Model of ultra-wideband signal transmission and reception using the pseudorandom carrier

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Abstract. We show the possibility of transmission and subsequent decoding of an ultra-wideband signal in an optical communication channel using a noise-like carrier. For an example, the simulation of the transmission of word encoded with Baudot telegraph code was realized. The necessary sequence of symbols was introduced into the noise-like carrier represented by a pseudo-random sequence of ultra short pulses. The possibility of the transmitted word decoding to a high degree of reliability was shown by calculation of auto- and cross-correlation functions. To some extent, the method can be treated as an analog of pulse-position modulation.

1. Introduction

One of the crucial points in the development of information transmission technical means using electromagnetic radiation of visible and even shorter wavelength optical range is the development of technology of all-optical methods allowing to implement the theoretical limit of the speed of information processing. This process is associated with the development and upgrading of femto- and attosecond generators of high power laser pulses containing only a small number of the electromagnetic field oscillations, as well as with improving of pseudo-random "white" light sources, as the emitters of so-called supercontinuum radiation characterized with very broad spectrum that leads to very small temporal coherence, but characterized with high spatial coherence [1, 2].

On the way to solution of general problem formulated above, are the problems associated with

• the introduction of digital information into the carrier wave using various methods of modulation of the light flow,
• the decoding of information at the end point of transmission line, and
• the reliability and security of the communication channel.

For the first two points, most of existing methods are based on the pulse-position modulation of ultrashort laser pulses [3]; in this case, the signal is formed by time-pulse modulation. The only information parameter is the position in time of the rising edge of the pulse. With this type of modulation, the position of each pulse depends on the instantaneous value of the modulating signal and varies with respect to the position of periodic reference pulses generated by the receiver itself. In order to transmit a logical zero, the working pulse has to be sent, for example, slightly earlier than its predetermined position in the pulse sequence, and vice versa, for the transmission of the logical unit.
One of the most promising approaches to the solution of optical communication problems is in the development of optical technologies based on the use of so-called "complex" signals and noise-like data carriers that are of the greatest information capacity [4]. As a rule, the signal generated by the source of white light is transmitted by the amplitude modulation of the light flow. At the same time, other methods of an optical signal formation are possible, which are close to phase and pulse-code modulation by their implication. The detection of a signal in this case is possible by applying correlation methods of analysis of the light flow, which outwardly represents a random process. It is well known that the measurement of auto- and cross-correlation functions is the optimum method of a signal of known form detection, against the background of random additive noise [5].

In [6], we experimentally demonstrated the possibility of using one of the simplest optical systems for introducing the information into a random (noise) light flow of a thermal source with a "white" spectrum, and consequent identification of the corresponding signal, i.e. decoding. In fact, we suppose that it is more promising to use the impulses of supercontinuum as the data carrier in a similar communication system [1, 2].

The easiest technique to introduce one bit of information into a random or pseudorandom light flow is in the delay of the corresponding wave for a fixed time at the condition of the exact reservation of wave amplitude dependence on time. The presence or absence of a pulse at a certain "location" due to delay of the copy of the part of wave with respect to the carrier is transferred to the binary sequence of 0 and 1, which allows to decode the transmitted signal. This procedure is equivalent to pulse-code modulation and can be applied to the radiation of both a thermal source and a pulsed supercontinuum source.

In this paper, different methods of introducing information into the light flow, based on the use of bipolar sequences and allowing to encode alphanumeric symbols are studied. The obtained results form the basis for the subsequent experimental implementation of coding, transmission and decoding of information by the optical method.

2. Model
2.1. Carrier
For the transmission of one bit into an ultra-wideband pseudo-random continuous or pulsed light flow, an additional implementation of the same process is made, but time-shifted by a certain interval. The spectrum of such coded signal by its external characteristics (amplitude and phase) can only slightly differ from the spectrum of the original signal, however, the correlation properties of the generated light flow vary significantly. In the cross-correlation function, additional maxima appear, corresponding to the presence of shifted copies of the original signal in general sequence of pulses. Based on the analysis of the position of maxima of the cross-correlation function, information is decoded.

For the formation of optical signal, the Legendre sequence is used as a pseudo-random sequence in our study. The binary Legendre or quadratic residue sequences exist for all lengths \( L \) which are prime. They can be constructed using the Legendre symbol \((i/L)\), a Legendre sequence \( a_0, a_1, \ldots, a_{L-1} \) is then formed by writing \( a_i = (i/L) \), \( 0 < i < L \), and the value of \( a_0 \) can be taken either as 1 or \(-1\) [7].

The main characteristics of pseudo-random sequences are an autocorrelation function, defined for a discrete real-valued sequence \( y \) as

\[
R_{yy}(l) = \sum_{n \in Z} y(n)y(n - l), \tag{1}
\]

and the cross-correlation function of two real-valued sequences \( f \) and \( g \):

\[
CC(n) = \sum_{m=-\infty}^{\infty} f(m)g(m + n). \tag{2}
\]
Figure 1. Autocorrelation function of the Legendre sequence for \( p = 1987 \) (a). Current dispersion of the autocorrelation function (b).

The “current” dispersion as a function of \( x_i \) is calculated than on the intervals \([i_k, i_k + N]\), \( k = 1, 2, 3 \ldots \):

\[
CV(x_i) = \frac{1}{N} \sum_{i_k}^{i_k+N} (x_{i_k} - \mu_k)^2, \quad \mu_k = \frac{1}{N} \sum_{i_k}^{i_k+N} x_{i_k}. \tag{3}
\]

The example of autocorrelation function of such a sequence is shown in Fig. 1 together with its “current” dispersion.

As can be seen from Fig. 1, the Legendre binary sequence composed of \(-1\) and \(1\) has distinctive correlation properties. In particular, the dispersion of the autocorrelation function is small at small shifts and increases with increasing delay.

2.2. Message
Telegraph codes like the 5-bit Baudot code [8] are the most easily implemented in the optical range.

We give an example of encoding and decoding of the short word “SPB”. According to the Baudot code table, such a message can be written as a sequence \([10100 \ 01101 \ 10011]\) (control characters are not included).

3. Results and Discussion
All calculations were performed for bipolar sequences generated using the Legendre symbol. The Legendre sequence for the prime number \( p = 3571 \) was used for the carrier sequence. Additional implementations of the pseudo-random process are introduced with an initial delay of 500 code elements. The delay between two logical units in a message is 20 elements. Logical “1” in the message is the introduction of an additional implementation of the original carrier with an appropriate delay of \( 500 + 20 \times (i - 1) \), where \( i \) is the running number of the unit in the message.

The results of transmission simulation are shown in Figs. 2 - 4.

In Fig. 2 the autocorrelation function is depicted of the initial sequence containing additional copies corresponding to the message “SPB”. The “zero” peak has an amplitude of \( A = 33143 \). With a short message, already at this stage, the autocorrelation function allows one to confidently determine the message itself (“code” in Fig. 2) with the signal-to-noise ratio \( \approx 4 \). But it should be noted that, besides the message, the autocorrelation function contains some beats (“beat” in Fig. 2), which make it difficult to detect the signal, especially if the message length is large.
Figure 2. The autocorrelation function of the sequence containing the encoded message.

\[ x_2 - x_1 > D, \]

where \( x_1 \), \( x_2 \) are the positions of the first and last characters in the message, \( D \) is the delay between the carrier start and \( x_1 \).

At the same time, the cross-correlation of the signal with the added copies and the original carrier yields only the message itself with no beats at the output (Fig. 3).

As it can be seen from Fig. 3, the cross-correlation gives the set of maxima corresponding only to logical units in the encoded message. In addition, the signal-to-noise ratio increases by two orders of magnitude, as is clearly seen in Fig. 4, where the neighborhood of maxima of the cross-correlation function is represented.

4. Conclusion
We show the principal possibility of the digital information introduction into an ultra-wideband pseudorandom carrier for its transmission and subsequent decoding using the simplest Baudot code. The high signal-to-noise ratio and rather simple engineering feasibility makes it possible

Figure 3. Cross-correlation of the original carrier and the sequence containing additional copies.
Figure 4. The neighborhood of maxima of the cross-correlation function given in Fig. 3.

to apply such a code for the experimental realization of the transmission and reception of signal using the optical correlator described in [7].

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