Traffic Simulation and Losses Estimation in Stratospheric Drone Network

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Research Article

Keywords: HAPS, stratospheric drone, RPAS, data traffic, dropped packets, BER, cellular network

Posted Date: June 6th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1640910/v1

Abstract

The use of stratospheric drones for data transmission requires reliable two-way communication. In this regard, it is necessary to explore the possibilities of combining existing air and ground networks for effective interaction with stratospheric drones during heavy data traffic. This article focuses on calculating the packet loss and the impact of traffic parameters on communication with drones. For the first time, traffic characteristics of the complex network “Base Station - Stratospheric Drone – RPAS - Ground Cellular Network” are obtained. The original models are created based on MATLAB Simulink and NetCracker software. Packet loss dependences on the transaction size for different numbers of cellular users are estimated using NetCracker software. Average load dependences on the size of the transaction are obtained. Channels with different throughput are considered and the influence of channel loading on the bit error rate is studied. Data transmission is simulated using MATLAB Simulink depending on the signal-to-noise ratio, nonlinearity levels of the base station amplifier, types of signal modulation and diameters of base station antennas. Data obtained make it possible to predict the operation of stratospheric drones.

Introduction

High-Altitude Platform Station (HAPS) according to Article 1.66A of the ITU Radio Regulations is defined as “a station on an object at an altitude of 20 to 50 km and at a specified, nominal, fixed point relative to the Earth”. Stratospheric Remotely Piloted Air Systems (RPASs) or Unmanned Stratospheric Vehicles (USVs) are attracting more and more attention (Fig. 1), since they can be used for both military and civilian missions. Therefore, a significant number of publications have been devoted to these issues. To implement applications using stratospheric drones, it is important to develop new structures for communication and information transfer in real time [1–3].

Many countries are researching and developing their own USVs that can be used as platforms for intelligence and communications, thereby replacing space-based communications satellites. Currently, the development of USVs has moved to a new stage in connection with the possibility of their use as geostationary satellites, but much cheaper and easily replaceable. Their economic efficiency in combination with the use of new technologies for long-term stay in one place determines their commercial value, especially in those regions that have not developed terrestrial infrastructure for cellular communications. USVs can land on the surface for maintenance and energy replenishment, making them cost effective. They can create communication and navigation systems, carry out thermal and aerial photography, monitor the environmental situation, support the work of emergency and rescue services [4]. The acquisition by Google and Facebook of companies that produce USVs has the same goal - to provide Internet coverage to remote regions of the Earth.

This work has been done in paradigm of using stratospheric drones as HAPS for transmitting data to users of cellular networks through a low-altitude RPAS. Stratospheric drones require reliable communication channels with minimal packet loss. Currently, there is not enough research in this area, and in the literature there is generally no data on the loss of data when exchanging information with stratospheric drones. In fact, the first estimate of the data loss in the drone's communication channel was published in the article [5].

Our article studies the centralized two-way line-of-sight channel for the ground Base Station (BS) with a stratospheric drone, which is connected through low-altitude RPAS to cellular network users. To predict the behavior of such a system, the following was done in the work:

- original models were created for simulating data exchange using MATLAB Simulink and NetCracker software;

- data traffic in the stratospheric drone network was first modeled using NetCracker software and packet loss was estimated for a different number of cellular network users; dependences of “Base Station - Stratospheric Drone” channel average load on the size of transmitted packets and data transfer rate were obtained;

- data transmission in a stratospheric drone network was investigated for the first time using the MATLAB Simulink software depending on the Signal-to-Noise Ratio (SNR), nonlinearity of the BS High-Power Amplifier (HPA), the type of signal modulation and diameters of the BS antenna;

- the obtained data are of practical importance and allow predicting the behavior of the network in critical conditions.

The rest of the paper is organized as follows. Section 1 covers related work. Section 2 presents the architecture and parameters of the model "Base Station - Stratospheric Drone – RPAS - Cellular Users", the simulation algorithm, the calculation method, the description of data traffic and results obtained using the NetCracker software. In Section 3, the model "Base Station - Stratospheric Drone – RPAS - Cellular Users" is considered using the MATLAB Simulink software and the influence of nonlinearity, modulation and diameters of the BS antenna is studied. Results are discussed in Section 4, and *Conclusions* are given at the end of the article.

1. Related Works

The review [6] is devoted to the history of HAPs and the current state of affairs without taking into account the aspects of the telecommunications sphere, which are among the main in this issue.

Airborne Communications Networks (ACNs) have received great attention as heterogeneous networks designed to use satellites, HAPs, and Low-Altitude Platforms (LAPs) as communication access. ACNs, unlike terrestrial wireless networks, are characterized by changing network topology and more vulnerable communication links. The review [7] covers communication networks based on LAPs, HAPs and integrated networks ACNs.

RPASs will become a component of 5G communication systems (and not only) to achieve global access to the Internet for everyone. The paper [8] proposes a new hierarchical network architecture that integrates inter-layer platforms for high and low altitudes into conventional terrestrial cellular networks. This provides additional bandwidth and expands coverage of underserved areas. Comparison and overview of various RPASs types for the provision of communication services are presented in the paper. An integrated architecture of an air-heterogeneous network is proposed and its characteristics are described.

RPASs need to effectively interact with each other and using the existing network infrastructure. The requirement for reliable communication is caused by errors in navigation, guidance and control systems that are introduced at each stage. Navigation systems introduce errors in the determination of the current coordinates and orientation parameters [9], and the guidance and control system may have corresponding deficiencies when a single drone is set to the required position [10].

RPASs deployment is seen as an alternative complement to existing cellular communications to achieve higher transmission efficiency with increased coverage and capacity. The article [11] provides an overview of advances in integrating 5G communications into wireless networks supported by RPASs. A taxonomy is given to classify existing research problems. Based on the proposed taxonomy, current issues and solutions for this newly emerging area are discussed.

The study [3] provides an overview of HAPS wireless service delivery in rural or remote areas using the cellular radio spectrum and focuses on the potential of using HAPS as an alternative to terrestrial systems. The feasibility of expanding the achievable wireless coverage using HAPS was investigated. This takes into account the coexistence of HAPS with terrestrial systems using intelligent techniques to dynamically manage radio resources and mitigate interference. The study has shown that effective intelligent radio resource and topology management can reduce intersystem interference. Potential techniques for extending coverage are discussed, such as using the spatial characteristics of lattice antennas, radio environment maps and inter-device communication.

With new technologies in autonomous avionics, antenna arrays, solar panel efficiency and battery energy density, HAPS has become an indispensable component of next-generation wireless networks. The review [12] presents the structures of future HAPS networks, proposes the integration of the emerging reconfigurable smart surface technology into the communication payload of HAPS systems, and discusses radio resource management in HAPS systems. The contribution of artificial intelligence to HAPS is noted, including machine learning in aspects of design, topology management, handover and resource allocation.

Terrestrial and satellite communication systems often face certain disadvantages and problems that can be solved by complementing them with HAPS systems. The article [4] considers HAPS as a base station for providing connectivity in a variety of applications. In contrast to conventional HAPS, which aims to reach a wide range of remote areas, it is expected that the next HAPS generation will have the necessary capabilities to meet the requirements for high throughput, low latency and compute resources. It focuses on the potential opportunities, target use cases, and challenges that are associated with the design and implementation of a future wireless access architecture.

In the review [13], RPAS networks are classified and the topology, control and behavior of the client server are investigated. Important aspects of self-organization and automated operations using Software-Defined Networks (SDN) are highlighted. The requirements of routing protocols for SDN networks and the need to create networks resistant to violations are discussed.

The review [14] outlines functions and requirements that are important to ensure reliable, efficient and energy efficient communications in basic UAV systems. The various UAV-to-UAV (U2U) and UAV-to-Infrastructure (U2I) network architectures and the various communication protocols that can be used at the network model layers are provided. A classification of data traffic that may be present in U2U and U2I communications is described. Various communication protocols and technologies are discussed that can be used for different channels and levels of the UAV-based network architecture. Efficient and uninterrupted communication in UAV-based networks is essential for their safe deployment and operation.

The book [15] focuses on the communication and networking aspects of UAVs and the fundamental knowledge required to conduct research in this area. The basic concepts and state of affairs in the field of UAV networks are outlined. Deployment procedures and risk analysis are discussed.

UAVs can be connected to cellular networks as a new type of user equipment, providing operators with significant revenues and guaranteeing service requirements. It is possible to upgrade UAV-based flying base stations that can move dynamically to increase coverage and spectral efficiency. Standards bodies are currently exploring the possibility of servicing commercial UAVs over cellular networks. The industry is testing prototypes of base stations and user equipment. Mathematical and algorithmic solutions for new problems arising in flying nodes in cellular networks are investigated. The article [16] provides an overview of developments that facilitate the integration of UAVs into cellular networks: types of consumer UAVs available off-the-shelf; interference problems; possible solutions for servicing aeronautical users with existing ground base stations; communication with flying repeaters and base stations created using UAVs.

The use of drone-based flying platforms is growing rapidly due to mobility, flexibility and adaptive altitude, which enables them to be used in wireless systems. UAVs can be used as aerial base stations to increase the coverage, capacity, reliability and energy efficiency of wireless networks. Drones can act as flying mobile terminals within a cellular network. These drones, connected to a cellular network, can use several applications, ranging from live video streaming to delivering goods. The article [17] provides detailed guidance on the UAVs use in wireless communications: 3D deployment, performance analysis, channel modeling and energy efficiency. Analytical foundations and mathematical tools such as optimization theory, machine learning, stochastic geometry, transport theory and game theory are described. The basic recommendations for the analysis, optimization and design of wireless communication systems based on UAVs are presented.

The main problem that needs to be solved for the successful introduction of drones in all areas is communication [18]. This review aims to outline the latest UAV communication technologies through research on suitable task modules, antennas, resource processing platforms, and network architectures. Methods such as machine learning and path planning are considered to improve existing communication methods with drones. Encryption and optimization techniques are discussed to ensure long-term and secure communications as well as power management. Applications of UAV networks are investigated for a variety of contextual purposes, from navigation to surveillance, ultra-reliable low latency communications, edge computing, and works related to artificial intelligence. The complex interaction between UAVs, advanced cellular communications and the Internet of things are the main topics of this article.

The best example of high-altitude RPAS with multisensory synthesis technology is the Global Hawk [19], which is equipped with an integrated surveillance and reconnaissance system HISAR (Hughes Integrated Surveillance & Reconnaissance). Such devices belong to the class HALE (High-Altitude Long Endurance), fly at an altitude of 20000 m and conduct strategic reconnaissance and target designation. The complex includes synthetic aperture radar and a moving target indicator, as well as optical and infrared sensors. All three subsystems can work simultaneously, and one processor works on their data. Digital data can be transmitted to the ground in real time with line-of-sight or over a satellite link at speeds up to 50 Mbps. RPASs such as the Global Hawk are expensive to manufacture and operate, which leads to the search for cheaper HAPS counterparts to provide Internet coverage in remote regions, target detection and recognition. There is interest in the development of low-cost UAVs networks, which together provide reliable communications, sufficient performance and have increased autonomy.

In the existing literature on HAPS and stratospheric drones, there is no quantitative information on the loss of data packets when communicating with drones. How is packet loss related to an increase in the number of cellular network users? How does the message size affect the percentage of losses? How does nonlinearity, modulation type, and antenna size affect packet loss? Our article is devoted to the development of these issues.

2. Traffic Losses Growth With Increase Of Cellular Users Number

2.1. Stratospheric Drone Network Architecture

Network models with different numbers of cellular users are based on ICAO documents [1, 2] and are designed using Professional NetCracker 4.1 software [20]. The number of cellular users N varied from one to five (N = 1–5) but results in the article are given only for N = 1, 3, 5. Models parameters are given in Table 1. The network model “BS – Stratospheric Drone – RPAS – Cellular Users” (Fig. 2) contains the BS, the high-altitude Stratospheric Drone (30 km from the BS), the low-altitude RPAS (50 km from the Stratospheric Drone) and Cellular Users (CUs) each on the distance 10 km from the RPAS.

Table 1
Parameters of the model “BS – Stratospheric Drone – RPAS – Cellular Users”

Parameters →	**Bandwidth**	**Length**	**BER**
Model elements ↓	**(Mbps)**	**(m)**	**(%)**
Base Station			
Tactical Control Data Workgroup	10	-	-
Common Data Server	10	-	-
TCD – Switch link	10	1	0
CD – Switch link	10	1	0
Switch	1000	-	-
Switch – Antenna link	44.736	10	0
Antenna	10	-	-
BS – Stratospheric Drone wireless link	2.048–44.736	30^5	0–0.05
Stratospheric Drone	Packet Latency – 0 s, Packet Fail Chance – 0		
Stratospheric Drone - RPAS wireless link	10	50^5	0
RPAS			
Antenna	1000	-	-
Antenna – Server link	44.736	10	0
Server	1000	-	-
RPAS – Cellular Users links	10	10^5	0
Cellular User			
Antenna	1000	-	-
Antenna – Switch link	44.736	10	0
Switch	10	-	-
Switch – Server link	10	1	0
Server	10	-	-

2.2. Algorithm and Calculation Method

The algorithm for traffic modeling using NetCracker software is described in the paper [5]. NetCracker is a real-time analytical simulator using mathematical equations. Its core is written in Java EE, its own application server is WebLogic, and Oracle is used as a database. We tested the capabilities of NetCracker software for realistic data traffic modeling in our article [20]. In this paper the data were calculated, which were subsequently confirmed. The model of the "Aircraft - Satellite - Ground Station" communication channel was built to simulate the transmission of ADS-B messages using the low-orbit satellite complex Iridium. The resulting dependences of the message transit time (1.4–1.9 s) on the number of satellites and aircraft were experimentally confirmed in 2017 by Aireon [21]. By tracking multiple aircraft with ADS-B 1090 Extended Squitter receivers for Iridium NEXT satellites, the system was able to deliver data to air traffic control centers with a delay of less than 1.5 seconds [22].

In our approach, the characteristics are divided into internal, which are obtained by mathematical modeling, and external, on which the internal characteristics depend. Channel load, data transfer time and the number of lost transactions were selected as internal characteristics. External characteristics included the size of the data packet, the time between messages, bit errors and the data transfer rate in the channel. The simulation made it possible to calculate the internal characteristics using the specified external characteristics.

The models parameters were simulated taking into account the Const probability distribution law ($\omega (x) = Const$, $\omega (t) = Const$) as statistical distributions for the Transaction Size (TS) and the Time Between Transactions (TBT). Formulas for the average length of the transmitted packets, the average time interval between two adjacent packets, the Average Utilization (AU) of the communication link, and the average packet travel time are given in the paper [5].

2.3. Data Traffic

Data transmission of drones in accordance with the ICAO requirements [1] is carried out in the form of C3 (Command, Control and Communication) traffic (Fig. 1), which consists of the Tactical Control Data (TCD) channel for flight control and the Common Data (CD) channel (for transmitting data from users of cellular networks, information from radars, optical, infrared systems, etc.).

Traffic with FTP client profile (File Transfer Protocol) for the Tactical Control Data (TS = 100 Kbps and TBT = 1 s with Const distribution law) and interLAN profile (Local Area Network) for the Common Data (TS and TBT with Const distribution law, TBT = 1 s) was set for our models. Command, control and communication traffic is carried out as two-way communication.

2.4. Results

The dependences of the average channel utilization on the transaction size and data transfer rate, the dependences of the bit errors number on the average channel utilization and the number of lost packets on the number of cellular users were investigated. Quantitatively packets loss is estimated as the percentage of packets lost in relation to sent packets. The numerical range of traffic parameters was chosen based on the experimental data presented in the work [23]. The distribution laws and the values of TS and TBT parameters are shown in the corresponding figures. The traffic parameters for TCD and CD parameters used in the simulation are indicated below the figures in each case.

Fig. 3 shows the dependences of the AU parameters for the “BS - Stratospheric Drone” channel on the size of the Common Data packet for a different number of cellular users N. At the same time, the TCD traffic remained constant with TS = 100 Kbits. The graphs obtained for N = 1, 3, 5 are of the same type. For TS values from 10 bits to 10 Kbits, the AU values practically do not change, slightly increasing only for TS = 100 Kbits. This increase in the AU parameter turns out to be greater the more users there are in the network. At TS values more than 100 Kbps, the channel is closed. This is due to the large amount of specified data transmitted in both channels. The increase in the number of cellular users naturally leads to an increase in the channel load. However, the important thing here is the order of such an increase. It follows from the graphs that an increase in the number of users from N = 1 to N = 5 leads to an increase in the AU parameter by about 3 times over the entire range of packet sizes. The values of the AU parameter for N = 5 vary from ≈ 17% to ≈ 44%.

Dependences of the AU parameters for “BS - Stratospheric Drone” channel on bandwidth for different number of cellular users are shown in Fig. 4. The bandwidth varied from T1 (1,544 Mbps) and E1 (2,048 Mbps) to E3 (34,368 Mbps) and T3 (44,736 Mbps). The transfer of fixed-size packages in both channels was considered. Channel AU increase with a decrease in data rate and with T1 bandwidth reaching ≈ 13% for N = 1 and ≈ 37% for N = 3.

The sensitivity of the stratospheric drone's communication system to bit errors is critical for the communication reliability. Fig. 5 shows the dependences of the BER on the AU parameter for the “BS - Stratospheric Drone” channel with a different number of cellular users. Dependences are given for TS = 10 Kbps for both TCD and CD traffic parameters. The data presented in Fig. 5 indicate a fairly high sensitivity of the channel to bit errors. It says about the need to encode the signal, which will be studied further using the MATLAB Simulink software.

Fig. 6 demonstrates the dependences of dropped packets number on the TS parameter for CD traffic. As the TS parameter increases from 10 bits to 1000 Kbits, the number of lost packets increases and reaches: for N = 1 approximately ≈ 12%, for N = 3 approximately ≈ 30%, for N = 5 approximately ≈ 51%. In general, the nature of all dependencies is similar, however, with the growth of users, packet losses increase more than 4 times with a fivefold increase in the number of users.

3. Model “base Station – Stratospheric Drone – Rpas – Cellular Users” In Matlab Simulink

3.1. Model Architecture

The model comprises of “Base Station” transmitter, “Uplink Path”, “Stratospheric Drone” transponder, “Downlink Path”, “RPAS” transponder, “Downlink Paths”, “Cellular Users” receivers, “Error Rate Calculation” block and “Display” (Fig. 7, Table 2).

Table 2
Model “BS – Stratospheric Drone – RPAS – Cellular Users”

“Base Station” transmitter	
Bernoulli Random Binary Generator	Generates random binary numbers using a Bernoulli distribution with parameter p, produces “zero” with probability p and “one” with probability 1-p (the value p = 0,5 is used).
Convolutional Encoder	Employs forward error correction coding in the form of convolutional encoding with Viterbi decoding [24]. A model uses a rate 3/4, constraint length 7, (r = 3/4; K = 7) convolutional code on both transmission and reception. The Convolutional Encoder block is using the poly2trellis(7, [171 133], 171) function with a constraint length of 7, code generator polynomials of 171 and 133 (in octal numbers), and a feedback connection of 171 (in octal). The puncture vector is [1; 1; 0; 1; 1; 0].
BPSK/QPSK Baseband Modulator	Modulates a signal using the binary phase shift keying method.
High Power Amplifier	Applies memoryless nonlinearity to complex baseband signal. Saleh model with standard AM/AM and AM/PM parameters [25] and linear gain are given. A HPA backoff level is used to determine how close the satellite high power amplifier is driven to saturation. The following selected backoff is used to set the input and output gain: 30 dB - the average input power is 30 decibels below the input power that causes amplifier saturation (in this case, AM/AM and AM/PM conversion is negligible); and 1 dB - severe nonlinearity.
Transmitter Dish Antenna Gain	Multiplies the input by a constant value.
“Uplink Path”	
AWGN	Add white Gaussian noise to the input signal.
Stratospheric Drone” transponder	
Receiver Dish Antenna Gain	Multiplies the input by a constant value.
Receiver System Temperature	Simulates the effects of thermal noise on baseband signal.
Complex Baseband Amplifier	Models an amplifier with noise (during simulations this setting was 0 K) and linear gain 10 dB.
Phase/Frequency offsets	Are equal to zero
Transmitter Dish Antenna Gain	Multiplies the input by a constant value.
“Downlink Path”	
AWGN	Add white Gaussian noise to the input signal.

“Base Station” transmitter	
“RPAS” transponder	
Receiver Dish Antenna Gain	Multiplies the input by a constant value.
Receiver System Temperature	Simulates the effects of thermal noise on baseband signal.
Complex Baseband Amplifier	Models an amplifier with noise (during simulations this setting was 0 K) and linear gain 10 dB.
Phase/Frequency offsets	Are equal to zero.
Transmitter Dish Antenna Gain	Multiplies the input by a constant value.
“Downlink Paths”	
AWGN	Add white Gaussian noise to the input signal.
“Cellular Users” receivers	
Receiver Dish Antenna Gain	Multiplies the input by a constant value.
Receiver System Temperature	Simulates the effects of thermal noise on baseband signal.
Viterbi Decoder	Decodes input symbols to produce binary output symbols. Unquantized decision type parameter was used.
“Error Rate Calculation” block and “Display”	

The relationship between the antenna gain, the antenna diameter and the wavelength is determined by the relation G = η(πD/λ)2, where η is the antenna efficiency. For calculations (here η = 1), the following parameters in the model were set up: for Stratospheric Drone and RPAS antenna gains were taken 1.55 (an antenna diameter ≈ 0.2 m at 1 GHz); for the BS the following antenna gains were taken − 6.2, 7.8 and 9.3 (an antenna diameters ≈ 0.8 m, ≈ 1.0 m and ≈ 1.2 m correspondently at 1 GHz).

The “effect of different distances” from low-altitude RPAS to CUs was modeled by setting different SNR (E_s/N_0) values in AWGN Channels 2–7. In Fig. 8 - Fig. 11 data are given when E_s/N_0 values were varied only in AWGN Channel 1. At the same time, the SNR values in other channels were set constant, with the help of which a decrease in the SNR level was simulated for each subsequent CUs. Such situation actually happens when the signal travels a greater distance (AWGN Channel 2 – E_s/N_0 = − 20 dB, AWGN Channel 3 - E_s/N_0 = − 25 dB, AWGN Channel 4 - E_s/N_0 = − 30 dB, AWGN Channel 5 - E_s/N_0 = − 35 dB, AWGN Channel 6 - E_s/N_0 = − 40 dB, AWGN Channel 7 - E_s/N_0 = − 45 dB,). These SNR values for the channels were chosen arbitrarily from considerations of the approximate “equidistance” of the curves with negligible

HPA nonlinearity for both considered modulations. In this case, it is possible to trace the influence of severe nonlinearity with an increase in the range to the RPAS.

3.2. Results

Figure 8 shows data for BPSK modulation with negligible HPA nonlinearity. When E_s/N_0 in AWGN channel 1 changes from − 32 dB to − 29 dB, the BER for the CU1 decreases from ≈ $5.2 \cdot 10^{-3}$ to ≈ $1.1 \cdot 10^{-6}$. For each subsequent CU channel, the BER values become larger due to distances increase and worse SNR values.

In the case of strong HPA nonlinearity, the situation changes dramatically (Fig. 9). For the operation under these conditions, much higher values of the SNR are required. When E_s/N_0 in AWGN channel 1 changes from − 19 dB to -15 dB, the BER for the CU1 channel decreases from ≈ $1.2 \cdot 10^{-1}$ to ≈ $1.1 \cdot 10^{-6}$. The BER for the CU3 channel reaches ≈ $9.4 \cdot 10^{-4}$ and for the CU5 channel reaches ≈ $4.8 \cdot 10^{-2}$ at E_s/N_0 = − 15 dB. This means that with an increase in the level of nonlinearity, communication with cellular users at large distances suffers first. This would seem to be an obvious conclusion, but the data obtained allow us to quantify the degree of such deterioration.

Figure 10 shows the dependences of the BER on the SNR for different BS antenna diameters with strong HPA nonlinearity (Stratospheric Drone and RPAS antennas diameters are ≈ 0.2 m in all cases). The high sensitivity of bit errors number depending on the size of the antenna is evident. The data are given only for the CU1, and for the rest of the CUs the situation is even more critical for this SNR range.

Figure 11 demonstrates the dependences of the BER on the SNR for severe nonlinearity in the case of QPSK modulation. Comparison with similar dependences for BPSK modulation (Fig. 9) shows that the transition to higher-level modulation requires a significant increase in the SNR. So for BPSK modulation the BER ≈ $1.1 \cdot 10^{-6}$, at E_s / N_0 = − 15 dB for the CU1, and for QPSK modulation the BER ≈ $1.2 \cdot 10^{-6}$ at E_s / N_0 = − 8 dB.

4. Discussion

Stratospheric drone operation is not possible without reliable communication channels with low-altitude RPASs, terrestrial cellular networks, other stratospheric drones and satellite communications systems. This is stated in almost all published works, but besides proposals for the possible network architecture, data protocols and wireless standards, no quantitative traffic characteristics can be found. In fact, apart from the work [23], there are no experimental data in the literature, with traffic parameters (the size of transactions, the time between them, the traveling time of the messages, the number of lost data packets, the rate of data transmission and its impact on the number of bit errors, the loading of channels, the impact of modulation type). There are also no theoretical studies developing methods of predictive analysis for drone's communication. There are no theoretical methods for assessing the parameters of real traffic in drone channels. This study is a case in which such methods are developed.

The data presented in Fig. 3 – Fig. 5 allow us to analyze the benefits of a certain mode of information sharing and to estimate the relative AU increase with the growth of cellular users. Figure 6 is key for understanding the conditions under which packets losses becomes unacceptable.

When using drones, the base station amplifier typically works at as much power as possible due to the small size of the drone antennas and the long distances to them. So, the inevitable nonlinearity of communication channels becomes critical. Obtained data can quantify the specifics of data transmission for different levels of the BS transmitter nonlinearity, signal modulations and the BS antenna diameters (Fig. 7 – Fig. 11). It was found how much you need to increase the SNR when transmitting data with an increase in nonlinearity and the transition to QPSK modulation.

It is worth noting the original models architecture for connection the stratospheric drone with the cellular network and the possibility of using the results to assess the quality of data transmission. This article is a continuation of our work on modeling drone channels operation.

Conclusions

Original models of the communication channel "BS - Stratospheric Drone - RPAS - CUs" were created using NetCracker and MATLAB Simulink software for simulation of messages transmission via a stratospheric drone.

This work is the first study with calculation of packet losses, convolutional signal coding and identifying the nonlinearity and signal modulation effects for the stratospheric drone communications. The impact of BS antenna diameter, which can significantly change the BER, has been quantified. The probability of bit errors is much lower for BS antenna with a diameter of more than 1.2 m. The results can be considered as a way to evaluate the parameters of such channels using MATLAB Simulink and NetCracker software.

The importance of the results lies in the ability to predict the channel operation, identify problems in the early stages of designing channels for stratospheric drones, as well as reduce time, cost and ensure scalability in new projects. It is obvious that such calculations become a necessary tool for developers of stratospheric drone communication systems.

Declarations

Ethical Approval and Consent to participate - "Not applicable"

Human and Animal Ethics - "Not applicable"

Consent for publication - All authors have read and agreed to the published version of the manuscript.

Availability of supporting data - All data generated and analyzed during this study are included in this article. The datasets generated during the current study are available from the corresponding author on request.

Competing interests - The authors have no relevant financial or non-financial interests to disclose.

Funding – No funding.

Authors' contributions - Conceptualization, V.K.; methodology, A.G.; investigation, A.G.; resources, V.K.; writing — review and original draft preparation, A.G.; writing — editing, V.K.; project administration, V.K.

Acknowledgements - “Not applicable”

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Figures

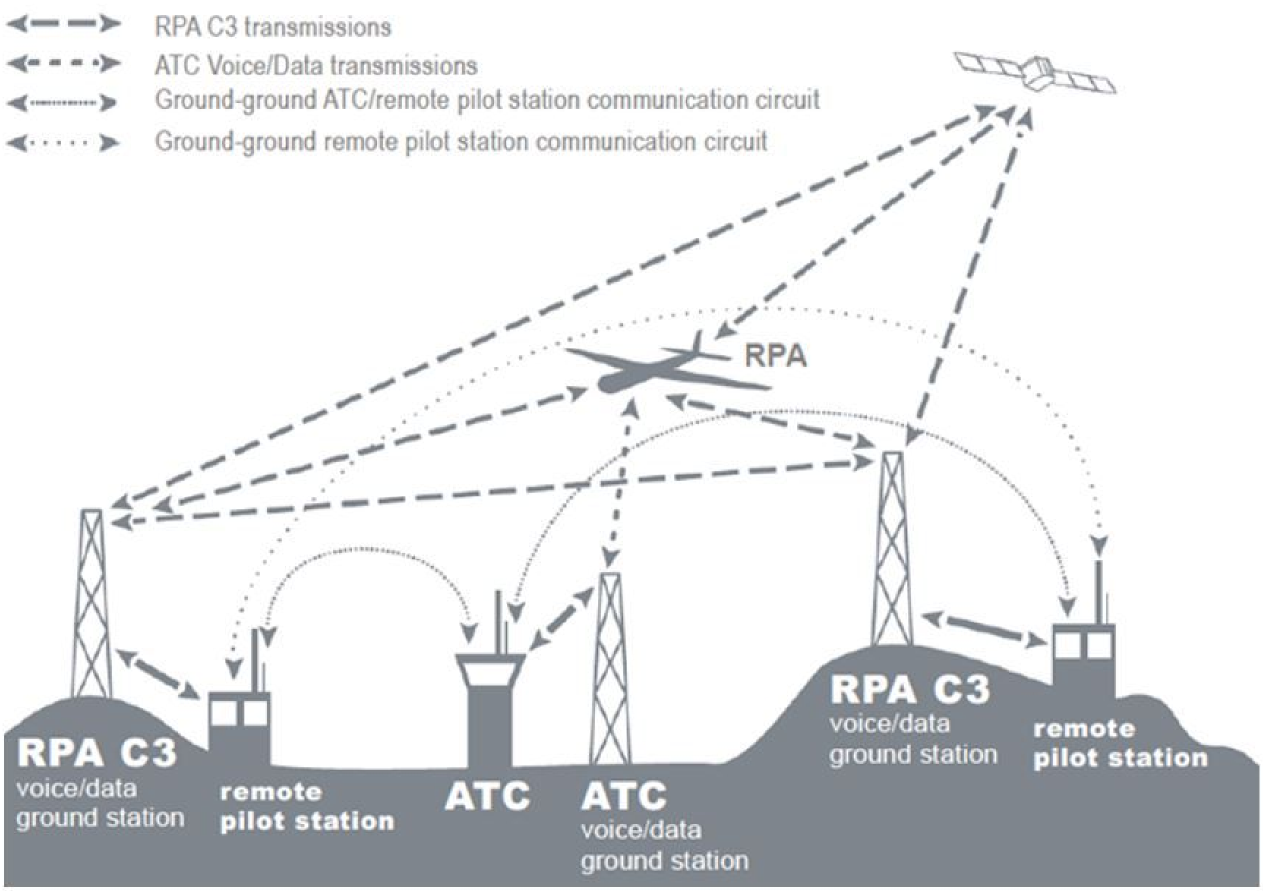

Figure 1

ICAO aeronautical RPAS communication links with stratospheric drone/satellite [1]

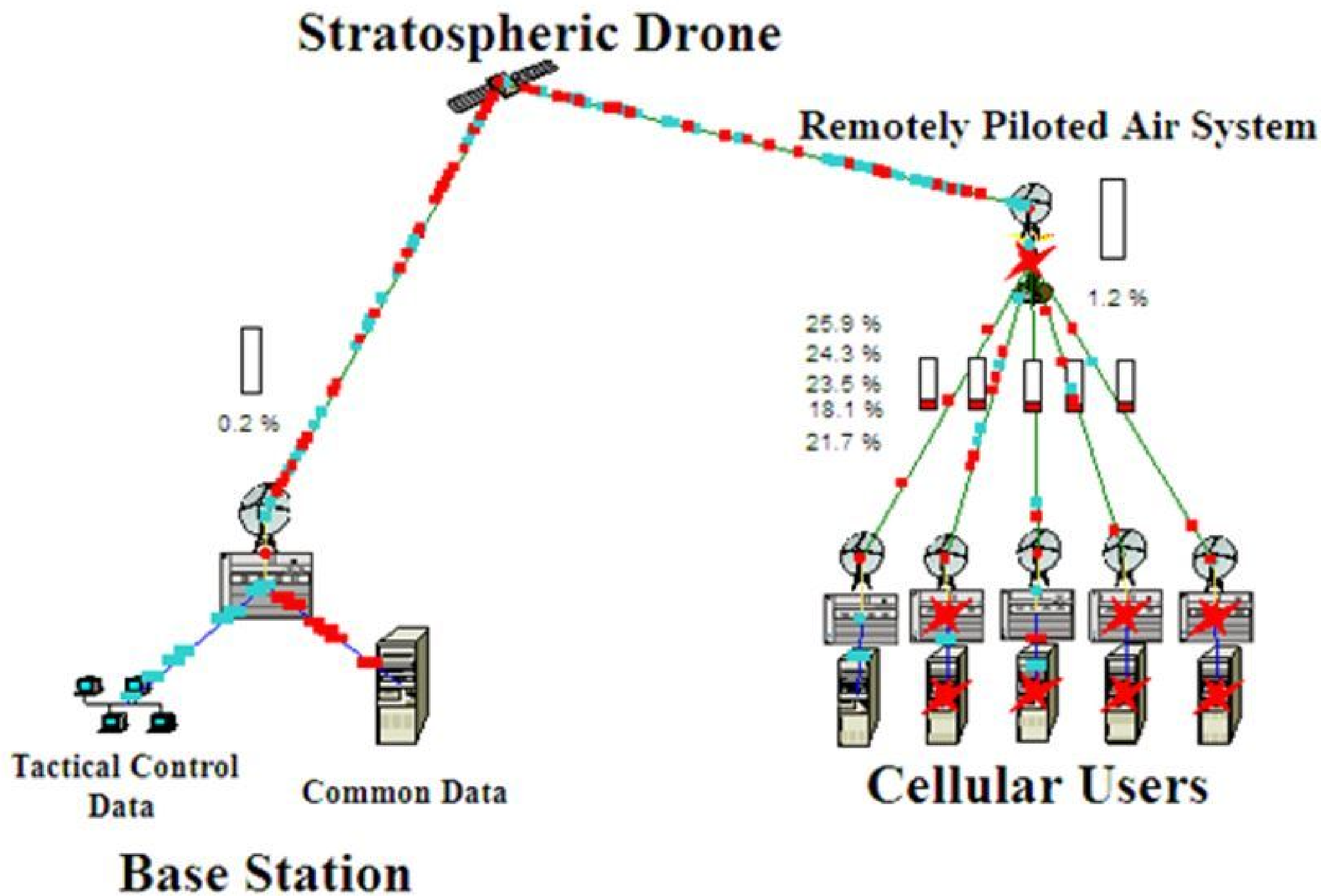

Figure 2

Stratospheric drone network with five cellular users

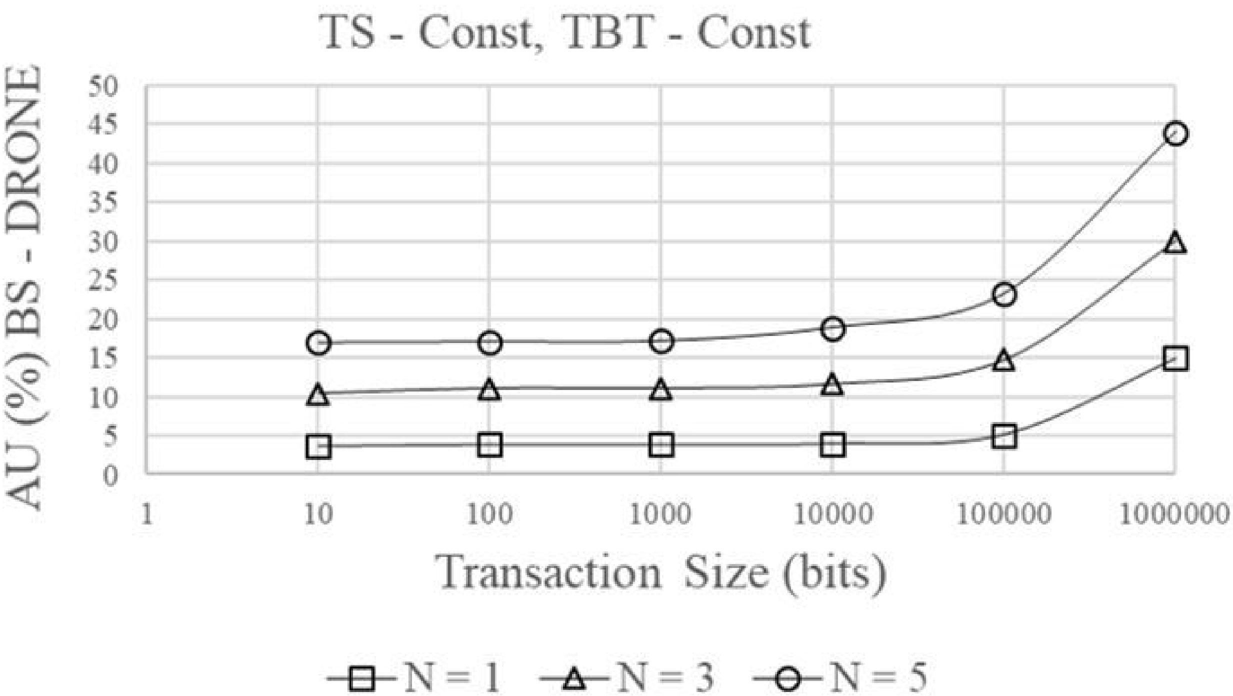

Figure 3

Dependences of AU for “BS – Stratospheric Drone” channel on CD TS (Traffic: TCD – FTP, TS = 100 Kbits and TBT = 1 s - with Const distribution law, CD – interLAN, TS and TBT - with Const distribution laws, TBT = 1 s)

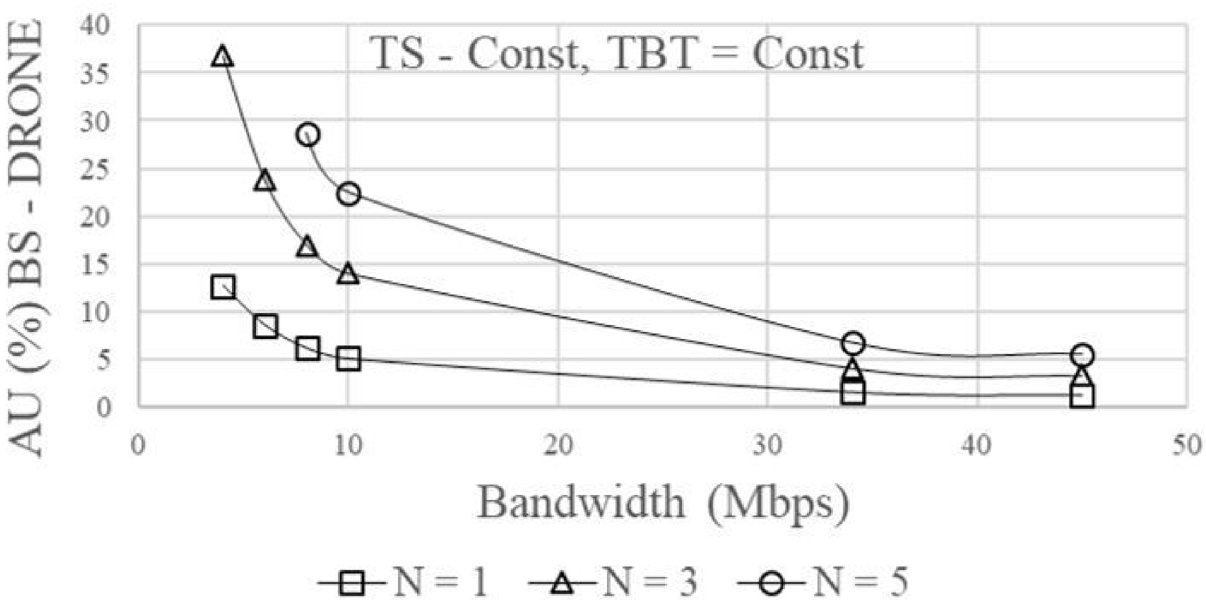

Figure 4

Dependences of AU for “BS - Stratospheric Drone” channel on bandwidth

(Traffic: TCD – FTP, TS = 100 Kbits and TBT = 1 s - with Const distribution law, CD – interLAN, TS = 100 Kbits and TBT = 1 s - with Const distribution law)

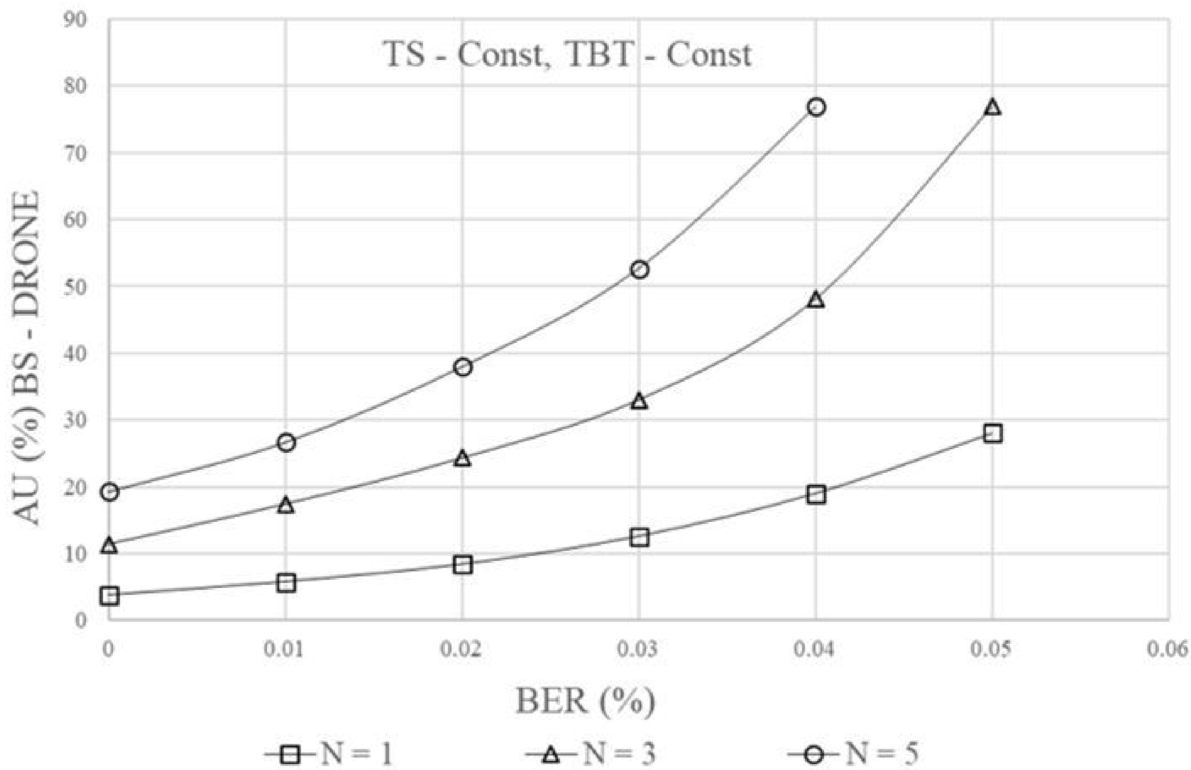

Figure 5

Dependences of BER on AU for “BS - Stratospheric Drone” channel (Traffic: TCD – FTP, TS = 10 Kbits and TBT = 1 s - with Const distribution law, CD – interLAN, TS = 10 Kbits and TBT = 1 s - with Const distribution law)

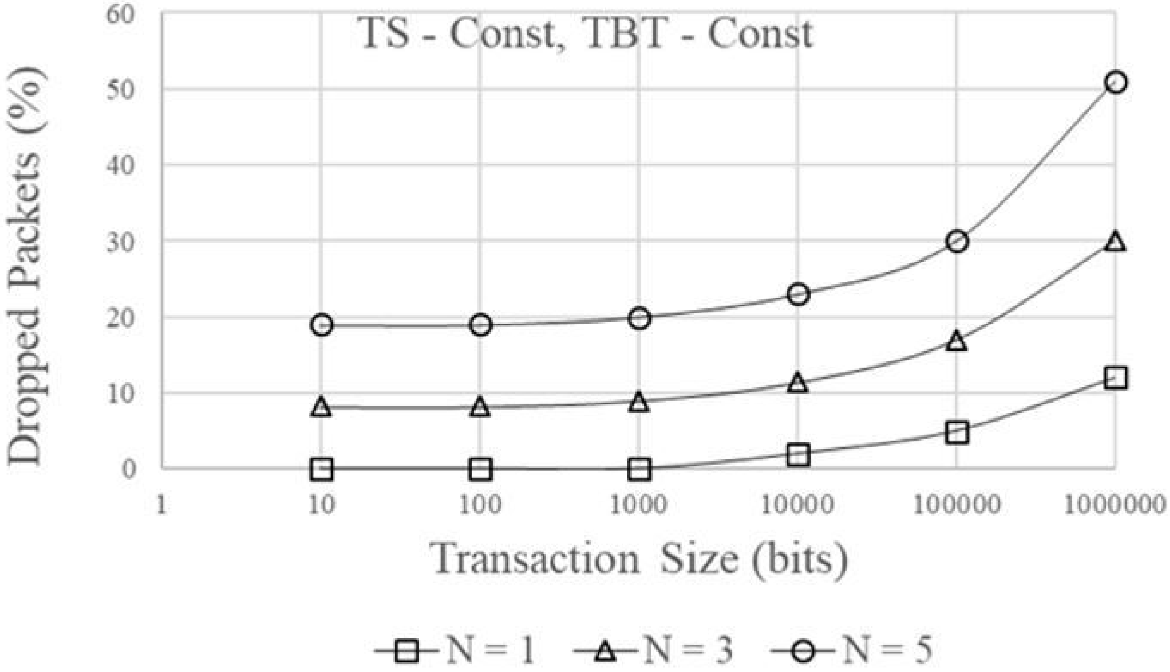

Figure 6

Dependences of BS Dropped Packets on CD TS for different number of cellular users (Traffic: TCD – FTP, TS = 10 Kbits and TBT = 1 s - with Const distribution law, CD – interLAN, TS and TBT - with Const distribution laws, TBT = 1 s)

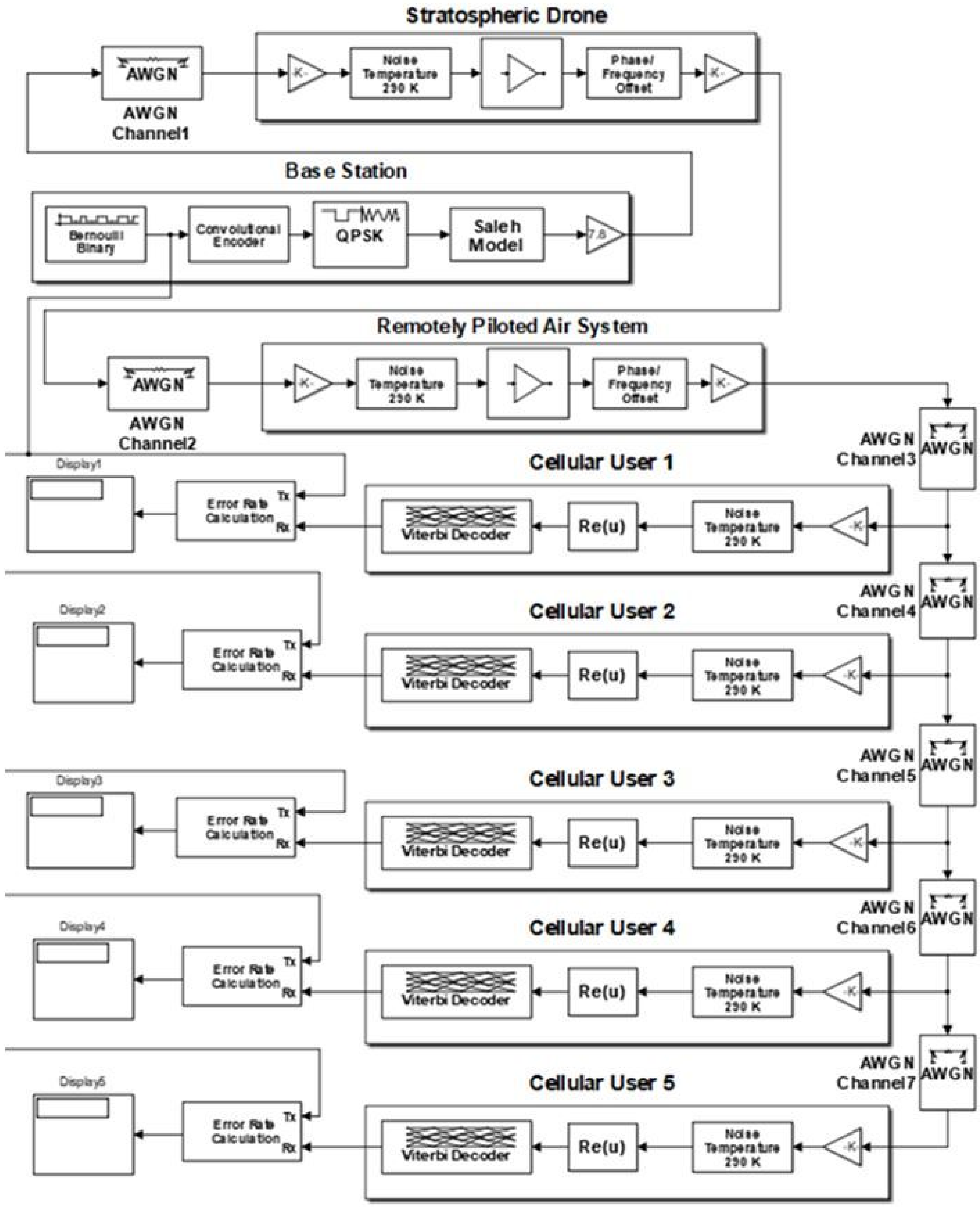

Figure 7

Communication links in Stratospheric Drone network

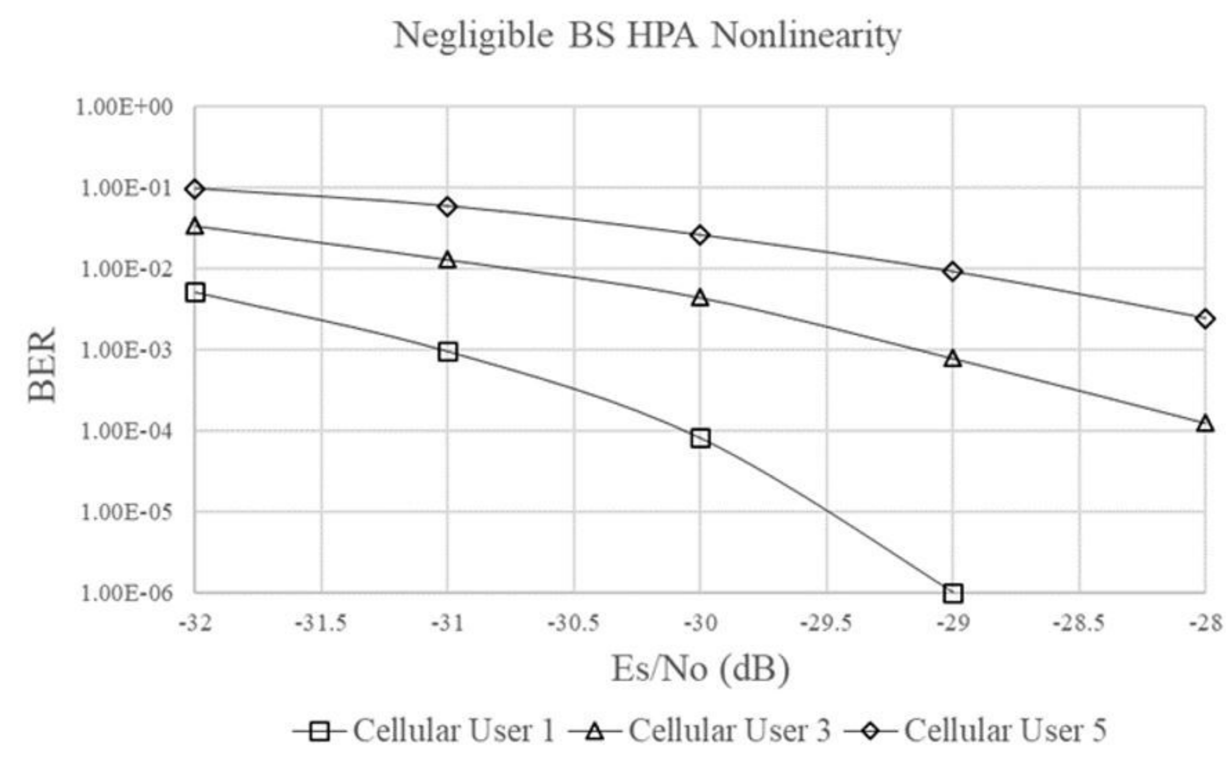

Figure 8

Dependences of BER on SNR for negligible nonlinearity (BPSK modulation, phase/frequency offsets 0º/0 rad, BS antenna diameter 1.0 m)

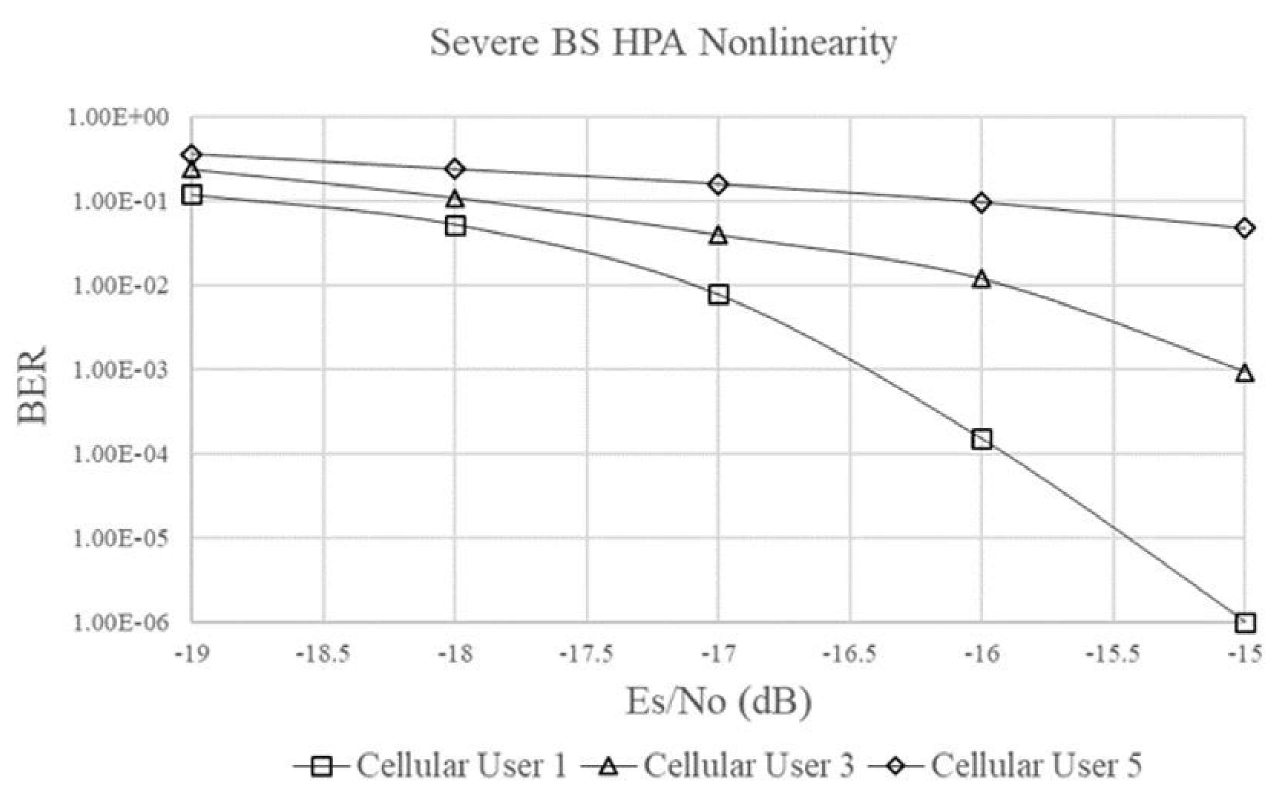

Figure 9

Dependences of BER on SNR for severe nonlinearity (BPSK modulation, phase/frequency offsets 0°/0 rad, BS antenna diameter 1.0 m)

Figure 10

Dependences of BER on SNR for different BS antenna diameters (BPSK modulation, phase/frequency offsets 0°/0 rad)

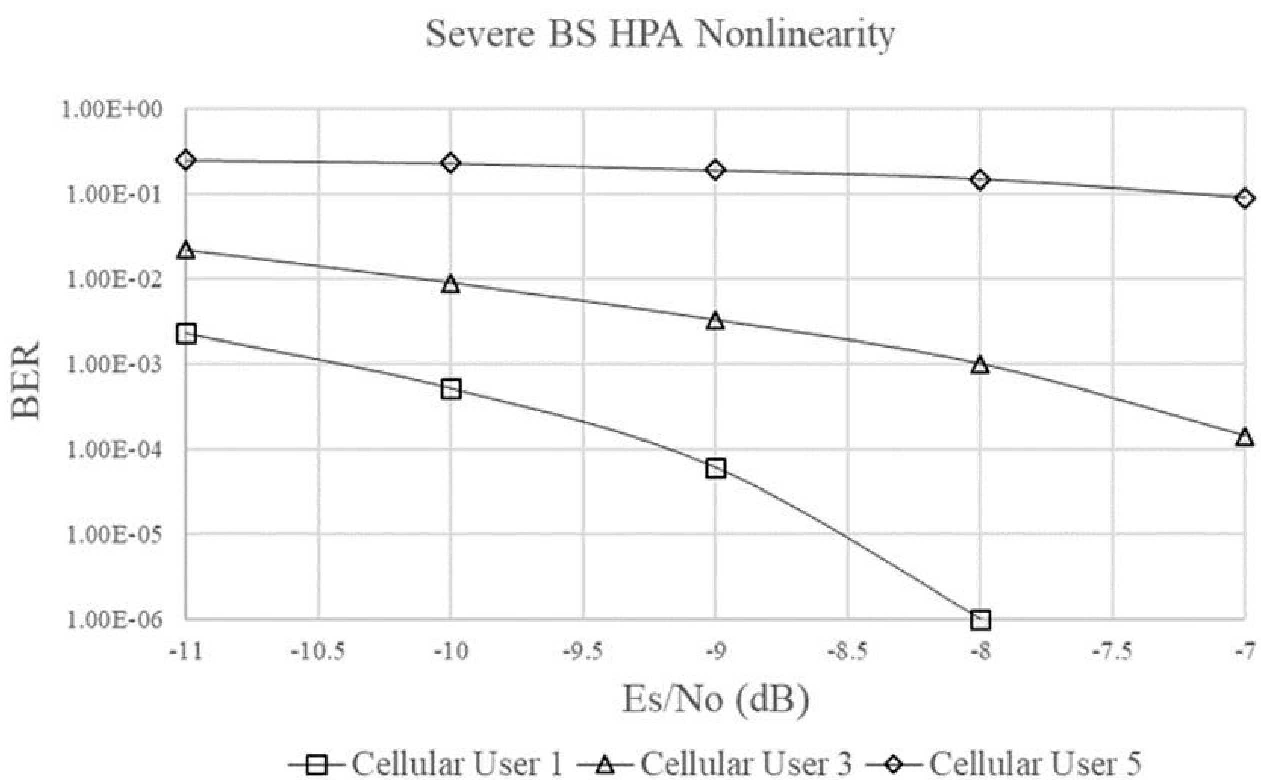

Figure 11

Dependences of BER on SNR for severe nonlinearity (QPSK modulation, phase/frequency offsets 0°/0 rad, BS antenna diameter 1.0 m)