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On Increasing the Spectral Efficiency and Transmissivity in the Data Transmission Channel on the Spacecraft–Ground Tracking Station Line

M. N. Andrianov*, V. I. Kostenko, and S. F. Likhachev

Astro Space Center, Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia

**e-mail: mihail-andrian@asc.rssi.ru*

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Abstract—The algorithms for achieving a practical increase in the rate of data transmission on the spacecraft–ground tracking station line has been considered. This increase is achieved by applying spectral-effective modulation techniques, the technology of orthogonal frequency compression of signals using millimeter-range radio waves. The advantages and disadvantages of each of three algorithms have been revealed. A significant advantage of data transmission in the millimeter range has been indicated.

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INTRODUCTION

In the existing and future projects of ground-space radio interferometry (GSR) with independent signal recording, the need arises to transmit the research information received in the space segment to the ground-based tracking station (GTS) to calculate the correlation function between the data of the space and terrestrial arms of the interferometer. In the implemented Radioastron project [1], the small radio signal reception band (128 MHz) and, accordingly, the low digital flux rate made it possible to implement the real-time scheme of direct transmission to the GTS.

For the future Millimetron (MM) project [2], the analyzed radio signal bands and, accordingly, the rates of discrete digitized video data at the onboard receiver output highly exceed the data-transmission rate in the Radioastron project. Thus, it is proposed to preliminarily record the discrete video data in the onboard memory. The recording rate may reach 32 GB/s. The modern technologies of data translation over a wireless channel taking into account the considerable range (1.5–1.75 million km) and energy limitations of the onboard transmitter, distortions on the tropospheric section, and one-way communication channel are not able to provide data transmission on the MM-GTS lines with the indicated rate and the requirements to the reliability of the received data (the error probability is $<10^{-5}$).

The rate of data reading from the onboard memory and transmitting them to the GTS via the wireless communication channel is assumed to be 1.2 GB/s. It is easy to calculate that the time of interferometer operation (research data reception and recording) will be 0.0375 of the time of data transmission to the GTS. The onboard memory will be rapidly filled with research data, and their reading and downlink transmission to the Earth will be significantly constrained. The application of the Nyquist filter with a small rounding factor ($\alpha = 0.25$) can significantly increase the amplitude of signal response at the GTS receiver filter output [3–5]. Because of the natural degradation of filter parameters in the space environment conditions, this can lead to growing intersymbol distortions and, accordingly, to increasing signal reception errors, even for the large signal-to-noise ratio (SNR) [3] at the receiver input. The consequence of these conditions is the limited time the onboard radio telescope operation in the ground–space interferometry mode, and, accordingly, the GSR limitations for solving the important astrophysical tasks with limited vital resources of a spacecraft (SC).

The present work studies the possibilities of practical increasing the spectral efficiency and transmissivity of wireless data transmission on the SC–GTS line to increase the efficiency of the continuous operation of the ground-space interferometer, when the space element in the Millimetron project moves to distances up to $\sim 2 \times 10^6$ km from the Earth.

MAXIMUM ACHIEVABLE DATA-TRANSMISSION RATES

We determine the maximum achievable data-transmission rates on the SC–GTS communication line, which in turn depend on the SNR at the receiver

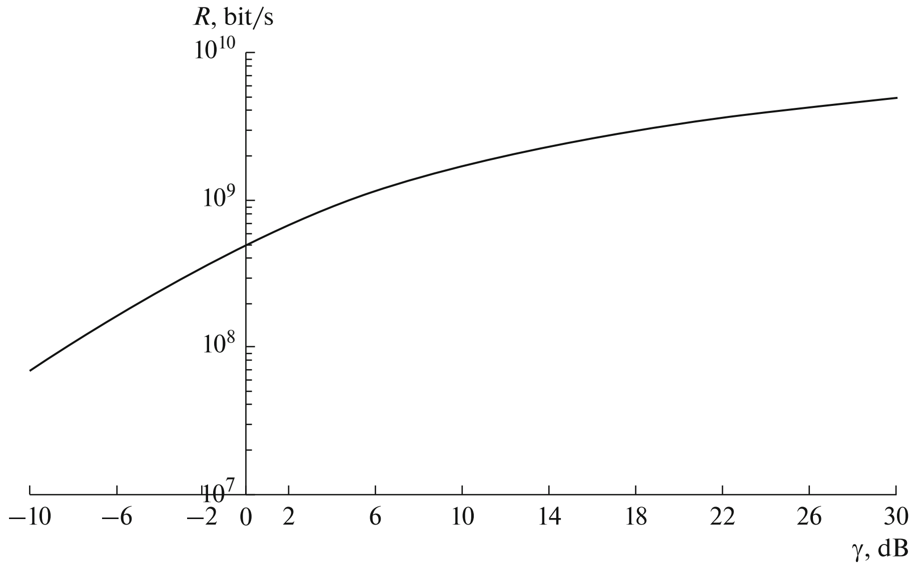

Fig. 1. Dependence of the communication channel transmissivity on the signal-to-noise ratio in channel band of 500 MHz.

input. For this purpose, we use the basic equation of radio communication (1)

$$P_r = \lambda^2 P_t G_t G_r/(4\pi d)^2, \tag{1}$$

where λ is the wavelength; d is the distance from the transmitter to the GTS; G_t and G_r are the gains of transmitting and receiving antennas, respectively; and P_t and P_r are the powers at the output of the transmitter and at the receiver input, respectively. The gains of antennas are defined by expression (2) as follows:

$$G = (4\pi/\lambda^2)S_A\nu\eta, \tag{2}$$

where S_A is the geometric area of the antenna aperture, determined in terms of the antenna diameter (D) $S_A = \pi D^2/4$, ν, and η are the surface utilization factor and the efficiency, i.e., the ratio of the power of radiation generated by the antenna to the power of the RF signal delivered to the antenna, respectively. For $\lambda = 2$ cm (the carrier frequency is 15 GHz), the diameters of transmitting and receiving antennas, which are equal to 2 and 22 m, respectively, and ν and η, which are equal to 0.5 and 0.95, respectively, the gains of transmitting and receiving antennas will be 52.25 and 67 dB, respectively.

At a maximum distance to the SC staying point (Lagrange L2 point) of $d = 1.75$ million kilometers [2], the power at the transmitter output is 200 W, the signal power at the GTS receiver input (P_r) will be about 4.4×10^{-11} W. For a communication channel bandwidth $\Delta f = 500$ MHz, the Gaussian noise power at the receiver input P_{noise} with an antenna output concordance with the receiver input in accordance with (3) will be 6.9×10^{-13} W as follows:

$$P_{noise} = kT\Delta f K_{noise}, \tag{3}$$

where k is the Boltzmann constant (1.38×10^{-23} J/K), T is the noise temperature of a receiver in Kelvin degrees, K_{noise} is the receiver noise factor. T and K_{noise} in (3) are taken to be equal to 50 K and 3 dB, respectively.

In this case, in accordance with expression (4), the signal-to-noise ratio (SNR) at the receiver input will be about 18 dB as follows:

$$\gamma = 10\log(P_r/P_{noise}). \tag{4}$$

The maximum allowable data-transmission rates, depending on the SNR at the receiver input, are determined, in accordance with the Shannon–Hartley theorem [3, 4] on the communication channel transmissivity (C), in accordance with expression (5), will be

$$C = \Delta f \log_2(1 + \gamma) \text{ bit/s}. \tag{5}$$

Figure 1 presents the dependence of C on γ for the channel transmission bandwidth $\Delta f = 500$ MHz.

Taking into account the necessary energy reserve of 3 dB, we determine the SNR at the receiver input as 15 dB. In accordance with (5) and Fig. 1, the maximum allowable transmissivity of the communication channel, for the given SNR and communication channel bandwidth of 500 MHz will be 2.514 GB/s, in this case, the normalized transmissivity (the spectral efficiency) ($C/\Delta f$) will be 5.028 bit/s/Hz. It should be noted that this transmissivity is the maximum achievable for the given SNR. For an SNR value of 15 dB, signals with rates of no more than 2.514 GB/s, can theoretically be transmitted with arbitrarily low error probability by applying sophisticated modulation and noise-immunity coding techniques [3, 5]. In the real wireless communication systems, the data are transmitted with a finite, nonzero error probability, and their transmission rate is always lower than the channel transmissivity.

Depending on the ability of error correction at the receiver's demodulator output, the codes are subdivided into the codes with very poor, poor, and good

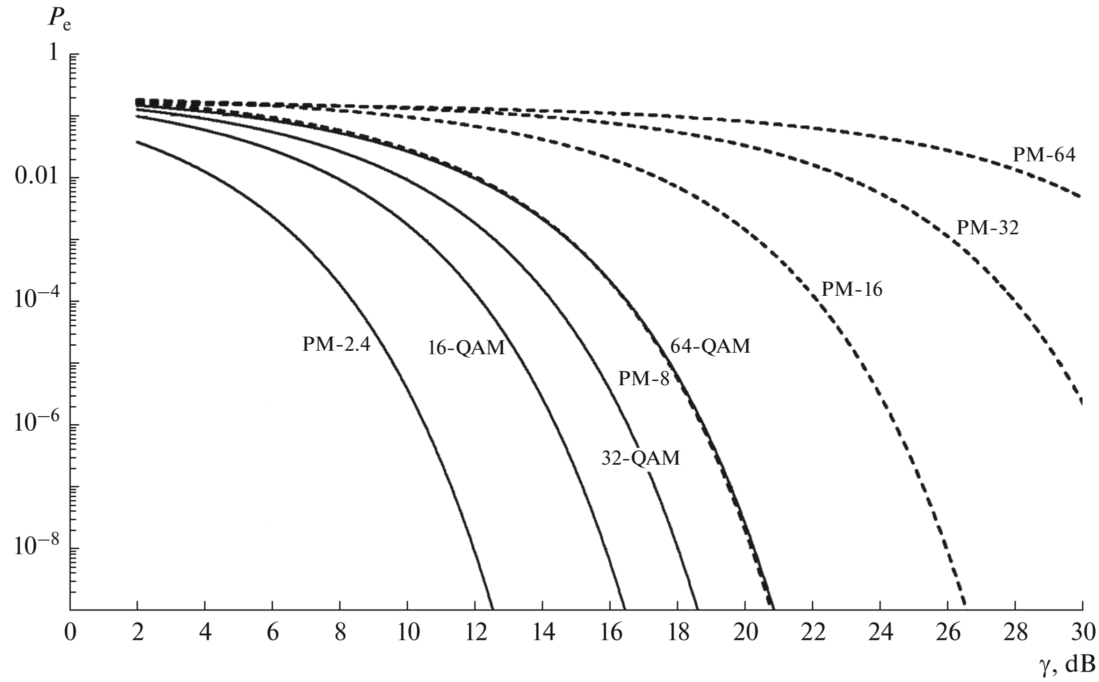

Fig. 2. Probabilities of bit error of coherent reception of phase-modulated signals (PM) with a constant envelope (dashed curves) and spectrally efficient signals with quadrature amplitude modulation (QAM).

code distance. The code distance represents the minimum distance (the measure of difference) between the code vectors of the closest allowable code combinations [6]. The minimum distance determines the code's correcting ability; the greater this distance, the greater the number of errors that the code is able to correct.

The codes with a very poor code distance include all linear algebraic and convolutional codes, the code distance of which remains unchanged with increasing code length. [6]. The codes with a poor code distance include constructions of several simple codes, and the composite codes, for which the code distance grows with increasing code length [6, 8], but their correcting ability drops because, with unlimited growth in the code length, the ratio of the code's distance to its length tends to zero.

The codes with a good code distance include the random linear codes, which are decoded by the maximum a posteriori probability technique. For this type of code, growth in the code distance with increasing code length is provided and the code's correcting ability grows because, with unlimited growth in the code length, the ratio of the code's distance to its length tends to the constant, the value of which depends on the type of code. Prominent examples of random codes include turbo codes [7] and the low-density codes with correction checking for parity, i.e., low-density parity check (LDPC) [8, 9]. The random codes can approach nearly the maximum achievable data-transmission rates while ensuring the low error probability [10].

TRANSMISSIVITY OF COMMUNICATION CHANNELS WITH THE APPLICATION OF SPECTRALLY EFFECTIVE SIGNAL MODULATION TECHNIQUES

To ensure the data-transmission rate for the specified (15 dB) SNR value, it is reasonable to apply spectrally effective modulation techniques at a relatively high noise immunity of the transmitted data. For example, to ensure a spectral efficiency of 5 bits/s/Hz, it is possible to apply 32-QAM (quadrature amplitude modulation). This type of modulation, along with a high spectral efficiency compared to the equivalent-in-spectral-efficiency phase-modulated signal PM-32 (phase modulation), has high noise immunity (Fig. 2).

A 32-QAM modulation signal with a spectral efficiency of 5 bits/s/Hz provides a data-transmission rate of 2.5 GB/s in the frequency band of 500 MHz, which nearly corresponds to the maximum achievable data-transmission rate in accordance with (5).

We determine the noise immunity of a radio line in terms of the probability of erroneous data reception per bit. In the presented communication channel, the Gaussian thermal noise will be present, the power of which is determined in accordance with (3). This channel relates to channels with good characteristics [3], in which there is neither slow Rayleigh nor fast (or frequency-selective) fading, which significantly decrease the channel coherence bandwidth and cause significant intersymbol interference during signal reception. Analytical expressions (6), (7) characterize the probability of the erroneous coherent reception of the data of PM and QAM signals [5, 11]

$$P_{c\_\mathrm{PM}} = (1/M)\,\mathrm{erfc}\left[\sqrt{\gamma}\sin(\pi/N)\right], \quad (6)$$

$$P_{c\_\mathrm{QAM}} = \left[\left(1 - 1/\sqrt{N}\right)/\log_2\left(\sqrt{N}\right)\right] \times \mathrm{erfc}\left[\sqrt{3\gamma\log_2\left(\sqrt{N}\right)/(N-1)}\right], \quad (7)$$

where N is the number of signal constellation points, $M = \log_2(N)$ and $\mathrm{erfc}(x) = 1 - \mathrm{erf}(x) = \left(2/\sqrt{\pi}\right)\int_x^{\infty}\exp\left(-t^2\right)dt$ is complementation of the function of errors [12].

It should be noted that the noise immunity of a phase-modulated PM-8 signal nearly coincides with the noise immunity of a signal with quadrature amplitude modulation 64-QAM (Fig. 2) (provided that the spectral efficiency of the latter one is twice higher relative to the first one) are equal to 3 and 6 bits/s/Hz, respectively.

The 32-QAM modulation proposed for applications in accordance with the transmissivity (15 dB) is more energetically efficient relative to the PM-8 modulation signal. For example, the error probability of 10^{-5} is provided by the 32-QAM modulation if the SNR value is about 2 dB lower than the corresponding error probability for the PM-8 modulation (Fig. 2). The spectral efficiency of signals with PM-8 and 32-QAM modulations will be 3 and 5 bits/s/Hz, respectively. It should be noted that, for presented types of modulation, spectral efficiencies of 3, 5, and 6 bit/s/Hz were obtained with filtering by an ideal rectangular Nyquist filter with zero roundness factor, which cannot be physically achieved. The practical use of this filter [3, 4], e.g., with $\alpha = 0.25$, will decrease the spectral efficiency of 3, 5 and 6 bit/s/Hz to 2.4, 4 and 4.8 bit/s/Hz, respectively, and the data-transmission rate in the 500 MHz channel will be decreased to 1.2, 2 and 2.4 GB/s.

The lack of a constant envelope in signals with the quadrature amplitude modulation, N-QAM (N = 16, 32, 64, 128, 256, ..., 2^n), is a serious disadvantage because, in this case, in the transmitter, for undistorted transmission of signal constellations, it is necessary to use the linear power amplifier (PA) with a large dynamic range and, accordingly, low efficiency. The modern techniques for increasing the linearity of output power amplifiers (PAs) [13] (pre-distortions, feedback, communication forwards, etc.) enable the effective application of powerful nonlinear PAs with high efficiency in the linear amplifying systems. Here, the losses from using nonlinear PAs in the linearization schemes amount to 0.5–0.7 dB.

To reduce the probability of erroneous reception of signals, it is reasonable to apply noise-immune, random, linear, and extended Euclidean-geometric (EG) LDPC code (EG-LDPC) with iterative SPA (sum-product algorithm) decoding [14]. The code parameters (524256, 507873) compose the informational and total code-word length, respectively. In this case, the code rate will be 0.967. The mentioned code provides the minimum redundancy and high correcting ability. The code characteristic, i.e., the probability of errors as a function of SNR, compared with the uncoded PM-2 signal (binary phases shift key, i.e., BPSK), is shown in Fig. 3.

TRANSMISSIVITY OF THE COMMUNICATION CHANNEL FOR TECHNOLOGY WITH ORTHOGONAL FREQUENCY DIVISION OF SIGNALS

Recently, in wireless data-transmission systems, the proportion of devices that operate by orthogonal frequency divide multiple (OFDM) technology has grown significantly. In this case, the data are transmitted by symbols that consist of a set of harmonic signals of particular frequencies (subcarriers), which are orthogonal relative to each other. The orthogonality is provided by the fact that, during the symbolic period, the harmonic signals have an integer number of half-periods, and their distinction from neighboring signals makes up one period. In this case, in accordance with (8), the output data are fully orthogonal as follows:

$$a(t) = \begin{cases} \int\limits_0^T \cos(\omega t + \varphi_1)\cos\left[(\omega + 2\pi/T)t + \varphi_2\right]dt \\ = 0.5\int\limits_0^T \left\{\cos(\varphi_1 - \varphi_2 - 2\pi t/T) + \cos\left[(2\omega + 2\pi/T)t + \varphi_1 + \varphi_2\right]\right\}dt = 0, \\ \int\limits_0^T \cos^2(\omega t + \varphi_1) = 0.5\int\limits_0^T \left[1 + \cos(2\omega t + 2\varphi_1)\right]dt = T/2 \end{cases} \quad (8)$$

where T is the orthogonality interval and ω, φ_1, φ_2 are the frequency and initial phases of harmonic signals. As follows from (8), the orthogonality does not depend on the initial phases of signals. During the

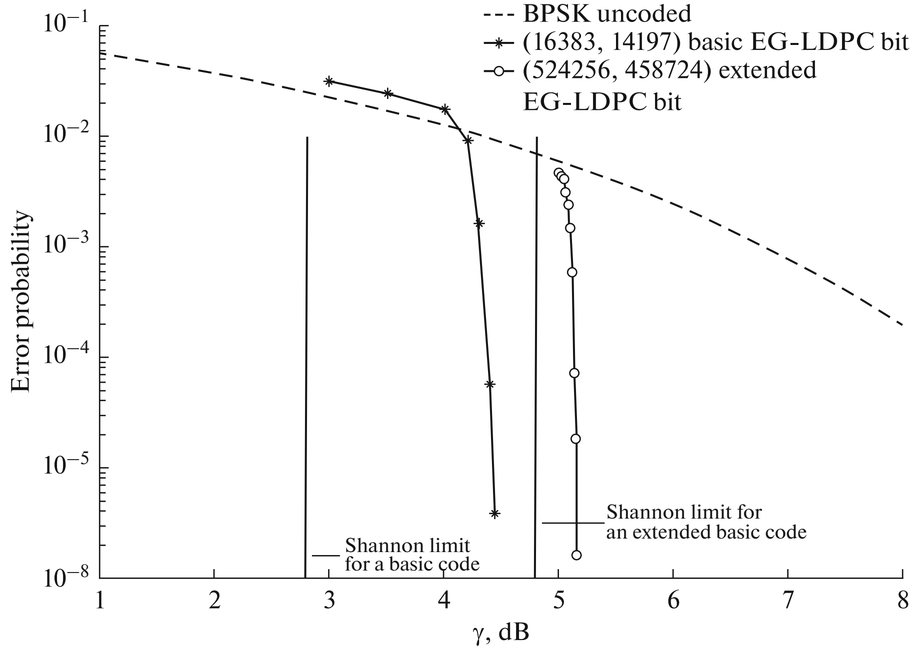

Fig. 3. Correcting ability of LDPC codes (16383, 14197) and of extended Euclidean geometric code, LDPC (524256, 507873) with iterative SPA decoding compared with uncoded BPSK signal.

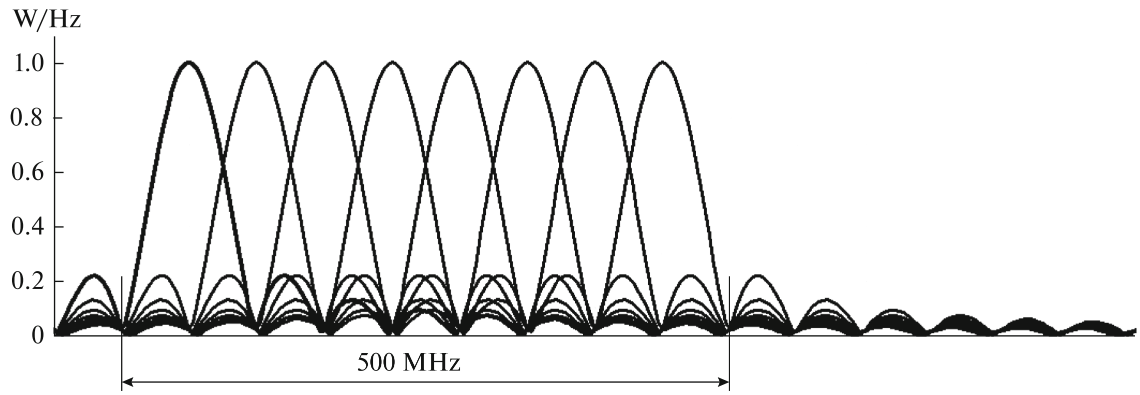

Fig. 4. Fragment of magnitudes of spectral density of voltage from eight orthogonal subcarriers.

orthogonality interval, which equals a symbol length, the phases of signals do not change and, during the modulation of orthogonal subcarriers, the change in phases occurs at the instant of transition from one symbol to another [15].

In the frequency domain, the OFDM signals represent the sum of spectra of orthogonal subcarrier signals, the spectra of which are in turn densely packed and mutually overlap with one another. Here, the interchannel frequency interference from individual subcarriers does not affect the others (Fig. 4) [15, 16].

The application of OFDM signals provides the spectral efficiency of transmitted data that is commensurate with filtering the radio signal with the ideal rectangular Nyquist filter. This technology provides the maximum possible spectral efficiency of data transmission for the given modulation type.

The formation of the OFDM signal subcarriers in the data transmission channel is accomplished either by applying the Fourier-transformation algorithms [15] or by the additive accumulation of the phase-modulated signals at the orthogonal frequencies from the PA outputs. Here, the amplification of signals of individual harmonic subcarriers with a low dynamic range is implemented by PAs at a higher efficiency, whereas the OFDM signal amplification from the Fourier-transformer output requires PAs with higher dynamic ranges and, accordingly, at a lower efficiency.

An additional advantage of the OFDM technology is the possibility of the effective functioning in the

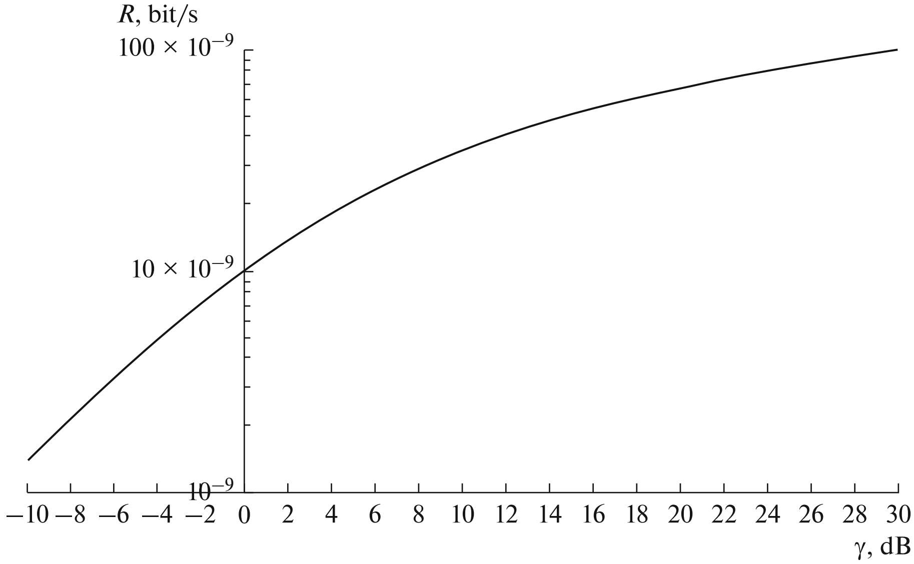

Fig. 5. Dependence of communication channel transmissivity on signal-to-noise ratio in channel band of 10 GHz.

channel with multipathing, where the channel coherence band is much less than the signal band. Here, the band of a subchannel of an individual subcarrier is 2^n times smaller than the signal band. Of course, in this small band, it is easier to ensure the coherence [16]. In the considered version of data transmission from the spacecraft board to the GTS due to the use of narrow-beam antennas with a high gain, multipathing is unlikely, except the time of antenna operation at low elevation angles. In general, the data transmission channel on the spacecraft–GTS line can be considered to be a channel with good characteristics. However, along with increased spectral efficiency, the application of OFDM technology allows one to maintain the reliability of the data transmission while lowering the coherence band in the transmitter's PA due to its degradation in the operation period. All of these considerations stipulated the acceptance of the International Telecommunication Union's recommendations ITU-R S. 1878 from December 2010 [17] on the transmission methods based on the many carriers for satellite systems.

INCREASE IN TRANSMISSIVITY OF THE COMMUNICATION CHANNEL WITH THE APPLICATION OF HIGH-FREQUENCY SIGNALS OF THE MILLIMETER RANGE OF RADIO WAVES

As was shown above, the signal frequency band is linearly related to the communication channel transmissivity (5). Based on this, to significantly increase the transmissivity, it is necessary to tend to the maximum possible extension of the frequency band of a communication channel. In turn, the increase in the communication channel band is closely associated with the use of the electromagnetic spectrum of radio waves. In accordance with the radio communication regulations, at present, the frequency range is allocated up to 275 GHz [18]. The frequencies are most densely occupied in the low-frequency range, up to millimeter range. However, whereas the frequency bands are mainly distributed in the meter, decimeter, and centimeter ranges of the electromagnetic radio wave spectrum and almost no free bands remaining in the millimeter part of a spectrum, which is poorly explored, there are relatively free sections of frequency bands.

In the millimeter range of radio waves, the E-band with frequencies of 71–76 and 81–86 GHz appears rather attractive because, in accordance with the SCRF resolution No. 10-07-04-1 from July 15, 2010, the radio frequency bands of 71–76 and 81–86 GHz were allocated for applications on the territory of the Russian Federation by the radio-relay stations of direct visibility, as well as by the legal entities and individuals without the issuance of separate SCRF resolutions.

In the indicated frequency band (71–76 and 81–86 GHz), which is 12 GHz, if we allocate (taking into account the real Nyquist filter parameters) a 10-GHz band for data transmission in the simplex mode, i.e., if we use the allocated frequency band for one-way data transmission from a transmitter to receiver, then the communication channel transmissivity will look as shown in Fig. 5. Using the basic radio communication equation (1), by changing the wavelength (4 mm) and the receiving antenna diameter (15 m), we determine the radio signal power at the receiver input (5.11×10^{-10} W). The noise power is determined from formula (3) (1.38×10^{-11} W), and the SNR value is determined from expression (4) (15.69 dB). In this

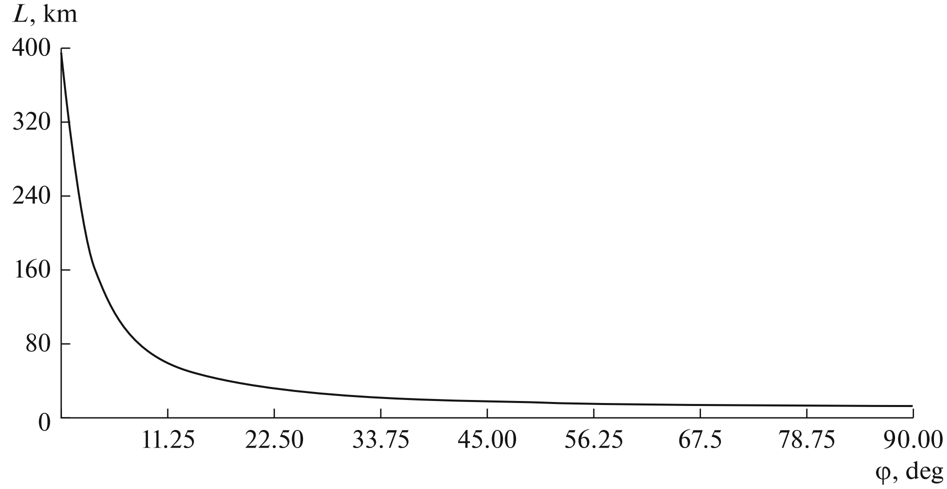

Fig. 6. Dependence of radio signal path length in troposphere depending on antenna elevation angle.

case, the signal power at the receiver input has grown compared to a wavelength of 2 cm, but the noise power has also grown. The first growth was caused by an increase in the gain of transceiver antennas, while the second growth was due to a sharp increase in the band of communication channel frequencies. Taking into account the required energy store of 3 dB, the SNR value at the receiver input will decrease to 12.7 dB.

Because the signal also propagates in the lower atmospheric layer (in the troposphere), it is necessary to take into account the resulting losses from water vapor, which increase with increasing signal frequency. In accordance with the recommendations of the radiocommunication sector of the International Telecommunication Union (Recommendation ITU-R P. 676-10 of September, 2013) on radio signals attenuations in atmospheric gases [19], the attenuation of the zenith radio signal at a frequency of 70–80 GHz (in the absence of hydrometeors) will be about 0.85 dB for the troposphere thickness of 10 km (at moderate latitudes, it varies in the range of 10–12 km). Figure 6 shows the change in the path length of the radio signal in the troposphere depending on the antenna's angle of elevation.

This dependence is determined from expression (9) by the theorem of cosines

$$L = R_E \cos(\pi/2 + \varphi) + \sqrt{R_E^2 \cos^2(\pi/2 + \varphi) - R_E^2 + (R_E + h)^2}, \quad (9)$$

where Earth's radius $R_E = 6400$ km, h is the thickness of the troposphere, and φ is the antenna's angle of elevation (the angle of inclination to the horizon). Here, the assumption is made that the Earth has a spherical shape.

It follows from Fig. 6 and formula (9) that, for $\varphi = 17.3°$, $L = 40$ km; for $\varphi = 23.5°$, $L = 30$ km; and, for $\varphi = 37°$, $L = 20$ km. For the maximum path length (40 km), at minimally presented elevation angle (17.3°), the signal attenuation will be (0.85 dB/10 km) × 40 km = 3.4 dB. As a result, the SNR value at the receiver input will be 12.69 – 3.4 = 9.29 dB.

It should also be taken into account that, while propagating in the turbulent troposphere, the radio signals of millimeter and submillimeter ranges undergo fluctuations in the amplitude described by a lognormal distribution [20]. Here, one should bear in mind that the probability density of the SNR of millimeter-range signals is also described by the lognormal law, and its variance, along with the wavelength, depends on the distance of signal propagation over the troposphere. Therefore, depending on the antenna elevation angle and, hence, on the propagation distance, an additional energy store of 1–3 dB is required, and it is unreasonable to install the antenna at an angle of elevation of less than 15°.

Based on the above considerations, we take the SNR value at the receiver input to be 7.3 dB. For this SNR value, the transmissivity of the communication channel will be determined taking into account (5) and Fig. 5 based on the value of 26.7 GB/s with a communication-channel band of 10 GHz. To transmit the data in the presented channel, it is reasonable to apply the QPSK (Quadrature Phase Shift Key) signal modulation that provides spectral efficiency of 2 bit/s/Hz; the constant envelope of this signal allows one to use the high-efficient, non-linear PAs.

Accordingly, in the channel with the 10 GHz bandwidth, for the indicated modulation type, the real data transmission with the rate of 20 Gbit/s is possible. This rate is commensurable with the rate of research data recording into the on-board memory, and, accordingly, it essentially increases the time resource of radio telescope operation in the ground-space interferometry mode. The probability of error in the reception of the QPSK-modulation signal, for the

Table 1

Methods of improving the data-transmission rate	Advantages of the method	Disadvantages of the method
Effective modulation	High spectral efficiency of data transmission	Necessity of PA linearization. Algorithmic complexity of implementation
Application of the OFDM technology	Maximum possible spectral efficiency for a given type of modulation. Flexibility of the technology. Indifference to the bandwidth coherence of the channel.	Necessity of PA linearization. Algorithmic complexity of implementation
Use of the millimeter range	High data-transmission rate	Technological complexity of implementation

SNR of 7.3 dB (Fig. 2), will be 5.2×10^{-4}. The above-described noise-immunity LDPC [14] random code (Fig. 3) will significantly lower the error probability.

Similar calculations in the millimeter range can be performed for the arbitrary wavelength. Here, one should note that the decrease of a wavelength, on one hand, provides signal amplification by transceiver antennas, and, on the other hand, the increase of a carrier frequency increases the signal power losses due to attenuation [19] and increases the variance in the lognormal fluctuations in the signal amplitude [20].

Data transmission in the millimeter *E* range (71–76, 81–86 GHz), with a signal band of 10 GHz, is now implemented [21]. The appropriate hardware allows that perform simplex transmission at a rate of up to 20 Gbit/s.

The paper [21] did not consider the effect of diffraction phenomena occurring due to some obstacles at small antenna tilt angles, which cause certain changes in the signal level at the receiver input. Another consequence of signal reception at small antenna tilt angles is the emergence of a two-beam signal reception model with reflection from the underlying surface and the resulting interference noise.

The main advantages and disadvantages of each of three (the effective modulation, the OFDM technology, the use of the mm range of radio waves) versions of increasing the data-transmission rate are tabulated in the paper.

CONCLUSIONS

The increase in the spectral efficiency and data-transmission rate in the organization of high-rate digital radio channels on the SC–GTS line is important for various space projects, which require data transmission at long distances, in particular in the Millimetron mission [2]. This will significantly increase the coefficient of continuous functioning of the ground-space interferometer and increase the efficiency of its operation. The present paper considers the following three effective ways of solving these problems:

—Spectrally effective methods of quadrature amplitude modulation (QAM), with equal spectral efficiency (compared with the phase modulation (PM)) benefit significantly in the noise immunity. For example, the application of a 32-QAM modulation signal in conjunction with a noise-immune code allows the transmission spectral efficiency of 4 bit/s/Hz to be achieved (2 Gbit/s in the band of 500 MHz).

—The technology of orthogonal frequency compression of signals provides the maximum possible spectral efficiency of data transmission for the given modulation type. The advantage of this technology is its flexibility, which if necessary allows one to transmit the data with variable rates.

—The application of the millimeter range enables the growth of the data-transmission rate due to the increasing frequency band of a communication channel, which, in contrast to the value of a signal-to-noise ratio at the receiver input, linearly increases the channel transmissivity.

In all three versions of increasing the data-transmission rate, to correct the resulting errors, it is reasonable to apply the efficient, noise-immune coding. For the MM project, on the SC–GTS line, it is necessary to use the millimeter range of radio waves, because, in spite of technological complexity of hardware implementation, it is just this range, in which it is possible to obtain the data-transmission rate commensurate with the rate of digital broadband data recording into the SC onboard memory and, thus, to ensure the continuous operation of a ground-space interferometer.

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