Time and phase synchronization in communication system with a digital pseudo-random modulation

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Abstract. The paper is concerned a model of a digital communication system where the samples of white Gaussian noise with zero mean and dispersion \(\sigma^2\) are used as a modulated (carrier) low-frequency signal. Methods of the digital-phase modulation are used in a system for transmission of information message. The communication technology reminds CDMA (Code Division Multiple Access). However, a key of feature of this system is that digital samples of white Gaussian noise are used to increase the spectrum of the information message instead of traditional Walsh-Hadamard binary sequences. In this system the repeat period of the pseudo-random sequence values is specified by the parameter and can be equal to the time (duration) of several information symbols contrast to CDMA, in which the duration of repetition period equals to the duration of modulating symbol. On the one hand, the solution allows you to increase the confidentiality of the transmitted message and more evenly expand its frequency spectrum as compared with the existing of CDMA methods. On the other hand, scientists face two significant scientific tasks that make the work meaningful. First, it is necessary to ensure the synchronous operation of pseudo-random sequence generators in the receiving and transmitting devices. Secondly, it is necessary to define a phase shift amount of the frequency-change oscillator in receiving device. Both problems are the result of the asynchronous starting of the receiver. A control signal is used to solve these problems in the radio communication system which is transmitted simultaneously with an information message. So the result of modulator work is the sum of both information and control modulated signals. The proposed methods and algorithms provide the coherent signal processing with the digital pseudorandom modulation in the receive path of communication channel. The paper is a course of early research studies and it contains a detailed mathematical description of modulation and demodulation signals in the communication system with the digital pseudorandom modulation. The numerical model of the system is described in MatLab language. All numerical experiments were carryout in a mathematical computing system of MatLab.

1. Introduction
Since the middle of the last century, chaotic signals have been actively used in communication systems to expand the spectrum of the transmitted message. Initially, until the 60s, spread spectrum signals were used only in a military radio equipment to ensure safe communication under the conditions of deliberate interference and the threat of signal interception \([6]\). Nowadays spread spectrum systems are the core of commercial applications such as mobile and satellite communications. In civilian communication systems the main requirement imposed on number of subscribers simultaneously using the communication channel. Today, not only people can be cellular subscribers, but also devices. This feature has already been incorporated into the fifth generation cellular communication system (5G NR).
Multiple access technologies are used to maintain a large number of subscribers in the network. Wireless communication with multiple accesses is possible if the transmitted signals, in a sense, are separable and orthogonal. In practice, signals can be spaced in time (Time-Division Multiple Access (TDMA)), separated in frequency (Frequency-Division Multiple Access (FDMA)), or using code (Code-Division Multiple Access (CDMA)). CDMA technology is implemented through the Direct Sequence Spread Spectrum (DSSS) method, the essence of which is to replace each bit of an information message with a sequence of 10 or more zeros and ones. All signals simultaneously use the entire selected spectrum, but for each signal, the spreading sequences or frequency jump patterns are different. Information theory indicates, CDMA achieves the same efficiency as TDMA or FDMA systems in an isolated cell only if there are optimum numbers of subscribers in the network. However, even with a single-user detection mode, the CDMA architecture is beneficial for cellular networks, so it allows to manage flexible and efficient of radio resources (i.e., assign frequency bands, time intervals, power levels) and, more importantly, naturally implement the dynamic channel reallocation procedure. The main disadvantage of CDMA methods are the correct choice of extension sequences and their relative phases. The number of these sequences is too small and the number of subscribers in the network is directly connected with it [2]. More often in the modern cellular networks Walsh-Hadamard binary orthogonal sequences are used CDMA.

The paper is concerned the communication system based on the method of direct expansion of the signal spectrum like CDMA. However, digital pseudorandom samples with zero mean and dispersion σ² generated by the Mersenne Twister algorithm [3] are used as the spreading sequence unlike CDMA. In the future, this approach can significantly increase the number of subscribers which can simultaneously use a common communication channel. For detecting the message bits the correlation methods are used. The proposed type of modulation can be used in navigation systems of unmanned ground transport and provide an opportunity to navigate under the conditions of multiple accesses (for example, under the conditions of traffic congestion). The work is a continuation of [4-5] and includes the entire mathematical apparatus that is necessary to describe the operation of communication system with a pseudo-random digital modulation.

2. Transmitting part of the system

The figure 1 shows the functional diagram of the transmitting part of the system. In block 1, each pair of bits of the information message is mapped to one of the points of the QPSK (Quadrature Phase Shift Keying) constellation, forming the complex signal I(t, t_s) + iQ(t, t_s). The real part of the complex signal modulates the samples of pseudo-random sequence (PRS) ξ(t, t_n) generated in block 2. Similarly the values Q(t, t_s) modulate pseudo-random samples η(t, t_n) generated by block 3. The time t_n for which the values at the output of the generators of pseudo-random sequences ξ(t, t_n) and η(t, t_n) are changed is several tens of times less than the time t_s, for which the values of I(t, t_s) and Q(t, t_s) are changed.

The blocks located at the bottom of the diagram and highlighted with a dotted line are used to form a signal message. A pre-known sequence S(t, t_s) of signal message bits is translated into bipolar form, and modulates pseudo-random samples ζ(t, t_n) generated by block 4. This signal is supplied to the switch input K1. The values ζ(t – Nt_n, t_n) delayed by N time intervals of t_n come to the input of the K2 switch. The delay value N is a parameter of the communication system. As a result, during the transmission of a signal message, a complex signal S(t, t_s)ζ(t, t_n) + iζ(t – Nt_n, t_n) is formed at the outputs of the switches K1 and K2. Denote by N_{bits} the number of bits in the signal message. Immediately, after the transmission of the signal message (N_{bits} * t_s is transmission duration), the switches K1 and K2 switch to the second input, which receives M samples of the pseudo-random sequence ζ(t, t_n) generated in block 5. The values ξ(t, t_n), and η(t, t_n) ξ(t, t_n) and ζ(t, t_n) are uncorrelated counts of white Gaussian noise with zero mean and variance σ². The control unit 6 is the source of the predefined signal message bits S(t, t_s), and also monitors the status of switches K1 and K2. In addition, after the last bit of the signal message is transmitted, block 6 restarts the pseudo-random sequence generator (block 5 in figure 1). After that, after a period of time equal to one character interval
(ts) block 6 restarts the pseudo-random sequence generators ξ(t, t_n) and η(t, t_n) (blocks 2 and 3, respectively). The signal message generation procedure is then repeated.

![Figure 1](image.png)

**Figure 1.** The functional diagram of the transmission system with a pseudo-random digital modulation.

The complex signal containing the signal message generated in the lower part of the flowchart is added to the pseudo-random complex counts containing the information message. The obtained result is transferred by heterodyning to the high-frequency region with the central frequency \( \omega_0 \). Expression 1 describes a modulated high-frequency signal \( X(t, t_n, ts) \):

\[
X(t, t_n, ts) = \begin{cases} 
[I(t, ts)\zeta(t, t_n) + S(t, ts)\zeta(t, t_n)\cos(\omega_0t)] \cos(\omega_0t) - \\
-(Q(t, ts)\eta(t, t_n) + \zeta(t - Nt_n, t_n)) \sin(\omega_0t)], & 0 < t \leq N_{bits}^S * ts, \\
[I(t, ts)\zeta(t, t_n) + \zeta(t, t_n)\cos(\omega_0t)] + \\
+(Q(t, ts)\eta(t, t_n) + \zeta(t, t_n)) \sin(\omega_0t)], & N_{bits}^S * ts < t \leq (N_{bits}^S + 1) * ts,
\end{cases}
\]

where value \((N_{bits}^S + 1) * ts\) is the retry period for sending the signal sequence.

3. **Receiving part of the system**

Figure 2 shows the functional diagram of the receiving part of the system. The modulated high-frequency signal with carrier frequency \( \omega_0 \) after multiplication by inphase and quadrature components of the carrier oscillation and filtering by low-pass filters (blocks 1 and 2 in the scheme) is transferred to the zero frequency. An expression 2 and 3 describe the signals \( Y_I(t, ts, t_n) \) and \( Y_Q(t, ts, t_n) \) on the outputs of the low-pass filters (blocks 1 and 2 in figure 2):
The sign of the difference signal \( Y(t, t_s, t_n) \) is determined by the values of the bits of the signal message \( S(t, t_n) \). Reception of the signal message (control unit 6 on the diagram) allows us to solve at once two problems, traditionally, facing developers of systems of digital communication with pseudo-random digital modulation. Firstly, the determination of the time of reception of the last bit of the signal message provides a synchronous restart of pseudo-random sequence generators in the transmitting and receiving points of communication. This, in turn, provides the possibility of coherent signal processing when detecting information messages. Secondly, the same moment indicates the moments at which the modulation QPSK-symbols of the information message replaces each other. Thus, the reception of a signal message provides a solution to the problem of temporary synchronization of the receiving and transmitting points of communication.

After detecting the last bit of the signal message, the control unit 6 generates a restart signal for pseudo-random sequence \( \zeta(t, t_n) \) generator (block 5), changes the state of keys K1 and K2, switching the pseudo-random sampling sequence \( \zeta(t, t_n) \) to the inputs of correlators 3 and 4. As a result, signals defined by expressions 6 and 7 are generated on the outputs of correlators within one character interval \( t_s \):

\begin{align*}
\langle Y(t, t_s, t_n), \zeta(t, t_n) \rangle &= \frac{1}{2} \sigma^2 \zeta(t, t_n)(\cos(\varphi) - \sin(\varphi)), N_{\text{bits}}^S \ast t_s < t \leq (N_{\text{bits}}^S + 1) \ast t_s \quad (6) \\
\langle Y_Q(t, t_s, t_n), \zeta(t, t_n) \rangle &= \frac{1}{2} \sigma^2 \zeta(t, t_n)(\sin(\varphi) + \cos(\varphi)), N_{\text{bits}}^S \ast t_s < t \leq (N_{\text{bits}}^S + 1) \ast t_s \quad (7)
\end{align*}
Figure 2. Functional diagram of the receiving system.

It allows to calculate the phase multiplier that compensates the local oscillators of receiver and transmitter phase difference:

\[
\sigma^2(t, t_n)e^{-i\phi} = \left( \langle Y_I(t, t_s, t_n), \zeta(t, t_n) \rangle + \langle Y_Q(t, t_s, t_n), \zeta(t, t_n) \rangle \right) - \\
- i \left( \langle Y_Q(t, t_s, t_n), \zeta(t, t_n) \rangle - \langle Y_I(t, t_s, t_n), \zeta(t, t_n) \rangle \right)
\]

The control unit 6 restarts the generator 7 of complex pseudo-random sequence \( \xi(t, t_n) + i\eta(t, t_n) \) later one character interval of time \( t_s \) after detection of the signal message and sets the value \( \sigma^2(t, t_n)e^{-i\phi} \) of the turning coefficient at the input of the multiplier in the receiving path of the information message. As a result, the first input of the correlator 9 generates a signal defined by the expression 9:

\[
\left( J(t, t_s)\xi(t, t_n) + i(Q(t, t_s)\eta(t, t_n)) \right) \sigma^2(t, t_n) = \\
= \left( Y_I(t, t_s, t_n) + iY_Q(t, t_s, t_n) \right) \sigma^2(t, t_n)e^{-i\phi}
\]

The complex pseudo-random samples \( \xi(t, t_n) + i\eta(t, t_n) \) are progressed to the second input of this correlator. By force to the mutual noncorrelatedness \( \xi(t, t_n) \) and \( \eta(t, t_n) \) signs of the real and imaginary parts of the signal at the output of the correlator 9 are completely determined by values of bits of the information message. Block 10 of the receiving system maps the QPSK constellation points to the values of information message bits.

4. Results
The numerical model of the receiving-transmitting system was implemented in the environment for the scientific calculations Mathworks MatLab. The following system parameters were used in the simulation. The variance Gaussian pseudorandom sequences \( \xi(t, t_n) \), \( \eta(t, t_n) \), \( \zeta(t, t_n) \) and \( \zeta(t, t_n) \) was
set equal $\sigma^2 = 1$. The delay $N$ in the formation of a pseudo-random signal for a quadrature channel containing a signal message was equal to $N = 10t_n$. The character time interval was equal to $t_s = 64t_n$.

Figure 3 shows examples of waveforms obtained in the simulation of the communication system. Waveform 1 represents waveform of the sequence of information bits for the common-mode channel at the input of the transmitting device. Oscillogram 2 represents waveform of the signal in the common-mode channel of the receiving path at the output of the low-pass filter. As expected, this signal was white Gauss noise.

![Figure 3. Examples of waveforms obtained in the simulation of the communication system.](image)

Waveforms 3-5 represent the waveforms of the real part of a signal at the output of block 9 at the angles of rotation of the phase (0°, 90° and 180°, respectively, without phase adjustment of the input values. It is seen that in the absence of a phase shift, the sign on the waveform 3 is determined by the value of the modulating bit (waveform 1). If the phase shift value is 90°, the level of correlation maxima is 0, it is impossible to detect the information message. At the value of the phase rotation angle equal to 180°, the signal inversion is observed (waveforms 5). The waveforms 6 represent the waveform of the real part of the signal from the output of block 9 when performing phase correction. It is seen that the sign of the signal at the output of the correlator is determined by bits values of the information message.

5. Summary
Waveforms obtained during the simulation fully confirm the efficiency of the proposed scheme of the communication system with pseudo-random digital modulation. Detection of the signal message provides synchronization of pseudo-random sequence generators, as well as solving issues related to the time and phase synchronization of the receiving and transmitting points of communication.

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