication channels of the terrestrial GRTN network is the same, i.e. $\mu_{hi} = \mu_j$. Then we get (Eq. 8):

$$\{F_0 = exp \left\{\frac{-\mu_p}{M\mu - \lambda \sum_{n=0}^{\infty} F_n}\right\} \ldots F_i = F_{i-1} + \left(\frac{\mu_p}{M\mu - \lambda \sum_{n=0}^{\infty} F_n}\right)^i / i! * exp \left\{\frac{-\mu_p}{M\mu - \lambda \sum_{n=0}^{\infty} F_n}\right\} \tag{8}$$

Summing up the left and right parts in Eq. 8, we obtain the Eq. 9 transcendental:

$$\sum_{n=0}^{\infty} F_k = \sum_{n=0}^{\infty} \sum_{i=0}^{n} \left(\frac{\mu_p}{M\mu - \lambda \sum_{n=0}^{\infty} F_n}\right)^i \frac{}{i\,!} \quad exp\, exp \left\{\frac{\mu_p}{M\mu - \lambda \sum_{n=0}^{\infty} F_n}\right\} \tag{9}$$

Since the function $\Sigma_{n=0}^{\infty} F_n$ can be considered sufficiently smooth, well-known methods can be used as a numerical method for solving the last equation, for example, the method described in Forsythe *et al.* (1977).

The average network delay of requests in the terrestrial segment of the communication network T_h is determined by the well-known Eq. 10 (Kleinrock 1976):

$$T_h = \frac{1}{\lambda_\Sigma} \sum_{j=1}^{M} \lambda_j T_j \tag{10}$$

where $\lambda_{\Sigma} = \lambda \sum_{j=1}^{M} \sum_{k=0}^{\infty} p_j^k F_k, \lambda_j = \lambda \sum_{k=0}^{\infty} p_j^k F_k$

Then:

$$T_h = \frac{\sum_{j=1}^{M} \sum_{k=0}^{\infty} p_j^k F_k \left(M\mu - \lambda \sum_{k=0}^{\infty} p_j^k F_k\right)^{-1}}{\left(\lambda \sum_{j=1}^{M} \sum_{k=0}^{\infty} p_j^k F_k\right)} \quad (11)$$

where F_k is determined by Eq. 8.

The average delay of requests when servicing through GEO communication channels is determined from the expression:

$$T_p = \frac{\sum_{k=0}^{\infty} k P_k}{\left[\lambda\left(1 - \sum_{k=0}^{\infty} P_k F_k\right)\right]} \quad (12)$$

where P_k from Eq. 1 are calculated as Eq. 13:

$$\{P_k = \frac{\rho^k \prod_{i=0}^{k-1} (1-F_i)}{\left[1+\sum_{k=1}^{\infty} \rho^k \prod_{i=0}^{k-1} (1-F_i)\right]} \; P_0 = \left[1 + \sum_{k=1}^{\infty} \rho^k \prod_{i=0}^{k-1} (1-F_i)\right]^{-1} \quad (13)$$

where $\rho = \lambda/\mu_p$

We define the average network delay of requests T in the combined communication network as a weighted (in terms of intensity) sum of Eq. 11 and 12.

RESULTS

Figures 3 and 4 show the obtained dependences of the normalized average delays calculated by the above ratios for the same throughput of communication channels of each GRTN node and the number of nodes $M = 10$. The following designations are adopted in the figures: $\mu_{\Sigma}T$, $\mu_{\Sigma}T_p$ and $\mu_{\Sigma}T_h$ are the average delays in information transmission in the integrated network, in the satellite and terrestrial segments of the network, respectively.

The dependences presented in the Fig. 3 were obtained for the case when the total throughput of the integrated network was assumed to be constant, i.e. $\mu_{\Sigma} = \mu(C_p + C_h) = const$. Figure 4 shows the dependencies when there were no restrictions on the total bandwidth of the communication network.

In the figures, the solid lines show the graphs of the dependence of the information transmission delays in the integrated communication network $\mu_{\Sigma}T$, the dotted lines show the delay in the terrestrial segment of the communication network $\mu_{\Sigma}T_h$, and the dotted curves show the delay in the satellite segment of the communication network $\mu_{\Sigma}T_p$ at two values of the network load ρ_{Σ}, equal to 0.8 and 0.6.

The calculations were performed when redistributing the total bandwidth of the communication network between the satellite and terrestrial segments, and the value of the bandwidth distribution coefficient μ_p/μ_h varied from 0.5 to 4. When the total network bandwidth is limited (fixed), then from the graphs in Fig. 3 it can be seen that, for example, with the total load of the integrated network communication channels ρ_{Σ}=0.8 and the redistribution of the communication channel bandwidth between the satellite and terrestrial network segments, in particular, when changing the ratio μ_p/μ_h from 0.5 to 4, there is a decrease in incoming traffic to the terrestrial GRTN network, which naturally leads to a decrease in delay from 1.45 to 0.6.

At the same time, respectively, there is an increase in the serviced traffic in the satellite segment of the network: the communication channels of the repeater satellite, which leads to an increase in the network delay from 0.15 to 0.4. In general, the dependencies in Fig. 3 show that with an increase in the share of bandwidth allocated for the channels of the satellite segment of the network, the network delay decreases by about 1.5 times.

Figure 4 shows delay calculations when there were no restrictions on the total throughput of the integrated network. This figure shows graphs when the throughput of the ground segment of the network remained constant, and the entire allowable increase in network throughput was assigned to the communication channels of the satellite segment. In this case, for example, an increase in the bandwidth of the communication channels of the repeater satellite from 1 to 4 times compared with the bandwidth of terrestrial communication channels made it possible to significantly reduce the network delay. In particular, with input traffic λ=1.3, the average network delay of information transfer decreased by more than 2 times. The graphs in Fig. 4 show that as the requirements for network delay become more stringent, an increasing part of the traffic must be served by the communication channels of the satellite segment of the network. However, it should be taken into account, as it was already indicated, that the energy potential of satellite radio links has a certain limit due to mass-dimensional restrictions and characteristics of onboard antennas.

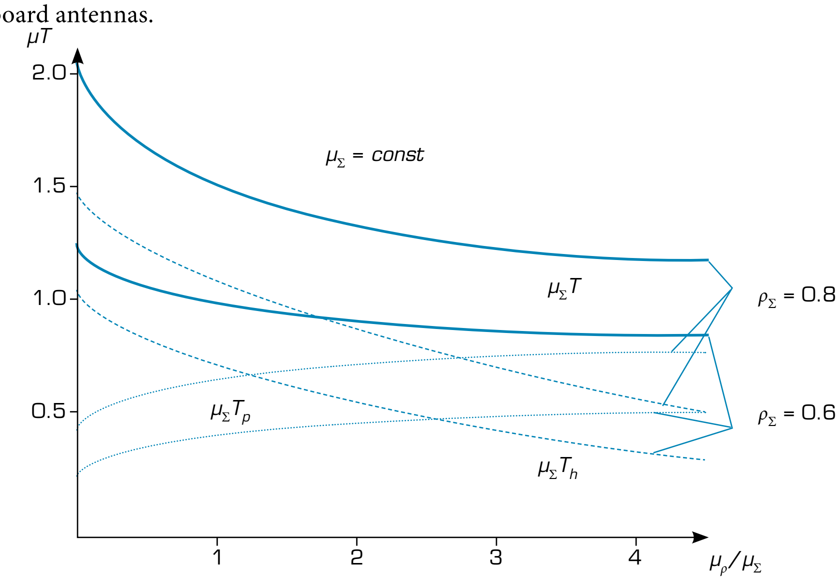

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Figure 3. Dependencies of normalized average delays at a fixed throughput of a combined communication network.

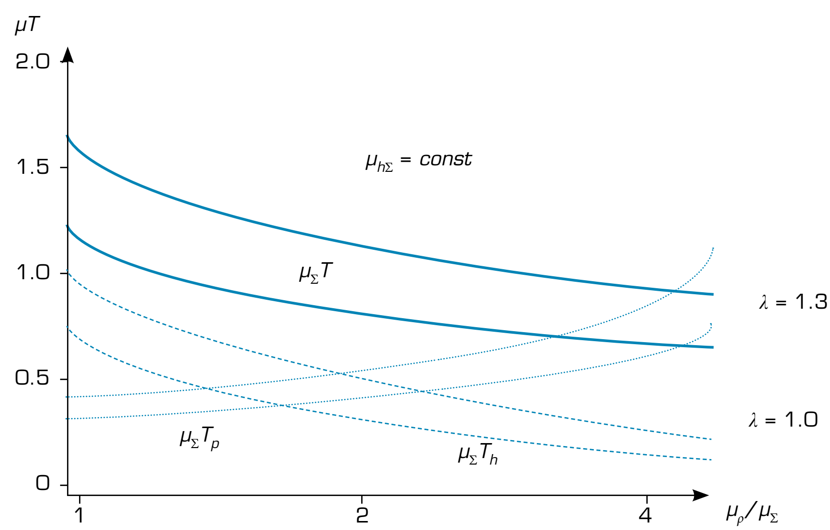

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Figure 4. Dependencies of normalized average delays at a fixed throughput of a combined communication network.

Thus, the ratios obtained make it possible to determine the main parameters of the network, in particular, the bandwidth of communication channels, at which the specified requirements for the speed of information exchange will be provided depending on the intensity of incoming traffic, the amount of information transmitted, the number of UAV and communication nodes.

The obtained results show that the integration of satellite and terrestrial communication networks using dynamic control of information flows can significantly increase the efficiency of information exchange with UAV compared to using only terrestrial or only satellite network segments, while the network delay of information transmission significantly depends on the ratio of the bandwidth of terrestrial and satellite channels.

DISCUSSION

The traditional method for studying the probabilistic and temporal characteristics of complex heterogeneous communication networks with a dynamically changing topology, which makes it possible to obtain the values of the most complete list of the studied performance indicators, is simulation modeling. But this process is associated with the development of rather complex and time-consuming models. Therefore, one of the tasks of the authors was to obtain a simplified computational and analytical model of a combined (satellite and terrestrial) communication network with UAV, which would make it possible to obtain an estimate of information transmission delays in the dynamic control of information flows circulating in a communication network, depending on the bandwidth of satellite communication channels, ground segments and other parameters. But even with the assumptions made by the authors when developing the mathematical model and using *M/M/1* model (when using TDMA), it was not possible to explicitly obtain simple analytical relations for calculating the information transmission delay as communication nodes, and it had to be content with numerical methods for solving the obtained formulas. In general, if the nodes of the communication network are multichannel (for example, when using frequency or code multiple access on a repeater satellite, respectively, FDMA and CDMA), then the proposed model and method for calculating the delay will remain the same, but the expressions for calculating the average delay will be more complex and cumbersome.

It is interesting to consider the case when a multibeam antenna system is used on the relay satellite and use the proposed model to calculate the average delay, taking into account the real information transfer rate, which depends on SNR. This transmission rate depends on SNR to ensure the specified reliability of information transmission, which, in turn, is mainly determined by the power of the transmitters, the gains of the transmitting and receiving antennas of UAV, ground nodes and satellites. repeaters, ranges of used radio frequencies, communication range, methods of noise-immune coding and modulation, as well as methods of multiple access, multiplexing and separation of communication channels.

The calculated ratios obtained were made under the assumption of an equiprobable distribution of UAVs over the service areas of communication nodes of the ground segment of the network and the same throughput of communication nodes. It is interesting to consider the functioning of the network with a significantly uneven distribution of UAVs over service areas and different throughput of network communication nodes. This problem is the subject of further research by the authors.

CONCLUSION

Thus, the model of a combined dynamically changing topology of communication network with UAV in the form of a queuing network presented in the article makes it possible to determine the main parameters of the network (quantity and bandwidth of communication channels) in accordance with the specified requirements for the efficiency of information exchange depending on the intensity of incoming traffic, the volume of transmitted information, the number of UAV and the communication nodes. The obtained analytical expressions for the average network delay of information transmission make it possible to evaluate the influence of the main parameters of the communication network on the efficiency of information exchange. It is shown that the integration of satellite and terrestrial communication networks using dynamic control of information flows can significantly increase efficiency of information exchange with UAV in comparison with the use of only terrestrial or only satellite segments of the network, while the network delay of transmitted data depends significantly on the ratio of bandwidths of terrestrial and satellite channels.

Theoretically, for example, for the case of communication systems with gaps in GRTN with UAV radio visibility zones or for the case of organizing information exchange between UAV and GRTN, the minimum average delay with the described control variant is achieved when the entire bandwidth of the communication network channels is allocated to GEO communication channels. However, as is known, in practice, the bandwidth of GEO-UAV radio links is limited by weight, size and technical characteristics of the transceiver equipment and antenna systems of GEO and UAV. This limitation does not allow the achievement of the theoretically possible reduction in the transmission delay of information.

CONFLICT OF INTEREST

There is nothing to declare.

AUTHOR CONTRIBUTIONS

Conceptualization: Chechin GV; Kalyagin MY; Kolesnichenko VE and Zamkovoi AA; **Data curation:** Chechin GV; Kalyagin MY; Kolesnichenko VE and Zamkovoi AA; **Formal analysis:** Chechin GV; Kalyagin MY; Kolesnichenko VE and Zamkovoi AA; **Acquisition of funding:** Chechin GV; Kalyagin MY; Kolesnichenko VE and Zamkovoi AA; **Research:** Chechin GV; Kalyagin MY; Kolesnichenko VE and Zamkovoi AA; **Methodology:** Chechin GV; Kalyagin MY; Kolesnichenko VE and Zamkovoi AA; **Project administration:** Chechin GV; Kalyagin MY; Kolesnichenko VE and Zamkovoi AA; **Resources:** Chechin GV; Kalyagin MY; Kolesnichenko VE and Zamkovoi AA; **Software:** Chechin GV; Kalyagin MY; Kolesnichenko VE and Zamkovoi AA; **Supervision:** Chechin GV; Kalyagin MY; Kolesnichenko VE and Zamkovoi AA; **Validation:** Chechin GV; Kalyagin MY; Kolesnichenko VE and Zamkovoi AA; **Visualization:** Chechin GV; Kalyagin MY; Kolesnichenko VE and Zamkovoi AA; **Writing - Preparation of original draft:** Chechin GV; Kalyagin MY; Kolesnichenko VE and Zamkovoi AA; **Writing - Proofreading and editing:** Chechin GV; Kalyagin MY; Kolesnichenko VE and Zamkovoi AA.

DATA AVAILABILITY STATEMENT

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

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