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TRANSMISSION EFFICIENCY OF MULTI-FREQUENCY SIGNALS IN MBC USING AMPLITUDE LIMITATION ON THE TRANSMITTING MODULE

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The ability to receive electromagnetic waves reflected from meteor traces is the basis for the construction of meteor burst communication (MBC) systems. MBC has a low data rate (about a few dozen kilobits per second). Therefore, from the point of view of increasing the information transfer rate, we can use multi-frequency signals, for example, OFDM signals. These signals occupy a smaller frequency band, but have a high peak-to-average power ratio. In this article, we used simulation modeling to transmit information in an MBC system using multi-frequency signals under the condition of amplitude limitation on the transmitting module.

Keywords: meteor burst communications, peak-to-average power ratio, amplitude limitation, MBC, OFDM, PAPR.

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ЭФФЕКТИВНОСТЬ ПЕРЕДАЧИ МНОГОЧАСТОТНЫХ СИГНАЛОВ В МЕТЕОРНОМ КАНАЛЕ ПРИ УСЛОВИИ АМПЛИТУДНОГО ОГРАНИЧЕНИЯ НА ПЕРЕДАЮЩЕМ МОДУЛЕ

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Возможность приема отраженных от метеорных следов электромагнитных колебаний лежит в основе построения систем метеорной связи. Метеорная радиосвязь имеет низкую скорость передачи данных (единицы-десятки бит в секунду). С точки зрения повышения скорости передачи информации мы можем использовать многочастотные сигналы, например, сигналы OFDM. Эти сигналы занимают меньшую полосу частот, но обладают высоким значением пик-фактора. Выполнено имитационное моделирование передачи информации в метеорном канале при использовании многочастотных сигналов при условии амплитудного ограничения на передающем модуле.

Ключевые слова: метеорная радиосвязь, пик-фактор, амплитудное ограничение, MBC, OFDM, PAPR.

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Introduction

When the Earth moves in the orbit, cosmic particles known as meteoroids daily enter the Earth's atmosphere. The meteoroid intrusion into the Earth's atmosphere occurs at a speed ranging from 11 to 73 km/s. It is accompanied by heating and complex destruction processes: melting, spraying, crushing and evaporation. Evaporated meteor molecules collide with air molecules and atoms and decompose into atoms, causing their excitation and ionization. Meteor atoms are mainly ionized, since their ionization potential is lower than the ionization potential of gas atoms. The size of the ionized trails formed along the trajectory of the meteoroid depends on the mass and speed of the meteoroid [1].

The length of the trail can reach tens of kilometers. The radius of the trail at its formation is about a meter and increases over time due to diffusion. Ionized trail of meteors is able to reflect radio waves, and therefore they can be observed in the radio spectrum. The ability to receive electromagnetic waves reflected from meteor trails is the basis for constructing meteor burst communication (MBC) systems (Fig. 1).

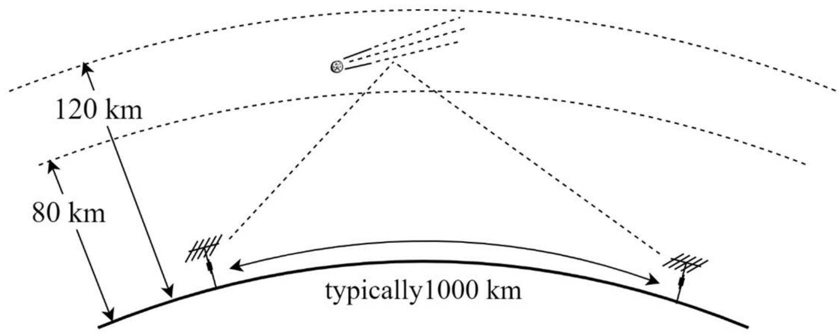

Fig. 1. Illustration of the principle of MBC [2]

As a rule, MBC uses a frequency ranging from 40 MHz to 100 MHz [3, 4]. The distance, at which communication can be established, is mainly determined by the height, at which the meteor trail is created, and the radius of curvature of the Earth's surface. The maximum communication distance between radio stations can be about 2000 km [1–3].

When transmitting messages over long distances, MBC systems provide a simpler solution to the problems of organizing communication than, for example, short-wave communication systems. So, in the short-wave communication systems, to ensure high quality of message reception, various independent carrier oscillation frequencies are used during daytime and nighttime operation, which is caused by a change in the height of the ionospheric layer during the day. Due to interference at the main frequencies, the introduction of reserve frequencies is required in these systems. Serious problems in short-wave systems arise due to the presence of selective fading, limitation on the maximum applicable carrier frequency, the choice of the optimal transmission frequency, and exposure to aurora in the northern regions. The indicated drawbacks are deprived of MBC systems, in which messages are transmitted on one fixed carrier frequency, and the range may vary from 300 to 2000 km. The transmission channel allows one frequency to automatically temporarily separate the work of hundreds of peripheral stations, which eliminates the need for transitions to other frequencies.

It should be noted that MBC has its drawbacks. The most obvious disadvantage of using MBC is a very low data rate (units to tens of bits per second). MBC is also limited by distance (no more than 2000 km). The third disadvantage of MBC is the impossibility of organizing voice communication and video communication due to the longer waiting time for the formation of a suitable meteor trail.

Usually, a single-frequency signal is used in an MBC system [5–9]. Frequency modulation signals are often used, since the peak-to-average power ratio (PAPR) of the emitted oscillations in this case will be minimal, which allows to maximize the efficiency of power amplifiers on the transmitting module. From the point of view of increasing the information transfer rate, we can use multi-frequency signals, for example, orthogonal frequency division multiplexing (OFDM) signals [10]. OFDM is a digital modulation scheme that uses a set of orthogonal frequency subcarriers. OFDM signals occupy a smaller frequency bandwidth, but have a high PAPR value [11, 12]. PAPR is the ratio of the maximum power P_{max} of the signal $s(t)$ to the average power P_{avg}:

$$\text{PAPR} = \frac{P_{max}}{P_{avg}}. \tag{1}$$

Reducing the PAPR value to increase the efficiency of the amplifier stages of the transmitting devices is possible by various methods of limiting the emitted oscillations, for example, by using the amplitude limit (i.e., the generated signal first passes through the amplitude limiter and only then through the power amplifier). An additional positive aspect of the amplitude limitation is an increase in the average signal power, which should have a positive effect on the transmission range of information at a fixed error probability or on a decrease in the probability of error at a fixed transmission distance. However, the introduction of a PAPR limitation leads to additional signal distortion. Signals located at adjacent subcarrier frequencies begin to influence each other, which ultimately leads to an increase in the probability of errors in reception.

Thus, the aim of this work is to assess the feasibility and effectiveness of the use of multi-frequency signals in the meteor burst communications under the condition of amplitude limitation of signal on the transmitting module.

Description of multi-frequency signals

We consider OFDM signals as a general form of multi-frequency signals. The OFDM signal is a multi-frequency signal with N subcarriers and complex modulation symbols C_k on each subcarrier without a cyclic prefix. OFDM symbols with a duration T_s have the following form [13]:

$$s(t) = \sum_{k=-\frac{N}{2}}^{\frac{N}{2}-1} C_k e^{j2\pi k\Delta f t}, t \in [0; T_s]. \tag{2}$$

In formula (2), the frequency spacing between adjacent subcarriers is $\Delta f = 1 / T_s$. In this article, we use the methods of generating and receiving OFDM signals presented in Fig. 2 [1].

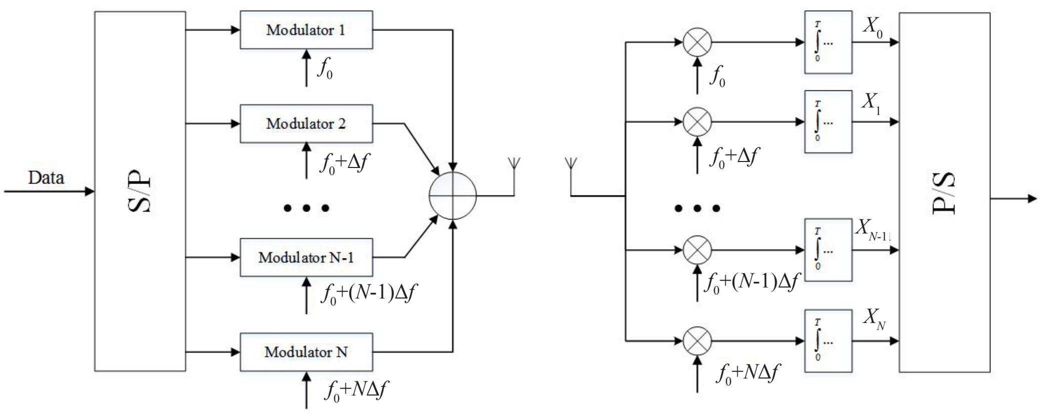

Fig. 2. Scheme of formation and reception of OFDM signals

Characteristics of meteor burst communications

To describe the processes occurring in the meteor channel, it is required to use the distribution of the duration, intensity of occurrence and power of meteor tracks. The intensity of the appearance of traces depends on the time of day and year. The average value of the duration of the meteor trail T_c and the interval between two consecutive traces ΔT_c are determined by the formulas:

$$T_c = \frac{\sum trails \quad duration}{number \quad of \quad trails}; \qquad \Delta T_c = \frac{\sum duration \quad between \quad two \quad trails}{number \quad of \quad trails}.$$

Depending on the concentration of electrons, meteor trails are divided into two main types: underdense and overdense. For underdense trail, the linear electron concentration n on the trace axis is less than $2.4 \cdot 10^{14}$ electrons per meter, and the incident radio wave is reflected in view of the effect of the secondary electron reemission [2]. The amplitude-time characteristic (ATC) of the radio reflection from an underdense trail after a rapid increase in amplitude has an exponential decline due to the recombination of free electrons and ions of the trail. For overdense trail ($n > 2.4 \cdot 10^{14}$ electrons per meter), the incident wave is reflected, as if from a metal cylinder of some critical radius [15]. The ATC of radio reflection from a classic overdense trail is as follows: after a phase of rapid growth, the reflection amplitude then slowly increases and, having reached its maximum, slowly drops to zero.

In this paper, we consider a model of a meteor channel based on an underdense trail, because this is the most frequently observed MBC mechanism [6, 16, 17]. In this case, the energy per bit to noise power spectral density ratio E_b/N_0 in the transmission channel will change in the same way as the ATC reflection, i.e. after a rapid increase in amplitude has an exponential decline.

According to the recommendation ITU-R F.1113[1], for a power level of a transmitting module of 200 W, when modeling, we select:

- mean duration of a meteor trail: $T_c = 330$ ms;
- mean duration between two meteor trails: $\Delta T_c = 800$ ms.

An example of the dependence of E_b/N_0 on time t at the input of the receiving module using the above parameters is shown in Fig. 3.

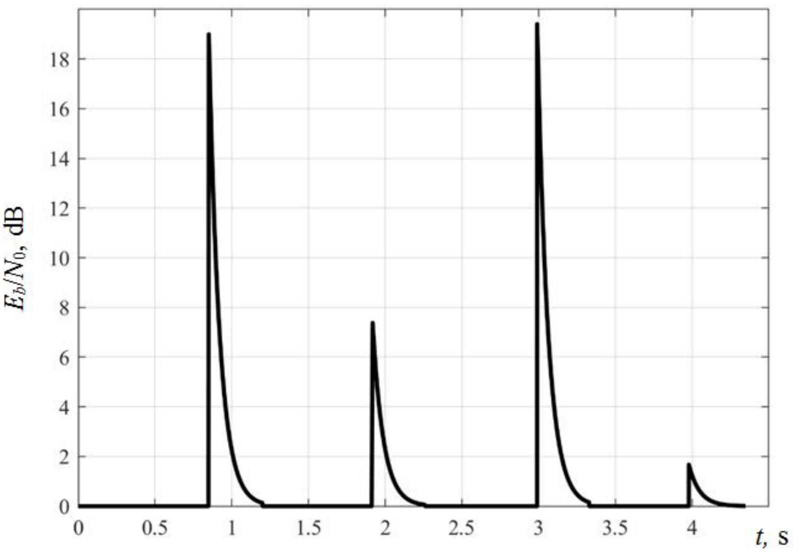

Fig. 3. An example of the dependence of E_b/N_0 on time for MBC

[1] Recommendation ITU-R F.1113. Radio systems employing meteor-burst propagation, 1994.

Simulation model

A simulation model for analyzing the effectiveness of the proposed signals under the condition of amplitude limitation on the transmitting module is presented in Fig. 4 and implemented in the Matlab system.

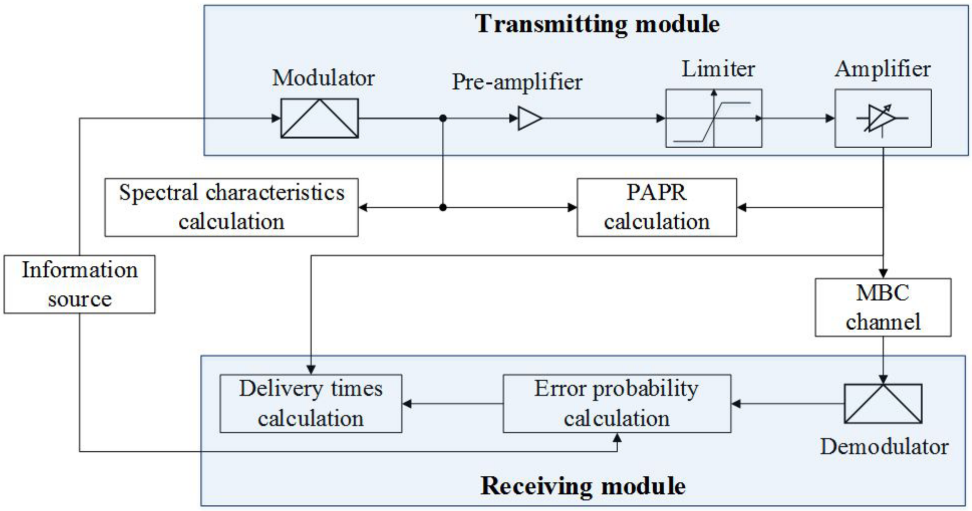

Fig. 4. Structural scheme of the simulation model

It includes an information source, a transmitting module block, spectral characteristics and PAPR calculation blocks, an MBC channel simulation block, a demodulator, error probability and delivery time calculation blocks.

In the information source a pseudo-random sequence of zeros and units of a given volume is formed depending on the number of subcarriers and equiprobable symbols used.

The transmitting module includes a modulator, pre-amplifier, limiter and power amplifier. The pseudo-random sequence received from the information source is fed to the input of the modulator. We used modulation scheme QPSK. The number of frequency subcarriers is 8. The generated symbols from the output of the modulator are fed to the input of the preamplifier to increase the average radiation power. Then, the received signal is sent to the limiter to limit the amplitude of the signal to the maximum amplitude of the output signal of the modulator. This means that the average signal power increases, while the peak signal power does not change, which leads to a decrease in PAPR.

The procedure for restricting PAPR of symbols is shown in Fig. 5. As long as level A, which determines the PAPR reduction value, does not exceed the A_{lim} value, the output value of U_{out} linearly depends on the input U_{in}. Starting from value A_{lim}, U_{out} stops changing.

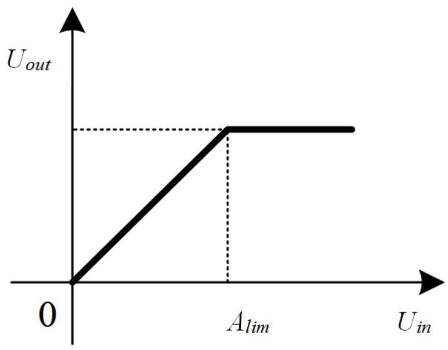

Fig. 5. Characteristic of the limiter

The amplified signal is transmitted to the blocks for calculating the spectral characteristics and PAPR values. The ratio of the PAPR of the received signal at the output of the modulator ($PAPR_{orig}$) to the PAPR of the signal received at the output of the power amplifier ($PAPR_{red}$) is defined as the value of PAPR reduction (PR):

$$\mathrm{PR} = \mathrm{PAPR}_{orig}\,(\mathrm{dB}) - \mathrm{PAPR}_{red}\,(\mathrm{dB}).$$

The signals received after passing through the MBC channel will be processed in the demodulator. Then they will be transferred to the following blocks to calculate the values of the probability of error and the delivery time.

In modeling, a broadcast protocol is used, which is usual for the meteor burst communication [18]. This approach provides the ability to transmit information without establishing a communication session between stations. Note that in this option there is no way to control the delivery of information. With the comparative inefficiency of this protocol, it is used for broadcast transmission of small amounts of information. The advantage of the broadcast protocol is that the receiving station does not waste energy, working only on reception, in contrast to the half-duplex protocol [18]. When using a broadcast protocol, the desired value is the delivery time T_d. We assume that the delivery time T_d is the time from the start of emission of a physical layer packet to the reception of this packet without errors. After receiving the packet, the received delivery time is recorded without errors and the simulation is restarted. Further, the obtained values are averaged. In the modeling process, at least 1000 iterations were used per one fixed set of modeling parameters. In an MBC system with transmission speed of 100 kbps, the FM signal used for transmission occupies a frequency band of 100 kHz. The choice of parameters of the OFDM signals is determined in such a way that the occupied frequency band without amplitude limitation does not exceed the 100 kHz band. The number of frequency subcarriers of the OFDM signal is selected equal to $N = 8$. The final simulation parameters:

- Duration of one OFDM symbol: $T_{OFDM\,symbol} = 10^{-4}$ s = 0.1 ms.
- Number of symbols in one packet: $N_{OFDM\,symbol} = 10^2$, $2 \cdot 10^2$ or $3 \cdot 10^2$ symbols.
- Duration of the package $T = 0.01$, 0.02 or 0.03 s (depend on the value $N_{OFDM\,symbol}$).
- Modulation scheme: QPSK.
- Sampling frequency $F_s = 10$ MHz.

The assumption of simulation is the absence of clock and symbol synchronization, that is, at the reception the moments of the beginning of OFDM symbols and the phase are always known. Also, no checksum was used to verify the integrity of the packet. Under these conditions, we are able to obtain a “lower estimate”, that is, minimum estimates of the delivery time.

Results

In the beginning, we consider the case without amplitude limitation (PR = 0 dB). In this case, the signal has a great PAPR value (more than 11 dB). The transmission of such signals will be inefficient in terms of the use of power amplifiers due to their low energy conversion efficiency. As you can see, it is required to reduce the PAPR.

Fig. 6 and 7 show examples of normalized instantaneous power $p(t)/\max(p(t)$ and energy spectrum of signals $|S(f)|^2/|S(0)|^2$ for various values of the PR value. Note that the energy spectrum of a random sequence of OFDM signals with a rectangular envelope has a low decay rate of out-of-band emissions (OOBE). With a stricter restriction on PAPR, significant additional distortions begin to appear due to an increase in the mutual influence of signals from neighboring frequency subcarriers due to an increase in OOBE of OFDM signals. At the level of energy spectrum up to 10 dB, we received a bandwidth of 100 kHz.

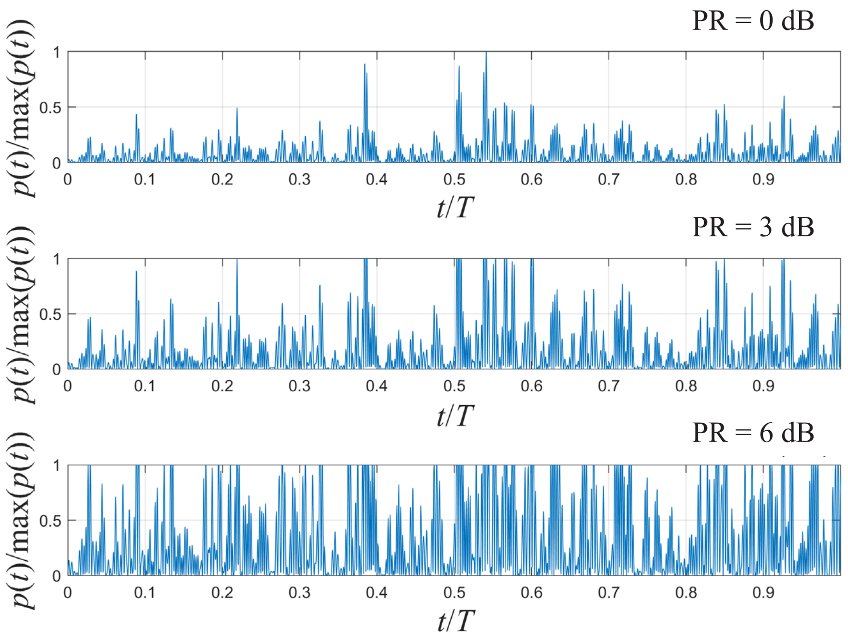

Fig. 6. Examples of normalized instantaneous signal power at different values of PR

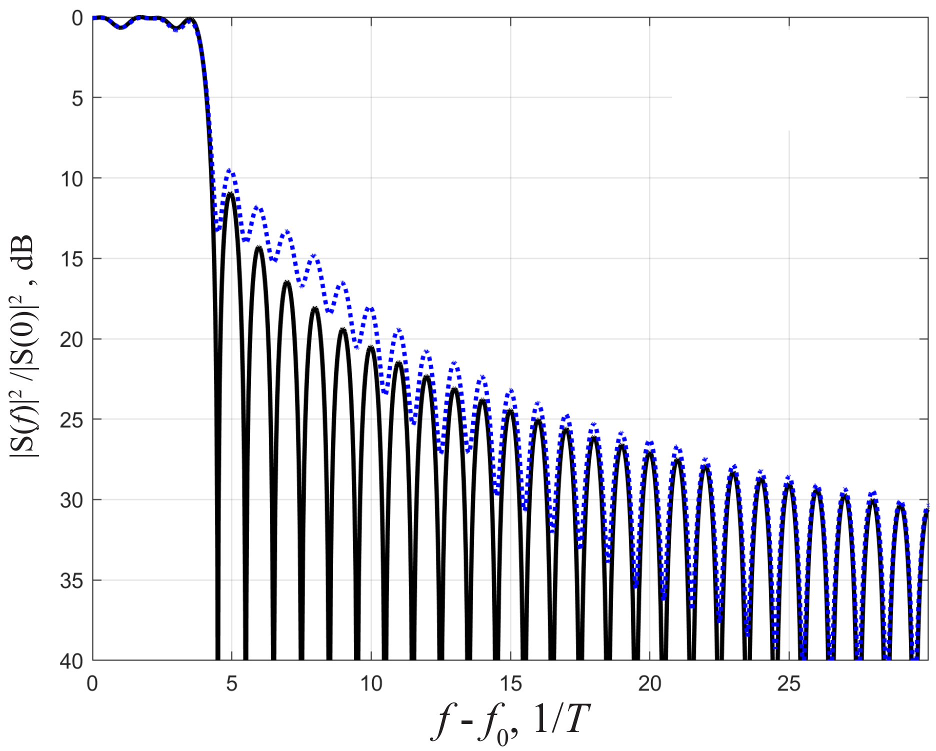

Fig. 7. Energy spectrum of signals at different values of PR
(—) – PR = 0 dB; (···) – PR = 6 dB

Fig. 8 *a* shows the dependence of the delivery time T_d on the level of the PR values for various values of the packet duration *T*. From the analysis of these graphs, we can conclude that with a decrease in PAPR by 5 dB, the delivery time is almost the same for OFDM signals. The resulting peak factor value is reduced to 5 dB, which significantly increases the overall efficiency of amplifiers and transmitting modules.

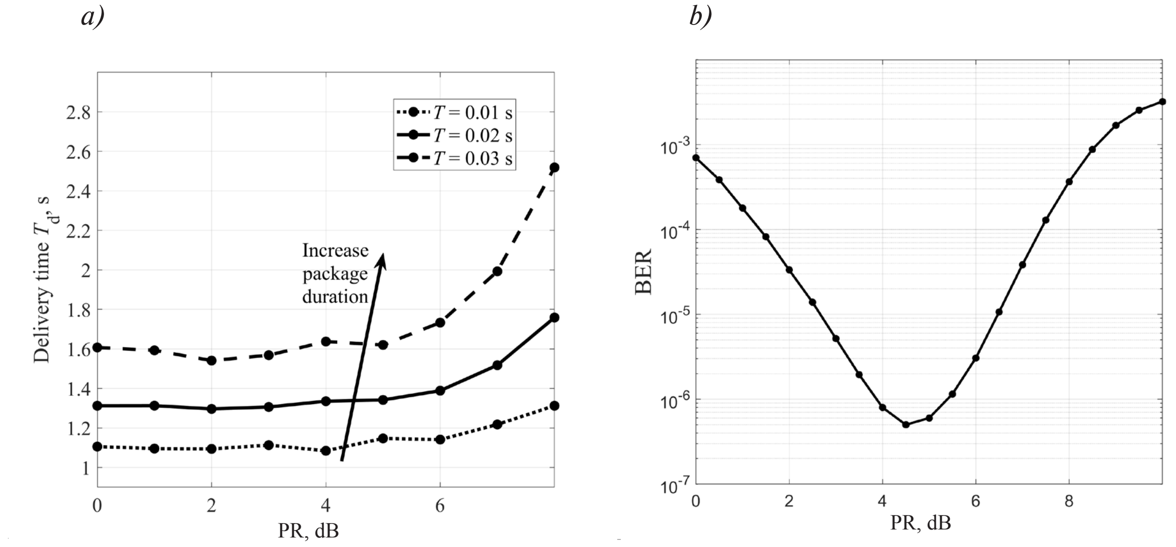

Fig. 8. Dependence of delivery time on the level of PR for various values of the duration of the packet *T*

In addition, the results also allow us to choose the appropriate values of the duration of the packet *T*, which helps to increase the speed of information transmission. For example, when increasing the duration of the packet *T* by 3 times, the delivery time increases from 1.1 s to 1.6 s, that is, it increases only 1.5 times. At the same time, the amount of transmitted information increases by 2 times. In [19], we have already found that, from the point of view of minimizing the probability of errors, the effective PR value for OFDM signals is 4.5–5 dB. This result is shown in Fig. 8 *b*. In the considered scheme of the transmitting module there is both a limiter and an amplifier. When limiting the value of the PAPR, the average power of the emitted oscillations increases, which reduces the error probability value for fixed signal-to-noise ratio values. However, with a further increase in the level of limitation, the signals from neighboring subcarrier frequencies start mutually affecting each other, which ultimately leads to an increase in the probability of error. These effects are also manifested in an increase in the message delivery time in the MBC channel (Fig. 8 *a*) when trying to limit the PAPR by more than 5 dB.

Combining the results of these researches, we can conclude that the combined use of amplifiers and limiters on the transmitting module can reduce the PAPR of the emitted oscillations. For the considered parameters of multi-frequency signals, the optimal PAPR reduction values to ensure a given delivery time in the MBC channel are about 5 dB.

Conclusion

In the process of simulation, the authors obtained estimates of the lower confine of the delivery time for the MBC channel in the case of the use of multi-frequency signals. We show it is possible to reduce the PAPR of the emitted oscillations by 5-6 dB for OFDM signals with 8 subcarrier frequencies. Also, with an increase in the packet size (the number of symbols transmitted in the OFDM packet) by 3 times, the delivery time increases only by 1.5 times. As a result, the total amount of information transmitted will increase by 2 times.

Further research will be associated with the addition of clock and symbol synchronization mechanisms, checksums, etc. to get closer to real conditions. In addition, we intend to test options for using smoothed optimal envelopes of multi-frequency signals.

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