UDC 519.25
DOI: 10.15587/2706-5448.2022.260346
Article type «Reports on Research Projects»

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ANALYSIS OF WAYS TO IMPROVE THE EFFICIENCY OF MODERN SATELLITE COMMUNICATION SYSTEMS

Nowadays, the satellite segment in telecommunications occupies an important place and provides positioning of the global coverage system. However, the development of satellite technologies, compared to terrestrial wireless technologies, is slow. For example, the new DVB-S2 (Digital Video Broadcasting via Satellite) satellite standard contains a small number of improvements and refinements over the previous DVB-S standard. The main improvements are the introduction of codes with low density of LDPC (Low Density Parity Check) and the introduction of adaptive modulation and coding. Given the above, the object of research is modern satellite communication system. The subject of the research is the way to increase the efficiency of modern satellite communication systems. The research aims to analyze the feasibility of using a number of effective technologies in modern wireless systems, such as OFDM, UWB and MIMO, in satellite communication systems. The implementation of the considered options for the use of MIMO technology in satellite communication systems will increase the bandwidth and efficiency of these systems. However, there is a need for additional research to adapt this technology in satellite communication systems. Thus, the analysis allows forming the main directions of improving the efficiency of modern satellite communication systems. This analysis allows:

– to formulate new approaches to increase the efficiency of modern satellite communication systems;

– to substantiate new technological solutions for the construction of transceivers of satellite communication systems;

– to identify possible areas of research to improve the efficiency of modern satellite communication systems.

Keywords: *satellite communication systems, electronic environment, special purpose information and telecommunication system.*

Received date: 23.05.2022
Accepted date: 27.06.2022
Published date: 30.06.2022

How to cite

Trotsko, O. (2022). Analysis of ways to improve the efficiency of modern satellite communication systems. Technology Audit and Production Reserves, 3 (2 (65)), 51–56. doi: http://doi.org/10.15587/2706-5448.2022.260346

1. Introduction

Nowadays, the satellite segment in telecommunications occupies an important place and provides positioning of the global coverage system. However, the development of satellite technologies, compared to terrestrial wireless technologies, is slow. For example, the new DVB-S2 satellite broadcasting standard (Digital Video Broadcasting via Satellite) contains a small number of improvements and refinements over the previous DVB-S standard [1, 2]. The main improvements are the introduction of codes with low density of LDPC (Low Density Parity Check) and the introduction of adaptive modulation and coding. At the same time, quite radical changes are taking place in the field of terrestrial wireless technologies. The most important of them are the development and implementation of:

- Orthogonal Frequency Division Multiplexing (OFDM) technologies;
- systems using multiple inputs and multiple outputs (MIMO, Multiple Input – Multiple Output);
- ultra-wideband signals (UWB, Ultra Wideband) [3–5].

Obviously, satellite and terrestrial communication systems have their own characteristics and, accordingly, they are the subject to different requirements and restrictions. Therefore, not all technologies designed for terrestrial wireless systems can be applied to satellite communication systems (SCS). One of the main reasons for the difference in the intensity of development between satellite and terrestrial wireless communication technologies is the different level of reliability required for the deployment and operation of terrestrial and satellite systems. High cost, impossibility of modernization and repair of satellite systems lead to the fact that only well-studied and tested technologies are used to minimize risks. The existence of strict requirements for the standardization of space systems also limits the list of possible technologies. In addition, the resources of the satellite's on-board equipment (memory, degree of integration and power consumption, etc.) are severely limited. However, it should be noted that the parameters of the equipment located on the satellite, such as the number of computing and energy resources are much higher than those of the terrestrial mobile terminal. Thus, the availability of a large number of resources potentially allows the satellite system to use a much wider range of technologies [6–8].

Problems of introduction of separate technologies of terrestrial wireless communication in systems of satellite communication are considered in a number of publications [8–11]. There are no proposals for a systematic approach to the use of these technologies.

Thus, *the aim of the research* is to analyze the possibility of applying a number of effective technologies of modern wireless systems, such as OFDM, UWB and MIMO, in satellite communication systems. *The object of the research* is modern satellite communication systems. *The subject of the research* is the way to increase the efficiency of modern satellite communication systems.

2. Research methodology

In the course of the research, classical methods were used:

- method of analysis to solve the problem of analysis of conditions and factors influencing modern satellite communication systems;
- synthesis method to substantiate ways to increase the efficiency of modern satellite communication systems.

3. Results of research and discussion

Let's look at the main approaches for improving the efficiency of modern satellite communication systems. MIMO technology [11–14].

Bandwidth and quality of MIMO information transmission. In general, the structure of the MIMO system in wireless systems can be significantly increased through the use of technology that includes M_t transmitters (transmitting antennas) and M_r receivers (receiving antennas) [15–17].

The high-speed data stream is split into M_t independent sequences at $1/M_t$, which are then transmitted simultaneously from several antennas, respectively, using only $1/M_t$ of their primary frequency band [18–20].

The data flow converter at the transmitting end of the communication line converts the serial stream into parallel and at the receiving end it performs the inverse conversion [21–23].

To implement the spatio-temporal distribution of signals in MIMO systems, the set of outputs (radiating antennas) transmits several (in the general case – set) paths (rays) and this set of signals is received as a set of streams on several receiving antennas (spaced in space) [24–26].

MIMO radio devices provide:

- expansion of a covering zone by radio signals and smoothing dead zones in it;
- the use of several independent ways of signal propagation, which increases the probability of work on routes where the impact of fading is less;
- increase the bandwidth of communication lines by forming physically different channels.

The application of MIMO technology in terrestrial wireless communication systems makes it the most promising for building new high-speed wireless systems.

However, MIMO technologies include a whole family of technological areas, such as single-user, multi-user and distributed (virtual) MIMO. Therefore, there is a question of choosing the type of MIMO-technologies that can be most rationally used in satellite communication systems, which differ from terrestrial systems in the coverage area, topology of the communication channel, the magnitude of the propagation delay, the level of interference in the communication channel. Moreover, satellite systems are distinguished depending on:

- the frequency bands that are used (the most widely used frequency bands are given in Table 1);
- number of end-user groups (individual transmission, group transmission, broadcast);
- multiple division schemes (Time Division Multiplexing (TDM) with one carrier, OFDM with several carriers);
- type of applications (tolerant to delays, not tolerant to delays);
- fading reduction technologies (constant modulation and coding, adaptive modulation and coding), etc.

Based on the peculiarities of satellite communication, the most promising options for the use of MIMO systems in SCS can be:

- single-user transmission scheme using one or two satellites;
- multi-user transmission scheme using a single satellite.

The space limitation in a single-satellite system can be ignored while using multiple satellites in single-user communication systems, so-called orbital diversity. The main disadvantages of orbital diversity are the irrational use of satellite bandwidth to transmit the same signal, and the need to synchronize the transmission from two independent satellites.

Table 1

Frequency bands of satellite communication systems

Range designation	UHF	L	S	C	X	Ku	Ka
Frequency band, GHz	0.3–3	1–2	2–4	4–8	8–12	12–18	26–40

The use of a single-user MIMO for a line-of-sight channel with tropospheric fading is complicated by the limited size of the satellite and the inability to spread the antennas to the required distance or, while using two satellites, by the lack of synchronization and high system cost. However, a broadband interactive multibeam satellite system serves a large number of terminals using multiple beams. Moreover, there is a direct analogy between a direct multi-beam satellite channel and a broadcast channel of a multi-user MIMO system. This analogy avoids most of the disadvantages of a single-user satellite MIMO channel. Multi-user MIMO schemes allow the use of multi-user multiplexing, less susceptible to the presence of direct visibility or correlation of antennas, and allow to benefit from spatial multiplexing without the need to equip terrestrial terminals with multiple antennas. This is important from an economic point of view, as there is no need to modify standard receiving terminals.

Ultra-wideband satellite systems [26–28].

Ultra-wideband terrestrial signals are used to transmit information over a very wide frequency range without a license and without interfering with narrowband systems, and are generally considered to be short-range terrestrial communication systems. The reason for using ultra-wideband signals only in short-range communication systems is to limit the power emitted in order to minimize the impact on other communication systems [29–31].

Ultra-wideband signals are most often used in high-speed wireless personal area networks (WPANs) with a small coverage area (less than 10 m in radius). Another important area of application is distributed sensor networks or low-speed WPANs. However, key features of ultra-wideband systems can also be used in satellite communications. To do this, it is necessary to change the power limit for the introduction of ultra-wideband satellite communications. It does not require a license, or to transfer the operating frequency range to frequencies above the Ka band, where a wide portion of the band is available for allocation when licensed for use.

In a satellite system using ultra-wideband technology, if the power transmitted from the satellite to the ground is at the same level as for terrestrial ultra-wideband devices. In this case, the level of the signal received on the ground will be very low, which will not allow establishing a reliable connection. However, if the spectral power density of signals transmitted from ultra-wideband satellites to the earth's surface is higher than that of terrestrial ultra-wideband transmitters, this makes it possible to organize high-speed data transmission.

If to have a look on the use of ultra-wideband communications in satellite systems, the key task is to research the impact of interference on terrestrial systems. At the same time, it is necessary to solve other important tasks: the choice of the frequency range for ultra-wideband SCS, determining the impact of interference generated by such a system for other satellite systems.

The advantages of licensed ultra-wideband satellite systems are lower element base complexity and less sensitivity to radio signal distortion. In this regard, the main purpose of using ultra-wideband transmission is to increase the transmission rate in the channel and the bandwidth of the system in relation to standard transmission methods that require a more complex element base and are more sensitive to radio distortion.

Although the telecommunication technologies used in existing satellites are fairly standard, the elemental framework required for their implementation is quite complex.

One of the main features of satellite communication is the transmission of a high-power signal so that the power of the received signal on the ground is sufficient for proper reception. Therefore, one of the most important elements of the radio frequency transmission circuit is a power amplifier.

Despite the latest advances in solid-state microwave power amplifiers (PA), tube amplifiers, such as a running wave amplifier or klystron, still provide the best possible ratio of power output, efficiency and bandwidth. PA can be divided into two groups: DC amplifiers and pulse amplifiers. Pulse amplifiers output a high-power radio frequency signal for a short period of time with a duty cycle of 10 %.

DC amplifiers and pulse amplifiers can be used while working with ultra-wideband signals with a constant carrier and pulsed ultra-wideband signals, respectively.

While using pulsed ultra-wideband signals, pulses of very short duration (usually less than a nanosecond) are transmitted. Due to this, the signal spectrum occupies several GHz in the frequency domain. Pulsed ultra-wideband signals do not have a carrier, therefore, simple and cheap to implement, as they do not require mixers and local oscillators. On the other hand, their formation requires high-speed digital-to-analog and analog-to-digital converters for digital signal processing. While using pulsed ultra-wideband signals to organize multi-station access, it is possible to use hopping time switching or CDMA.

Ultra-wideband communication using carriers is carried out using traditional local oscillators and can be implemented as a single or multi-band version. Such communication systems have more spectrum control than pulse. An example of ultra-wideband carrier systems is the multiband OFDM (MB-OFDM) system, which uses PM/KAM OFDM modulation with abrupt frequency change. MB-OFDM is a simple construction technology that is implemented using fast Fourier transform. While using four-position phase manipulation (PM), it is possible to reduce the bit size of digital-to-analog and analog-to-digital converters, and by increasing the distance between subcarriers to reduce the requirements for phase noise, inherent in OFDM technology, and synchronization error.

In the bands above Ka, the transmission power will not be limited by the previously described limits on the radiated power, as this frequency range is practically not used. In fact, satellite communications in the bands above Ka are limited only by the capabilities of modern technologies (in particular, power generators of the input stages of transmitters). In the case of pulsed ultra-wideband signals, this problem can be solved using modern space technology associated with the W-band (75–110 GHz), such as satellite radar for researching CloudSat clouds.

Ultra-wideband transmission technologies are less exposed to radio frequency distortions, such as: nonlinearity of power amplifiers, phase noise, imbalance of I/Q components.

An example of the use of ultra-wideband technology in satellite communications is the method of ultra-wideband transmission with frequency modulation FM-UWB (Frequency Modulation Ultra WideBand). This method of ultra-wideband transmission with constant bending uses frequency manipulation with a low modulation index in conjunction with analog frequency modulation with a high index to expand the band. The advantage of this method is the simplicity of implementation and low sensitivity to the nonlinearity of power amplifiers.

The prospect of combining ultra-wideband signals with MIMO technology [30–32].

High-speed satellite communication systems can be built by combining MIMO technology and ultra-wideband signals. A promising area of further research is the development of ultra-wideband MIMO systems (UWB-MIMO) to achieve gigabit speeds not only in terrestrial but also in satellite systems.

Research papers on UWB-MIMO can be divided into three groups: measurement and modeling of the UWB-MIMO channel; channel bandwidth estimation and spatio-temporal coding; forming an antenna pattern.

Changing the angle of the antenna and the polarization of the signal can be used to reduce the correlation of spatial channels or to increase system performance.

The probability of loss of communication decreases with increasing number of transmitting antennas, provided that the transmission rate is less than a certain threshold value, and increases if the transmission rate is above the threshold. This threshold value is determined by the level of fading and the signal-to-noise ratio on the transmitting side. It follows that it is not necessary to use several transmitting antennas if the specific transmission speed is higher than the threshold value (or the available transmitter power is very low). The number of transmitting antennas, the number of receiving antennas and the number of degrees of freedom of the scattering medium impose fundamental restrictions on the bandwidth of the system. The number of degrees of freedom imposes a limit on the rank of the matrix of the UWB-MIMO channel, and, accordingly, affects the number of independent channels.

An important issue for UWB-MIMO systems is to research the behavior of channel bandwidth at low power or low signal-to-noise ratios, which is especially important for SCS. For broadband systems, a very wide frequency band has a negative effect on performance if the power in the system is evenly distributed over time and frequency. Also, the operation of ultra-wideband transmitters using the algorithm of uniform power distribution and the algorithm of optimal power distribution was researched. With optimal distribution, the «water filling» algorithm was used to distribute power both in the frequency domain and between the transmitting antennas according to the state of the multidimensional channel. Optimal power distribution is much more efficient when the signal-to-noise ratio is lower than 20 dB. However, when the signal-to-noise ratio is higher than 10 dB, the uniform distribution allows to obtain the same bandwidth in the channel.

For UWB-MIMO with space-time coding, a compromise was found between the available signal-to-noise ratio, the coding interval and the number of transmitting antennas. If the signal-to-noise ratio is high enough, it is possible to gain from the coding by distributing the radiated power over a larger number of antennas and using longer codes. In other words, if the available signal-to-noise ratio is very low, it is better to use fewer antennas and shorter space-time codes.

The scheme of adaptive radiation for ultra-wideband systems is proposed and it was shown that the bandwidth of the signal has almost no effect on the width of the radiated beam or on the direction of radiation. Ultra-wideband emitters, in contrast to narrowband, have some unusual properties. For example, the use of ultra-wideband beam diffusers for different antenna branches increases the level of the side lobes. Therefore, the optimal beam generator is one in which the weighing filters in each branch are identical.

In this area of research, the most likely area of application of multi-antenna ultra-wideband technology is distance determination and sounding. With the help of multi-antenna technology, it is possible to get additional spatial parameters (for example, the direction of arrival or the direction of sending), which can lead to higher accuracy in determining the distance. Thus, it is promising to research the capabilities of UWB-MIMO systems, especially in the direction of their practical application in SCS.

OFDM technology. Orthogonal Distribution Multiplexing (OFDM) is widely used in modern communication systems. The main advantages of this technology are high resistance to frequency-selective fading in the channel with less computational complexity compared to systems with a single carrier and high spectral efficiency.

OFDM is used at the physical level of most wireless standards used, such as, for example, IEEE 802.11/WiFi, IEEE 802.16/WiMAX and in terrestrial digital video broadcasting (DVB-T) [32]. Until recently, this transmission technology was considered unsuitable for use in satellite communications because the OFDM signal is characterized by a large peak factor. For this reason, OFDM signals are sensitive to nonlinear distortion of transmitter power amplifiers, which is one of the most important indicators while working with satellite systems. However, it has recently been shown that the use of special OFDM signal encoding algorithms in combination with the use of the nonlinear distortion compensation method can provide satisfactory performance, even at an amplifier operating mode close to saturation.

The use of OFDM in satellite communications is of interest for the following reasons:

- high spectral efficiency in the conditions of multi-beam propagation;
- the possibility of reducing the total load on the satellite receiver (regenerative architecture is considered);
- new channel splitting architecture using OFDM principles;
- while using a terrestrial and satellite hybrid communication system, in the terrestrial segment with OFDM, the use of the same technology for the satellite component can reduce the complexity of the receiver.

The latter reason was the main one for the use of OFDM in the DVB-SH standard, with the necessary modifications and improvements compared to DVB-H. DVB-SH is a broadcast standard for providing multimedia services over a hybrid terrestrial/satellite network for a variety of small mobile and fixed terminals with compact antennas and limited directionality (e. g. portable devices). OFDM has also been used in military communications. In particular, it is used as a physical layer of a broadband network of an integrated tactical radio communication system. OFDM was also considered in the research of the optimal interface for MILSATCOM networks.

In all cases, the only unsolved problem is the high ratio of peak power to average, and, accordingly, low energy efficiency. Peak reduction methods for terrestrial systems are widely studied and can be used in satellite communications. However, one of the newest solutions for the satellite segment is the modification of OFDM with constant envelope (CE-OFDM, Constant Envelope OFDM) [23]. In the CE-OFDM system, the OFDM signal is varied by phase modulation techniques so that it becomes suitable for effective power amplification. At the reception before the OFDM demodulator, the inverse transformation (phase demodulation) is used. With the help of phase modulation, a signal with a constant envelope is obtained, which has a ratio of peak power to average equal to 0 dB. The CE-OFDM system has a higher bandwidth compared to conventional OFDM systems in channels with multi-beam fading, given the effect of nonlinear power amplification. The positive qualities of multi-carrier communication systems can be realized with the help of single-carrier systems with a cyclic prefix with frequency domain equalization (FDE, Frequency Domain Equalization).

The LTE (Long Term Evolution) standard uses an OFDM-based multiple access scheme for downlink and FDMA (Frequency Division Multiple Access) interleaving. This scheme is a variant of alignment in the frequency domain with one carrier (SC-FDE), while transmitting «up».

SC-FDE systems have similar efficiencies to multi-carrier systems, but have a low peak-to-average power ratio, making user terminals more energy efficient. Therefore, SC-FDE technology is more attractive for use in SCS than OFDM, while it remains compatible with OFDM because it uses a cyclic prefix and alignment occurs in the frequency domain.

It should be noted that promising broadband satellite systems will operate at frequencies above 40 GHz (Q/V band, and hereafter W-band). In this case, the advantage is also on the side of SC-FDE systems, rather than OFDM, due to their lower sensitivity to radio frequency distortion.

Thus, the analysis allows forming the main directions of improving the efficiency of modern satellite communication systems. This analysis allows:

– to formulate new approaches to increase the efficiency of modern satellite communication systems;
– to substantiate new technological solutions for the construction of transceivers of satellite communication systems;
– to identify possible areas of research to improve the efficiency of modern satellite communication systems.

4. Conclusions

1. The introduction of the considered options for the application of MIMO technology in satellite communication systems will increase the bandwidth and efficiency of these systems. However, there is a need for additional research to adapt this technology in satellite communication systems.

2. Ultra-wideband signals may be used in unlicensed satellite systems using a transmission license in some range with radiation restrictions to be laid down in the relevant regulations. It is necessary to investigate the effect of interference and power limitations on the efficiency of such satellite systems.

3. Combining ultra-wideband signals with MIMO technology (UWB-MIMO) can be the most promising when used in high-speed terrestrial and satellite communication systems.

4. Ultra-wideband signals may be used in licensed satellite systems without power limitation. This will not lead to optimal spectrum utilization, but may reduce the complexity of the hardware base and the sensitivity to radio frequency distortion, and therefore increase the bandwidth of the channel.

5. The use of OFDM technology in satellite communication systems can be effective for three main reasons: increasing the spectral efficiency of fixed SCS, reducing the overall complexity of the satellite receiver, reducing the complexity of integrating satellite and terrestrial mobile communication systems. However, SC-FDE systems can provide the same advantages as systems with multiple carriers, without having their disadvantages when used on satellites. Therefore, the introduction of SC-FDE technology in satellite communication systems is a promising area for further research.

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