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Analysis of Code Sequences for Multichannel Data Transmission Systems

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Abstract — **A comprehensive indicator of the quality of information transmission systems under the influence of interference of natural or artificial origin is noise immunity. The paper presents the results of studies on improving the noise immunity of systems through the use of broadband or noise-like signals based on Walsh functions for information transmission.**

Keywords— noise-like signal; pseudo-random sequences; Walsh function derivative; generating function.

I. INTRODUCTION

Any data transmission system, as an open system, is generally affected by interference and multipath fading caused by natural origin, and the communication channel is also subjected by artificial interference from systems of deliberate destruction of information, suppression or interception of data.

Noise immunity is the main comprehensive indicator of the quality of information transmission systems (ITS), which includes: noise immunity, energy secrecy, structural or parametric secrecy, cryptographic stability, imitation resistance, protection of information from deliberate interference, suppression and interception of signals, protection of information from unauthorized access [1].

At the same time, many of these indicators are successfully solved by using broadband or noise-like signals for information transmission.

II. MAIN PART

A. Theoretical statements

The broadband transmission method was discovered by C. Shannon, who first introduced into consideration the concept of channel capacity:

$$C = W\, log_2(1 + \frac{P_s}{P_n}) \qquad (1)$$

where C – channel capacity, bit/s; W – the bandwidth, Hz; P_s – signal power; P_n – noise power [1], [2].

This equation establishes a relationship between the possibility of error-free transmission of information over a channel with a given signal-to-noise ratio (SNR) and the bandwidth allocated for information transmission. It follows from the Shannon formula that an interchange between signal power and bandwidth is possible - the same channel bandwidth ability can be provided with a high useful signal level and a narrow bandwidth, or can de provided with a low useful signal level and a wide bandwidth. Moreover, the second option is preferable.

Noise-like radio signals **(NLS)** or spread spectrum radio signals refer to CDMA (Code Division Multiple Access) technology.

There are two code division multiple access methods:

– ***asynchronous (non-orthogonal)*** multiple access using sign-alternating periodic chip *non-orthogonal pseudo-random sequences (PRS);*

– ***synchronous (orthogonal)*** multiple access based on sign-alternating periodic chip *orthogonal* Walsh functions.

The term "chip" refers to an elementary pulse signal. The duration of the PRS chips or Walsh function chips is much shorter than the duration of the information signal bit *($T_{ch} << T_b$).*

Asynchronous (not orthogonal) access in multichannel communication is characterized by the fact that radio signals are transmitted simultaneously by many unsynchronized transmitters from different geographical locations on the same carrier frequencies by one of the types of manipulation. In each transmitter, the bits of information signals are encoded (modulated) by individual PRSs, the chip rate of which is significantly higher than the bit rate. The PRS period *T* characterizes the length of the PRS and contains *L* chips. If each bit of the information signal is encoded by *L* chips of PRS, then its spectrum is expanded by *L* times, which leads to the expansion of the radio signal spectrum also by *L* times.

With asynchronous access, a correlation technique is used, based on the selection of an outlier of the ***autocorrelation function (ACF)*** of a separate PRS. Pseudo-random sequences are chosen in such a way that they can be separated in the receiver, and then the desired information signal can be separated from its SRP.

To separate the SRP, it is necessary that they have a small cross-correlation (close to zero), i.e. they were almost independent.

Synchronous (*orthogonal*) access in multi-channel communication is characterized by the fact that a plurality of information signals are transmitted synchronously by one transmitter at one carrier frequency. In this case, the bits of each of the information signals in the transmitter are pre-coded (modulated) by the corresponding Walsh function of length *J*, the chip rate of which is significantly greater than the bit rate. The *Walsh functions are orthogonal, i.e. have a mutual correlation equal to zero.* Next, the second stage of coding (modulation) is carried out using a certain SRP of length *L = J.* In this case, the spectrum of each information signal is expanded by *L* times.

The resulting signals are added and form a single digital stream with an *L*-fold extended spectrum, which performs some kind of manipulation of the transmitter carrier frequency. In this case, a radio signal is formed with a spectrum extended by *L* times.

Synchronous access uses a correlation technique based on the orthogonality (independence) of the Walsh functions. The orthogonality property of the Walsh functions makes it possible to separate signals by chip integration with accumulation and thus to extract the transmitted information signals.

In this case, the complete SRP ensemble must be chosen such that the cross-correlation between any pair of sequences is sufficiently small. This allows to minimize the level of interference on adjacent channels. Theoretically, the cross-correlation value is equal zero for ensembles of orthogonal spreading signals (eg, basis functions of Fourier series and Walsh functions).

The dominant role in choosing the type of SRP for the formation of NLS in data transmission systems is played, first of all, by the mutual and autocorrelation characteristics of the signal ensemble, its volume, and the ease of implementation of devices for signals generating and "compressing" (convolution) in the receiver [1] –[4].

Discrete signals with the best ***cross-correlation function (CCF)*** structure include signals which are encoded using the corresponding Walsh function [1], [2].

The most common orthogonal system used in multichannel code division systems are Walsh-Hadamard matrixes of order *N = 4k (k* is an integer), which is determined by the recursive rule:

$$W_{2N} = \begin{bmatrix} W_N & W_N \\ W_N & -W_N \end{bmatrix}, \quad (2)$$

where W_N is the Walsh–Hadamard matrix of order N, is assumed that $W_1 = 1$, or in the signed form $W_1 = +$.

However, a feature of orthogonal codes is that the orthogonality of these codes is performed only at the “point”, i.e. in the absence of time shifts. In reality, such conditions are not met, orthogonality is violated. This, in turn, leads to an increase in the level of multiple access interference and to the appearance of errors in the processing of input data. Therefore, to eliminate these shortcomings various methods are used.

One of the ways to improve the properties of correlation functions (ACF and CCF) of the Walsh signal system is the construction of the so-called systems of *derivative* signals [5].

A ***derivative*** signal is such a signal that is obtained as a result of element-wise (symbol-by-symbol) multiplication of two signals. A system composed of derivative signals is called a derivative system [1], [2].

As a generating signal, such a signal is chosen so that the *derivative* system has good correlation properties.

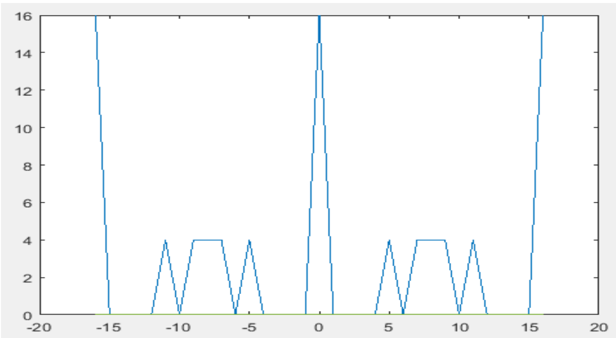
B. Experimental data

Let’s consider the correlation properties of the *derivatives* of the Walsh functions, if we take as the *generating* functions M–sequence with a generating polynomial $f(x) = x^4 \oplus x^3 \oplus 1$ and a composite combination of 5 and 11-bit Barker codes [5].

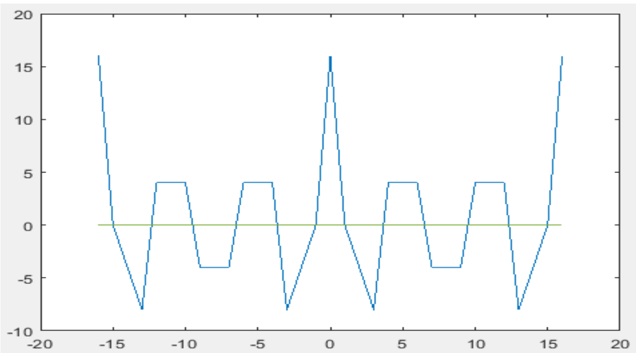
The PRS, that is generated by generator for M - sequence in the form of a shift register with linear feedback under certain initial conditions (A = 1000), in the bipolar representation will be B_1 = +1+1+1+1-1+1 -1+ 1+1-1-1+1-1-1-1, and the sequence of Barker codes will be B_2 = +1+1+1 -1+1+1+1+1-1-1-1+1-1- 1+1-1.

Consider the correlation functions of the derivatives of the Walsh functions (for example, the 2nd and 12th [1]), with the generating functions B_1 and B_2, respectively. Since the length of M - sequence is $L = 2^n - 1 = 2^4 - 1 = 15$, then in the original Walsh matrix, when constructing the derivatives of the Walsh functions, the highest bit remains unchanged. In this case, the 2nd and 12th derivatives of the Walsh function with the generating function *in the form of M - sequence* B_1 will look like B_3 = +1+1+1-1+1+1+1+1+1-1-1+ 1+1+1-1+1 and B_4 = +1-1-1+1+1+1-1-1-1+1-1+1-1-1-1+1 respectively. And the 2nd and 12th derivatives of the Walsh function with the generating function *in the form of a composite combination of Barker codes* will look like: B_5 = +1-1+1+1+1-1+1-1-1+1-1-1 -1+1+1+1 and B_6 = +1-1-1-1+1-1-1+1+1-1-1-1+1-1+1+1 respectively.

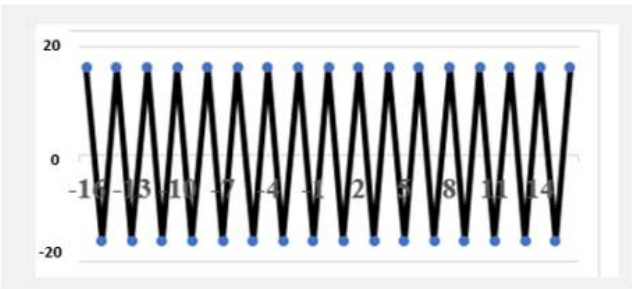
On fig. 1 is shown the results of calculating the *periodic autocorrelation functions* ***(PACF)*** of the selected derivatives (a, b) and the *original* (c) Walsh functions.



a)



b)



c)

Figure 1. PACF of the 2nd (a) and 12th (b) derivatives of the Walsh functions with generating function $\mathbf{B_1}$, PACF of the 2nd original Walsh function (c)

As can be seen from Fig. 1, the considered PACFs have better autocorrelation functions, in contrast to the PACFs of the original Walsh functions (where there is no central maximum and side lobes).

To ensure the synchronization during reception, it is necessary to eliminate the influence of side lobes, while the suppression coefficient - *the ratio of the amplitude of the main lobe of the ACF to the maximum value of the amplitude of the side lobe* - ranges from 4 for the 2nd PACF to 2 for the 12th PACF of the Walsh function derivative.

Fig. 2 presents the cross-correlation function **(CCF)** of the 2nd and 12th derivatives of the Walsh functions with the generating function in the form of M - sequence $\mathbf{B_1}$**.**

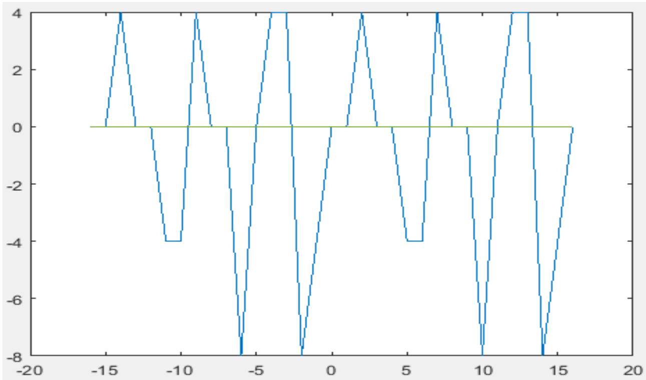
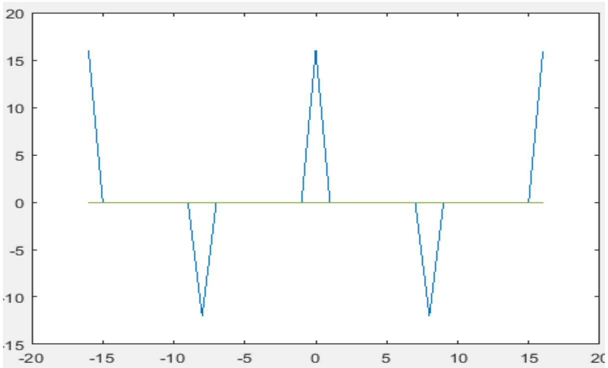


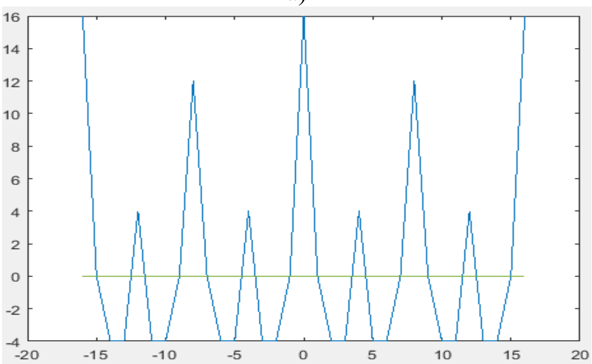
Figure 2. CCF of the 2nd and 12th derivatives of the Walsh functions with the generating function **B1**

From Fig. 2 follows that the CCF of the considered *derivatives* of the Walsh functions can be considered satisfactory, the CCF is more or less uniform, without extreme emissions and can be used in code division systems using decision devices that do not respond to CCF emissions within the specified limits.

On fig. 3 shows the PACFs of the *derivatives* of the Walsh functions with the other generating function - $\mathbf{B_2}$. As can be seen from fig. 3, the PACFs of the *derivatives* of the Walsh functions do not have very good autocorrelation functions. The suppression coefficient for both functions is only 1.33. In contrast to the periodic one, the *cross-correlation function* CCF of the derivative functions shown above can be considered satisfactory, as they have no extreme outliers, which are within values ±4 (Fig. 4).



a)



б)

Figure 3. PACF of the 2nd (a) and 12th (b) derivatives of the Walsh functions with the generating function $\mathbf{B_2}$

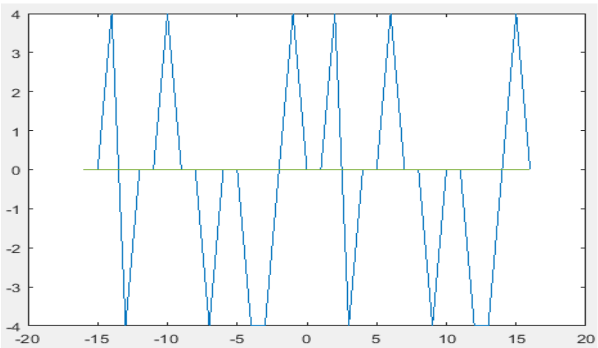


Figure 4. CCF of the 2nd and 12th derivatives of the Walsh functions with a generating function $\mathbf{B_2}$

III. Conclusion

The carried out researches and analysis of their results allows to make following conclusions:

1. To increase the noise immunity of data transmission systems, it is necessary to use broadband (noise-like) signals, which must have certain correlation properties: the autocorrelation function of the ACF of such signals must have one central maximum and a minimum level of side lobes, and the mutual correlation function must be equal to 0.

2. It is known that such properties are possessed by orthogonal functions, on the basis of which orthogonal signal systems are built, for example, signals based on Walsh functions.
Correlation characteristics of Walsh functions that are orthonormal have good cross-correlation functions, which are equal to zero between two different Walsh functions. However, these functions have such properties only at the point of zero shift. In real conditions, orthogonality is violated and the cross-correlation function is nonzero. This leads to an increase in the level of multiple access interference and signal (or channels) separation errors.

3. The analysis of the correlation properties of the ***derivatives*** of the Walsh functions (for different generators) has shown that they have a much better suppression coefficient in contrast to the original Walsh functions.

4. To reduce the level of interference of multiple access, the ***derivatives*** of the Walsh function must be orthogonal, since in CDMA all subscribers operate in the same frequency band. The cross-correlation function (CCF) will be zero for any shifts τ if the signals are orthogonal. However, due to the linearity of the Fourier transform, this is possible only if the product of the spectral densities of both signals $U(\omega)V^*(\omega) = 0$ on the entire frequency axis. The zero CCF means that two signals are orthogonal for any τ only if their spectra do not overlap. However, *this cannot be achieved in multi-channel code division systems.* The consequence of this is the occurrence of inter-user interference, i.e. non-zero response of the receiver of the k-th user to the signals of other subscribers. Therefore, *the article analyzes what form the CCF of derivatives of Walsh functions must have, depending on the type of generating functions, to obtain the best correlation characteristics*, that ***is very important for CDMA systems. This is the first time such a specific analysis has been carried out.***

5. It was found that a large length of the extension code based on the *derivatives* of the Walsh functions makes it possible to distribute the signal energy over the spectrum, which *increases the noise immunity* of the system. In addition, by masking the useful signal with noise, *reliable protection against unauthorized access is provided.* Also, a low signal level *improves electromagnetic compatibility* with neighboring radio systems.

The obtained research results can be used in the development of broadband communication systems and information transmission systems *with reliable* *protection against unauthorized access*. Such systems with the studied signals make it possible to reduce the energy characteristics, i.e. improve the efficiency of information transmission systems.

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