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Development of an inter-satellite data transmission network for space debris evasion systems

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Abstract. The space debris problem was revealed. Research of space debris situation data from open sources of information such as European Space Agency was carried out. Methods of satellite protection were revealed. Collision avoidance system was proposed. It consists of satellites with a built-in location system and low speed mesh-network. Location satellites are used for long-range precise detection of objects with trajectories which are dangerous for protected spacecrafts, while the data is transmitted with CubeSat chain. The aim of this work is to develop an inter-satellite network for technical information exchange. As a result of the research, LoRa technology is selected because of low power consumption and significant coverage range of a single device. The network operation was simulated using MATLAB software and calculated results confirmed that the proposed method is adequate.

Keywords: inter-satellite network, LoRa, network simulation, mesh network, space debris, collision avoidance

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Разработка межспутниковой сети передачи данных для систем уклонения искусственных спутников земли от космического мусора

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Аннотация. Обоснована проблема, связанная с повреждением спутниковых группировок в результате столкновения с неиспользуемыми объектами на орбите Земли.

Предложена система для уклонения искусственных спутников Земли от космического мусора. Она состоит из спутников с бортовыми радиолокационными станциями и кубсатов, объединенных в меш-сеть. Модель сети была разработана в среде MATLAB. Оценка качественных параметров сети показала возможность применения такой конфигурации для передачи данных.

Ключевые слова: межспутниковая сеть, mesh-сеть, модель сети, LoRa, космический мусор, уклонение от космического мусора

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Introduction

Artificial Earth Satellites (AES) are among the most powerful tools across a wide range of fields, such as science, telecommunications, radio navigation, and many others [1–3]. Satellite systems are extremely important; therefore, all space nations strive to improve their operational reliability and efficiency [4, 5]. However, modern spaceflights must contend with space debris, which poses a threat to both AES and manned spacecraft [6]. Under the conditions of accumulating space debris in low Earth orbit (LEO), the safety of spacecraft is becoming one of the key challenges of modern astronautics. According to the European Space Agency (ESA), there are more than 40000 objects larger than 10 cm in orbit, and the number of small debris fragments amounts to hundreds of millions [7, 8]. A collision with such objects could lead to damage or complete destruction of satellites, which would result in significant economic losses and pose a threat to further space exploration.

A complex solution to the abovementioned problem is required, consisting of specialized AES carrying equipment to detect potentially dangerous trajectories of small space debris and the creation of inter-satellite networks for exchanging operational information needed to adjust the orbital parameters of the threatened spacecraft. This paper examines one variant of such a network. The structural diagram of the network and its operational principle are shown in Figure 1.

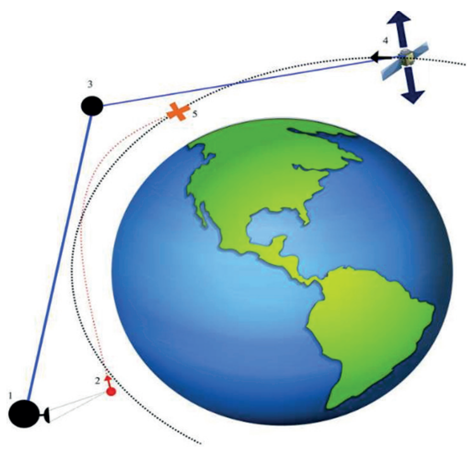

Fig. 1. Structural diagram of the network; 1 – AES detecting space debris; 2 – space debris; 3 – AES – participant of the mesh network; 4 – satellite threatened by the detected object; 5 – intersection of the debris trajectory and the orbit of the at-risk satellite

Materials and Methods

Technologies of the Internet of Things (IoT) were considered as the main devices for organizing networks because of their low power consumption which is necessary for implementation on CubeSats.

Among the different ones, LoRa technology was chosen as the primary transmission scheme.

LoRa (Long Range) is a wireless communication technology based on Chirp Spread Spectrum (CSS) modulation, designed for low-power, long-range data transmission in the sub-GHz bands. It is widely used in low-power wide-area networks (LPWANs). In this work, the LoRa physical layer is considered with reference to the SX1276 transceiver chip, which implements the modulation and coding schemes defined by the datasheet [9].

The justification for this choice is in use of CSS modulation, which provides a large processing gain and enables long-range communication compared to other low-power IoT technologies. Moreover, LoRa can reliably decode signals at very low signal-to-noise ratios down to around negative tens dB for high spreading factors with additional robustness provided by forward error correction at the physical layer. These properties make LoRa particularly suitable for long-distance communication in low Earth orbit scenarios, where link budgets are highly constrained.

Simulation in MATLAB software, a time-based discrete event simulator, was used to calculate the main parameters of the network.

The simulations were performed specifically for the LoRa32 platform, which integrates the SX1276 transceiver operating at a carrier frequency of 868 MHz. The modeling included the estimation of maximum communication distance using the Friis free-space propagation model, the achievable data rate as a function of spreading factor and coding rate, and the probability of bit error under various channel conditions.

Detail review of simulation stages:

1. Parameters of the transceiver devices are specified: transmitter power, minimum receiver sensitivity threshold below which the signal cannot be detected, carrier frequency, and the gain of the transmitting and receiving antennas.

2. The orbital altitudes for satellites within one orbital plane are defined, along with the observation time for simulation visualization.

3. Orbital planes are generated for three groups: equatorial, polar, and inclined. It is possible to adjust the inclination, the right ascension of the ascending node, and the number of orbital planes in each group. Satellites are evenly distributed along each orbit within the group, according to the specified number and initial phase. For each satellite, the true anomaly and Cartesian coordinates are calculated. All satellite parameters are stored in a global matrix.

4. After the physical placement of satellites is completed, they are considered as nodes of a data transmission network.

A classic case of CubeSat stabilization in a single plane is considered, where the main lobe of the antenna radiation pattern points toward the Earth. The antenna orientation for each node is defined by the angle relative to the velocity vector in the plane formed by that vector and the orbital plane normal. This angle can also be changed to model the stabilization type.

The deviation of the dipole antenna pattern from the isotropic pattern in the direction of every other node is calculated. A dipole antenna is chosen due to its omnidirectional coverage capability, required under varying satellite orientations, and its low mass.

5. The communication range is calculated, and a connectivity matrix is built according to the Distance-Vector routing protocol model. This stage includes: calculation of free-space path loss as a function of wavelength; 5 dB noise to simulate various network losses reducing communication range; calculation of received power based on transmitter power, antenna gains with anisotropy taken into account, free-space attenuation, and distance losses; application of a function specific to LoRa technology (SX1276 chip), which collects metrics for each inter-satellite channel pair using received power, bandwidth, spreading factor, and coding rate. Signal-to-noise ratio and bit error rate are computed.

For each channel, the maximum communication distance is determined and, along with the SNR (threshold SNR = −20 dB for LoRa in this case), the feasibility of communication is decided and reflected in the connectivity matrix. Radio propagation delay is also calculated for each channel and stored in a separate matrix.

6. Isolated clusters and individual satellites are identified.

7. Nodes with the largest physical separation are identified, and the most efficient route in terms of transmission time is constructed using the Distance-Vector protocol model. Key parameters are evaluated, including packet transmission time, relative bit rate, signal-to-noise ratio at each hop and bit error probability along the route. Arbitrary node pairs may also be selected for analysis.

8. The same procedure is performed for the pair of nodes with the maximum propagation delay in the network. This allows assessment of the same parameters under worst-case conditions, ensuring that performance between arbitrary nodes will be superior to this worst-case baseline.

9. Visualization of all calculations described above is carried out.

Example of such visualization is shown in the Figure 2.

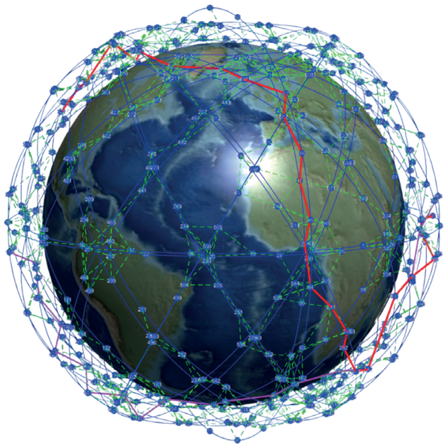

Fig. 2. Model of the network

Results and Discussion

Key results of the simulation are represented in Table 1.

They were calculated as average between twenty simulations with 20 minutes difference in time for 500 satellites.

Table 1

Results of simulation

Transmitter	SX1276
Antenna gain	2 dBi
Calculated max link distance	1945.27 km
Time delay for 30-byte packet (15256 km)	21.7 s (purple)
Time delay for longest link in the network	28.9 s (red)
Mean SNR for purple path	1.82 dB
Mean SNR for red path	1.56 dB
Relative transmission rate	11.07 bps (purple)
Relative transmission rate	8.31 bps (red)

The maximum link distance was determined from the longest successfully established connection, implying that the SNR in that channel remained above −20 dB and the distance did not exceed the value predicted by the Friis propagation model.

End-to-end delays were calculated assuming the highest achievable LoRa coding rate and including routing hopping for a 30-byte packet, which was selected as the minimal payload required for collision avoidance.

The reported mean SNR values account for the entire multi-hop mesh path.

Relative transmission rates were obtained by dividing the packet payload by the corresponding transmission time and are presented to enable comparison with alternative communication systems.

Also, the calculation of bit errors was performed for chosen nodes 1 and 500. The topology is represented in Figure 3.

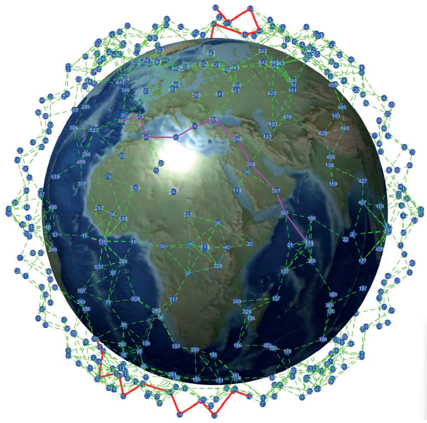

Fig. 3. Model of bit errors calculation

Table 2

Results of bit errors calculation

channel	BER
From 1 to 367	5.5235e-04
From 367 to 387	2.2218e-04
From 387 to 366	6.1843e-04
From 366 to 386	1.0180e-04
From 386 to 365	6.1857e-04
From 365 to 540	3.2315e-05
From 540 to 560	2.2215e-04
From 560 to 346	5.8258e-04
From 346 to 325	6.3956e-04
From 325 to 500	1.3506e-04

Bit errors for intersatellite channels were calculated using the following formula because it is suitable for lora chirp spread spectrum modulation:

$$BER = \frac{erfc\left(10^{\frac{SNR}{10}}\right)}{2}.$$

Errors are not larger than six ten thousandths. They can be lowered using code rate enlargement. Each node recovers errors of previous transmission.

A mesh network meets all the requirements regarding architecture and scalability. It allows many nodes to be integrated, which will connect all satellites around the Earth so each individual device can send and receive data with any other node in the network thanks to signal routing. Therefore, the transmitter and receiver do not require direct radio contact, unlike in peer-to-peer networks. Moreover, this architecture is supported by many modern variants of technologies.

Also, IoT devices and protocols can achieve significant efficiency in space because of low signal path loss, low transmission power and small sizes of the telecommunication devices [10, 11].

Conclusion

The model for intersatellite mesh network was developed. It contains mechanism for different satellite orbits creation including true anomaly calculation, so that model is basically discrete time-event simulator, tx/rx parameters setting, distance vector protocol simulation and delay and snr estimations for chosen links.

It should be noted that a network like this will significantly reduce the threat of collisions with space debris for satellites of various types, as well as make manned space expeditions much safer.

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