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# Loss Estimation for Network-Connected UAV/RPAS Communications

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**ABSTRACT** The recent applications of Unmanned Aerial Vehicles (UAVs) and Remotely Piloted Air Systems (RPAS) often require reliable and fast two-way communications between UAVs, base stations and consumers using terrestrial cellular networks. Two crucial questions are whether existing ground networks can effectively interact with UAVs in three-dimensional space during intensive traffic and under what data transmission modes it is possible to provide the necessary Quality of Service (QoS). To answer this question, the UAV/RPAS communication channel model "BS-ATM-HUB-RPAS" with a ground network was designed and investigated. The dependencies of dropped packets, message Travel Time (TT) and HUB Average Utilization on the Transaction Size (TS), the link bandwidth, the Bit Error Rate (BER) and the Packet Fail Chance for different distribution laws of Time Between Transactions (TBT) were analyzed. A significant benefit has been observed in using the LogNormal TBT distribution law rather than the Const and Exponential TBT distributions for the dependencies of dropped packets versus TS, HUB Average Utilization versus TS, and HUB Average Utilization versus link bandwidth. However, for the dependency of message Travel Time on the Transaction Size, the type of TBT distribution did not play a significant role; for all distributions, with increasing transaction size, the time of their transmission via the channel was increased. The importance and usefulness of such a numerical analysis lies in the ability to set traffic parameters and observe the resulting throughput, packet loss, and number of bit errors and QoS in a channel under certain transmission modes.

**INDEX TERMS** Bandwidth, bit error rate (BER), communication channel, data traffic, dropped packets, remotely piloted air systems (RPAS), statistical distribution law, transaction size (TS), time between transactions (TBT), travel time (TT), unmanned aerial vehicles (UAV).

## I. INTRODUCTION AND ANALYSIS OF PUBLICATIONS

The increased functionality and reduced operating costs of Unmanned Aerial Vehicles (UAVs) and Remotely Piloted Air Systems (RPAS) has led to an increase in their use as airborne wireless platforms for connecting ground users, the Internet of Things (IoT) and the Internet of Drones (IoD). In the near future, the expansion of the conventional terrestrial Internet will turn into air networks consisting of UAVs and space networks consisting of satellites. This raises the problem of providing high-performance and reliable two-way communications of UAVs with base stations and consumers using terrestrial cellular networks in these new integrated systems. The three-dimensionality of such communication channels imposes restrictions on the coverage range for Line-of-Sight/Non-Line-of-Sight channels, in which it is necessary to consider the nature of fading in the channel, the presence of noise, and the nonuniform antenna gain of drones and base stations. An important issue is whether existing ground networks can effectively interact with UAVs in three-dimensional space during explosive traffic and under what data transmission modes it is possible to provide the necessary Quality of Service (QoS). Therefore, this study is devoted to obtaining numerical characteristics of RPAS

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channel traffic including estimating the number of dropped packets, increasing transaction travel time, and possible limit values for the network hub loading.

The achievements and future trends in the field of modeling UAV/RPAS communication channels and air networks are considered in the literature [1]–[4]. The review [1] is devoted to a comprehensive survey on UAV communication channel modeling. The smart UAV is considered [2] as the next large revolution in UAV technology, promising to provide new opportunities in terms of reducing risks and costs. The review [2] discusses research trends and major issues for civilian UAV applications, including charging problems, collision avoidance, swarm problems, network connectivity, and security.

The inherent mobility, flexibility and adaptive height of UAVs allow potential applications in wireless systems as airborne base stations to improve the coverage, capacity, reliability and energy efficiency of wireless networks [3]. UAVs can operate as mobile terminals in a cellular network and provide several applications, ranging from real-time video streaming to delivery of goods. The article [3] considers three-dimensional deployment, performance analysis, channel modeling and energy efficiency. Analytical foundations and mathematical tools are described, such as optimization theory, machine learning, stochastic geometry, transport theory, and game theory.

There is an urgent need to ensure that UAVs and their networks can be protected from cyberattacks in flight. One approach is Software-Defined Network (SDN)-based solutions. Network programming, increasing the visibility of the network, and the network's ability to help eliminate security vulnerabilities in UAV networks were studied. The article [4] provides an overview of the latest achievements and the state of the art related to security vulnerabilities and countermeasures with SDN support.

The paper [5] presents a new 3D system model to incorporate UAV users and proposes an analytical framework to characterize uplink/downlink coverage performance. A generalized Poisson multinomial distribution was introduced to model the discrete interference states, and a novel lattice approximation technique was used to obtain the interference distribution.

The work [6] used Multi-Objective Evolutionary Algorithm (MOEA) techniques to optimize the UAV node placement considering more than one objective and multiple constraints to best UAV positioning. This paper extends previous investigations, where the use of a UAV swarm was considered as flying access points forming a mesh network among themselves, providing connectivity to ground nodes.

Models for path loss exponents and shadowing for the radio channel between UAVs and cellular networks were obtained in the article [7]. The results show that the path loss exponent decreases as the UAV moves upward. The findings support the need for height-dependent parameters for describing the propagation channel for UAVs at different heights.

Base stations installed on drones were considered in the paper [8]. Drones freely move to serve mobile users on the ground in accordance with a given mobility management algorithm. It has been found that constant movement increases throughput and reduces the number of drones needed.

A survey on machine-learning techniques for UAV-based communications was provided in the paper [9]. The machine-learning techniques have been used for improving various design and functional aspects such as channel modeling, resource management, positioning, and security.

The architecture of radio access networks using drones was proposed in [10]. In this case, drones were used to transfer data between base stations and users. The proposed swarm optimization algorithm is used for spatial deployment of drones. Modeling has shown that this algorithm allows for a higher coverage ratio with less complexity.

UAVs and satellites were proposed in [11] as possible solutions to facilitate the integration of the Internet of Things (IoT) into the 5G structure. The proposed methods for this integration overcome the limitations of ground-based infrastructure, covered areas and the increasing number of IoT devices.

It was shown in [12] that the use of RPAS in combination with a conventional network can improve the cellular system. The operation of UAVs using cellular networks [13] expands the capabilities of remote navigation and long-distance flights. In this case, the advantages of UAVs are combined with the wide availability of cellular networks. The proposed model provides a simple and accurate forecast of losses in the communication channel, which is useful for researchers and network operators.

The capabilities of traffic parameter predictions using the NetCracker software application were tested in our publication [14] in 2014, where dependencies of message traveling time (1.4 – 1.9 s) on the number of satellites and aircraft were obtained. These calculated data were experimentally confirmed in 2017, when Aireon provided air traffic surveillance data to its partners NavCanada, NATS, ENAV, IAA, and the FAA [15]. Harris Corporation built 81 ADS-B 1090 Extended Squitter receiver payloads for Iridium NEXT satellites. By tracking over 10,000 aircraft, the system delivered data to air traffic control centers with a latency of under 1.5 s [16]. These data practically coincided with our previously calculated values and confirmed the realism of the results obtained for communication channel models using NetCracker software.

Simulations of RPAS data transmission via satellites using MATLAB and NetCracker software were described in our papers [17–20], where satellite channel parameters based on IEEE 802.11a, 802.11 b, 802.16 and Long-Term Evolution (LTE) standards and RPAS satellite traffic characteristics were estimated.

## II. THEORETICAL APPROACH AND AIM OF THE WORK

This article uses NetCracker as a research method — the system of structural-logical design and simulation of computer networks. NetCracker as analytical simulator uses mathematical equations to predict network and application performance.

The algorithm for calculating the communication channel characteristics is as follows.

Denote the values of the internal characteristics of the communication channel to be simulated at time $t_k$ by $Y_1(t_k)$, …, $Y_n(t_k)$; the values of the external characteristics at time $t_k$, affecting the internal, through $U_1(t_k)$, …, $U_r(t_k)$; average rates of the internal characteristics change on the time interval $[t_k, t_k + 1]$ as $F_i(t_k, Y_1(t_k), \ldots, Y_n(t_k), U_1(t_k), \ldots, U_r(t_k))$, $i = 1, \ldots, n$. Then, having the values of the internal and external characteristics at the moment $t_k$, it is possible calculating the values of internal characteristics at the time ($t_k$+ 1). To do this, the segment $[t_0, T]$ is divided into $K$ parts by the points $t_0, t_1, \ldots, t_k, \ldots, t_K = T$. If the values of internal characteristics at time $t_0$ and average rates of the internal characteristics change on each segment $[t_k, t_k+ 1]$ are known, then using the following relations it is possible calculating the values of internal characteristics for all $t_k$, $k = 1, \ldots, K$:

$$Y_i(t_k + 1) = Y_i(t_k) + \Delta t F_i(t_k, Y_1(t_k), \ldots, Y_n(t_k), U_1(t_k), \ldots, U_r(t_k)),$$

where $i = 1, n$; $k = 0, 1, \ldots, K - 1$. In mathematics, the last relations are called a discrete dynamical system. External characteristics are often called inputs to system, and the internal characteristics - outputs. The internal characteristics of the communication channel, which was simulated in this study, were the Average Utilization (AU), the Travel Time (TT), and Dropped Packets. The external characteristics, affecting the internal – the Transaction Size (TS), the Time Between Transactions (TBT), the Bit Error Rate (BER), the link Bandwidth, the Packet Fail Chance.

A discrete dynamical system determines the values of the internal characteristics of the process under study at discrete time instants $t_k$, $k = 1, \ldots, K$. If the process is such that it is possible to talk about the values $Y_1(t)$, …, $Y_n(t)$ for any value $t$ of the interval $[t_0, T]$ and it is natural to consider the functions $Y_1(t)$, …, $Y_n(t)$ continuous and having derivatives, then together with the discrete model it is possible to describe the process using the "continuous" model, which has the form

$$dY_i/dt = F_i(t, Y_1, \ldots, Y_n, U_1, \ldots, U_r),$$

where $i = 1, \ldots, n$. Here the functions $F_i(t, Y_1, \ldots, Y_n, U_1, \ldots, U_r)$ are the "instantaneous" rates of change for the corresponding internal characteristics. If the value of $\Delta t$ is sufficiently small, then it is possible to assume that these are the same functions that appear in the discrete model. During a simulation, it is possible to calculate the values of model parameters using a computer. In practice, this means that the dependence of the values of internal characteristics on time and/or external characteristics is not expressed using elementary functions.

When calculating the characteristics of the UAV/RPAS communication channel, it is necessary to know the distribution law of the transmitted packet lengths $\omega(x)$ and the distribution law of time intervals (TBT) between them $\omega(t)$. In the proposed model, the following probability distribution laws were used: Const law - $\omega(x) = const$, Exponential law - $\omega(x) = \lambda e^{-\lambda x}$, and LogNormal law - $\omega(x) = \frac{1}{x\sqrt{2\pi\sigma^2}}\exp(-\frac{(\text{lnx-a})^2}{2\sigma^2})$.

The average length of the transmitted packets is determined as the mathematical expectation:

$$TS = \int_{-\infty}^{\infty} x\omega(x)dx,$$

and the average time interval between two adjacent packets:

$$TBT = \int_{-\infty}^{\infty} t\omega(t)dt.$$

Based on the values of TS and TBT parameters, the Average Utilization on the communication link is determined by the formula:

$$AU = TS/TBT = TS/\mu,$$

where $\mu = 1/TBT$ is the packet transmission rate over the communication channel. An analysis of this expression shows that the utilization of the communication channel depends both on the size of the transmitted packets and on the intensity of their generation. If the value of the AU parameter is greater than the maximum data rate of the communication channel, then some of the transmitted packets will be lost with probability

$$P = 1 - \frac{AU_{link}}{AU}.$$

The average packet travel time over the communication channel is determined by the formula

$$TT = \frac{TS}{AU_{link}}.$$

NetCracker provides real-time "what-if" statistics and interactive simulations that can help optimize a network once all model devices are assembled and connected. NetCracker allows computer experiments with models, and the results of such simulations can be used to justify the choice of the network type, communication channel, transmission media and network components. NetCracker software tools allow one to create a network, perform the necessary simulation experiments, determine the ultimate characteristics, collect relevant data about expandability, change topology and modify the network equipment to further improve and develop it. It is possible to design computer networks of various sizes and purposes from local networks with several dozen computers to interstate global networks with satellite communications.

NetCracker simulation functions provide means for specifying the traffic characteristics of various protocols, means for visually monitoring the specified parameters, means for accumulating statistical information and generating reporting documentation on the experiments.

The objectives of this paper are 1) to create a model of a RPAS communication channel with the ground network using NetCracker software and 2) to analyze the dependencies of the HUB dropped packets, the Travel Time (TT) and the HUB Average Utilization (AU) on the Transaction Size (TS), the bandwidth, the Bit Error Rate (BER) and the Packet Fail Chance for different distribution laws of the Time Between Transactions (TBT).

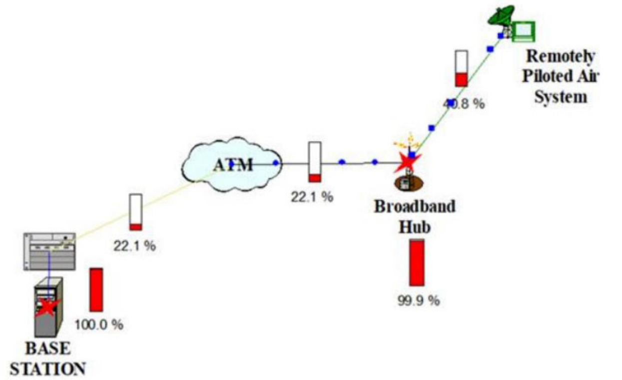


**FIGURE 1.** "BS – ATM – HUB – RPAS" communication channel.

## III. RPAS COMMUNICATION CHANNEL SIMULATION

The model architecture presented in this paper is simple in sense that it contains the minimal necessary set of elements for RPAS communication channel simulation. It may serve as a basis for further study of RPAS data transmission in swarms, Radio Access Networks and the Internet of Things [5, 7, 11, 12]. The RPAS communication channel model (Fig. 1) was designed using NetCracker Professional 4.1 (https://www.netcracker.com/). The functional characteristics of the model were simulated considering the data transfer protocol, statistical parameters of transactions, and the time between transactions. In addition, the number of dropped packets was estimated for the specified traffic parameters.

The model contains the Base Station (BS), the ATM cloud, the HUB–Wireless Local Area Network (WLAN) station, and the RPAS. Only two parameters, "Packet Latency" and "Packet Fail Chance," can be user defined in the ATM cloud. The same possibility exists for other clouds available in NetCracker software (e.g., X.25, Frame Relay, SMDS, PSTN, ISDN, SONET, WAN). ATM resembles a network with both circuit switching and packet switching. This feature is suitable for the RPAS two-way data exchange with the BS. In this case, both command data traffic for flight control and real-time content with low latency, such as the actual operational situation on the battlefield, should be processed with high throughput.

A traffic with LAN peer-to-peer profile was specified for the created model with the topology according to Fig. 1. This means decentralized network based on the equal rights of participants. There are no dedicated servers in such a network, and each peer is both a client and acts as a server. Such an organization allows to maintain the network's operability for any number and any combination of available nodes, which are understood here as RPASs.

The BS contains an Ethernet server and Ethernet switch with 10 Mbps bandwidth. The BS–HUB link is a fiberoptic cable with a T3 (44.736 Mbps) data rate, a Packet Latency of zero seconds and BER = 0.

The HUB–RPAS link has a T3 data rate, a Packet Latency of zero and BER = 0. The RPAS is the standard WLAN equipment with a bandwidth of 10 Mbps.

Modeling was provided until "saturation" of calculated parameters, when they stop their changing.

Fig. 2 shows the dependencies of HUB dropped packets on the transaction size, the time between transactions, and the type of statistical distribution law. The general distribution law (Const) is selected for the TS parameter, and three different laws are used for the TBT parameters — Const (Fig. 2a), Exponential (Fig. 2b) and LogNormal (Fig. 2c). The values of the TS parameter varied from 10 bits to 10 Mbits, and the TBT parameter took values of 1 s, 0.1 s, and 0.01 s. This allowed the change in channel operation to be simulated and critical situations to be determined in terms of information loss during data transfer.

Fig. 2a, 2b, 2c show the maximum possible packet sizes for transmissions under the specific conditions shown in the figures. For example, the largest possible packet size (for TBT with the Const law) is 10 Mbits for TBT = 1 s, 1 Mbits for TBT = 0.1 s, and 100 Kbits for TBT = 0.01 s (Fig. 2a). The same will apply to Fig. 3, 4. The obtained data show that the smaller the TBT parameter, the lower the maximum value of the transaction that can be transmitted. This is true for all distributions of the TBT parameter, with the exception of LogNormal distribution (Fig. 2c) with TBT = 0.1 s and TBT = 0.01 s, for which the maximum packet sizes are the same (TS = 1 Mbits).

Fig. 3 shows the dependencies of message travel time on the size of transactions and the time interval between them for different statistical distributions. The same laws (Const) are selected for the TS parameters in Fig. 3a, 3b, and 3c. The similar types of dependencies are observed in Fig. 3 for all TBT distributions; with increasing transaction size, the time of their transmission via the channel increases. The travel time increases with increasing packet size and turns out to be $\approx$ 1.0 s for TS = 100 Kbits (Fig. 3a – TBT Const law, Fig. 3b – TBT Exponential law) and $\approx$ (0.7-1.3) s for TBT LogNormal law with TS = 1 Mbits (Fig. 3c).

Fig. 4 gives the dependencies of the HUB Average Utilization (HUB AU) on the size of transactions and the time between them for different statistical distribution laws of the TBT parameters. The common Const law of the TS

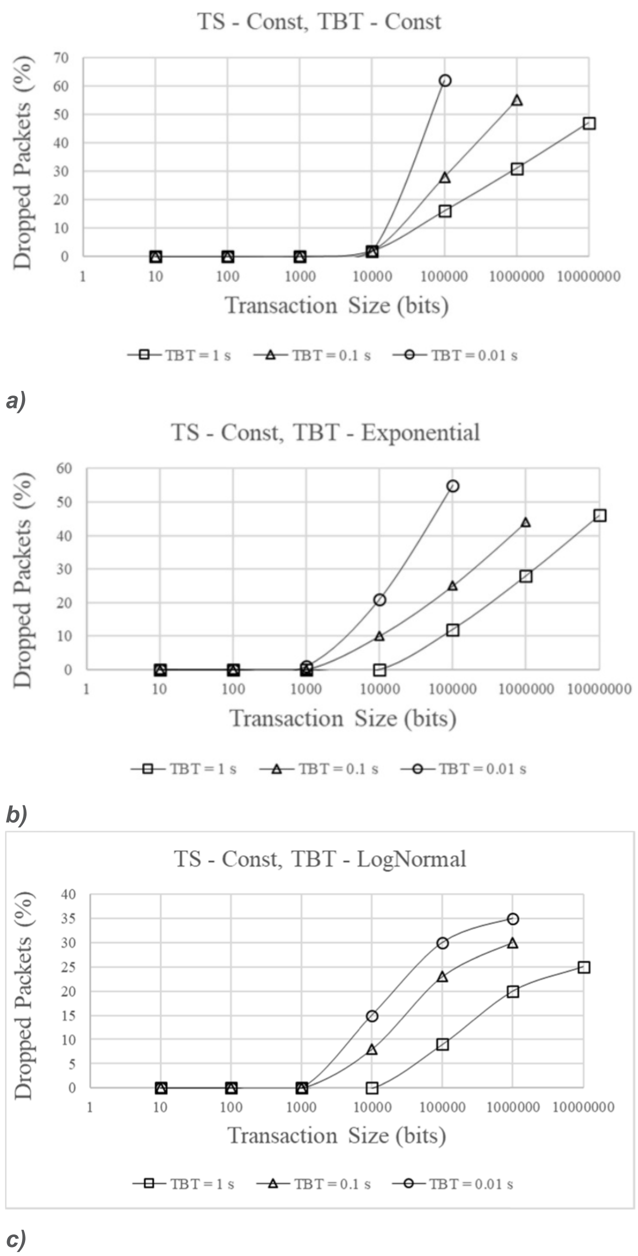


**FIGURE 2.** Dependencies of HUB dropped packets on TS (RPAS link with T3 bandwidth).

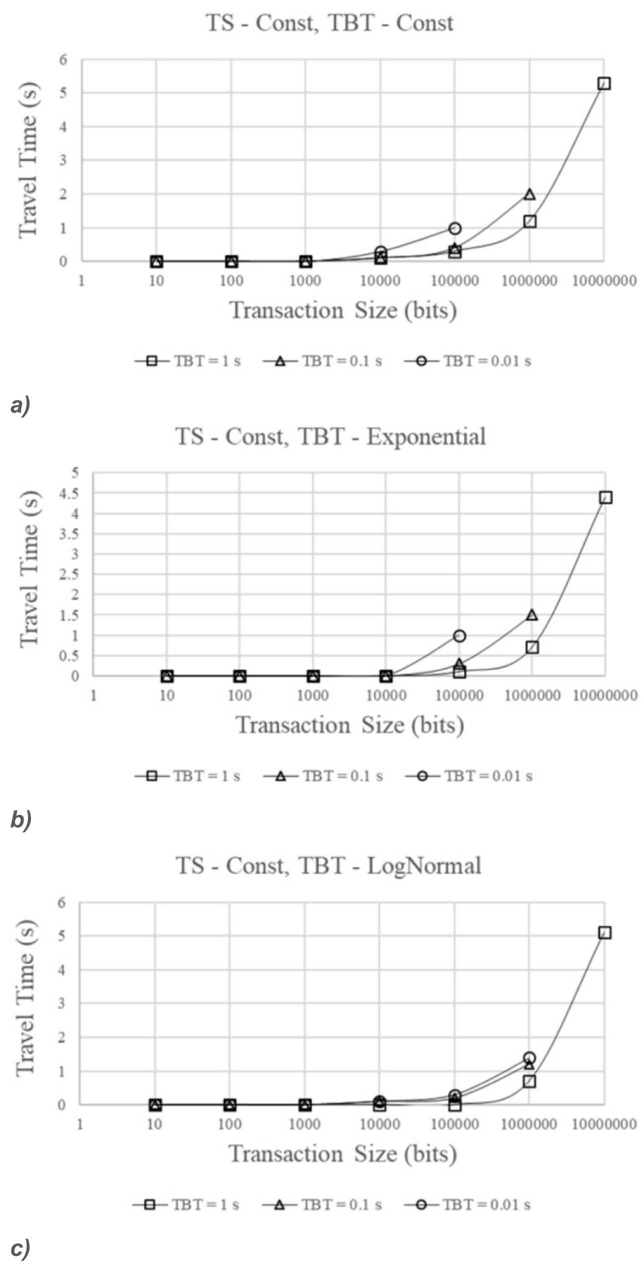


**FIGURE 3.** Dependencies of transaction Travel Time on TS (RPAS link with T3 bandwidth).

parameter distribution is selected in Fig. 4, and data for the maximum possible packet sizes are shown. The HUB AU does not exceed ≈ 20% for Const and LogNormal TBT distributions with TBT = 1 s (Fig. 4 a, 4c). The HUB AU increases (Fig. 4a, 4b) with decreasing TBT parameter, and the maximal packet size decreases (Fig. 4a, 4b, 4c). The TBT parameter is critical for Const and Exponential TBT laws (Fig. 4a, 4b) with its decrease. This means that if for TBT = 1 s and TBT = 0.1 s, the value of the HUB AU parameter is less than 60%, for TBT = 0.01 s, the HUB AU reaches ≈ 98% for the Const and Exponential TBT laws (Fig. 4a, 4b). Completely different behavior is observed for the LogNormal TBT law (Fig. 4c), where the HUB AU is ≈ (14-16) % for all three TBT intervals.

Packet losses (Fig. 5a), travel times (Fig. 5b) and HUB AU (Fig. 5c) dependencies on the bandwidth are decisive in data transmission. The transaction with TS = 500 Kbits and TBT = 1 s with various statistical distribution laws was studied as an example. A channel with a bandwidth of less than 10 Mbps results in the loss of more than half of all transmitted packets (Fig. 5a). The smallest percentage of packet losses is observed for the LogNormal law with E3 = 34.368 Mbps and T3 = 44.736 Mbps bandwidths (Fig. 5a).

The TT parameter decreases with increasing bandwidth rate and turns out to be almost the same (TT ≈ 0.5 s) for all distributions at T3 bandwidth (Fig. 5b). For the bandwidth E1 = 2.048 Mbps, the TT parameter increases and can reach values ≈ (1.0-1.5) s.

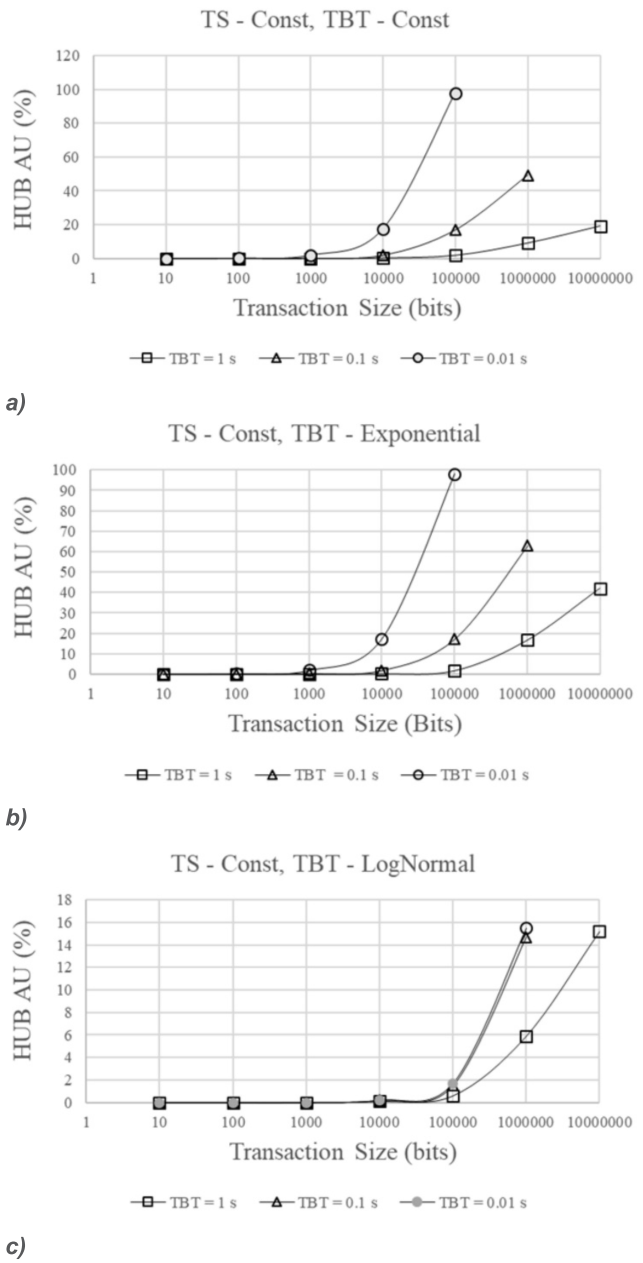


**FIGURE 4.** Dependencies of HUB AU on TS (RPAS link with T3 bandwidth).

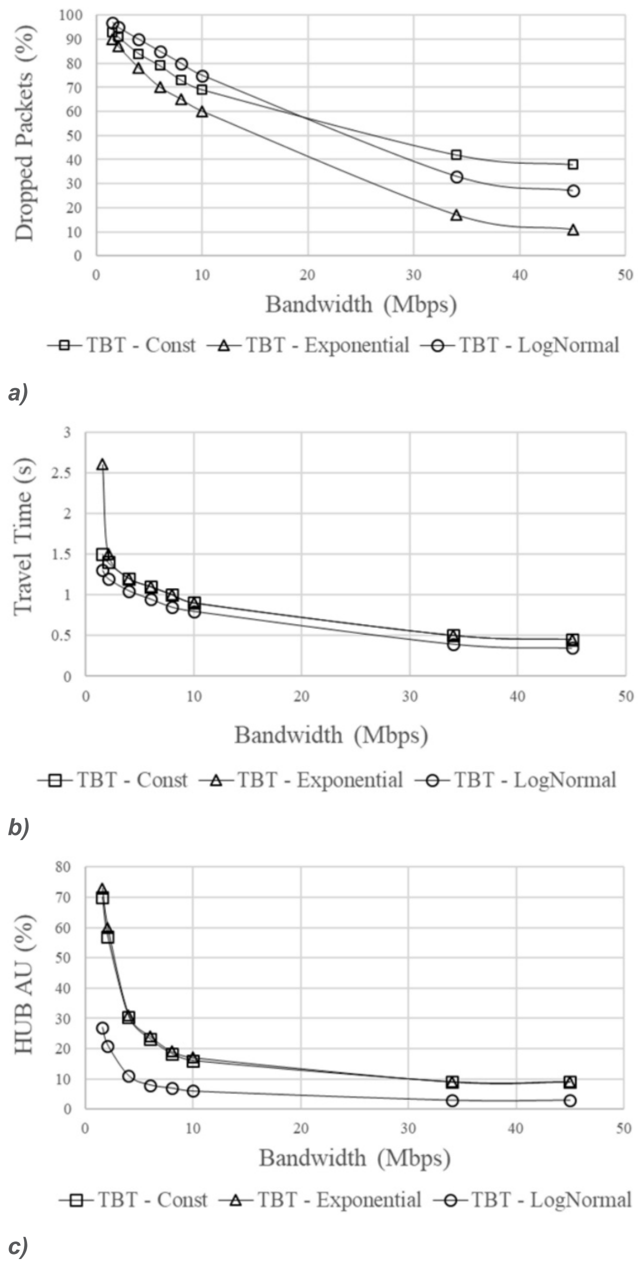


**FIGURE 5.** Dependencies on HUB-RPAS bandwidth (TS =500 Kbits – Const law, TBT =1 s).

The HUB AU is less than 10% for E3 and T3 bandwidths for all distributions, but the smallest is for the LogNormal law (Fig. 5c). For T1 bandwidth, the HUB AU can reach ≈ (70-75) % for the Const and Exponential TBT laws but is less than ≈ 30% for the LogNormal TBT law.

The number of bit errors, travel times and HUB AU increase with traffic growth. Fig. 6 demonstrates these processes using the example of the transaction with TS = 1 Kbits (Const law) and TBT = 1 s for all considered TBT statistical distributions when the BER parameter is varied from zero to 0.7%. The dependencies of the TT parameters on the BER (Fig. 6a) are almost the same for all TBT laws up to BER = 0.6%. Moreover, the travel time does not exceed 1.6 s for values up to BER = 0.3%. Thus, bit errors do not critically affect the travel time for messages with the selected parameters. From Fig. 6b, it follows that HUB AU almost does not increase when transmitting selected test messages up to BER = 0.3%. The HUB AU increases and can reach ≈ 11% for the Const TBT law, ≈ 12% for the Exponential TBT law and ≈ 4.5% for the LogNormal TBT law (Fig. 6b).

Fig. 7-9 demonstrate the role of ATM clouds in data transmission. Packets losses (Fig. 7), travel times (Fig. 8) and HUB AU (Fig. 9) dependencies on the ATM Packet Fail Chance are investigated when packet failure varies in the range (0.0 - 0.8).

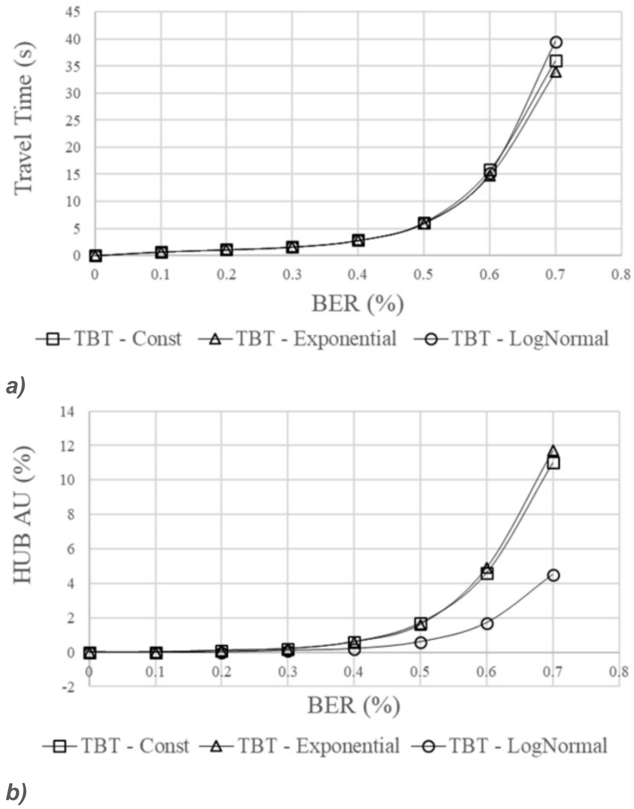


**FIGURE 6.** Dependencies of TT and HUB AU on HUB-RPAS BER (TS =1 Kbits – Const law, TBT =1 s, RPAS link with T3 bandwidth).

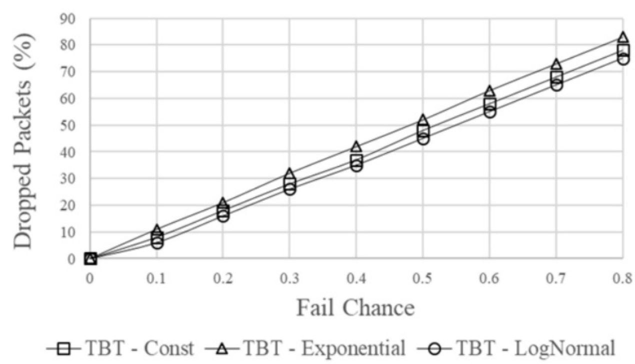


**FIGURE 7.** Dependencies of dropped packets on ATM packet fail chance (TS = 1 Kbits with Const law, TBT = 1 s, RPAS link with T3 bandwidth).

The transaction with TS = 500 Kbits and TBT = 1 s with various distribution laws was used as an example. Packet losses can be caused by errors in data transmission over networks or network congestion. Quantitatively, packet loss is estimated as the percentage of packets lost in relation to the sent packets.

It can be seen (Fig. 7) that with the growth of the Packet Fail Chance from 0.0 to 0.8, the number of lost packets increases linearly from zero to ≈ (75-82) % for all TBT distributions. Knowing these dependencies is useful in planning the loading of a network hub and can be used to predict critical situations.

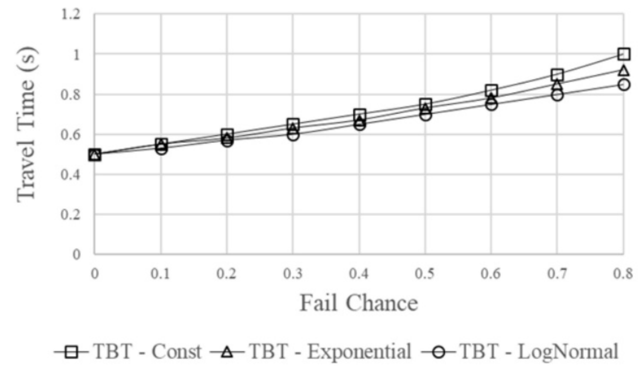


**FIGURE 8.** Dependencies of TT on ATM packet fail chance (TS = 1 Kbits with Const law, TBT = 1 s, RPAS link with T3 bandwidth).

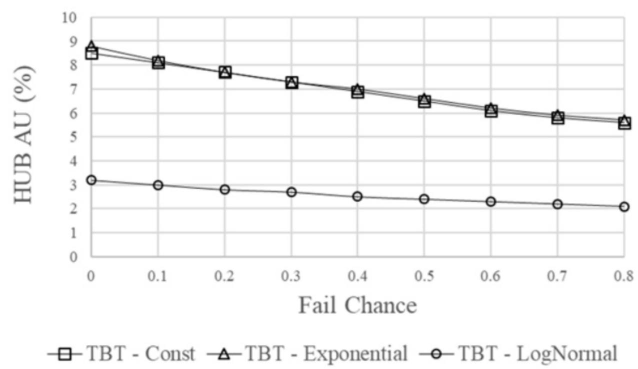


**FIGURE 9.** Dependencies of HUB AU on ATM Packet Fail Chance (TS = 1 Kbits with Const law, TBT = 1 s, RPAS link with T3 bandwidth).

The dependencies of travel times on the probability of packet losses (Fig. 8) are the same for all TBT distribution laws and demonstrate an almost linear increase in the TT parameter from ≈ 0.5 s to ≈ (0.8-1.0) s with an increase in the probability of packet losses from 0.0 to 0.8. Therefore, it is possible to conclude that the probability of packet loss is not critical specifically for the selected test message.

The HUB utilization decreases (Fig. 9) with increasing probability of packet losses. However, as seen in the graphs, the decrease is not very significant for the test transaction under consideration: from ≈ (8.5-9.0) % to ≈ 5.5% for the Const and Exponential laws and from ≈ 3% to ≈ 2% for the LogNormal law with increasing probability from 0.0 to 0.8.

## IV. CONCLUSION

When creating communication channels for drones and choosing their operating modes, it is important to know when a critical situation emerges and communication becomes unreliable or is completely interrupted. This is important for transmitting useful data, especially commands and control, as such a situation could lead to the loss of the drone. Therefore, when creating new UAVs/RPASs, the theoretical foundations of their communication channels are continuously being developed, which is necessary to predict their behavior. The urgency of the problem is connected with the inclusion of ground and space networks in communication channels and the creation of integrated UAV/RPAS communication systems. Quantitative information regarding the loss of two-way traffic for the UAV/RPAS channel containing the terrestrial network is currently unavailable in the literature. In this work, such information was obtained using the model shown in Fig. 1, and the calculated traffic characteristics were presented in Figs. 2–9.

The dependencies of lost packets on the network hub (Fig. 2), the transaction travel time via the channel (Fig. 3) and the average utilization of the hub (Fig. 4) on the transaction size with different distribution laws for the time between transactions were analyzed. The dependencies of lost packets on the hub (Fig. 5a), the travel time (Fig. 5b), and average hub utilization (Fig. 5c) versus bandwidth for various distribution laws for the time between transactions were obtained. The dependencies of the travel time (Fig. 6a) and the average utilization of the HUB (Fig. 6b) on the number of bit errors with different distribution laws for the time between transactions were investigated. The dependencies of packet losses (Fig. 7), packet travel time (Fig. 8), and average hub utilization (Fig. 9) were given as a function of packet fail chance on the hub.

The importance and usefulness of such a numerical analysis lie in the ability to set traffic parameters and observe the resulting throughput, packet losses, number of bit errors and QoS in a channel under certain transmission modes.

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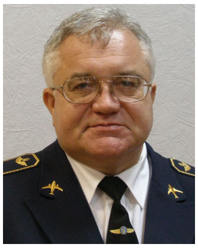

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