Noncoherent Detection of Optimal FTN Signals with Differential Encoding

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Abstract. Noncoherent signal detection has a long history of application in the data transfer systems. Currently, this method is being considered for application in 6G communication standards. This article is devoted to the study of the possibility of joint use of noncoherent detection algorithm and optimal Faster than Nyquist (FTN) signals. The optimal FTN signals are obtained as a solution to the optimization problem in accordance with the criterion of the fixed reduction rate of out-of-band emissions. These signals are characterized by controlled interference in time, which allows you to get the desired level of bit error rate (BER) performance. The article presents the results of simulation modeling of data transmission in the channel with additive white Gaussian noise (AWGN) using the proposed optimal differential FTN (DFTN) signals and noncoherent symbol-by-symbol detection. A similar experimental study based on the software defined radio (SDR) platform was also conducted. The difference between the results of simulation and experiment is determined by the influence of symbol synchronization inaccuracy and is not more than 1 dB.

Keywords: Differential Faster than Nyquist signaling · Optimization problem · SDR platform

1 Introduction

In packet transmission, application of differential encoding gives the possibility not to use pilot subcarriers. It significantly simplifies implementation of the receiver since noncoherent algorithms may be used for signal processing. Noncoherent detection is mostly used in cases when it is difficult to provide high stability of frequency for reference generator at the transmitter and to provide the absence of phase jump of high-frequency oscillation in phase-locked loop at the receiver. For instance, such challenge takes place while developing the equipment for data transmission in low orbit small-sized telecommunication devices.

In paper [1] a thorough analysis of the sixty-year development of noncoherent detection methods is done. Special attention is paid to improvement of the

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ideas for such signal processing in the context of 6G. Terahertz communication systems and space-air-ground integrated network are considered in detail as well as non-orthogonal multiple access (NOMA) technology. In this work, the possibility of exploiting extra resources of the energy spectrum due to optimization of transmission channel capacity and improving the energy efficiency of detection is discussed as one of 6G development strategies for the next 10–15 years.

Spectral requirements for the operation of highly efficient telecommunication systems are considered in [2] to a certain extent. It is shown that new systems must work under conditions of spectral efficiency equal to 3–8 bps/Hz. It may be achieved only by application of Faster than Nyquist (FTN) signals. The challenges of overcoming the "Nyquist barrier" with minimum energy losses when using optimal coherent detection in an additive white Gaussian noise (AWGN) channel are considered in numerous works [2–4]. In [5,6] the possibility of binary signal transmission at the symbol rate $R = 1/\xi T$ $(0 < \xi < 1)$ which is 25% above the "Nyquist barrier" is established. The mentioned increase in the symbol rate does not cause bit error rate (BER) performance degradation.

The method of differential Faster than Nyquist signaling which is applied in channels with fading and Doppler frequency shift is presented in [7]. It allows to achieve rather high values of the spectral efficiency up to 0.96 bps/Hz for packet length 2048 bits in case of using signals based on root raised cosine (RRC) pulses with the roll-off factor $\beta = 0.3$.

The attempts to find the optimal possibilities to increase the symbol rate in the occupied frequency bandwidth have been made in [8]. It shows that an increase in the capacity of smooth transmission channel may be obtained by the solving of the optimization problem using well-known water-filling algorithm [9]. Due to this solution, the resources of spectral efficiency improving in channels with AWGN and nonrectangular shape of amplitude-frequency characteristic can be estimated according to Shannon. However, the obtained solutions to this problem do not give instructions how to use any type of modulation or pulse shape in practice.

The objective of this work is the study of the possibility of applying differential encoding to FTN signals which shapes are obtained as a result of solving of the optimization problem conforming to the criterion of the maximum reduction rate of out-of-band emissions. We use packet communication protocol and noncoherent detection algorithm in AWGN channels.

The rest of the paper is organized as follows. Section 2 contains the method of constructing optimal FTN signals with differential encoding and a basic diagram of information transmission system. In Sect. 3, the simulation model of transmitting differentially encoded data over AWGN channels is proposed and the results of the simulation modeling are presented. In Sect. 4, the possibility of practical implementation of the information transmission system is discussed. Finally, Sect. 5 summarizes the results of applying differential encoding and concludes the work.

2 Optimal FTN Signals with Differential Encoding

The synthesis of optimal FTN signals has been the subject of several works [3,4,10–13]. Let us consider a packet consisting of N modulation symbols. Each modulation symbol is transmitted by a signal of duration $T_s = LT$ $(L \geq 1)$ with an arbitrary pulse shape $a(t)$ and a maximum value A_0 at a carrier frequency f_0. Then the signal packet can be written in the following form (1):

$$s(t) = A_0 \sum_{k=0}^{N-1} a(t-kT)d^{(k)} \cos(2\pi f_0 t + \phi_0), \tag{1}$$

where $d^{(k)}$ is the value of the modulation symbol. For example, for binary phase shift keying (BPSK) $d^{(k)} = \pm 1$. It is assumed that the random initial phase ϕ_0 is uniformly distributed in the interval $[0,\, \pi]$.

The optimization problem is formulated as the search for the function $a(t)$ that provides the minimum of the functional J with the constraints on the signal energy (we take $A_0 = 1$), on the reduction rate of the out-of-band emissions (OOBE) and on the minimum level of intersymbol interference (ISI) [4,10]:

$$\arg\{\min_{a(t)} J\},\ J = \int_{-\infty}^{\infty} g(f) \left| \int_{-\infty}^{\infty} a(t) \exp(-j2\pi f t) dt \right| df. \tag{2}$$

The weighting function $g(f) = f^{2n}$ in (2) determines the occupied frequency bandwidth and the reduction rate of OOBE. The coefficient n in (2) is specified as a constraint on the solution to the optimization problem. The occupied frequency bandwidth ΔF will be determined by the criterion of the level $|S(f)|^2$ relative to the maximum value of the energy spectrum. For example, $\Delta F_{-30\text{dB}}$ corresponds to the occupied frequency bandwidth defined according to the level of the energy spectrum –30 dB.

The constraints on the signal energy and the boundary conditions that determine the reduction rate of OOBE have the following form [4,10]:

$$\int_{-T_s/2}^{T_s/2} a^2(t)dt = 1;\ \ a^{(k)}(t)\Big|_{t=\pm T_s/2} = 0,\ \ k = 0...(n-1), \tag{3}$$

where $a^{(k)}(t)$ is the k-th derivative of function $a(t)$.

The constraints on the level of ISI can be expressed numerically by cross-correlation coefficient. This coefficient takes into account the main effect on the value of K_0 of one nearest signal. Under these conditions, the expression for K_0 has the next form [4,12]:

$$K_0 = \max_{k=1...(L-1)} \int\limits_{-T_s/2+kT}^{T_s/2} a(t)a(t-kT)dt. \tag{4}$$

Another constraint is the constraint on the symbol rate R. It is included in (4) indirectly. When R is increased twice ($\xi = 0.5$, it means that the "Nyquist barrier" is exceeded by two times), the function $a(t - kT)$ in (4) is replaced by $a(t - kT/2)$.

Since $a(t)$ is symmetric with respect to zero or $T_s/2$, the original optimization problem (2) may be reduced to the problem of searching for the set of coefficients which minimizes the function of many variables [4]:

$$J(\{a_k\}_{k=1}^{m}) = \sum_{k=1}^{m} a_k^2 (2\pi k)^{2n}. \tag{5}$$

Note that the set of coefficients of the Fourier series in (5) is limited by m. The number m is chosen in accordance with the root mean square (RMS) error of $a(t)$ representation. In this work, m corresponds to the RMS error not more than 0.1%.

The optimization problem is solved for each set of constraints. The result of the solving is the Fourier series coefficients a_k in (5).

The methodology of the numerical solving of (5) is presented in [4]. The solutions for optimal FTN signals which will be used in the simulation modeling and experimental research are given below. The reduction rate of OOBE of the spectrum corresponding to optimal signal sequence is at least $1/f^6$ ($n = 2$ in (2)). Due to the cross-correlation coefficient $K_0 = 0.01$ the energy loss relative to the theoretical BER performance is limited by 0.3 dB.

Figure 1, a) shows the pulse shapes $a(t)$ for signal duration $T_s = 2T,\ 8T,\ 16T$ and the symbol rate $R = 1/T$. The values of $a(t)$ are normalized according to (3). In Fig. 1, b) the normalized energy spectra $|S_a(f)|^2/|S_a(0)|^2$ of random signal sequences are plotted.

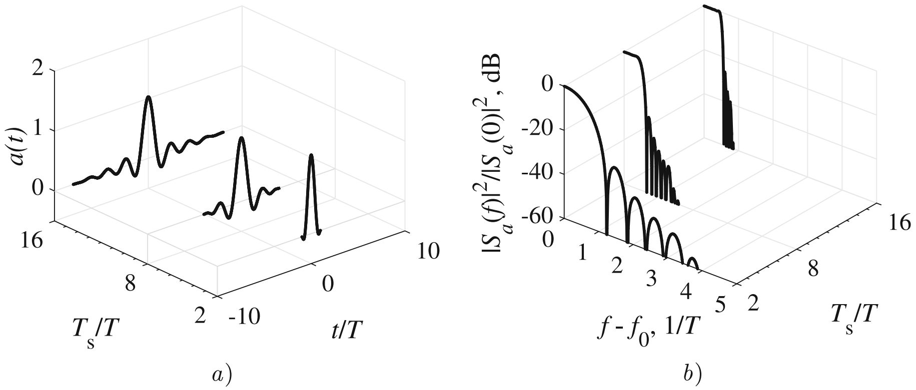


Fig. 1. Optimal pulses $a(t)$ (a) and corresponding normalized energy spectra (b).

To detect an FTN signal packet under conditions of an unknown initial phase ϕ_0, differential Faster than Nyquist signaling (DFTN) is used. In Fig. 2 the block diagram of data transmission using DFTN signals is presented. Information symbols generated in the block "Binary source" go to "BPSK mapper", where the original bits $\{0/1\}$ are transformed into $\{+1, -1\}$. The transformed symbols of the channel alphabet undergo differential encoding. The block "Modulator of optimal FTN signals" forms optimal pulse shape $a(t)$ and modulates a carrier frequency. The signal packet on the output of this block is determined by $a(t)$ shape, signal duration T_s and by the symbol rate R. The formed signal is amplified and transmitted over AWGN channel.

The mixture of DFTN signal and noise is fed to a low-noise amplifier (LNA) and then to the block "Demodulator of optimal FTN signals". Here the signal is demodulated according to the pulse shape $a(t)$, its duration and the symbol rate R. The decisions $\{+1, -1\}$ from the output of the demodulator go to the block "Differential Decoding" and then to "BPSK demapper". Finally, the sequence of detected information bits is formed.

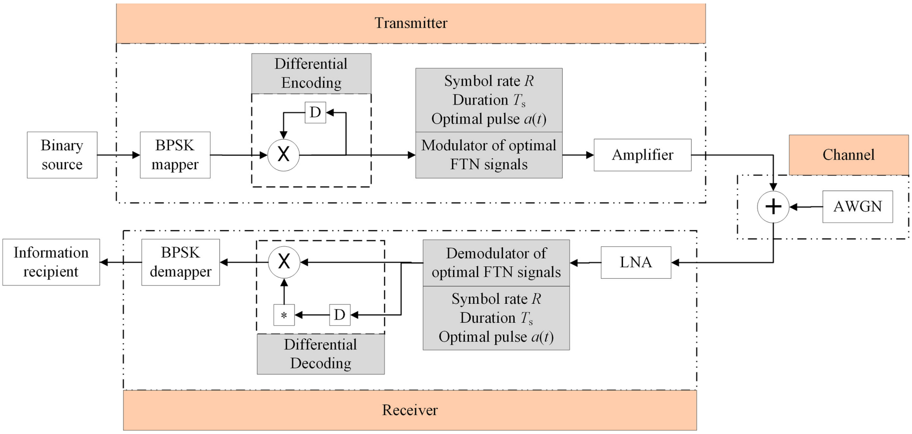


Fig. 2. Block diagram of data transmission using DFTN signals.

Let us analyze noncoherent detection of optimal FTN signals with the pulse shapes which are the solutions to the optimization problem conforming to the criterion of the maximum reduction rate of OOBE. This analysis is done with the help of simulation modeling and experimental research on the block diagram in Fig. 2.

3 The Simulation Model of Data Transmission Using Differential Encoding

The purpose of the simulation modeling is to estimate BER performance of noncoherent symbol-by-symbol detection for optimal binary FTN signals at the symbol rates from $R = 1/T$ to $R = 2.5/T$. In order to exclude symbol synchronization errors, we use the same pulse sequence at a clock rate to control the operation of the blocks "Modulator of optimal FTN signals" and "Demodulator of optimal FTN signals" (Fig. 2).

The simulation model is shown in Fig. 3. Information bits are generated in the block "Binary source". The bits are transformed into modulation symbols and differentially encoded. Then, modulation with the use of optimal FTN signals with the specified symbol rate R, the signal duration T_s and the required reduction rate of OOBE n is performed.

The formed signal goes to the block called "Calculating of energy spectrum". Here the occupied frequency bandwidth is determined for further estimation of the spectral efficiency. The signal sequence is transmitted through the "Channel", where AWGN is added. The value E_b/N_0 is set in the block of initialization of the simulation parameters. The signal energy E_b calculated by (3) is constant for all T_s. $N_0/2$ is average power spectral density of AWGN.

The mixture of DFTN signal and noise is fed to the input of the receiver where demodulation and decoding are carried out. The obtained estimations of the information bits are used for calculating of the error probability p. At least 10^6 information bits are transmitted to calculate each value of p.

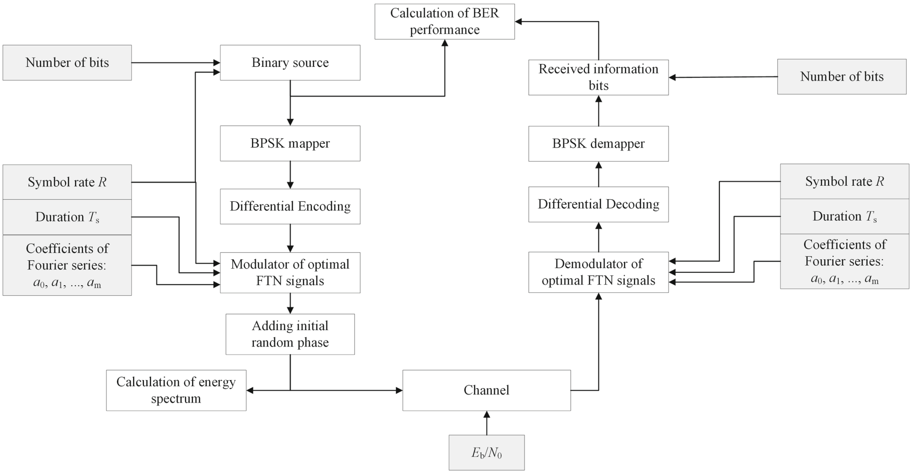


Fig. 3. Block diagram of simulation model of data transmission using DFTN signals.

The obtained spectral characteristics are given in Fig. 4. Optimal signals with $n = 2$, $K_0 = 0.01$, $T_s = 8T$ transmitted at the symbol rate $R = 1/T$ and $R = 2/T$ have been used. During simulation, the sample rate has been equal to 1 MHz, $T = 100\,\mu s$, $R = 1/T = 10$ kbits/s, $R = 2/T = 20$ kbits/s. As it is seen in Fig. 4, the occupied frequency bandwidth defined by the energy spectrum level −30 dB is equal to $\Delta F_{-30\,\mathrm{dB}} = 24.2$ kHz for $R = 2/T$ and $\Delta F_{-30\,\mathrm{dB}} = 15.2$ kHz for $R = 1/T$. The occupied frequency bandwidth defined by the energy spectrum level -50 dB is equal to $\Delta F_{-50\,\text{dB}} = 45\,\text{kHz}$ for $R = 2/T$ and $\Delta F_{-50\,\text{dB}} = 38\,\text{kHz}$ for $R = 1/T$.

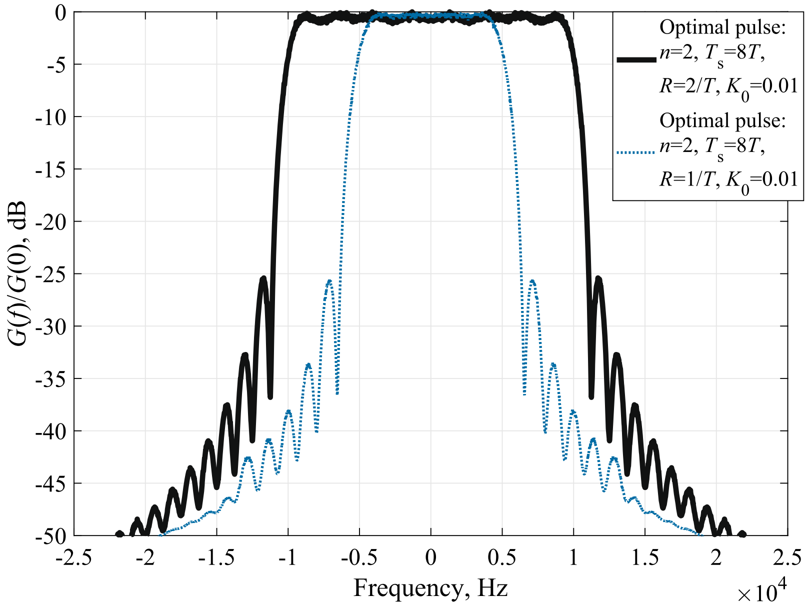


Fig. 4. Spectral characteristics of optimal DFTN signals.

The studied BER performance of noncoherent detection of optimal DFTN signals is presented in Fig. 5. Analyzing the dependencies plotted in Fig. 5, we can make the following conclusions.

First of all, BER performance of noncoherent detection for optimal DFTN signals obtained for the rate $R = 1/T$ and $R = 2/T$ almost equal to the one which conforms to the case of classical differential BPSK (DBPSK) signals with a rectangular pulse shape. The energy losses relative to these signals do not exceed 0.5 dB.

Secondly, noncoherent detection of optimal DFTN signals causes the energy losses about 1 dB compared to coherent detection of classical BPSK signals.

Thirdly, when optimal DFTN signals synthesized for $R = 2/T$ are transmitted at the rate $R = 2.5/T$ (2.5 times above the "Nyquist barrier"), the energy losses grow significantly. Thus, for $p = 4{\cdot}10^{-2}$ the energy losses reach 6 dB.

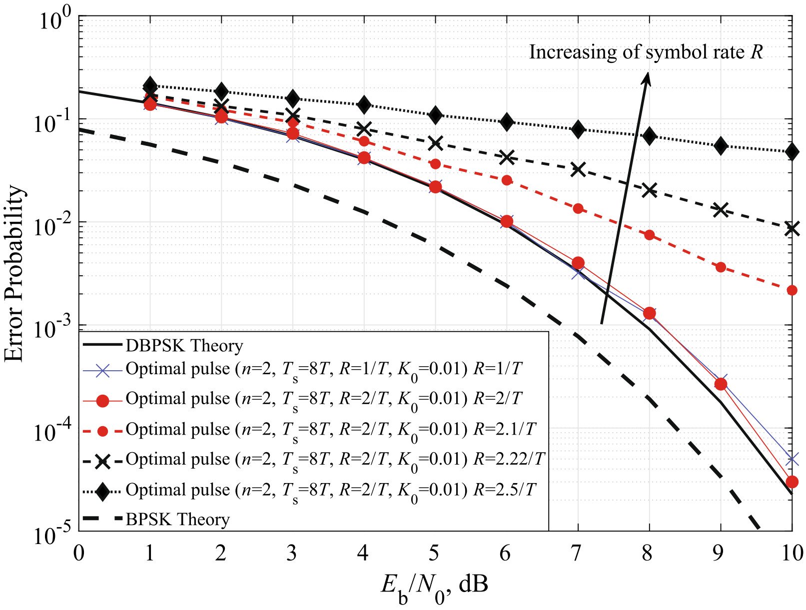


Fig. 5. BER performance of optimal DFTN signals during simulation modeling.

4 Experimental Research

The experimental research is done to estimate BER performance of noncoherent detection of binary optimal FTN signals at the rates $R = 1/T$ and $R = 2/T$ under real conditions with symbol synchronization. We use packet communication protocol and noncoherent detection algorithms in AWGN channel. The packet includes the preamble which represents 64-bit synchronization sequence, and 2048 information bits which correspond to the informational part of the packet. Optimal FTN signals are applied in the informational part of the packet.

The SDR platform NI USRP 2920 is used in the experimental research. The transmitting module consists of the soft modem and the SDR platform (Fig. 6). The soft modem forms the packet with adding the preamble to detect the beginning of the transmission at the receiver. Then the formed packet goes to the block “BPSK Mapper”. Then, the resulting modulation symbols are differentially encoded and fed to the block “Modulator of optimal FTN signal”. From the output of this block, the samples of quadrature components are transmitted to the SDR platform NI USRP 2920 via Ethernet for digital to-analog conversion (DAC) and for radiation at the carrier frequency.

The spectrum analyzer Agilent Technologies N9342C is used to monitor the spectrum. In the experiment, the carrier frequency is equal to 402 MHz, the sample rate is equal to 1 MHz, $T = 100\,\mu s$, $R = 1/T = 10$ kbits/s, $R = 1/T = 20$ kbits/s.

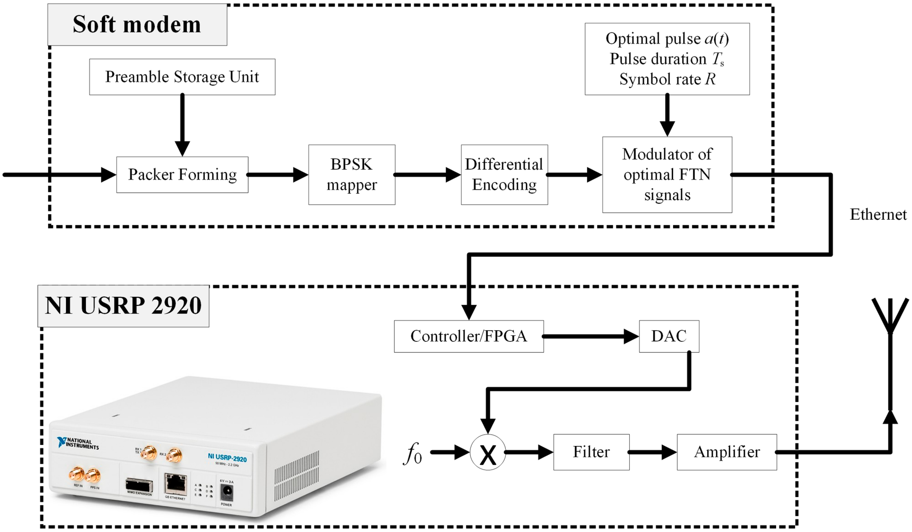


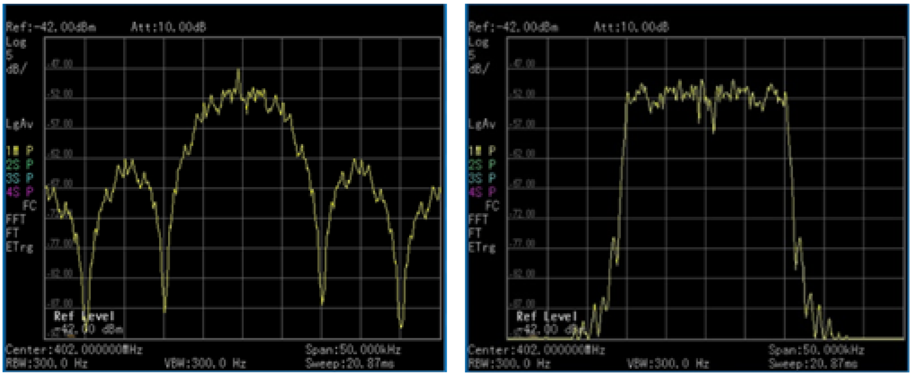
Fig. 6. Block diagram of the transmitter module of DFTN signals based on the SDR platform.

The results of the experiment for optimal FTN signals of duration $T_s = 8T$ with $K_0 = 0.01$ are given in Fig. 7. Figure 7, *a*) represents the spectrum of the signals with rectangular pulse shape used in the packet preamble. Figure 7, *b*) shows the energy spectrum of optimal FTN signals for the rate $R = 2/T = 20$ kbits/s. The occupied frequency bandwidth defined by the level −30 dB of the energy spectrum reaches 24.5 kHz for $R = 2/T$. These results correspond to the results of the simulation modeling (Fig. 4).

The block diagram of the receiver module for the case of DFTN signals is illustrated in Fig. 8. From the output of the receiving antenna the mixture of the signal and noise goes to the input of the SDR platform NI USRP 2920. At first, the signal with noise passes through a LNA. Then the signal is shifted to zero frequency and fed to analog-to-digital converter (ADC). At the final stage, the quadrature components are formed and transmitted to the soft modem via Ethernet.

During the first step of the reception the preamble must be found. If the preamble is found successfully, at the second step the samples of the quadrature components go to the demodulator of optimal FTN signals. The processing is carried out taking into account the symbol rate R and signal duration T_s. On the output of the demodulator the values of detected modulation symbols $\{\pm 1\}$ are formed. The sequence of detected modulation symbols must be differentially decoded and fed to "BPSK demapper". As a result, we obtain the sequence of detected information bits.

The detected information packet is compared with the transmitted one for calculation of BER. BER performance is estimated by variation of the signal-



a)   *b*)

Fig. 7. Experimental spectral characteristics of optimal DFTN signals.

to-noise ratio. At each value of the signal-to-noise ratio at least 10^5 information bits are transmitted (the transmission of the information packets is repeated, if necessary).

The experimental results of BER performance estimation for optimal DFTN signals with $T_s = 8T$ and $K_0 = 0.01$ can be seen in Fig. 9. The transmission rate is $R = 1/T,\ 2/T,\ 2.22/T,\ 2.5/T$. The experiment has been carried out with the help of the model presented in Figs. 6 and 8 for an AWGN channel.

It can be noticed that the energy costs significantly grow with an increase in the transmission rate. Thus, if the "Nyquist barrier" is exceeded by 2.5 times,

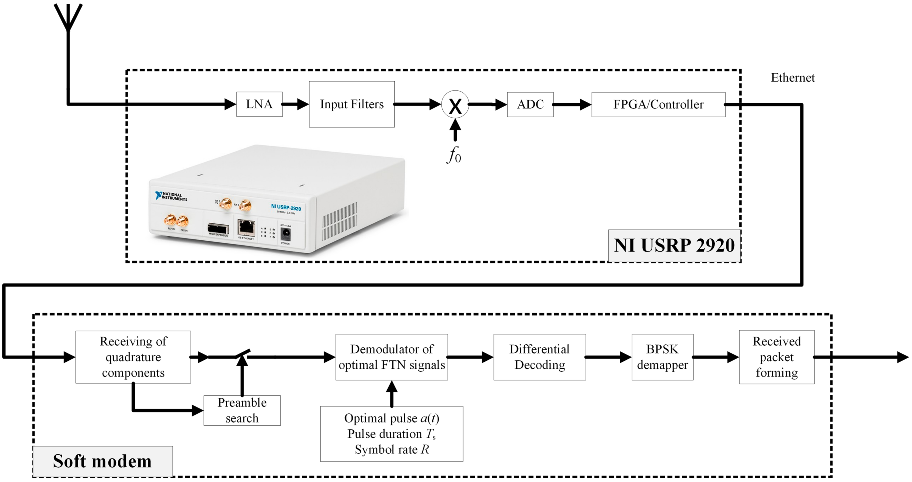


Fig. 8. Block diagram of the receiver module of DFTN signals based on the SDR platform.

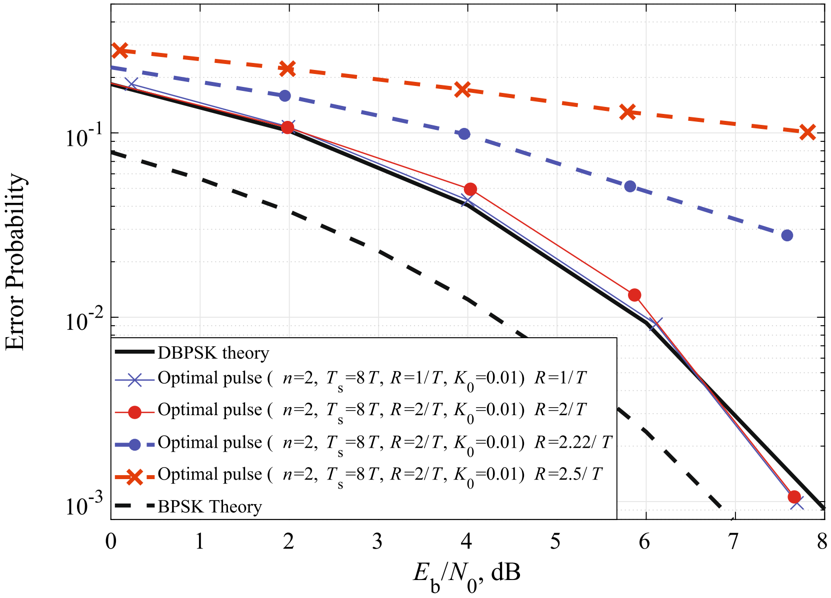


Fig. 9. Experimental BER performance of optimal DFTN signals.

the energy losses reach 5.8 dB at the error probability $p = 10^{-1}$. These values differ from the values obtained by the simulation modeling (Fig. 5) at most by 1 dB. Therefore, we can conclude that the influence of symbol synchronization inaccuracy with the preamble of 64 bits turns out to be insignificant for implementation of noncoherent symbol-by-symbol detection of optimal FTN signals with differential encoding, when the transmission rate is 2–2.5 times above the “Nyquist barrier”.

5 Conclusions

In this work, the possibilities of application of differential encoding for FTN signals with optimal pulse shapes conforming to the criterion of the maximum reduction rate of OOBE are considered under conditions of packet communication protocol and noncoherent detection algorithm in channels with AWGN. It is shown that noncoherent detection of optimal DFTN signals obtained for the symbol rate $R = 1/T$ and $R = 2/T$ provides almost theoretical BER performance of classical DBPSK signals with rectangular pulse shape. The energy losses compared to these signals are not more than 0.5 dB.

When optimal DFTN signals obtained for the symbol rate $R = 2/T$ are transmitted at the rate increased up to $R = 2.5/T$ (2.5 times above the “Nyquist barrier”), the energy losses grow significantly. Thus, at the error probability $p = 4 \cdot 10^{-2}$ the energy losses are about 6 dB.

The results of the experimental research show that symbol synchronization inaccuracy is insignificant and leads to the energy losses at most 0.2 dB in case of packet transmission.

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