Simulation of RPAS/UAV Data Traffic Using Space-Air-Ground Networks

Svitlana Ilnytska (ilnytskasv84@gmail.com)
Wenzhou University
Fengping Li
Wenzhou University
Andrii Grekhov
National Aviation University: Nacional'nij Aviacijnij Universitet
Vasyl Kondratiuk
National Aviation University: Nacional'nij Aviacijnij Universitet

Research Article

Keywords: SAGIN , RPAS , UAV , data traffic , transaction size , BER , dropped packets

Posted Date: May 24th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-449619/v1

Noname manuscript No.
(will be inserted by the editor)

Simulation of RPAS/UAV Data Traffic Using Space-Air-Ground Networks

Svitlana Ilnytska · Fengping Li · Andrii Grekhov · Vasyl Kondratiuk

Received: date / Accepted: date

Abstract The latest applications of Remotely Piloted Air Systems (RPAS) for telecommunication data transmission require reliable two-way communications. In this regard, it is necessary to answer two questions: how can existing space, air and ground networks be combined for effective interaction with RPASs during heavy traffic and under what data transmission modes can the required Quality of Service (QoS) be ensured. To answer such questions, this study was undertaken. Models of space, air and ground networks were created to simulate remote data transmission. Models including the Base Station (BS), the Public Terrestrial Network (PTN), the Low-Orbit Satellite, and different number of RPASs were designed using NetCracker Professional 4.1 software. For the first time, quantitative characteristics of traffic in Space-Air-Ground Integrated Network (SAGIN) communication channels were obtained. The Average Utilization (AU) dependencies of BS links on the Transaction Size (TS) were obtained and analyzed. BS links with different bandwidths were studied. Effect of the Bit Error Rate (BER) on the AU parameters was considered. The

Svitlana Ilnytska
Institute of Laser and Optoelectronics Intelligent Manufacturing, Wenzhou University
Wenzhou 325035, China
E-mail: ilnytskasv84@gmail.com

Fengping Li
Institute of Laser and Optoelectronics Intelligent Manufacturing, Wenzhou University
Wenzhou 325035, China
E-mail: lfp@wzu.edu.cn

Andrii Grekhov
Department of Air Navigation Systems, National Aviation University,
Kyiv, Ukraine
E-mail: grekhovam@gmail.com

Vasyl Kondratiuk
Research Training Center "Aerospace Center", National Aviation University,
Kyiv, Ukraine
E-mail: kon vm@ukr.net

dependences of the dropped packets on the TS parameters were studied. SAGIN traffic characteristics for terrestrial and satellite communication channels were compared.

Keywords SAGIN · RPAS · UAV · data traffic · transaction size · BER · dropped packets

1 Introduction

Space-Air-Ground Integrated Networks (SAGINs) more and more are used for operation in complex conditions. SAGINs can provide Beyond Line of Sight (BLOS) communications C3 (Command, Control and Communications) for the Remotely Piloted Air Systems (RPASs) or Unmanned Aerial Vehicle (UAV) shown in Figure 1 [1]. SAGINs can interconnect multiple networks to increase a topology of the global telecommunications network, which improves the ability efficiently exchange information and resources. At the same time, the corresponding means of communication between mobile platforms and air-ground links are limited by technology with a low data rate. In addition, supporting services requires high bandwidth channels to process many data in real time [2] – [6].

Deploying remote SAGIN communications faces challenges in effectively integrating the various segments of such a network. Satellites have limitations for use in SAGIN due to time delay and data rate. Special attention should be paid to adapting SAGIN to traffic loads. In addition, a 3D network connection to the RPAS anywhere and anytime must be provided. To simulate the SAGIN operation, it is necessary to build models for the mobile ad hoc network, using which it will be possible to study broadband communications and perform numerical analysis. Models should provide insight into the operation of the SAGIN architecture with the wide area network. Quantitative results of model research should allow drawing conclusions about achievable QoS in real communications [3], [4].

Reliable and high-performance wireless links are essential to ensure efficient interoperability in RPAS/UAV swarms. The existing requirements for the control and monitoring take into account the peculiarities of communication between RPASs/UAVs, as well as air-ground links. The mission information is transmitted to the ground station by the air-to-ground communications system for flight control and display. In addition, telecommunications information is shared in the swarm by means of an air-to-air communication system between RPASs/UAVs.

In this article, SAGIN is considered as an extension of cooperative telecommunication networks, for which data traffic modeling is carried out. During the simulation, realistic data traffic was specified for SAGIN links, including space-to-air, space-to-ground, and air-to-ground links. As fragments of SAGIN, four models with different architectures are considered. In the first model, the Base Station (BS) controls the RPASs via the ground/air HUB, which is a Wireless

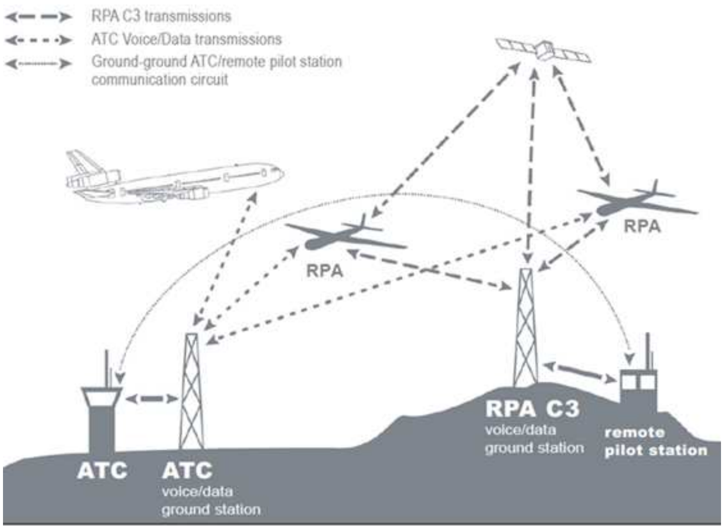

Fig. 1 ICAO aeronautical RPAS communication links [1]

Local Area Network (WLAN) station. In the second model, the BS communicates with the HUB and RPASs using the Public Terrestrial Network (PTN). In the third model, the BS controls the RPASs via the Low-Orbit Satellite. The fourth model is the closest to real SAGIN and contains satellite and the PTN for communication with the HUB. The main contributions of this paper are the following.

First, original models for integrated space-air-ground RPASs/UAVs networks were designed and traffic quantitative characteristics were obtained for the first time. Secondly, due to the complexity of the problem for the created models, the approach based on simulation modeling was proposed. Third, the dependences of BS channels Average Utilization (AU) on the Transaction Size (TS) were obtained and analyzed. BS links with different throughput were investigated. The influence of the Bit Error Rate (BER) on the AU parameters was considered. The dependences of dropped packets on TS parameters were studied. Fourth, a comparison of SAGIN traffic characteristics for terrestrial and satellite communication channels is carried out. This is of practical value, since it allows using the obtained dependences to predict the channel's behavior when the transaction size, channel bandwidth and bit error rate change.

The rest of this article is organized as follows. Section 2 summarizes related work. Section 3 overviews models architectures, algorithm, and calculation methods. Section 4 presents results of simulations. Section 5 includes a discussion, and Section 6 concludes the paper.

2 Related Works

The authors of this article began to publish their works on modeling SAGIN telecommunications [7] and SAGIN teletraffic [8] in 2012 and summarized in the book [9] . In the article [8] , data were obtained that were later confirmed experimentally. The model of communication channel "Aircraft - Satellite - Ground Station" was built for modeling of Automatic Dependent Surveillance - Broadcast (ADS–B) messages transmitting with the help of low-orbit satellite complex Iridium. The resulting dependences of the message travel time (1.4 – 1.9 s) on the number of satellites and aircraft were experimentally confirmed in 2017 by Aireon [10], which provided its partners with air traffic observation data. Tracking more than 10,000 aircraft with ADS–B 1090 Extended Squitter receivers for Iridium NEXT satellites, the system delivered data to air traffic control centers with a delay of less than 1.5 seconds [11].

The number of publications devoted to SAGIN issues is growing. Reviews and tutorials have been published on SAGIN networks and communications in recent years. An overview of the main functions, services and requirements of UAV-based network architectures, services at the middleware level, and a case study focusing on the use of UAVs are described in the review [2].

The fundamental knowledge required for research in the field of UAVs is presented in book [3]. The main concepts of the topic, the state of affairs in the field of UAVs and their networks are considered. Deployment rules, policies and procedures (including risk-benefit analysis) are discussed. The review [4] addresses physical layer characteristics and spectrum allocation, mobility management and traffic offloading. Routing, proposed integrated architectures, and network performance analysis are summarized in the overview. Several existing network architectures have been identified that are applicable to SAGIN. The authors point out technical challenges and future directions.

The potential Space-Terrestrial Integrated Network (STIN) architecture is presented in the review [5]. The extended space network consists of a multi-satellite space backbone, a data center ground backbone and ground access nodes. A number of key technical issues related to STIN are presented, including physical layer transmission technologies, network protocols, routing, resource management, security, and test bench design.

The article [6] is devoted to the performance analysis of SAGIN over an arbitrarily correlated multivariate Free-Space Optical (FSO) channel. The different technologies for SAGIN links are presented and compared. The performance of the FSO system is affected by fading caused by atmospheric turbulence. UAVs operation in swarm mode in the SAGIN system can lead to channel correlation and system degradation. The work takes into account the effect of the randomly correlated FSO channel on the system performance. For this, an exponential model is used to simulate correlations between apertures. Spatial correlation in air-ground communication as well as air-air communication in the SAGIN system is considered using a multivariate gamma-gamma distribution.

It is especially important for SAGIN to study traffic involving UAV swarms. Severe visibility conflicts and short window times make scheduling tasks in SAGIN difficult. SAGIN needs more efficient and intelligent planning schemes. To efficiently transfer data and manage tasks in SAGIN, it is necessary to develop a task schedule. The article [12] presents the SAGIN model for reducing the number of satellite orientation adjustments and increasing the task planning time, which is created by satellites, UAV swarms and ground stations. An algorithm for intelligent coordinated planning with adaptive swarm optimization is proposed.

UAV swarms have advantages such as flexibility, accuracy, stability, and reliability. However, external communications traffic potentially exposes them to an additional level of failure, disruption, uncertainty, and cyberattack, which can propagate error from one component to other network components. Problems such as the complex nonlinear dynamics of UAVs in swarms, the need for collision avoidance, speed negotiation, and communication setup all lead to significant data traffic. The article [13] discusses the issues of joint control of UAVs and related practical approaches.

The article [14] notes that since deploying SAGIN in real life is complex and prohibitive, it is necessary to pre-simulate SAGIN. This article presents the SAGIN simulation platform with support for a variety of space, air, and terrestrial network protocols. A case study is presented with dynamic selection of different radio access networks according to their QoS requirements.

The SAGINs did not receive widespread attention until full-fledged UAV communications and special flying networks (FANET) appeared. Since then, the SAGIN architecture has gradually become a potential solution to support next generation networks due to the undeniable advantages of SAGIN in terms of coverage, capacity, reliability and flexibility. The article [15] examines SAGIN from the point of view of collaborative communications and introduces relay network technologies for modeling and building the SAGIN structure. The characteristics of SAGIN outage performance and the outage probability are analyzed. Numerical results provide insight into the applicability of SAGIN.

One of the best examples of the RPAS with air-ground communication technology to date is the Global Hawk [16], which is equipped with an integrated surveillance and reconnaissance system HISAR (Hughes Integrated Surveillance & Reconnaissance). The complex includes SAR/MTI (Synthetic Aperture Radar/Moving Target Indicator) radar, as well as optical and infrared sensors. All three subsystems can work simultaneously, and a single processor processes their data. Digital data can be transmitted to the ground in real time with Line-of-Sight (LOS) or through a satellite link at rates up to 50 Mbps.

The article [17] proposes a software-defined integrated architecture for a space-air-ground automotive network. The working relations, the hierarchical network operation and big data-assisted networking are presented. The proposed open network architecture can achieve network agility, flexibility, and simplify network management. The problem of ultra-dense networks is discussed in article [18]. When compacting a large number of small cells, problems arise in the cost of deployment, energy consumption and control. The article develops software-defined space-air-ground integrated moving cells (SAGE-CELL). Four typical applications are presented and a case study is carried out based on the topology of real roads.

The Multi-Layered Space-Terrestrial Integrated Network (MLSTIN) is seen as a promising wireless data access in the upcoming 5G networks [19]. However, due to the inherent heterogeneity of MLSTIN, it is challenging to manage the diverse physical devices for large amounts of traffic delivery with optimal network performance. This article proposes a cross-domain software-defined architecture and discusses the design and implementation details of that architecture. The system performance was tested on two practical examples. The results have corroborated that proposed architecture is able to significantly reduce control time overhead of configuration updating and decision making. In the article [20], the choice of an inter-layer gateway is considered as a limited optimization problem in a satellite-aerial-terrestrial network. A solution is proposed to efficiently determine the optimal set of gateways from the aerial network, which serves as a relay layer for data delivery between the terrestrial and satellite layers. Numerical results are presented that confirm the effectiveness of such solution.

SAGIN significantly enhances the capabilities of terrestrial wireless networks, which, on the other hand, can also help space space-air networks to perform resource-intensive or energy-intensive tasks, increasing their capabilities. The article [21] identifies the key role of network reconfiguration in coordinating disparate SAGIN resources and explores how virtualization of network functions and service function chain provide flexible offloading of missions. The case study confirms the performance gains from bi-directional unloading. It is noted that the bi-directional mission unloading structure opens up a new path in unlocking the full potential of SAGIN. Cellular-connected UAVs integrate UAVs into the cellular network as aerial platforms and are considered in articles [22], [23]. Such communication between the UAV and ground users has special characteristics, which creates new opportunities. The article [22] provides an overview of this new technology and presents the simulation results. Models of cellular-connected RPASs with different architectures were created in our paper [23]. The relationships between models' performance and traffic parameters were obtained. The dependences of the channel average utilization on the transaction size were analyzed. The effects of different channel bandwidths and the bit error rate were studied. The traffic characteristics in all models were compared.

There is no data on traffic losses in UAV/RPAS communication channels in the mentioned works concerning SAGIN. Losses estimation for network-connected UAV/RPAS communications was obtained for the first time in our article [24]. The first experimental UAV data traffic will be presented only in May this year at the IEEE INFOCOM conference, 2021 [25]. Simulations of RPAS data transmission via satellites using MATLAB and NetCracker software were described in our papers [26] – [28]. Satellite channel parameters based on IEEE 802.11a, 802.11 b, 802.16, Long-Term Evolution (LTE) standards were obtained and RPAS satellite traffic characteristics were estimated. However, until now in the literature there are no quantitative characteristics of data traffic in SAGIN. There are practically no theoretical studies devoted to the development of predictive analysis methods in the field of SAGIN data synthesis. There are no methods for assessing the efficiency and traffic parameters for such systems. Our research focuses on the development of such methods. To understand the ways to fulfill the requirements for the SAGIN delay, reliability, bandwidth, and QoS this study was undertaken.

3 Architectures, Algorithm, and Calculation Methods

3.1 Models Architecture

The architecture of the SAGIN communication channel models (Figure 2) was based on ICAO documents [1] (Figure 1). RPAS channel models (Figure 2) were designed using Professional NetCracker 4.1 software [29]. Models with different numbers of RPASs (N = 1, 3, 5) for the case of LOS communications (Figure 2a) were also built and considered. Parameters of the models shown in Figure 2 are given in Table 1.

Model 1: "BS – HUB – RPASs" (Figure 2 a) contains the BS, the HUB — ground/air Wireless Local Area Network (WLAN) station on the distance 10 km from the BS, and the RPASs each on the distance 1 km from the HUB.

Model 2 PTN: BS – PTN – HUB – RPASs" (Figure 2 b) contains the PTN cloud in addition to Model 1 on the distance 10 km from the BS. Only two parameters, namely "Packet Latency" and "Packet Fail Chance", can be user defined in the PTN cloud. The HUB is on the distance 100 km from PTN cloud. Model 3 SAT: "BS – SAT – HUB – RPASs" (Figure 2 c) contains the Low-Orbit Satellite at an altitude of 1000 km and the HUN on the distance 1000 km from the Satellite in addition to Model 1.

Model 4 SAT PTN: "BS – SAT – PTN – HUB – RPASs" (Figure 2 d) contains the Low-Orbit Satellite at an altitude of 1000 km, the PTN cloud on the distance of 1000 km from the Satellite, the HUB on the distance of 100 km from PTN cloud in addition to Model 1.

Among presented in Figure 2 models, the SAGIN concept is described by the Model 4 SAT PTN in the most adequate manner. Since communication with the HUB is wireless in all models, the HUB itself can be implemented as air or ground node.

3.2 Algorithm

The algorithm for calculating the communication channel characteristics is described in our paper [24]. The created models (Figure 2) are complex, that is why the forecast of their behavior is not currently available by mathematical

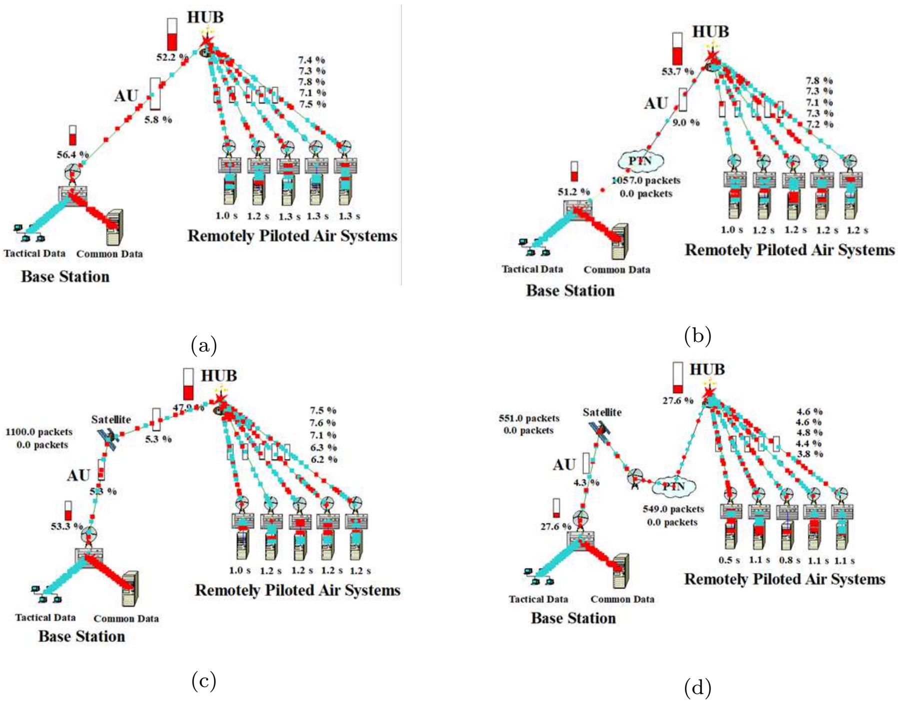

Fig. 2 Models with five RPASs:
a) Model 1: "BS – HUB – RPASs"; b) Model 2 PTN: "BS – PTN – HUB – RPASs";
c) Model 3 SAT: "BS – SAT – HUB – RPASs"; d) Model 4 SAT PTN: "BS – SAT – PTN – HUB – RPASs". The figures show links for which the AU parameter was calculated

means and can be carried out only by simulation methods. Such methods combine the features of the experimental approach and the use of computer technology. The term "simulation" usually means calculating the values of some model characteristics developing in time by reproducing the flow of this process on a computer using its mathematical model.

Simulation models belong to the class of models, which use a set of relations between the model characteristics. These characteristics are divided into internal and external. Internal characteristics are those whose values are obtained using mathematical modeling tools, external - those on which the internal characteristics depend significantly. The internal modeled characteristics were the average utilization of channels and nodes, the messages transit time, the number of dropped packets, etc. The external characteristics, affecting the internal are the transaction size, the time between transactions, the bit error rate, and the link bandwidth. Simulation models are capable of predicting the values of internal characteristics and are discrete dynamic systems that allow, gradually, calculating the internal characteristics of a model from known external characteristics. NetCracker as a research method is the system of structural-logical networks simulation and as analytical simulator uses mathematical equations to predict network performance. NetCracker provides

Table 1 Models parameters

Parameters → / Model elements ↓	**Bandwidth (Mbps)**	**Length (m)**	**BER (%)**
Model 1: "BS – HUB – RPAS"			
Base Station			
Tactical Data Workgroup	10	-	-
Common Data Server	10	-	-
TD – Switch link	10	1	0
CD – Switch link	10	1	0
Switch	10	-	-
Switch – Antenna link	44.736	10	0
Antenna	10	-	-
BS – HUB wireless link	2.048 - 44.736	10^5	0 – 0.05
HUB	10	-	-
HUB - RPASs wireless link	10	10^3	0
RPAS			
Antenna	10	-	-
Antenna – Switch link	44.736	10	0
Switch	10	-	-
Switch – Server link	10	1	0
Server	10	-	-
Model 2 PTN: "BS – PTN – HUB – RPAS" (in addition to Model 1)			
BS – PTN fiber link	44.736	10^3	0
PTN cloud	Packet Latency = 0 s, Packet Fail Chance = 0		
PTN-HUB wireless link	44.736	10^5	0 – 0.05
Model 3 SAT: "BS – SAT – HUB – RPAS" (in addition to Model 1)			
BS-SAT wireless link	2.048 - 44.736	10^6	0 – 0.05
SAT	Packet Latency = 0 s, Packet Fail Chance = 0		
SAT-HUB wireless link	44.736	1000000	0
Model 4 SAT PTN: "BS – SAT – PTN – HUB – RPAS" (in addition to Model 1)			
BS-SAT wireless link	2.048 - 44.736	10^6	0 – 0.05
SAT-Antenna wireless link	44.736	10^6	0
Antenna-PTN link	44.736	10^3	0
PTN cloud	Packet Latency = 0 s, Packet Fail Chance = 0		
PTN-HUB wireless link	44.736	10^5	0 – 0.05

real-time "what-if" simulation. The core of the product is written in Java EE, the native application server is Weblogic, and Oracle is used as a database.

3.3 Calculation Methods

Common to all articles mentioned above is that traffic data are transmitted to the BS via a wireless communication channel and this data transmission process is characterized by the given parameters (the size of transactions and the time between them, the statistical law of distribution for these parameters, the protocol profile, the message transit time, bandwidth, channel load, number of lost packets).

The functional characteristics of the models (Figure 2) were simulated taking into account statistical parameters of transactions, the TS and TBT parameters, the BER, the links bandwidth and the data transfer protocols.

In the proposed model, the following probability distribution laws were used: Const law - $w(x) = Const$, Exponential law - $w(x) = \lambda \cdot e^{-\lambda x}$, and LogNormal law –

$$w(x) = \frac{1}{x \cdot \sqrt{2\pi\sigma^2}} \cdot exp\frac{-ln(lnx - a)^2}{2 \cdot \sigma^2} \tag{1}$$

Formulas for calculating the average length of the transmitted packets, the average time interval between two adjacent packets, the average utilization of the communication link, and the average packet travel time are given in our paper [24].

3.4 Data Traffic

In accordance with the ICAO circular [1], to transmit RPAS data it is necessary to organize C3 data traffic (Figure 1). C3 is an information system consisting of the Tactical Data transmission channel (Command and Control) for RPAS flight control and the Common Data channel for transmission of remote data (data from radars, optical, infrared systems, etc.). A traffic with FTP (File Transfer Protocol) client profile for Tactical Data (TS = 100 Kbits and TBT = 1 s with Const distribution law) and inter LAN (Local Area Network) profile for Common Data (TS and TBT with Const distribution law, TBT = 1 s) was specified for the created models with the topology according to Figure 2. Command, Control and Communication traffic is performed as two-way communication.

4 Results

During the simulation, the average utilization of channels and nodes, the messages travel time, the number of dropped packets, etc. were calculated. Average channel utilization (load) is the average traffic on a particular channel as a percentage of the total bandwidth of the channel.

The AU dependences (Figures 3 – 5) were studied for different number of RPASs ($N = 1, 3, 5$), and the results were compared (Figures 6 – 8) for Models 1 – 4 with $N = 5$. Comparative assessment of packet losses in communication channels is shown in Figures 9 and 10. The distribution laws and values for parameters TS and TBT are pointed out in Figures 3–10. Traffic parameters for Tactical and Common Data, set during the simulation, are indicated under the figures in each case.

Figure 3 demonstrates dependences of AU parameters for BS – HUB link on Common Data packet size for different RPAS number in Model 1. At the same time, the traffic of Tactical Data remained constant with TS = 100 Kbits. It can be seen from the graphs that for all $N = 1, 3, 5$ the nature of the dependences is the same. For TS values from 10 bits to 10 Kbits, the AU values practically do not change, slightly increasing only for TS = 100 Kbits.

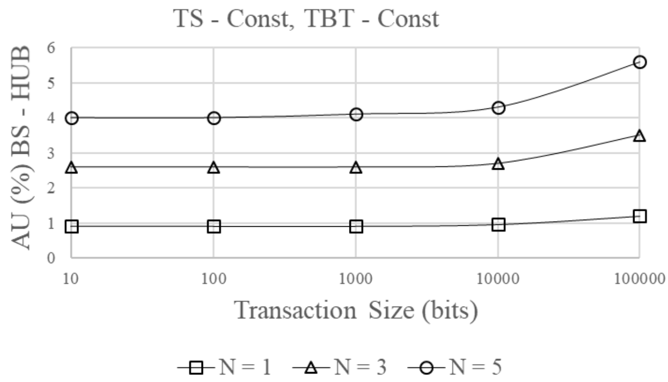

Fig. 3 Dependences of AU for BS – HUB link on Common Data TS in Model 1 (Tactical Data – FTP, TS = 100 Kbits, TBT = 1 s; Common Data – interLAN, TBT = 1 s; BER = 0)

This increase in the AU parameter is the greater, the more is N. When TS is more than 100 Kbits, the channel is closed and the transmission of Common Data becomes impossible in the case of the selected transmission conditions with such Tactical Data volume traffic. With increasing N, the AU parameter also grows - an increase in the number of RPASs from $N = 1$ to $N = 5$ leads to an increase in the AU parameter by more than 4 times. AU parameter values for $N = 5$ are 4 % – 5.8 % (see Figure 3, $N = 5$).

Dependences of AU parameters for BS – HUB link on bandwidth for different RPAS number in Model 1 are shown in Figure 4. The bandwidth was changed from T1 (1.544 Mbps) and E1 (2.048 Mbps) to E3 (34.368 Mbps) and T3 (44.736 Mbps). Dependences are given for TS = 100 Kbits for both Tactical and Common Data traffic. The AU parameter increases with the data rate decrease, and at T1 bandwidth it reaches ≈ 72 % for N = 1, ≈ 77 % for $N = 3$, and ≈ 89 % for $N = 5$.

Figure 5 presents dependences of the BER on AU parameters for BS – HUB link in Model 1 with different RPAS number. Dependences are given for TS = 10 Kbits for both Tactical and Common Data traffic. The BER value for channels without additional error protection usually is $10^{-4} - 10^{-6}$, and for fiber -10^{-9}. Bit distortions occur both due to the presence of interference in the channel and due to distortion of the waveform in channels with the limited bandwidth. The value of the BER parameter 0.01 % in Figure 5 corresponds to a value of 10^{-4}. The data shown in Figure 5 indicate rather high sensitivity of the channels to bit errors.

Figures 6 – 8 compare the simulation results for models 1 – 4 with $N = 5$ in order to clarify the advantages and disadvantages of one or another way of transferring information in SAGIN.

Figure 6 shows dependences of AU parameters for BS link on Common Data TS for $N = 5$ in Models 1 – 4. Dependences are given for TS = 100 Kbits for Tactical Data traffic. In general, the dependencies are similar to Figure 3.

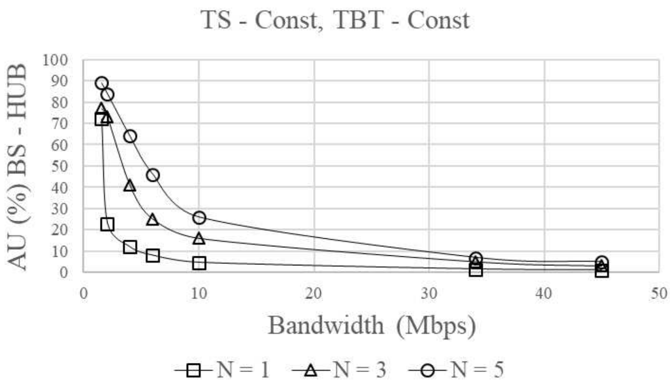

Fig. 4 Dependences of AU for BS – HUB link on bandwidth in Model 1
(Tactical Data – FTP, TS = 100 Kbits, TBT = 1 s;
Common Data – interLAN, TS = 100 Kbits, TBT = 1 s; BER = 0)

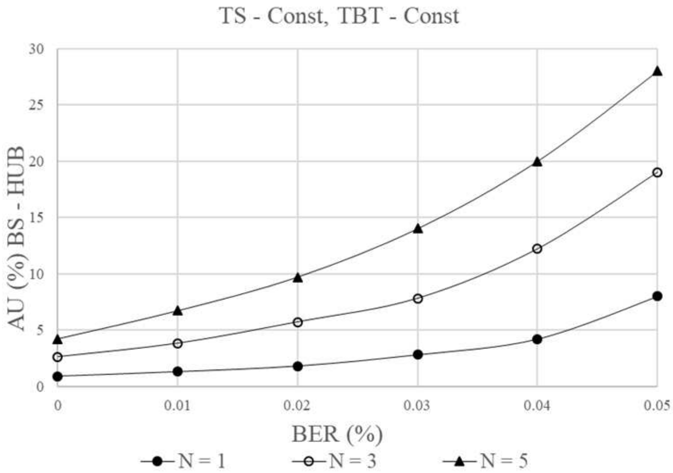

Fig. 5 Dependences of BER on AU for BS – HUB link in Model 1
(Tactical Data – FTP, TS = 10 Kbits, TBT = 1 s;
Common Data – interLAN, TS = 10 Kbits, TBT = 1 s)

The data for Model 3 with satellite and Model 4 with the satellite and the PTN cloud are very close to those for Model 1 with LOS data. Slightly above the Model 1 values are the AU values for Model 3 with data transmission over the PTN cloud. But in general, minor differences should be noted for all models. Data for models with satellite do not show significant difference in AU values due to the long distance to the satellite. This is supported by our previous study [24], which showed that for wireless connections changing the distance between devices significantly affects travel times and has little effect on average workload and average channel utilization.

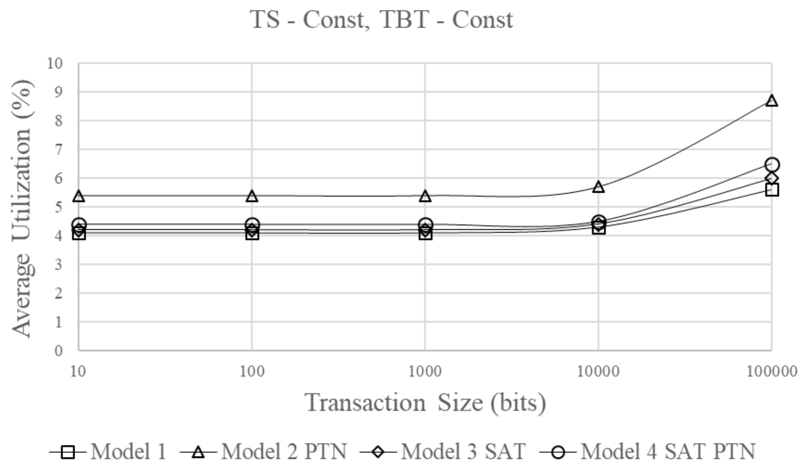

Fig. 6 Dependences of AU for BS link on Common Data TS for N = 5 in Models 1 – 4 (Tactical Data – FTP, TS = 100 Kbits, TBT = 1 s; Common Data – interLAN, TBT = 1 s; BER = 0)

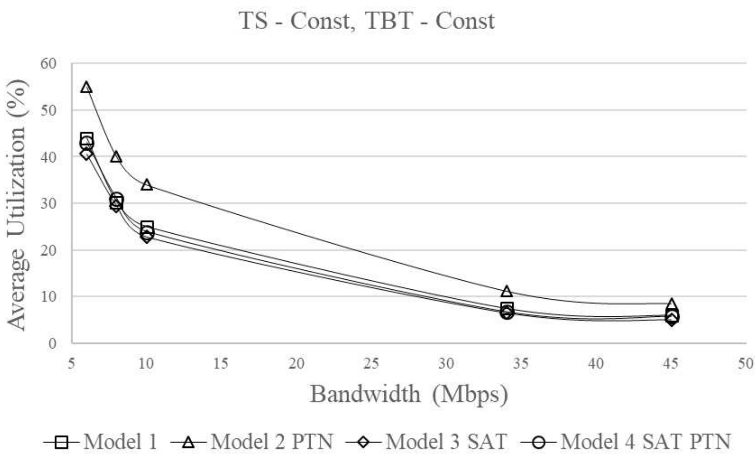

Fig. 7 Dependences of AU for BS link on bandwidth for N = 5 in Models 1 – 4

Figure 7 demonstrates dependences of AU parameters for BS link on bandwidth for $N = 5$ in Models 1–4. The bandwidth was changed from 6 Mbps to E3 (34.368 Mbps) and T3 (44.736 Mbps). Dependences are given for Tactical and Common Data traffic with TS = 100 Kbits. The AU parameter increases with the data rate decrease, and at 6 Mbps it reaches ≈ 44 % for Model 1, ≈ 55 % for Model 2, ≈ 41 % for Model 3, and ≈ 43 % for Model 4. The results for Models 1, 3, 4 are very close, and only the values for Model 2 with a public terrestrial network are larger.

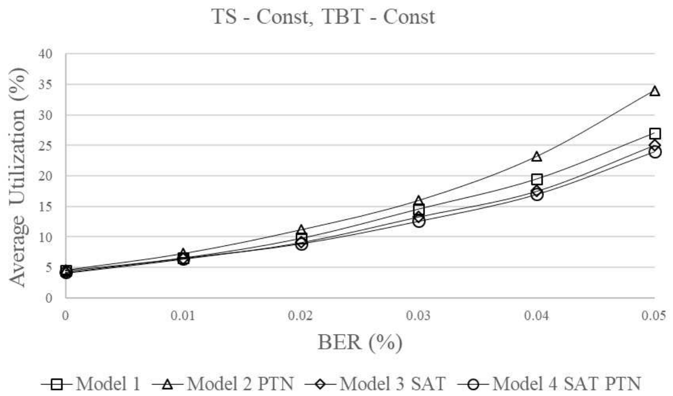

Fig. 8 Dependences of BER on AU for BS link for N = 5 in Models 1 – 4 (Tactical Data – FTP, TS = 10 Kbits, TBT = 1 s; Common Data – interLAN, TS = 10 Kbits, TBT = 1 s)

In Figure 8 dependences of the BER on AU parameters for BS link in Models 1 – 4 with $N = 5$ are shown. Dependences are given for Tactical and Common Data traffic with TS = 10 Kbits. As in the previous cases, the results for Models 1, 3, 4 are very close, and only the AU values for Model 2 are larger. The results obtained for all models show a significant effect of bit errors on the quality of data transmission.

Figure 9 shows the dependences of dropped packets on the TS parameter for interLAN Common Data traffic. As the TS parameter grows from 10 bits to 100 Kbits, the number of lost packets also increases: for Model 1 by ≈ 64 %, for Model 2 by ≈ 66 %, for Model 3 by ≈ 74 %, and for Model 4 by ≈ 76 %. The lowest losses are observed for Model 1 with LOS, and maximum packet losses are observed for Model 2 with the PTN cloud. The loss values for Models 3 and 4 are intermediate, although Model 3 with transmission via satellite gives lower packet losses than Model 4 with satellite and the PTN cloud. In general, the nature of all dependences is similar and there is not a single model that is clearly and much different in losses.

In Figure 10, the same dependences as in Figure 9 are presented for three distribution laws (Const, Exponential and LogNormal) of the TBT parameter for Common Data traffic. At the same time, the Const distribution law is used for the TS and TBT parameters of Tactical Data traffic and the TS parameter of Common Data traffic. The minimum packet losses are obtained for the LogNormal law, and the maximum - for the Exponential law. With an increase in the TS parameter from 10 bits to 100 Kbit, the number of lost packets also increases: for Const law by ≈ 56 %, for Exponential law by ≈ 50 %, and for LogNormal law by ≈ 100 %.

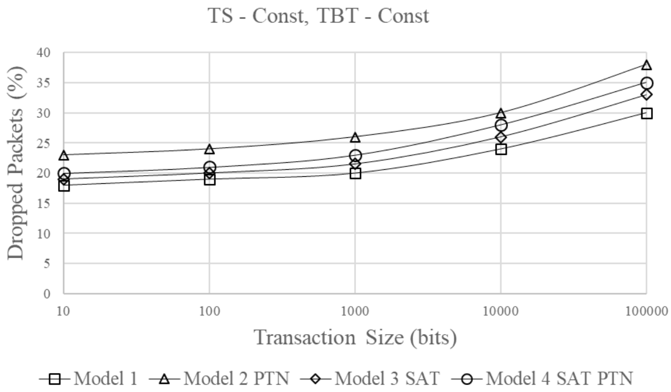

Fig. 9 Dependences of HUB Dropped Packets on Common Data TS for N = 5 in Models 1 – 4 (Tactical Data – FTP, TS = 100 Kbits, TBT = 1 s; Common Data – interLAN, TBT = 1 s; BER = 0)

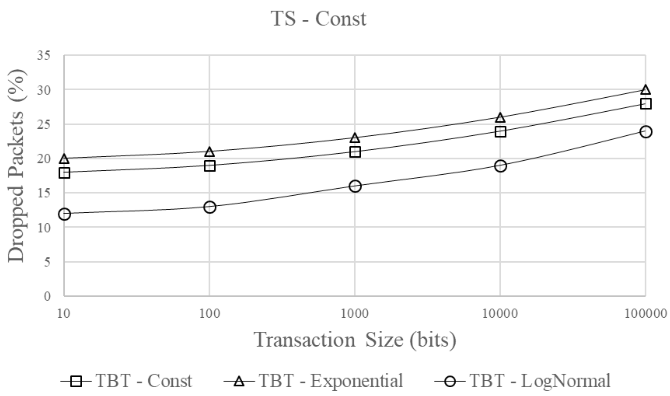

Fig. 10 Dependences of HUB Dropped Packets on Common Data TS (Const law) for N = 5 in Model 4 with different distribution laws for Common Data TBT parameter (Tactical Data – FTP, TS = 100 Kbits, Const law, TBT = 1 s; Common Data – interLAN, TBT = 1 s; BER = 0)

5 Discussion

The papers discussed in the introduction demonstrate developments in the field of SAGIN performance analysis. However, we were unable to find quantitative information on the impact of traffic parameters on SAGIN operation. What is the relationship between channel throughput and the length of transactions? How do the statistical distribution of traffic parameters affect the channel operation? What is the effect of the bandwidth on channel loading for a given traffic parameters? What and how affects the quality of service, namely the increase in the number of bit errors and lost packets? There are no answers to these questions in the literature.

Our article emphasizes three main aspects: the architecture of channel models, the algorithm for parameters calculation, and the application of the results to assessing the quality of data transmission. This work is devoted to the development of theoretical methods for predicting the behavior of RPAS telecommunications channels in SAGIN. Presented study is a logical continuation of our previous works and expands them for modeling RPAS communication channels in swarms.

Several integrated systems have been created that are used in wireless telecommunications – the Globalstar [30], the Global Information Grid (GIG) [31], the Transformational Satellite Communications System (TSAT) [32], the Integral Satcom Initiative (ISICOM) [33] , the OneWeb constellation [34], O3b satellite system [35], IridiumNEXT [29], and SpaceX Starlink [36]. However, SAGINs must provide ubiquitous communications and data processing with high data rates, low latency, low data losses, high reliability and cost-effectiveness.

The key question is whether there are preferred RPAS channels for data transmission, including LOS transmission (Model 1), PTN cloud transmission (Model 2), LEO satellite transmission (Model 3), and the PTN cloud plus satellite transmission (Model 4). The relationship between SAGIN performance and network factors (traffic parameters, channel bandwidth, bit errors, lost packets, and topological manifestation) was investigated and the results obtained allow comparison of these capabilities (Figures 3 – 10).

From the data of Figure 6 (dependences on the transactions size) and Figure 7 (dependences on the bandwidth), it follows that the highest AU values are for Model 2 with the PTN cloud, and Models 1, 3, 4 have very close, but smaller values. At BER = 0 % (Figure 8), the AU values for all models coincide. Nevertheless, with the growth of the BER, the differences between the models increase and the situation for Model 2 with the PTN cloud turns out to be the most unfavorable. Models 1, 3, 4 in this case too have very close, but smaller values of the AU parameters. There is no advantage for any of the models in terms of packet losses (Figure 9). However, for Model 2, the losses are again the largest. As the data in Figure 10 show, the most preferred distribution law is the LogNormal law.

None of the considered SAGIN data transmission channels has a clear advantage. It is possible to select the correct operating conditions and successfully transfer telecommunication data from the RPAS using obtained data about traffic characteristics (Figures 3 – 10).

Future areas of our research include estimating parameters of telecommunication channels in RPAS swarms, coordinated multi-point transmissions among ground base stations, RPAS satellite radio access networks and predicting the behavior of channels in critical conditions. This is necessary for the design and creation of effective, reliable and resistant to external influences RPAS telecommunication systems.

6 Conclusions

The presented study contains RPAS traffic parameters for SAGIN. The study uses models based on ICAO recommendations. Data transmission channels contain space, air and ground components, for which quantitative characteristics of RPAS traffic were first obtained.

The dependences of the average channel utilization on the transaction size, the influence of different bandwidths, the impact of the bit error rate, as well as dependences of dropped packets on the transaction size and statistical distribution laws were obtained and analyzed.

The importance of the numerical analysis lies in the ability to set traffic parameters and observe the resulting throughput, packets losses, and the number of bit errors in the channel. Traffic characteristics in the models with space, air and ground communication channels were compared. Such comparison showed that it is possible to achieve the required quality of service in the SAGIN using setting the right transmission parameters. The results obtained show that all channels are suitable for data transmission and differ insignificantly. Setting up a real physical infrastructure for transmitting telecommunications data is faster and more reliable when using the information received.

Author Contributions:

Conceptualization, A.G. and S.I.; methodology, A.G.; validation, S.I., F.L., A.G. and V.K.; investigation, A.G. and S.I.; resources, F.L. and V.K.; writing — original draft preparation, A.G.; writing—review and editing, S.I.; supervision, F.L.; project administration, F.L. and V.K.; funding acquisition, F.L. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

Funding:

This work was supported in part by the Wenzhou Municipal Key Science and Research Program under Grant ZG2020036 from Wenzhou bureau of science and technology.

References

1. ICAO Circular 328-AN/190, Unmanned Aircraft Systems (UAS), 2011.

2. Jawhar, I., Mohamed, N., Al-Jaroodi, J., Agrawal, D. P., and Zhang, S. (2017). Communication and networking of UAV-based systems: Classification and associated architectures. Journal of Network and Computer Applications, 84, 93–108. doi:10.1016/j.jnca.2017.02.008
3. Namuduri, K., S. Chaumette, J. H. Kim, and J.P.G. Sterbenz. 2018. UAV Networks and Communications. Edited by Kamesh Namuduri, Serge Chaumette, Jae H. Kim, and James P. G. Sterbenz. UAV Networks and Communications. Cambridge University Press. https://doi.org/10.1017/9781316335765.
4. Liu, J., Shi, Y., Shi, Y., Fadlullah, Z. M., and Kato, N. Space-Air-Ground Integrated Network: A Survey. IEEE Communications Surveys and Tutorials, 2018, pp. 1–1. doi:10.1109/comst.2018.2841996.
5. Yao, H., Wang, L., Wang, X., Lu, Z., and Liu, Y. The Space-Terrestrial Integrated Network (STIN): An Overview. IEEE Communications Magazine, 2018, pp. 2 – 9. doi:10.1109/mcom.2018.1700038
6. Alimi, I. A., Mufutau, A. O., Teixeira, A. L., and Monteiro, P. P. (2018). Performance Analysis of Space-Air-Ground Integrated Network (SAGIN) Over an Arbitrarily Correlated Multivariate FSO Channel. Wireless Personal Communications, 100(1), 47–66. doi:10.1007/s11277-018-5620-x.
7. V. Kharchenko, YM Barabanov, AM Grekhov. Modeling of Satellite Channel for Transmission of ADS-B Messages. Proceedings of the National Aviation University 3, 9-14, 2012.
8. V. Kharchenko, B. Wang, A. Grekhov, M. Kovalenko. Investigation of ADS-B messages traffic via satellite communication channel. Proeedings of the National Aviation University, 7-13, 2014.
9. Grekhov, A.M. Recent Advances in Satellite Aeronautical Communications Modeling. IGI Global, 2019.
10. M. Collins, "First space-based ADS-B satellites in orbit", AOPA, Jan. 18, 2017. [Online]. Available: https://www.aopa.org/news-and-media/all-news/2017/january/18/first-space-based-ads-b-satellites-in-orbit.
11. "Iridium-NEXT", Spaceflight101. Available online: https://spaceflight101.com/spacecraft/iridium-next/ (accessed on 26 February 2021).
12. Dai, C.-Q., Li, X., and Chen, Q. (2019). Intelligent Coordinated Task Scheduling in Space-Air-Ground Integrated Network. 2019 11th International Conference on Wireless Communications and Signal Processing (WCSP). doi:10.1109/wcsp.2019.8928112.
13. Sargolzaei A., Abbaspour A., Crane C.D. (2020) Control of Cooperative Unmanned Aerial Vehicles: Review of Applications, Challenges, and Algorithms. In: Amini M. (eds) Optimization, Learning, and Control for Interdependent Complex Networks. Advances in Intelligent Systems and Computing, vol 1123. Springer, Cham. https://doi.org/10.1007/978-3-030-34094-$0_1$0
14. N. Cheng, W. Quan, W. Shi, H. Wu, Q. Ye, H. Zhou, W. Zhuang, X. Shen, and B. Bai. A Comprehensive Simulation Platform for Space-Air-Ground Integrated Network. IEEE Wireless Communications (Volume: 27, Issue: 1, February 2020), Page(s): 178 – 185.
15. Ye, J., Dang, S., Shihada, B., and Alouini, M.-S. (2020). Space-Air-Ground Integrated Network: Outage Performance Analysis. IEEE Transactions on Wireless Communications, 1–1. doi:10.1109/twc.2020.3017170.
16. RQ-4 Global Hawk U.S. Air Force fact sheet Available online: https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104516/rq-4-global-hawk/ (accessed on 13 October 2020).
17. N. Zhang, S. Zhang, P. Yang, O. Alhussein, W. Zhuang, and X. S. Shen, "Software defined space-air-ground integrated vehicular networks: Challenges and solutions," IEEE Communications Magazine, vol. 55, no. 7, pp. 101–109, Jul. 2017.
18. Zhou, Z., Feng, J., Zhang, C., Chang, Z., Zhang, Y., and Huq, K. M. S. (2018). SAGE-CELL: Software-Defined Space-Air-Ground Integrated Moving Cells. IEEE Communications Magazine, 56(8), 92–99. doi:10.1109/mcom.2018.1701008.
19. Shi, Y., Cao, Y., Liu, J., and Kato, N. (2018). A Cross-Domain SDN Architecture for Multi-Layered Space-Terrestrial Integrated Networks. IEEE Network, 33(1), 29–35. doi:10.1109/mnet.2018.1800191.
20. Shi, Y., Liu, J., Fadlullah, Z. M., and Kato, N. (2018). Cross-Layer Data Delivery in Satellite-Aerial-Terrestrial Communication. IEEE Wireless Communications, 25(3), 138–143. doi:10.1109/mwc.2018.1700354.

21. S. Zhou, G. Wang, S. Zhang, Z. Niu, and X. S. Shen, Bidirectional mission offloading for agile space-air-ground integrated networks, IEEE Wireless Communications, vol. 26, no. 2, pp. 38–45, Apr. 2019.
22. Zeng, Y., Lyu, J., and Zhang, R. (2018). Cellular-Connected UAV: Potential, Challenges and Promising Technologies. IEEE Wireless Communications, 1–8. doi:10.1109/mwc.2018.1800023.
23. A Grekhov, V Kondratiuk, S Ilnytska. Data Traffic Modeling in RPAS/UAV Networks with Different Architectures. Modelling 2 (2), 210-223, 2021.
24. Ilnytska, S. I., Li, F., Grekhov, A., and Kondratiuk, V. Loss Estimation for Network-Connected UAV/RPAS Communications. IEEE Access, 2020, 1–1. doi:10.1109/access.2020.3011956.
25. Aygün Baltaci et al.: Experimental UAV Data Traffic Modeling and Network Performance Analysis. Accepted for publication in Proc. iEEE INFOCOM, 2021.
26. Grekhov, A., Kondratiuk, V., and Ilnitska, S. RPAS Satellite Communication Channel Based on Long-Term Evolution (LTE) Standard. Transp. Aerosp. Eng., vol. 8, no. 1, pp. 1–14, 2020, doi: 10.2478/tae-2020-0001
27. Grekhov, A., Kondratiuk, V. and Ilnitska, S. RPAS Satellite Communication Channel Based on IEEE 802.11b Standard. Transp. Aerosp. Eng., vol. 7, no. 1, pp. 32–40, Jan. 2019, doi: 10.2478/tae-2019-0004
28. Grekhov, A., Kondratiuk, V. and Ilnytska, S. RPAS Communication Channels Based on WCDMA 3GPP Standard. Aviation, 2020, vol. 24, no. 1, pp. 42 – 49. doi:https://doi.org/10.3846/aviation.2020.12166
29. Available online: https://www.netcracker.com/. (accessed on Day Month Year).
30. Globalstar's web-site. Available Online: https://www.globalstar.com/en-us/corporate/about/our-technology (accessed on 13 October 2020).
31. Albuquerque, M., Ayyagari, A., Dorsett, M. A., and Foster, M.S. Global Information Grid (GIG) Edge Network Interface Architecture. MILCOM 2007 - IEEE Military Communications Conference. doi:10.1109/milcom.2007.4455139
32. Pulliam, J., Zambre, Y., Karmarkar, A., Mehta, V., Touch, J., Haines, J., and Everett, M. TSAT network architecture. MILCOM 2008 - 2008 IEEE Military Communications Conference. doi:10.1109/milcom.2008.4753508
33. Vanelli-Coralli, A., Corazza, G. E., Luglio, M., and Cioni, S. The ISICOM Architecture. 2009 International Workshop on Satellite and Space Communications. doi:10.1109/iwssc.2009.5286409
34. Radtke, J., Kebschull, C., and Stoll, E. Interactions of the space debris environment with mega constellations—Using the example of the OneWeb constellation. Acta Astronautica. 2017, vol. 131, pp. 55–68. doi:10.1016/j.actaastro.2016.11.021
35. Blumenthal, S.H. Medium Earth Orbit Ka Band Satellite Communications System. MILCOM 2013 IEEE Military Communications Conference. doi:10.1109/milcom.2013.54
36. SpaceX Starlink web-site. Available Online: https://www.spacex.com (accessed on 13 October 2020).

Figures

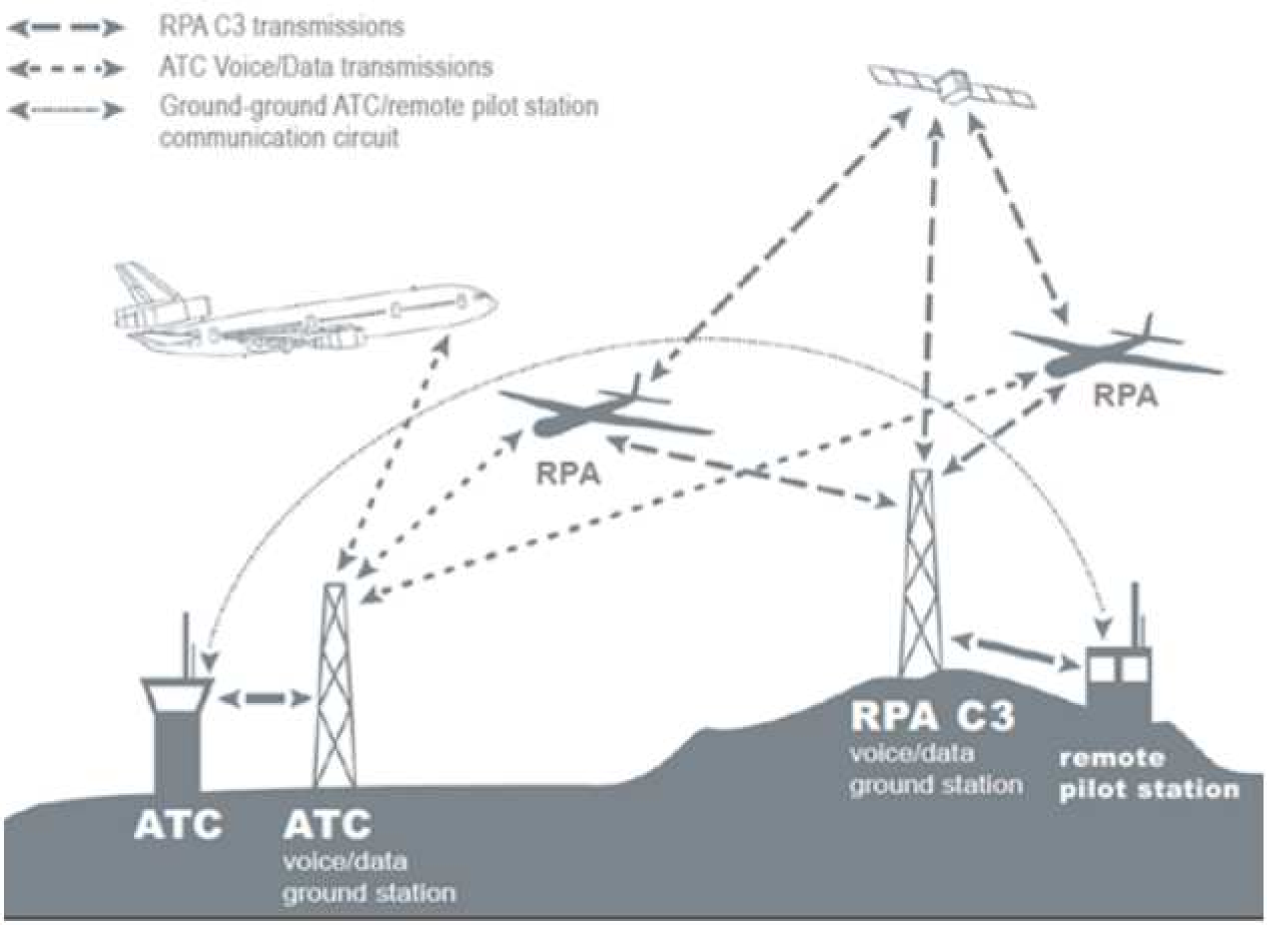

Figure 1

Please see the Manuscript PDF file for the complete figure caption

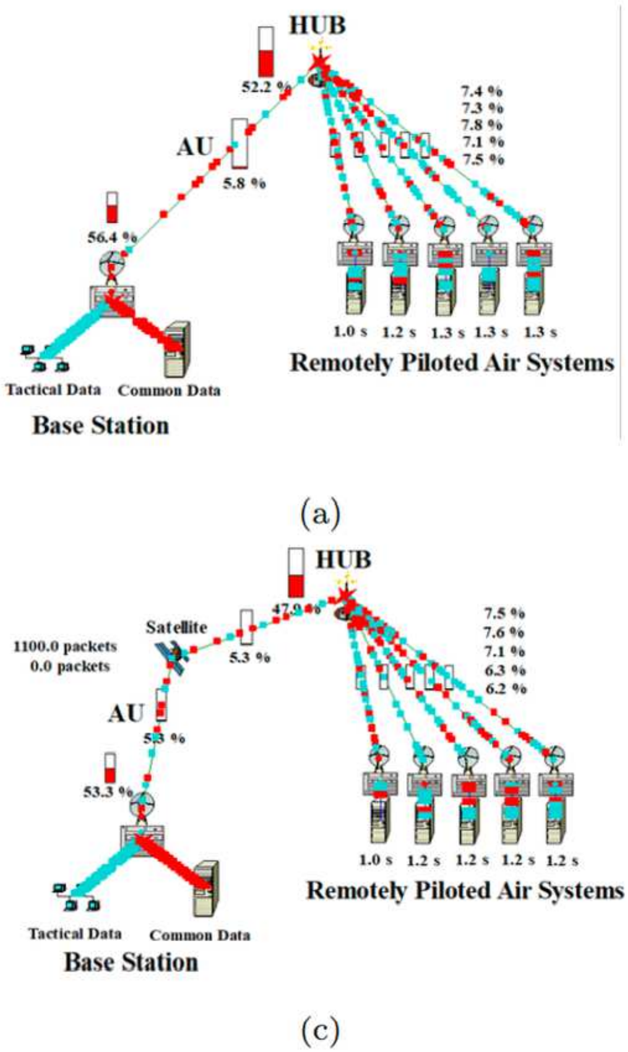

Figure 2

Please see the Manuscript PDF file for the complete figure caption

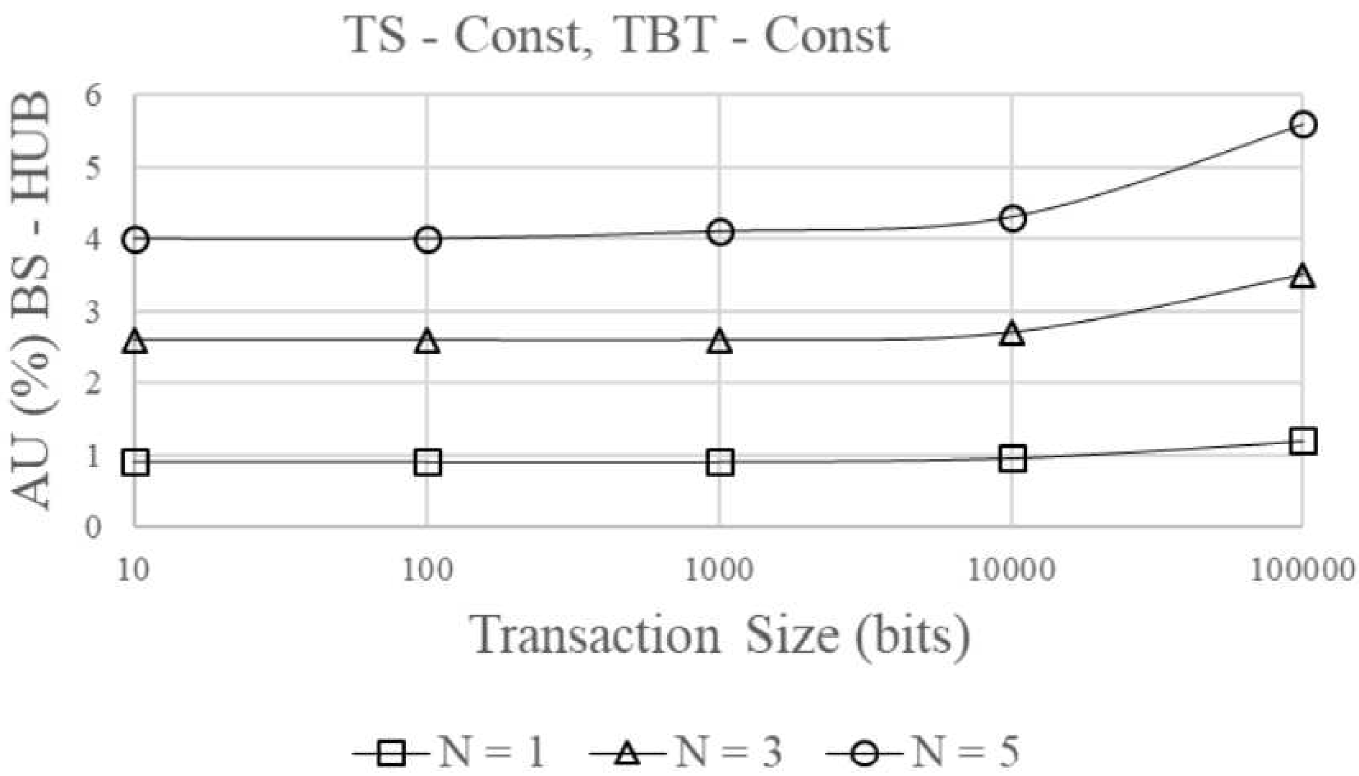

Figure 3

Please see the Manuscript PDF file for the complete figure caption

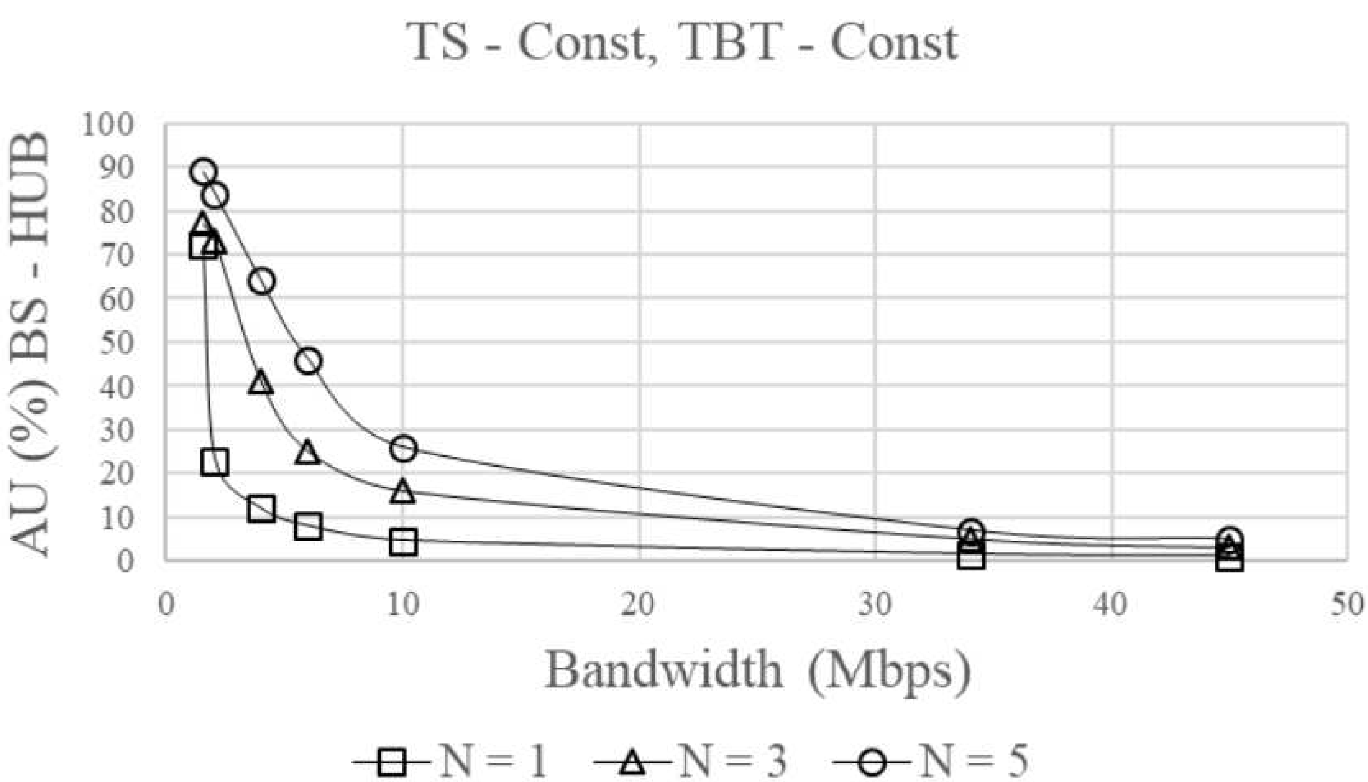

Figure 4

Please see the Manuscript PDF file for the complete figure caption

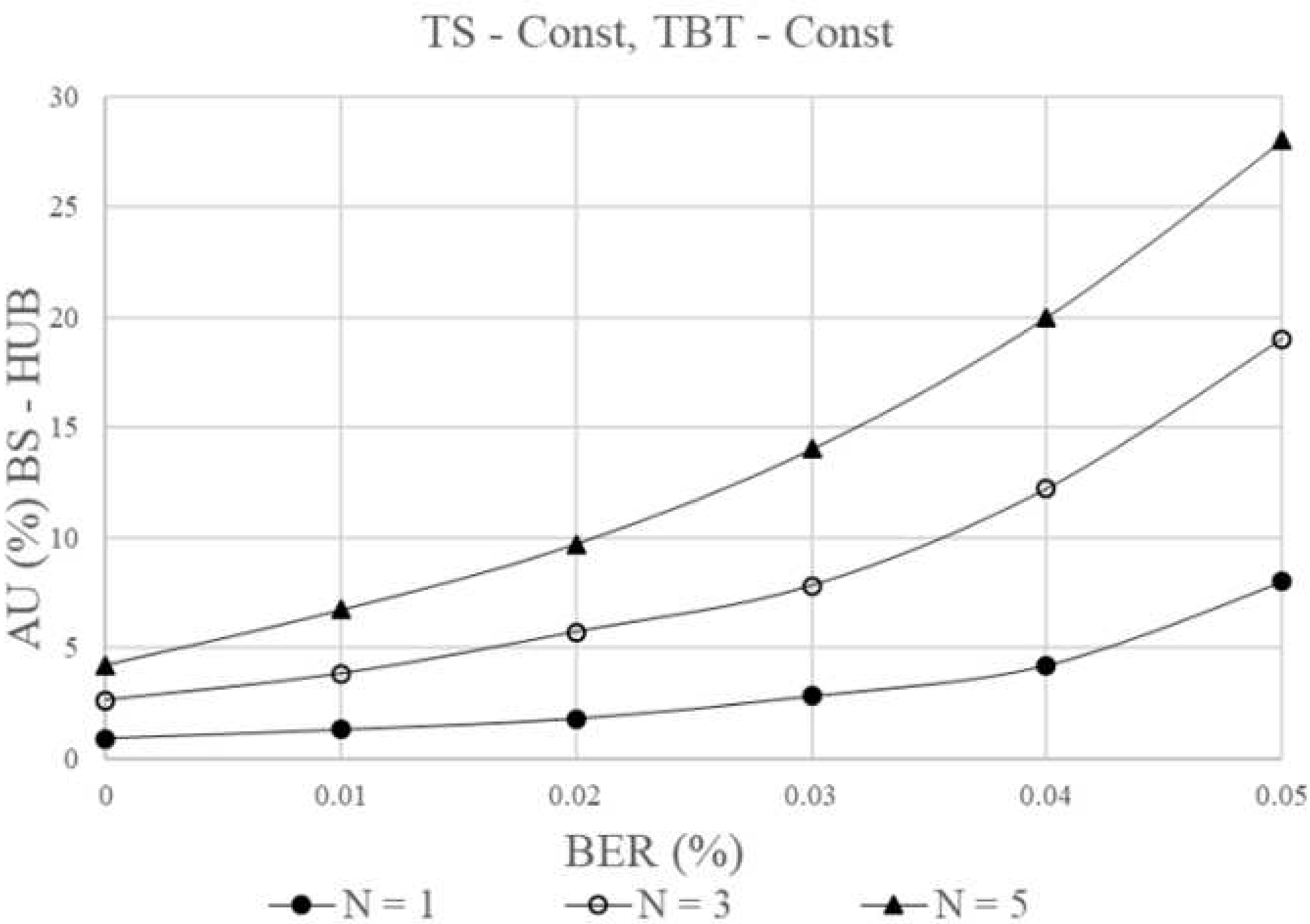

Figure 5

Please see the Manuscript PDF file for the complete figure caption

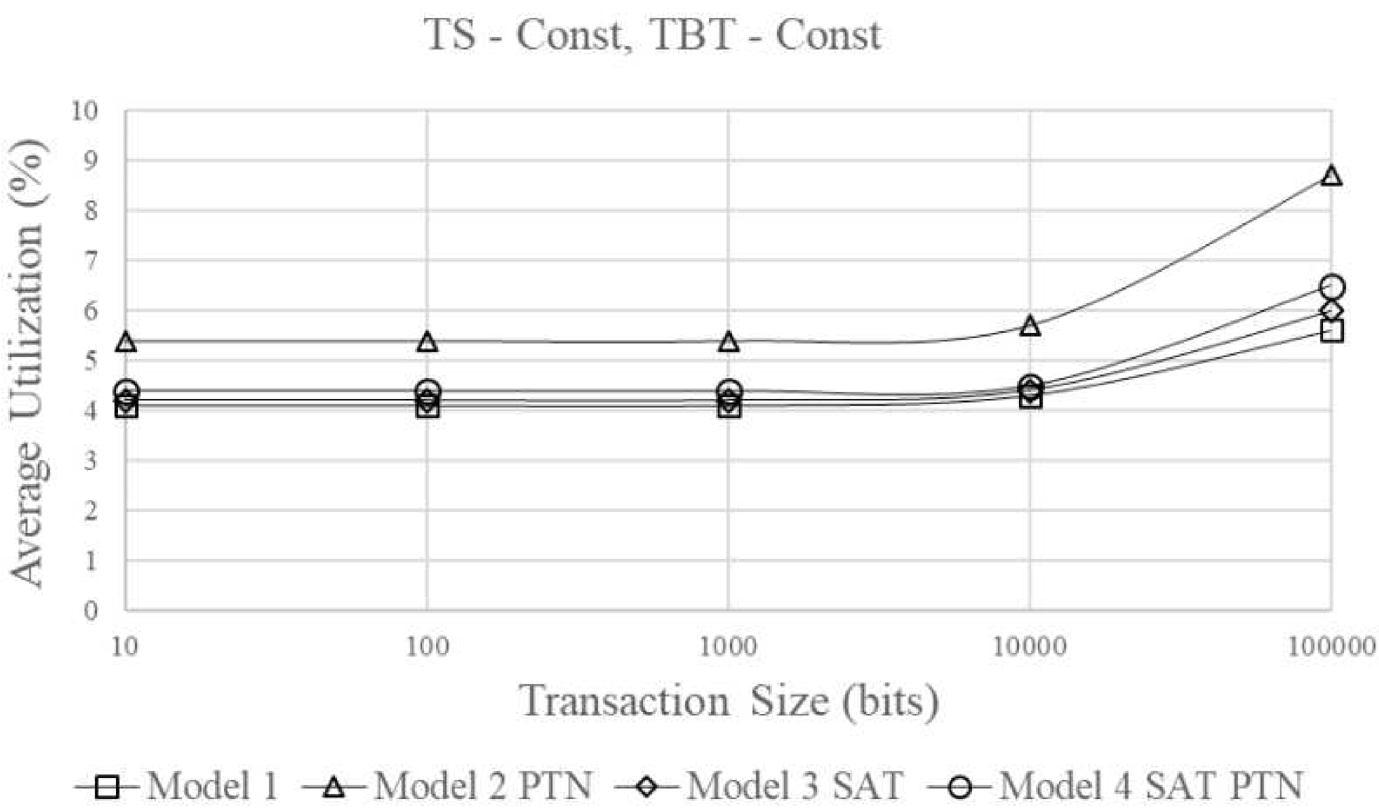

Figure 6

Please see the Manuscript PDF file for the complete figure caption

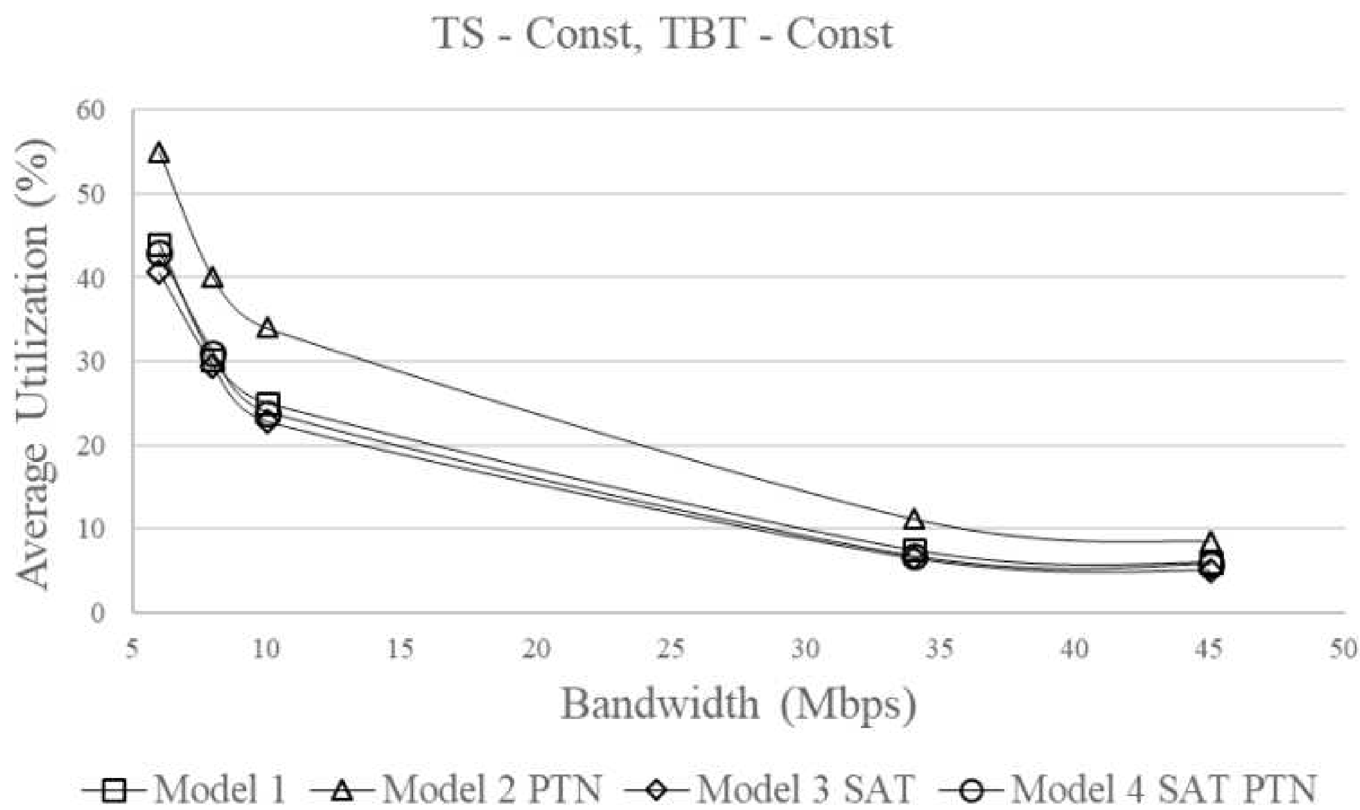

Figure 7

Please see the Manuscript PDF file for the complete figure caption

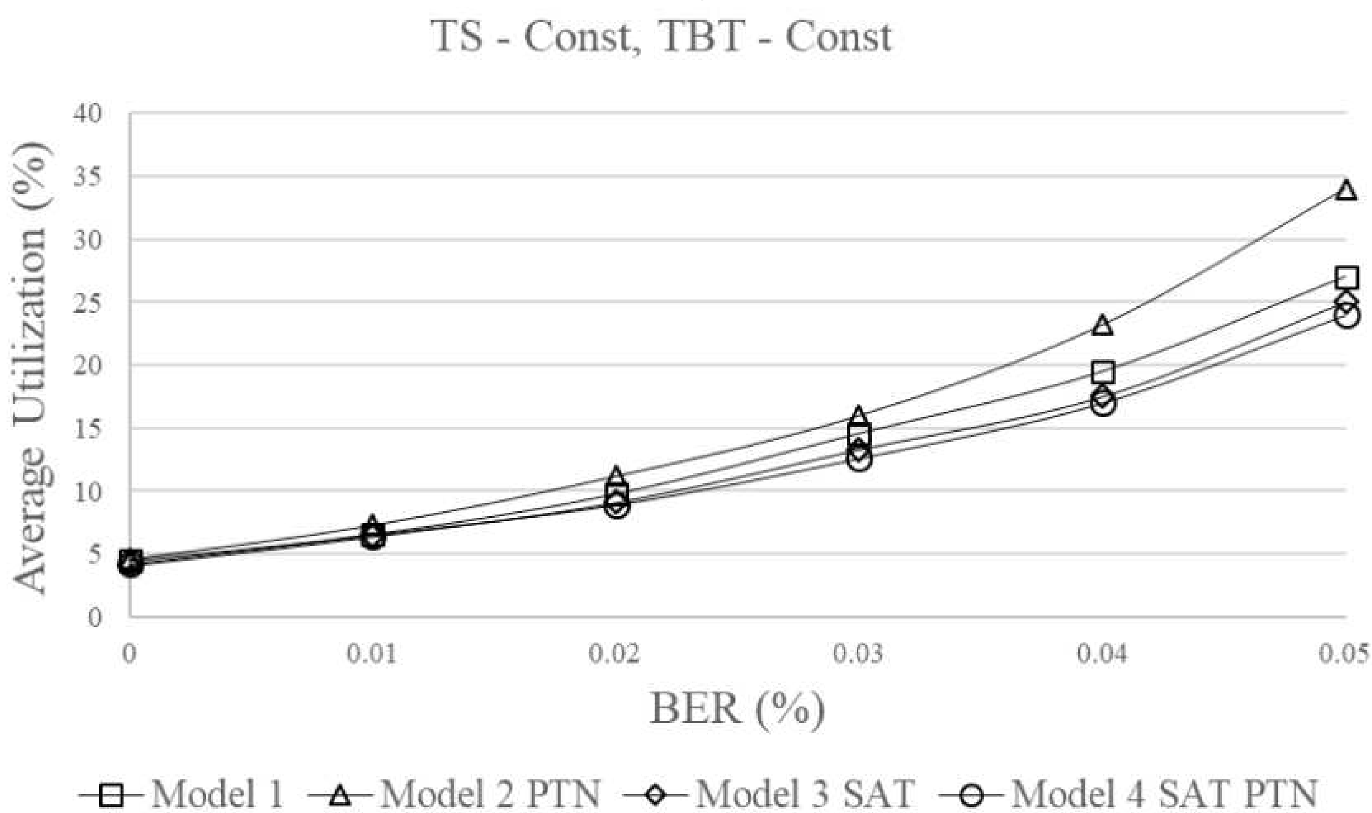

Figure 8

Please see the Manuscript PDF file for the complete figure caption

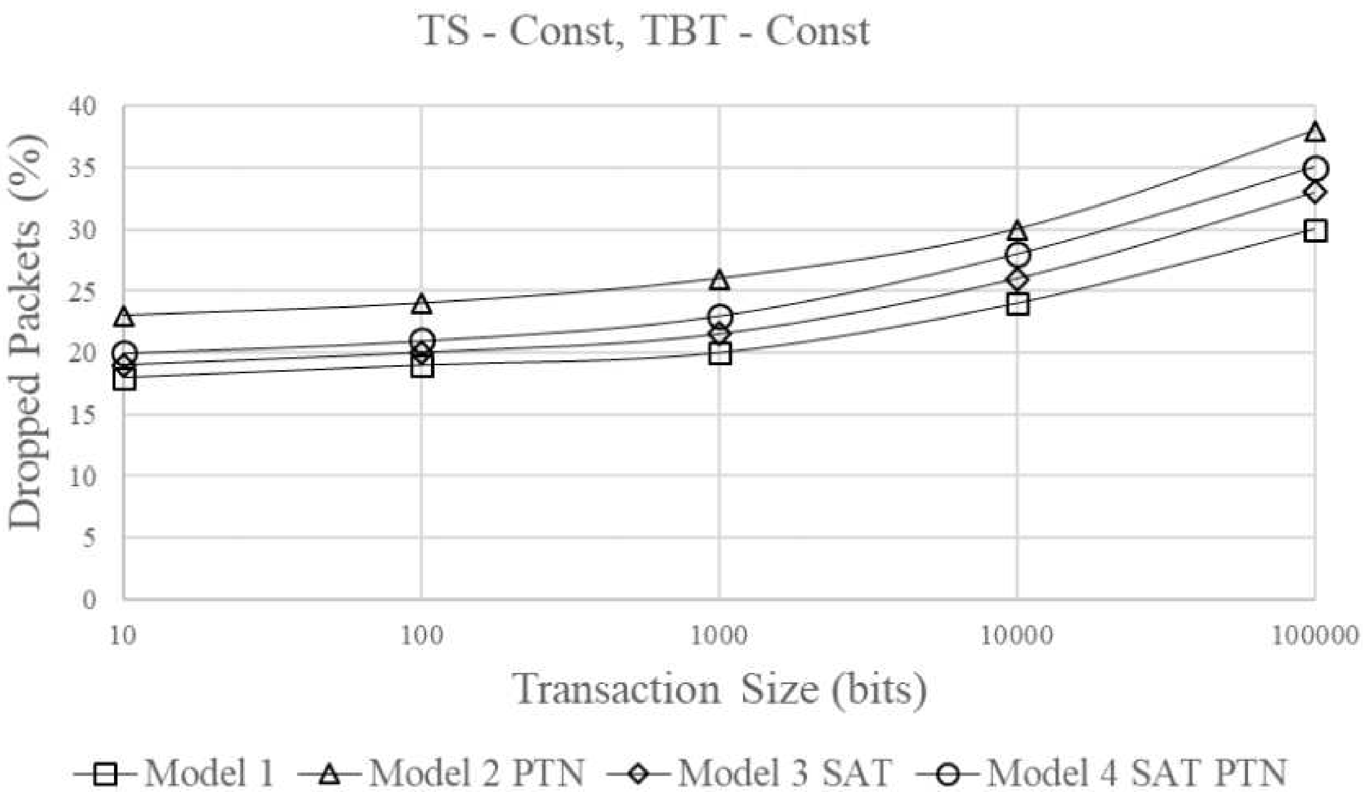

Figure 9

Please see the Manuscript PDF file for the complete figure caption

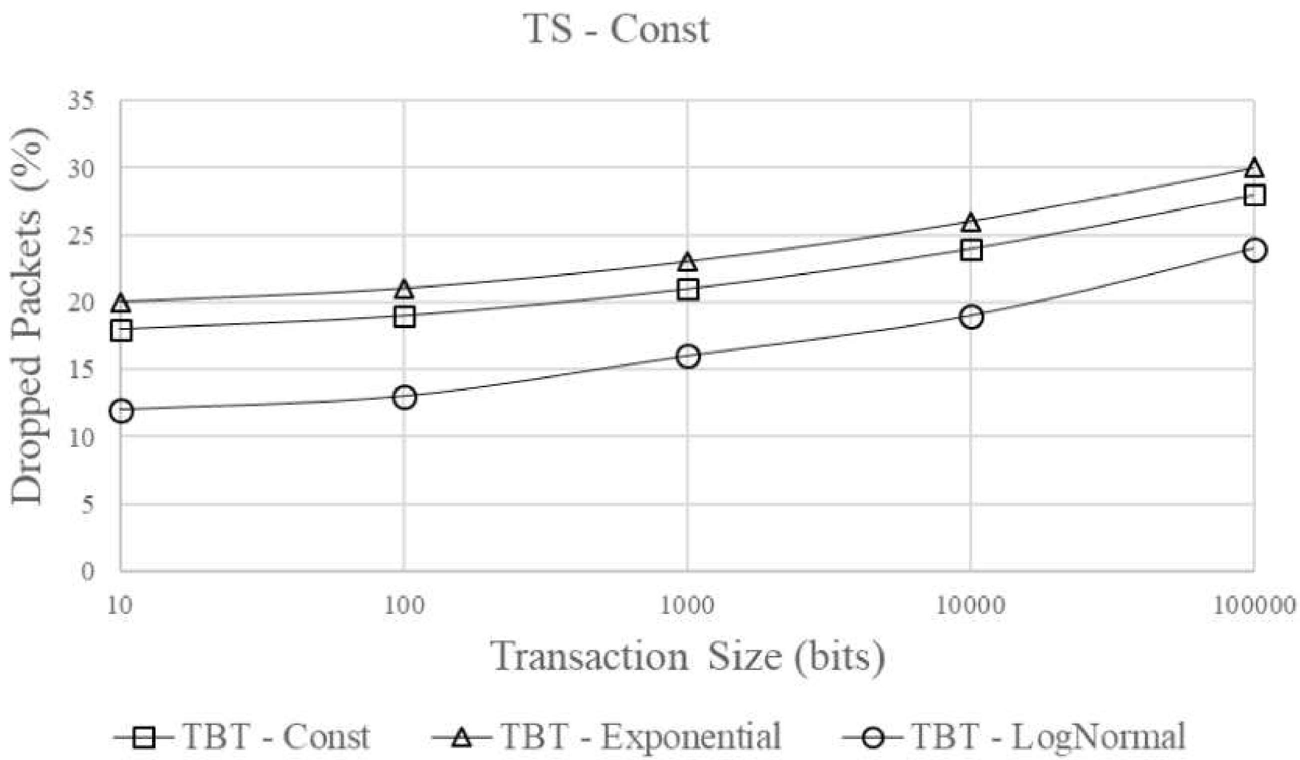

Figure 10

Please see the Manuscript PDF file for the complete figure caption