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RESEARCH OF THE FEATURES OF DIGITAL SIGNAL FORMATION IN SATELLITE COMMUNICATION LINES

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ABSTRACT

Context. Remote sensing of the Earth is now widely used in various fields. One of the challenges of remote sensing is the creation of inexpensive satellite systems operating in polar circular orbits. These systems require the development of a reception-transmission system that allows tens of gigabits of video information to be transmitted to an earth receiving station within ten minutes. That is, there is a need to create a communication system that provides high speed data transmission from small satellites weighing up to 50 kg.

Objective. The aim of the work is to study the features of digital signal formation in modern satellite communication lines and to develop a communication system with a high data transfer rate (usually 300 Mbit/s), which can be applied to small Earth Observation satellites.

Method. Proposed concept for building a high-speed data transmitter from a remote sensing earth satellite using commercially available off-the-shelf technology. Calculations of the power flow density created at the input of the receiving earth station were performed to find out the possible power of the on-board transmitter.

Results. A diagram of a communication system based on the DVB-S standard using the technology of commercially available off-the-shelf products has been developed. The high-speed data transmitter is implemented on a Xilinx® Zynq Ultrascale+ ™ MPSoC FPGA microchip, which is located on an Enclustra Mercury XU8 module with a high-performance dual 16-bit AD9174 DAC. The on-board transmitter with a power of up to 2 W meets the requirements of the ITU Radio Regulations for the power flux density on the surface of the Earth, which is created by the radiation of the space station EESS in the range 8025–8400 MHz. It is shown that the energy reserve of the communication line of 3 dB is achieved for various commands for coding and modulation changes with an increase in the elevation angle, which allows to increase the speed of information transmission.

Conclusions. An original receiving-transmitting system was developed for use in small satellites for remote sensing of the Earth. It is shown that the function of adaptive modeling of ACM of the DVB-S standard allows you to automatically change the transmission parameters in real time depending on the changing conditions of the channel, providing opportunities for more flexible and effective data transmission in various conditions, which will allow to increase the volumes of information transmitted by communication session. The proposed system operates in the X-band and is built using commercially available off-the-shelf products. An antenna with double circular polarization is used as the emitter. Two physical channels represent two polarization modes: right circular polarization and left circular polarization, each of which has three frequency channels.

KEYWORDS: small satellite, low Earth orbit, remote sensing of the Earth, power flow density, X-band, DVB-S.

ABBREVIATIONS

ACM – Adaptive Coding and Modulation;
ADC – Analog-Digital Conversion;
BER – Bit Error Ratio;
CCSDS – Consultative Committee for Space Data Systems;
COTS – Commercially available off-the-shelf;
DAC – Digital-Analog Conversion;
DC – Direct Current;
DVB-S2 – Digital Video Broadcasting – Satellite – Second Generation;
EESS – Earth Exploration Satellite Service;
EO – Earth Observation;
IF – Intermediate Frequency;
ISARA – Integrated Solar Antenna and Reflective Antenna;
ITU – International Telecommunication Union;
FCC – Federal Communications Commission;
FEC – Forward Error Correction;
PFD – Power Flow Density
FFH – Fast Frequency Hopping;
FPGA – Field Programmable Gate Array
HDT – High-speed Data Transmitter;
HSD2 – High Speed Downlink Version 2;
LEO – Low Earth Orbit;
LHCP – Left-Hand Circular Polarization;
MGA – Middle-Gain Antenna;
MIMO – Multiple Input Multiple Output;
MODCOD – changing modulation and coding;
NCO – Numerically-Controlled Oscillator;
NGSO – Non-Geostationary Orbit;
OCSD – Optical Communications and Sensor Demonstration;
OFDM – Orthogonal Frequency Division Multiplexing;
QAM – Quadrature Amplitude Modulation;
RF-DAC – Radio Frequency Digital-Analog Converter;
RHCP – Right-Hand Circular Polarization;
SCSs – Satellite Communication Systems;
SDR – Software Defined Radio;
TT&C – Telemetry, Tracking, and Control;
UHF – Ultra High Frequency.

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NOMENCLATURE

E_b/N_0 – signal-to-noise density ratio;
C/N_0 – carrier-to-noise density ratio;
M_t – number of transmitting antennas;
M_r – number of receiving antennas.

INTRODUCTION

The use of small satellites began in the 1980s. Such satellites are usually used in Low Earth Orbits. Explicitly, by the end of 2021, more than 4700 LEO satellites have been successfully launched, accounting for nearly 86% of the total launch volume of all types of satellites [1]. During these years, LEO SCSs have found a plethora of applications, including media broadcasting, backhauling, mobile communication, and broadband Internet [1–6].]. In fact, LEO SCS is a supplement to ground systems in areas where there is no coverage. There is now a convergence of ground systems with LEO SCS.

Currently, Earth observation satellite is being widely implemented [7]. In this technological process (EO), satellites are used for non-contact collection of information about objects or phenomena on the Earth's surface. Thanks to EO technology, it is possible to obtain information about changes on the Earth's surface, study climatic and natural phenomena, monitor the use of land plots, detect changes in ecosystems, etc. [8–9]. EO technology is becoming more and more important for monitoring and managing the resources of our planet, as well as for solving various scientific, environmental and economic tasks. Satellites send large volumes of data collected by EO technology to Earth through communications systems. This requires fast and reliable communication systems. The development of advanced data transmission technologies is becoming important to ensure effective information exchange.

Satellite communication systems for EO have specific requirements because their tasks include transmitting and receiving large amounts of real-time data from satellites surveying the Earth's surface. The main requirements for communication systems of EO satellites include:

– wide bandwidth: the system must have a wide enough bandwidth to transmit large volumes of data captured by Earth imaging satellites;

– low signal delay: for additional applications, such as navigation or natural disaster monitoring, low signal delay is important to ensure fast information exchange;

– high bandwidth: the system must have a large bandwidth to process a large flow of data in real time;

– resistance to interference: the satellite system must be resistant to various types of interference, such as atmospheric phenomena, electromagnetic distortions and other interferences;

– global coverage: the system must provide coverage of the entire surface of the Earth in order to have the availability of communication at any point;

– autonomy and reliability: the system must be autonomous and reliable, able to work without human intervention for a long time;

– energy efficiency: the system must be energy efficient, since satellites have limited energy resources;

– compatibility with communication standards: the satellite system must be compatible with communication standards, which ensures its integration with existing networks.

These requirements make it possible to ensure effective operation of EO satellite communication systems and high-quality data collection and transmission for further analysis and use. But there are many technical problems when using near-Earth space. However, the biggest problem is not only the high cost of manufacturing a spacecraft, but also its development and launch into orbit. These problems can be solved with the help of small spacecraft. Their production is cheaper, development takes less time and does not require a large team of specialists.

It is small satellites that have recently begun to play an important role in the EO process. Small satellites include spacecraft with a total mass of 100–500 kg.

In this work, the authors propose an original communication system that provides a high speed of information transmission, and which can be used on small EO satellites.

The object of study is satellite communication system.

The subject of the study is satellite communication system for EO.

The purpose of the work is research into the features of digital signal formation in modern satellite communication lines and the development of a communication system with a high data transfer rate (usually 300 Mbit/s), which can be applied to small EO satellites.

1 PROBLEM STATEMENT

It is known that there are several main ways to increase the speed of information transmission in the "satellite-Earth" line [10]. Ka-band bandwidth is many times the available bandwidth compared to X-band, so NASA is moving to Ka-band to increase radio communication speed.

However, the Ka-band has higher attenuation in the atmosphere and clouds, as well as heavy attenuation during rain. For Ka-band, there is limited availability of COTS components such as amplifiers, filters, and mixers compared to X-band [11–12].

Optical communication seems to be a more attractive option for small satellites due to the presence of practically unlimited bandwidth, enormous speed, and the absence of regulations regarding the operation of lasers in comparison with the radio spectrum, which is regulated by the FCC and ITU [13]. However, optical communication terminals are quite expensive, costing about 1 million dollars each. In addition, the availability of optical communication strongly depends on the presence of cloud cover.

The use of hardware or software that can be purchased from commercial suppliers without the need for special

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development or modification can significantly reduce the budget of a satellite project. The simultaneous use of several communication channels of the DVB-S2 standard [14] using COTS makes it possible to implement a high-speed data transmitter for small EO satellites.

The purpose of the work is to study the features of digital signal formation in modern satellite communication lines and to develop a communication system with a high data transfer rate (usually 300 Mbit/s), which can be applied to small EO satellites.

2 REVIEW OF THE LITERATURE

CCSDS develops standards for various aspects of space communication and data exchange. Here are some recommendations from the CCSDS that may be useful for organizing satellite communications in the context of EO:

– CCSDS Proximity-1 Space Data Link Protocol (CCSDS 211.0-B-3). This standard defines the protocols and services that can be used to exchange data between satellites and ground stations. It provides basic guidelines for the organization of communication [15].

– CCSDS Space Link Extension (CCSDS 232.2-B-1). This standard regulates the extension of the CCSDS protocol to ensure reliable and efficient communication in space. It can be useful for satellite systems that require high reliability [16].

– CCSDS Advanced Orbiting Systems (CCSDS 910.0-M-1). This standard provides guidance on data transmission, and command and control for orbiting satellites. It can be useful for organizing communications and managing satellites in EO systems [17].

– CCSDS File Delivery Protocol (CFDP) (CCSDS 727.0-B-4). This standard defines a protocol for efficient file transfer between different spacecraft. It can be used to transmit data collected by EO satellites to the ground station [18].

– CCSDS Mission Operations (CCSDS 911.0-M-1). This standard provides guidance and principles for mission operations, including mission planning, control, and execution, which may be important for EO satellite missions [19].

These CCSDS recommendations can be used as a basis for the development of satellite EO systems, simplifying the interaction between satellites and other elements of the communication system.

The document [20] contains recommendations on the use of the DVB-S2x standard for space systems. These CCSDS recommendations for the specific application of DVB-S2x for the transmission of information from the EO satellite suggest:

– for the transmission of high-speed EO images, such as high-resolution images, DVB-S2X can be used with QAM modulation with redundancy. This will allow you to achieve high data transfer rates and ensure high image quality;

– for transmission of low-speed data, such as weather and telemetry data, DVB-S2X can be used with amplitude modulation with redundancy. This will make it possible to achieve acceptable signal quality with a limited channel bandwidth.

It is important to note that choosing a specific application of DVB-S2X for transmitting information from EO satellite is a complex task that requires taking into account a number of factors, such as:

– the data transfer rate that is required for a specific space system;

– channel bandwidth that is available for a specific space system;

– reliability of data transmission, which is required for a specific space system.

To ensure high data transmission reliability, it is recommended to use error control protocols such as FEC. Technologies such as MIMO are recommended to ensure high channel bandwidth utilization. Technologies such as OFDM are recommended to ensure high immunity to interference.

Conventional large satellites are equipped with a downlink system that provides speeds of several hundred Mbps and consumes high DC power of 100–200 W, in some cases more. However, a small satellite can only generate a total power of about 100 W. A high-speed communication system requires about 40 watts for a 10-minute communication session. This limits the use of high data rate communication systems for small satellites.

Thus, a cost-effective approach to increasing the downlink data volume is to increase the downlink data rate to an earth station that has a short communication session with the satellite – about 10 minutes.

Most CubeSat satellite communication systems operate in the UHF, S-band, and X-band [11]. Higher speed commercial X-band radios are capable of speeds of around 50–100 Mbps. Satellites in larger form factors have higher X-band speeds, such as Planet’s Skysat satellites with a downlink speed of 480 Mbps and Japan’s Hodoshi 4 satellite, which demonstrated an uplink speed of 505 Mbps.

In February 2015, the University of Tokyo published a “record 348 Mbit/s microsatellite downlink event” in a press release [21]. At the ISAS Sagamihara campus, the 3.8-meter ground station antenna received 348 Mbps data from the Hodoyoshi-4 microsatellite with 16 QAM modulation and successfully demodulated/decoded it without errors. This communication rate is half that of ALOS-2/Daichi-2, a Japanese Earth observation satellite weighing about 2 tons. This result indicates that the data transmission capabilities of a small satellite are approaching those of a large satellite.

Digital Globe’s WorldView-2 and Worldview-3 satellites operate at 800 Mbps and 800/1200 Mbps respectively but have a much larger form factor and weigh over 2500 kilograms [22]. The data collected by each satellite’s on-board camera is processed, stored, and transmitted together with basic telemetry data in the 8025–8400 MHz band (X-band) to the corresponding ground stations. For TT&C functions, the satellites will receive command communications over the primary uplink using the band

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2025–2110 MHz (S-band) which is permitted in the EESS subject to the following conditions.

It is known that the available bandwidth of Ka-band is many times higher than that of X-band. Therefore, NASA is switching to the Ka-band to increase the speed of radio communication. However, the Ka-band has higher attenuation in the atmosphere and clouds, as well as heavy attenuation in rain. For Ka-band devices, there is limited availability of COTS components such as amplifiers, filters, and mixers compared to X-band.

The NASA-sponsored ISARA mission successfully demonstrated the capability of CubeSat communication in the Ka-band at a speed of 100 Mbit/s [23]. This technology uses an antenna that is made in the form of a reflective grid, which is integrated into a modified "Turkey Tail" solar cell that covers the hull of the spacecraft (almost zero volume is required for its placement). Such an antenna has a high gain – 33 dBi. The mass of the ISARA antenna is 0.5 kg and meets the requirements of a 3U spacecraft. This system has demonstrated the ability to transmit data downlink at 100 Mbit/s using a relatively simple ground station with a 70 cm parabolic reflector antenna, enabled by the spacecraft's ability to precisely point the antenna at the ground station. The most productive commercial Ka-band radio that was used in flight demonstrated a data rate of only 320 Mbit/s on a 6U CubeSat [23]. This station has the following parameters:

– DC power consumption is 20 W;
– the central frequency is 26.8 GHz;
– radio frequency output power – 27 dBm;
– built-in horn antenna with a gain of 23 dBi;
– variable data transfer rate: from 35.3 Mbps to 320.6 Mbps.

Optical communication seems to be an attractive option for small satellites due to the availability of practically unlimited bandwidth, enormous speed and the absence of laser regulations compared to the radio spectrum regulated by the FCC and ITU [24].

In low Earth orbit, the OCSD mission addresses two major capabilities of value to many future small spacecraft missions: high-speed optical data transmission and small spacecraft rendezvous operations [25]. The OCSD project develops and uses technologies consisting of a low-power laser communication system, proximity sensors and a compact power plant. The second two-satellite OCSD mission was launched on November 12, 2017, as part of the Cygnus (OA-8) resupply mission. Modified with lessons learned from the first mission, the two satellites entered the operational phase of the mission in April to demonstrate the world's first high-speed laser link between a CubeSat and a ground station. This showed the possibility of organizing optical communication. To date, OCSD has successfully demonstrated optical communication at 200 megabits per second using a ground-based 30 cm telescope.

The AMS Beacon payload was integrated into the Agile Microsat (AMS) 6U platform built by MIT Lincoln Laboratory to function as a space-based point source for high-speed adaptive optics control [26]. In addition to the built-in 500 mW laser, this platform is equipped with a reflector and a photodiode with a readout frequency of 1 kHz. The system was successfully launched in May 2022 into low Earth orbit.

However, optical communication terminals are expensive, the availability of optical communication strongly depends on cloud coverage. Considering that about 70% of the Earth's territory is covered by clouds every day, several terrestrial optical terminals are needed to ensure timely data transmission. However, the process of licensing the radio frequency spectrum is a difficult bureaucratic procedure, which may encourage the transition to the optical spectrum.

The Planet company has achieved good results in the development of HSD2 X-band radio communication [27]. Planet's HSD2 is a compact, lightweight and low-power next-generation radio that was built and deployed on a 3U CubeSat in December 2018. This system operates in the X-band and is built using COTS parts. It has a dual-polarized antenna. Two physical channels represent two polarization modes: RHCP and LHCP, and each physical channel uses a common bandwidth of 300 MHz. Within each physical channel are three logical channels located between 100 MHz frequency centers. The DVB-S2 commercial digital television broadcasting standard is used for modulation and coding. The ACM scheme is used to dynamically change the modulation and coding for each channel separately based on the available channel set [28].

Currently, the main systems operating high-speed "satellite-Earth" channels are EO systems and satellites-aggregators of information flows from third-party small satellites. The transmission of high-resolution photographs, as well as the ability to receive information by a limited number of ground stations, lead to requests to increase the speed of the space-to-ground channel by more than 1 Gbps in the X- or Ka-band. Currently, the speed of information transmission over X-band radio lines is 300 Mbit/s. The speed of data transmission while maintaining the necessary probability of an error per bit can be increased by increasing the energy of the radio line or by building the receiving and transmitting equipment with better characteristics, which include the quality factor of the receiving system, which depends on the noise temperature, the gain of the antenna, losses that related to antenna guidance, distribution in the antenna-feeder path, signal processing in the modem. According to the recommendation [29], the following modulation methods are proposed in the X-band: phase modulation without GMSK phase break with the break-in filter parameter $\alpha = 0.25$; four-position OQPSK phase modulation with quadrature shift; modulation using 4D-8PSK-TCM convolutional code. Due to the spectral efficiency of no more than 2 bits/(s·Hz) in the selected frequency band (X-band), OQPSK modulation does not reach 1 Gbps even without interference-free coding. Due to the spectral efficiency of no more than 2 bits/(s·Hz) in the selected frequency band (X-band), OQPSK modulation does not reach 1 Gbps even without interference-free coding.

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In addition to phase modulations, it is possible to use amplitude-phase methods, such as the DVB-S2 standard [29], which make it possible to achieve a spectral efficiency of up to 4.45 bits/(c·Hz) and a ratio of E_b/N_0 for BER = from 10^{-7} to 15.90dB.

To achieve a bit rate of R = 2000 Mbit/s with a bandwidth of no more than 375 MHz in the X-band, the spectral efficiency of the used signal code scheme is at least 5.33 bit/s·Hz in relation to the final bandwidth of the radio signal. Modulation types widely used in advanced foreign samples do not meet these requirements, and higher-order modulations, such as 64QAM or 64APSK, are unacceptable due to a significant range of variations in the amplitude of the complex envelope. Therefore, it is necessary to switch to the Ka-band due to the much greater availability of this frequency range.

An increase in the speed of information transmission is possible due to adaptive modems, in which the speed of information transmission is adaptively increased when the communication range is reduced during the flight of the satellite. When the spacecraft moves from the edge of the horizon to the zenith, the communication range can change from the maximum value d to the value of the height of the orbit H at the zenith, which will lead to an increase in the energy potential due to a decrease in signal losses during its propagation and a decrease in the noise temperature of the receiving system. This feature can be used to increase the speed of information transfer.

Ensuring high data transfer rates can be realized due to the redistribution of the spectrum considering the capabilities of SDR technology, which involves replacing some of the analog components, such as mixers, filters, amplifiers, detectors, with digital processing. With the help of this technology, the received useful signal is fed directly to the ADC or a pre-amplifier located before the ADC. To implement systems based on SDR technology, it is possible to use PLD technology, which allows creating systems on a crystal with many complex digital blocks. The data transmission speed of SDR systems is determined by the capabilities of analog-to-digital and digital-to-analog conversion schemes, as well as the speed of operation of digital units.

For the development and manufacture of faster devices, it is possible to use foreign manufacturers of microcircuits, such as UMC, TSMC or IHP. TSMC provides the ability to manufacture chips with design standards down to 40nm, a transistor cutoff frequency of ≈ 400GHz, UMC up to 65nm, and a transistor cutoff frequency of ≈ 360GHz. Designing mixed-signal circuits (ADC/DAC) using these technologies is a challenge, as process standards fall below 100 nm, transistors have very low intrinsic gain, which can lead to low effective ADC/DAC bitrates.

Bandwidth and quality of information transmission can be increased in the case of using MIMO technology, which includes the presence of a certain number of M_t and M_r. The high-speed data stream is divided into Mt independent sequences at a rate of $1/M_t$, which are then transmitted simultaneously from several antennas, respectively, using only $1/M_t$ of their primary frequency band. The data flow converter at the transmitting end of the communication line converts a serial flow into a parallel one and performs the reverse conversion at the receiving end [30]. Implementation of spatio-temporal distribution of signals in MIMO systems allows to increase the bandwidth of communication lines due to the formation of physically different channels. The application of MIMO technology in terrestrial wireless communication systems makes it the most promising for the creation of new high-speed wireless systems. Therefore, the question arises of choosing the type of MIMO technology that can be most rationally used in satellite communication systems that differ from terrestrial systems in terms of coverage area, communication channel topology, propagation delay, and the level of interference in the communication channel. Based on the features of satellite communication, the most promising options for using MIMO systems can be:

– single user transmission scheme using one or two satellites;

– multi-user transmission scheme using one satellite.

The space limitation in a single-satellite system can be negligible when using multiple satellites in single-user communication systems, the so-called orbital diversity. The main disadvantages of orbital separation are the inefficient use of the satellite bandwidth for transmitting the same signal, as well as the need to synchronize transmissions from two independent satellites [30].

3 MATERIALS AND METHODS

In the course of the work, an X-band HDT was developed. The transmitter is designed to transmit data from the EO systems to the ground receiving station. The proposed transmitter scheme is based on the industry standard DVB-S2 modulation scheme. However, to reduce costs in this scheme, COTS modulators and demodulators are used. The structural diagram of the HDT is shown in Fig. 1.

The main features of the developed HDT are as follows:

1. The use of a high-speed DAC allows you to implement the entire path of high-frequency modulation in the digital domain. The analog modulation tract is traditionally implemented with discrete components and is difficult to optimize.

2. Parallel use of several DVB-S2 modulators, the outputs of which are divided by frequency and polarization within the permissible bandwidth using RF-DAC. This allows the use of inexpensive COTS demodulators at ground stations. A demodulator for a high data rate Earth observation mission is a very expensive component. In the case of using the 6-channel version, the price of demodulators becomes very high. Whereas standard DVB-S2 COTS demodulators are available at low cost.

3. Using DVB-S2 as a modulation scheme. In the proposed scheme, DVB-S2 was designed in such a way to use any excess of the communication channel by increasing the data throughput. The ability to change the code rate and modulation scheme in real time when the quality

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of communication changes allows the DVB-S2 channel to maximize data throughput.

Two physical communication channels implement two polarization modes: RHCP and LHCP, and each physical channel uses a common bandwidth of 300 MHz. Inside each physical channel there are three logical channels, located at 100 MHz from each other between frequency centers. The symbol frequency of a separate channel is 76.8 Msec/s.

Each physical channel has an output RF power of 1 W and is connected to an antenna with a gain of 15 dBi.

Field Programmable Gate Array (FPGA) is widely used in satellite communication [31]. In the developed HDT, an FPGA (Enclustra Mercury XU8) multiplexes the input data into six DVB-S2 cores that modulate and provide FEC. Data packets are encapsulated into DVB-S2 baseband frames with a data transfer rate of 76.8 Msec/s, shifted in frequency, combined into two physical channels, and converted to an analog baseband signal using a high-speed DAC. Two independent superheterodyne transmitters are used to convert baseband signals to X-band signals.

The input data is encoded through several DVB-S2 modulators/encoders. Parallel channels fed to RF-DAC (via high-speed digital interface). RF-DAC mixes different channels to different intermediate frequency (using fully digital control and mixers). Channels are added and fed to two high-speed DACs. The DAC typically outputs the modulated and combined channels at the S-band IF. All the processing done by the RF-DAC (other than the actual DAC output) is done digitally. The IF signals are converted to X-band and amplified by two power amplifiers. The two outputs of the amplifier can be used to forward the signal to the antenna(s) with left and right circular polarization. The earth station receives the radio frequency signal, separates the two polarizations, and transmits the result to the DVB-S2 demodulators, which demodulate the incoming data streams. Data streams are combined to create an output data stream.

During the entire pass, DVB-S2 modulators receive a MODCOD command to ensure the maximum bandwidth of the data channel within the given communication field.

Let's consider in detail the functional architecture of HDT. Fig. 2 shows the physical blocks (PCBs / modules), as well as the interfaces of the external and internal connectors of the HDT scheme.

The power board basically contains the DC-to-DC converter that is required to operate the HDT from the 28V bus. The regulator provides galvanic isolation and provides a fixed 12 V (or 15 V) output from which all internal voltages come. The Power Board also serves as a plinth for the digital board that provides the standard Cubesat form factor. The interface between the two boards is carried out through a standard PC104 connector.

The digital board contains an FPGA module (Enclustra Mercury XU8) and two RF-DACs. The digital card also contains high-speed data transfer interfaces in the form of two GTX links. By default, this interface type uses two SMP connectors per channel. An Enclustra Mercury XU8 digital board and two RF-DACs are connected via the JESD204b interface. Both FPGAs and RF-DACs require an external heatsink to dissipate heat.

The HDT is implemented on the Xilinx® Zynq UltraScale+™ MPSoC FPGA, which is a high-performance system-on-chip device developed by Xilinx. This device combines a programmable logic matrix and ARM Cortex-A53 and Cortex-R5 processor cores, as well as several built-in functions and interfaces. The FPGA is located on the Enclustra Mercury XU8 module (Fig. 3). This is done to save time, cost, and design complexity, as it means that the auxiliary circuitry (SDRAM, flash memory, power supplies, etc.) requires no design effort. The main role of the FPGA is to package the input data stream of the GTx interface into DVB-S2 frames, which are converted into I and Q channels. The values of I and Q are then transmitted to the RF-DAC via the JESD204B interface.

The digital board contains an FPGA module (Enclustra Mercury XU5), as well as an RFDAC and an upconverter of the RFDAC output to S-band. This is done for this board to contain everything needed for use in a CubeSat (that is, it meets the needs of CubeCom). The board form factor is the standard CubeSat form factor. The board contains all the local regulators to allow it to operate from the voltage normally present in the Cubesat (as well as the intermediate voltage provided by the Power Board). The digital board also contains high-speed data transfer interfaces in the form of two GTX channels. By default, two SMP connectors per communication channel are used for this type of interface. The digital board has a heatsink that will cover its top and bottom parts. Both FPGAs and RFDACs need some way to dissipate heat. The transmitter is controlled via the CAN interface.

Consider a digital-to-analog converter. The HDT circuit uses a low-power AD9174 multi-channel dual DAC, which reduces power consumption in high-bandwidth and multi-channel applications while maintaining the required performance. The AD9174 is known to be a high-performance dual 16-bit DAC that supports DAC sampling rates up to 12.6 GSPS (Fig. 4). This device features an 8-lane 15.4Gbps JESD204B data input port, a high-performance on-chip DAC, and digital signal processing capabilities designed for single-band and multi-band direct-to-RF wireless applications.

The AD9174 has three integrated data input channels per RF DAC data channel. Each input channel is fully bypassed. Each data input channel (or channelizer) contains a configurable gain stage, an interpolation filter, and a numerically controlled channel oscillator for flexible multi-band frequency planning. The AD9174 supports input data rates up to 3.08 GSPS complex (in-phase/quadrans (I/Q)) or up to 6.16 GSPS non-complex (real) and can distribute multiple complex input data streams to dedicated channels for individual processing. Each group of three channelizers is summed into a corresponding main data path for additional processing when needed. Each main data channel contains an interpolation filter and one 48-bit main NCO before the RF DAC core.

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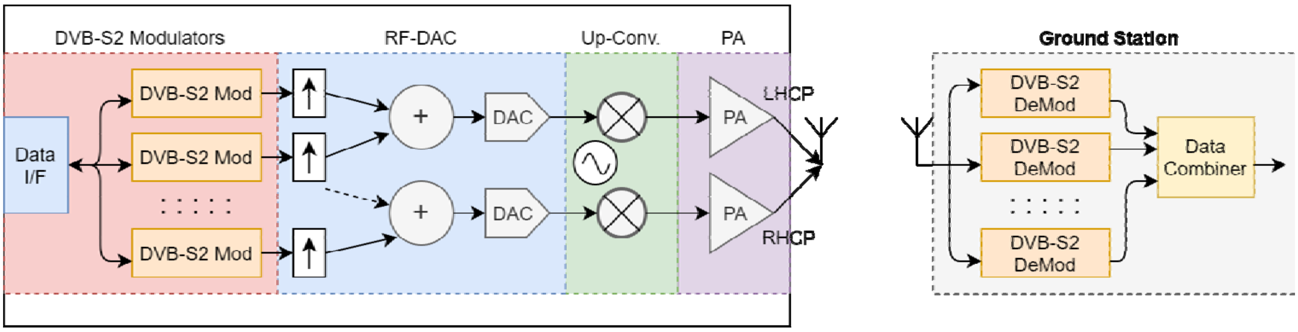

Figure 1 – Structural diagram of the proposed HDT

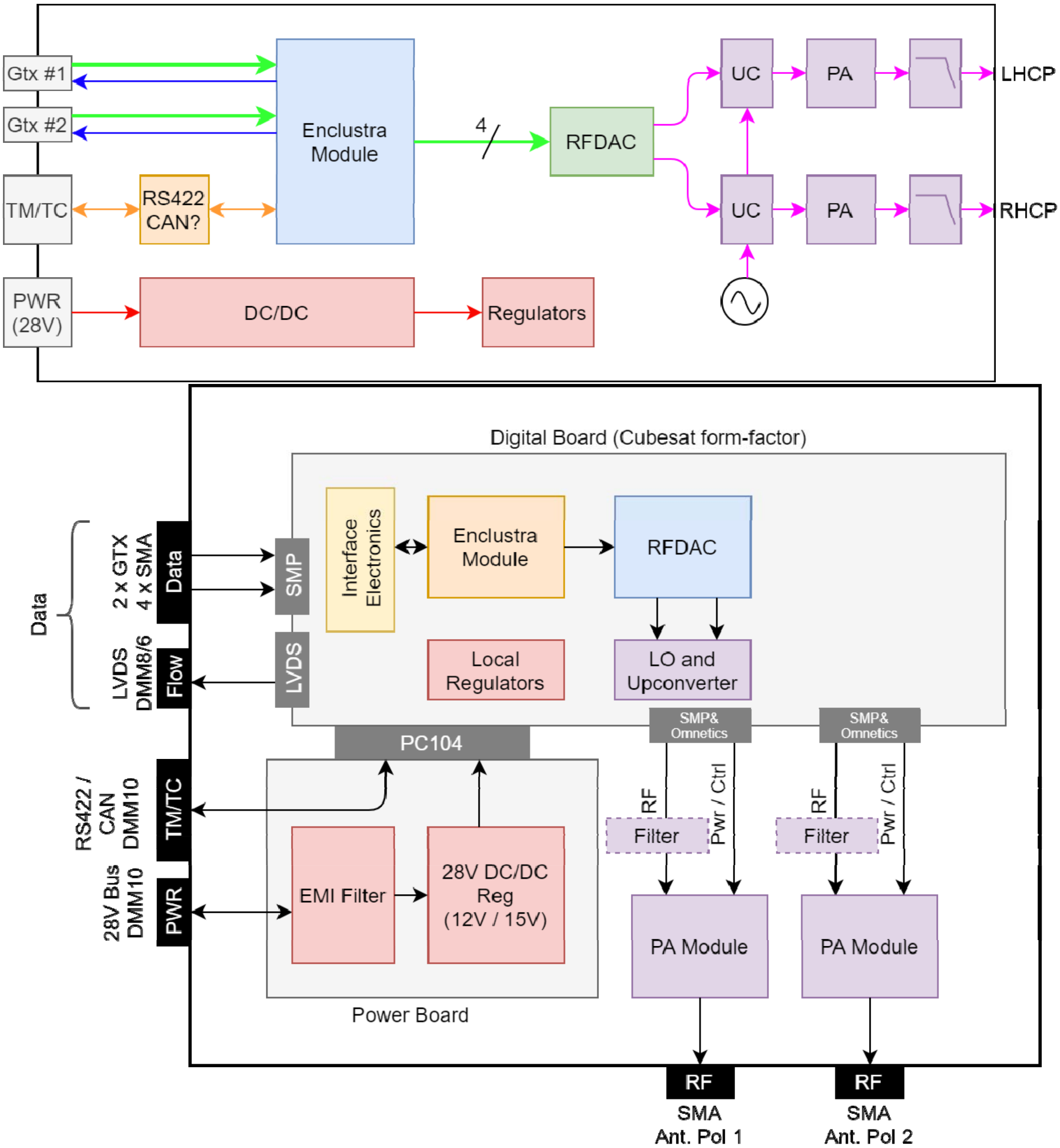

Figure 2 – HDT functional diagram

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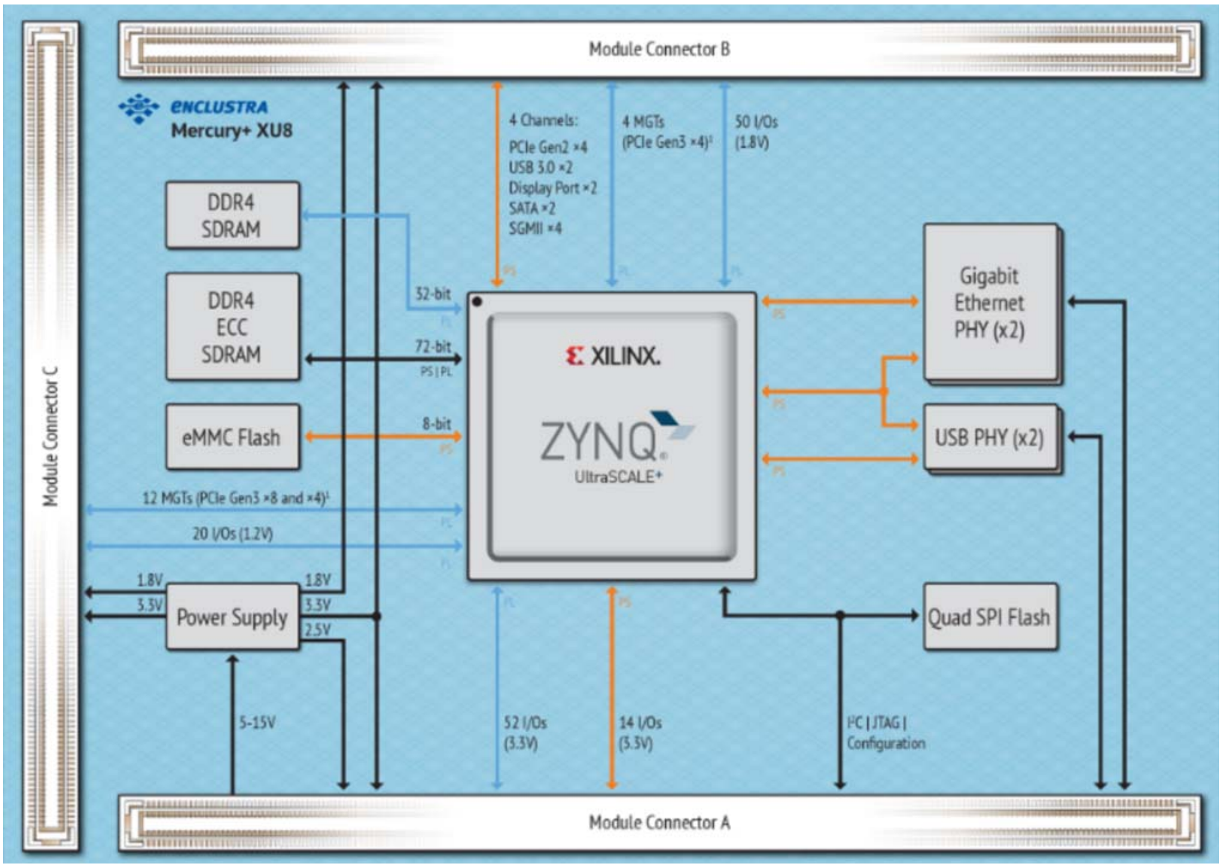

Figure 3 – Block diagram of the Enclustra Mercury XU8 module

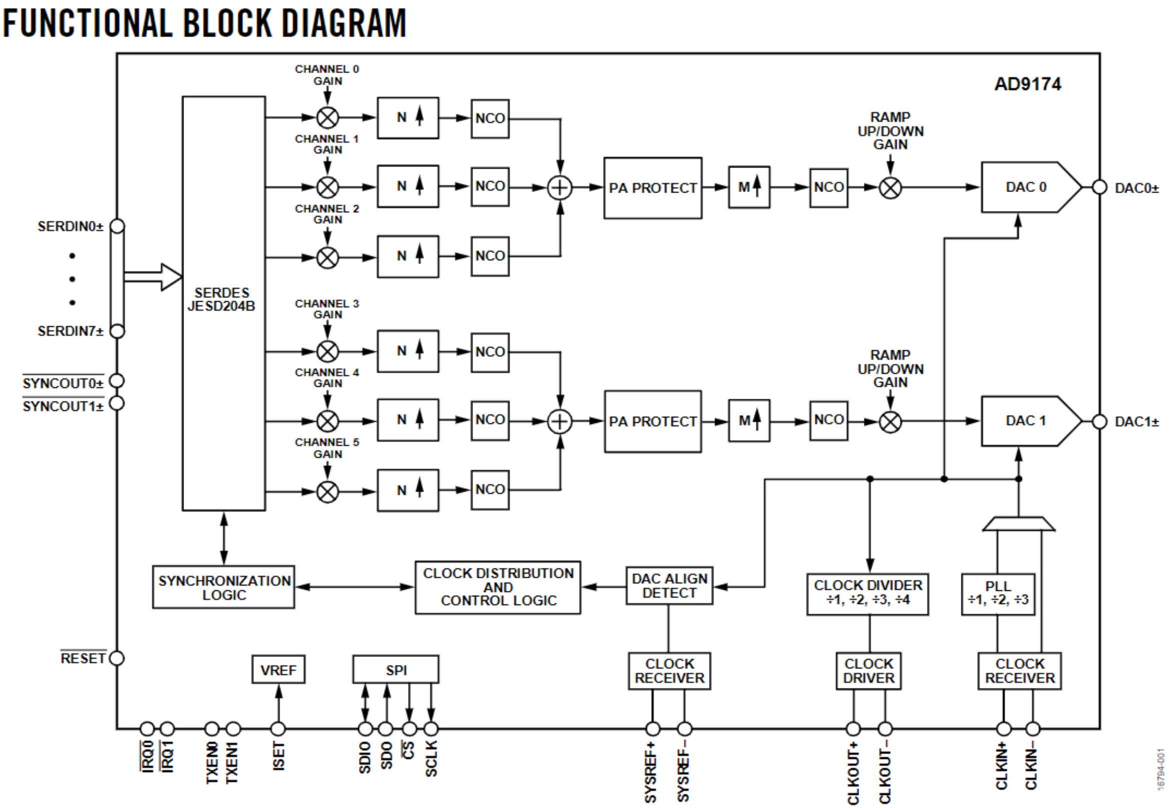

Figure 4 – Functional diagram of AD9174

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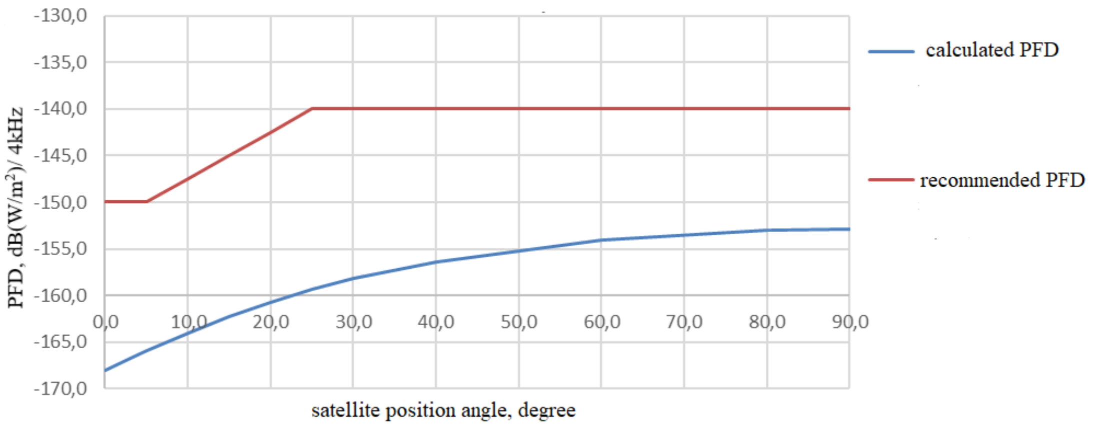

Figure 5 – Dependence of the PFD depending on the angle of the satellite site for the nominal height of the orbit of 400 km, with a transmitter power of 1 W

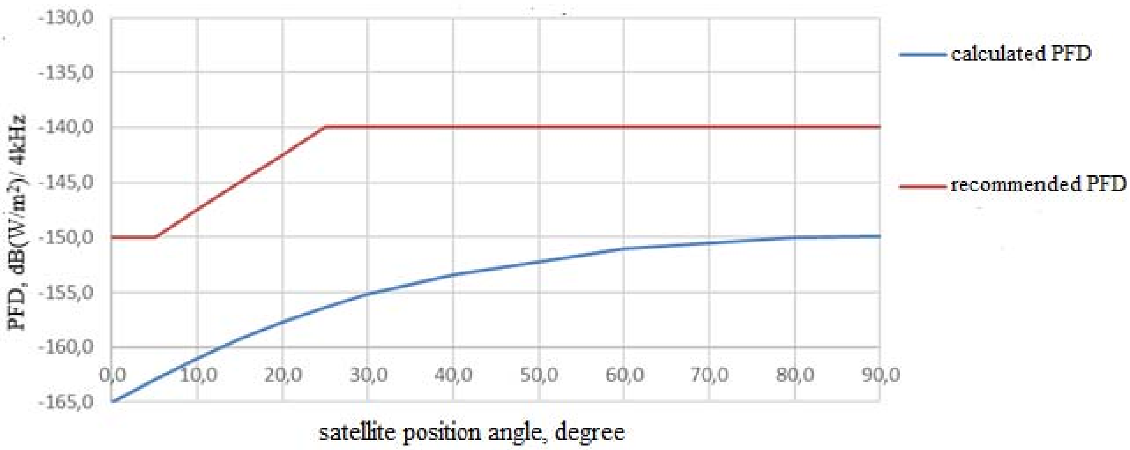

Figure 6 – Dependence of the PFD depending on the angle of the satellite site for the nominal height of the orbit of 400 km, with a transmitter power of 2 W

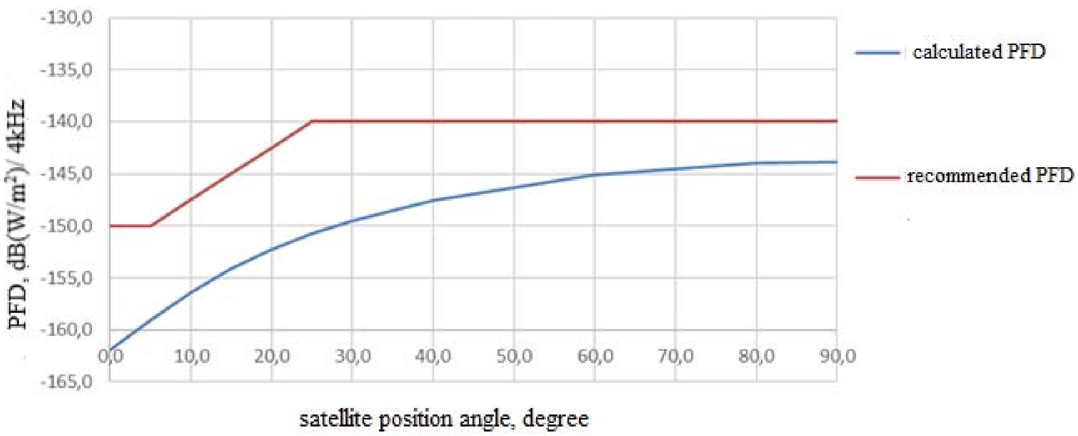

Figure 7 – Dependence of the PFD depending on the angle of the satellite site for the nominal height of the orbit of 200 km, with a transmitter power of 2 W

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With a modulator switch, the main data path outputs can be routed to DAC0 alone for single DAC operation, or to both DAC0 and DAC1 for dual IF DAC operation.

The AD9174 also supports Ultra High Data Rate modes, which bypass the channel switch and primary data paths to provide maximum data rates of up to 6.16 GSPS as a single 16-bit DAC, up to 3.08 GSPS as a dual 16-bit DAC. Additionally, the main NCO blocks in the AD9174 contain a bank of 31 32-bit NCOs, each with an independent phase accumulator. Combined with an 80MHz serial peripheral interface for NCO programming, this bank provides phase coherent fast FFH for applications where NCO frequencies are continuously adjustable during operation.

Consider a power amplifier. Two separate PA modules are used to operate the LHCP and RHCP antennas. They consist of an S-band to X-band up-converter and a power amplifier. There are two more separate PAs. They are placed separately and have good thermal contact with the chassis/body. PA modules connect to the digital board via radio frequency communication (using the SMP connector) and the power and control channel (using the Omnetics connector). This is the internal interface. Note that it may be necessary to add additional filters in the RF lines to ensure compliance with ITU standards. Power amplifier modules have a radio frequency output (in the form of an SMA connector). PA modules are connected to the digital board through a radio frequency channel and a power and control channel.

4 EXPERIMENTS

As part of this study, experiments were carried out with a high-speed downlink with 16 QAM: 100 Mbit/s for 237 Mbit/s (ACM13) and 348 Mbit/s (ACM17). During the experiment, an MGA antenna (horn antenna with an average gain of 13.5 dBi, a beam width of 20º) was used to ensure communication. The performance of the proposed system was shown.

In the course of this work, experiments were carried out with the transmission of high-speed data on the downlink, when the satellite passed at an elevation angle of >70º in the Earth orientation mode. In this state, the earth station was within half the beam width of the on-board antenna. The transmitter retransmitted fixed known data (PN code). The received signals were demodulated and decoded by a software receiver. The calculated C/N_o ratio obtained based on the adopted IF spectrum was about 9.6 dB/Hz at the ground antenna elevation angle of 84.5º and the tilt range of 622 km. The measured bit error rate was $1.2\ 10^{-3}$ without error correction. After the turbo decoding process, the measured bit error rate was less than $1.7\ 10^{-9}$.

The dependence of the power flux density at the input of the receiving antenna of the earth station, depending on the angle of the satellite at the receiving point, was investigated. A comparison of the calculated PFD for the proposed communication system and the recommended PFD according to the ITU Radio Regulations was made. Calculations were carried out in the Excel program, considering the typical values of the parameters of the satellite-Earth radio link.

5 RESULTS

In Fig. 5 shows the dependence of the maximum PFD in the 4 kHz band near the Earth's surface depending on the satellite's elevation angle for a nominal orbit height of 400 km, with a transmitter power of 1 W. The blue curve shows the estimated PFD for the developed EO satellite communication system. The red curve corresponds to the recommendations of the ITU Radio Regulations.

In Fig. 6 shows the dependence of the maximum PFD in the 4 kHz band near the Earth's surface depending on the satellite's elevation angle for a nominal orbit height of 400 km, with a transmitter power of 2 W.

In Fig. 7 shows the dependence of the maximum PFD in the 4 kHz band near the Earth's surface depending on the satellite's elevation angle for a nominal orbit height of 200 km, with a transmitter power of 2 W.

6 DISCUSSION

It is known that the ITU Radio Regulations impose a limit on the power flux density on the surface of the Earth for a signal coming from a satellite.

On the other hand, satellite communication systems must ensure very high reliability of reception of transmitted messages. Therefore, the use of multi-level modulation signals ensures high reliability of reception. In addition, reliability can be ensured by increasing the level of the signal arriving at the receiver input, that is, due to the use of sufficiently powerful transmitters, as well as due to receiving and transmitting antennas with a high gain, or due to the use of complex FEC coding.

It should be noted that section 25.208 of the Commission's regulations does not contain limits on the power flux density on the Earth's surface, which is generated by the radiation of NGSO EESS space stations operating in the 8025–8400 MHz range.

However, Table 21–4 of the ITU Radio Regulations states that for Earth Exploration Satellite Service (Space-Earth) and Space Exploration Service (Space-Earth) PFDs on the surface of the Earth generated by EESS space station emissions in the range 8025–8400 MHz , should not exceed the following values:

- 150 dB (W/m²) in any range of 4 kHz for angles of incidence from 0 to 5 degrees above the horizontal plane;
- – 150 + 0.5 (d^{-5}) dB (W/m²) in any range of 4 kHz for angles of incidence d (in degrees) from 5 to 25 degrees above the horizontal plane;
- – 140 dB (W/m²) in any 4 kHz range for incidence angles from 25 to 90 degrees above the horizontal plane.

These PFD limitations can be compared with the calculated PFD that can be obtained considering the standard conditions of electromagnetic wave propagation in free space, considering the typical losses in the transmission path (filters, power cables, splitters) of the proposed HDT.

From Fig. 5 – 7 the PFD on the surface of the Earth, which is generated by the X-band transmitter, in all

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modes of operation and at satellite altitudes of 200 and 400 km corresponds to the PFD limits of the ITU Radio Regulations for all angles of arrival at a transmitter power of up to 2 W.

CONCLUSIONS

The paper considers the concept of building a high-speed data transmitter using COTS technology and implements a communication system scheme based on the DVB-S standard using COTS. The analysis of the main features of the digital signal formation in the DVB-S standard and the improved DVB-S2X standard was carried out. It was established that even with the use of the DVB-S2X standard, it is impossible to fully reach the Shannon limit.

HDT is implemented on a Xilinx® Zynq Ultrascale+™ MPSoC FPGA, which sits on an Enclustra Mercury XU8 module with a high-performance dual 16-bit AD9174 DAC. It is shown that the function of adaptive modeling of ACM of the DVB-S standard proposed for the communication system allows automatic changes of transmission parameters in real time depending on the changing conditions of the channel. This provides an opportunity for more flexible and effective data transmission in various conditions, which allows to increase the amount of information transmitted during a communication session.

Performed calculations of the power flow density at the receiving location on Earth to find out the possible power of the on-board transmitter. An on-board transmitter of up to 2 W has been shown to meet the requirements of the ITU Radio Regulations for PFDs on the Earth’s surface generated by EESS space station radiation in the 8025–8400 MHz range.

The scientific novelty of the obtained results lies in the fact that for the first time a scheme of a communication system based on the DVB-S standard using COTS, which can be applied to small EO satellites, is proposed.

The practical significance of the obtained results lies in the fact that an original scheme for building a high-speed data transmitter using COTS technology for small EO satellites has been developed. Formulated recommendations for improving the operation of the satellite communication system. It is shown that the use of the ACM adaptive modeling function of the DVB-S standard allows you to automatically change the transmission parameters in real time depending on the changing conditions of the channel. The obtained results can be applied in the construction of small EO satellites.

Prospects for further research are the study of OCSD systems for EO needs

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ДОСЛІДЖЕННЯ ОСОБЛИВОСТЕЙ ФОРМУВАННЯ ЦИФРОВОГО СИГНАЛУ В СУПУТНИКОВИХ ЛІНІЯХ ЗВ'ЯЗКУ

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АНОТАЦІЯ

Актуальність. Дистанційне зондування Землі нині знаходить широке застосування в різних галузях. Однією із проблем дистанційного зондування є створення недорогих супутникових систем, що працюють на полярних кругових орбітах. Дані системи потребують розробки прийомо-передавальної системи, що дозволяє передавати десятки гігабіт відеоінформації на земну приймальну станцію протягом десятка хвилин. Тобто існує потреба у створенні системи зв'язку що забезпечує високу швидкість передачі даних з малих супутників, вагою до 50 кг.

Мета. Метою роботи є дослідження особливостей формування цифрового сигналу в сучасних супутникових лініях зв'язку та розробка системи зв'язку з високою швидкістю передачі даних (зазвичай 300 Мбіт/с), яка може бути застосована до малих супутників дистанційного зондування Землі.

Метод. Запропонована концепція побудови високошвидкісного передавача даних із супутника дистанційного зондування землі із використанням технології комерційно готових або комерційно доступних готових продуктів. Виконані розрахунки щільності потоку потужності для з'ясування можливої потужності бортового передавача. Виконані розрахунки бюджету радіолінії супутник-Земля із застосуванням передбачених режимів команд на зміни кодування та модуляції.

Результати. Розроблена схема системи зв'язку на основі стандарту DVB-S з використанням технології комерційно готових продуктів. Високошвидкісний передавач даних реалізовано на FPGA Xilinx® Zynq Ultrascale+ ™ MPSoC, який розташований на модулі Enclustra Mercury XU8 з високопродуктивним подвійний 16-розрядним DAC AD9174. Бортовий передавач потужністю до 2 Вт задовольняє вимогам Регламенту радіозв'язку ITU до щільності потоку потужності на поверхні Землі, який створюється випромінюванням космічної станції EESS у діапазоні 8025–8400 МГц. Показано, що енергетичний запас лінії зв'язку в 3 дБ досягається для різних команд на зміни кодування та модуляції при збільшенні кута місця, що дозволяє збільшувати швидкості передачі інформації.

Висновки. Розроблена оригінальна прийомо-передавальна система для застосування в малих супутниках дистанційного зондування землі. Показано, що саме функція адаптивного моделювання ACM стандарту DVB-S дозволяє автоматично змінювати параметри передачі в реальному часі в залежності від змінюваних умов каналу, надаючи можливості більш гнучкої і

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ефективної передачі даних у різних умовах, що дозволить збільшити об'єми інформації, які передаються за сеанс зв'язку. Запропонована система працює в X-діапазоні і побудована з використанням деталей COTS. У якості випромінювачів використовуються антенами с двійною поляризацією. Два фізичні канали представляють два режими поляризації: праву кругову поляризацію і ліву кругову поляризацію, кожна з яких має три частотні канали.

КЛЮЧОВІ СЛОВА: малий супутник, низька земна орбіта, дистанційне зондування Землі, густина потоку потужності, X-діапазон, DVB-S.

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