Multiple access interference protection in multichannel data transmission systems

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Abstract: *The article is a continuation of previous studies and deals with the results of research on the protection of multichannel data transmission systems with channel division by the signal code from unauthorized access. It is proposed to use derivatives of Walsh functions (with different generating functions) as spreading codes for the formation of noise-like signals in multichannel communication systems. The analysis showed that the correlation properties of the derivatives of Walsh functions used as spreading codes have significantly better correlation characteristics than the original ones. An analysis of various types of Walsh functions used as spreading codes for signals transmitted in multi-channel systems was carried out. As a result, there were defined the types of pseudo-random sequences for Walsh generating functions, in which multiple access interference is absent. It was justified the advantage of using these signals in the development of CDMA systems in order to protect against interference from multiple and unauthorized access.*

Keywords: *CDMA SYSTEM, NOISE-LIKE SIGNALS, SPREADING CODES, WALSH FUNCTION DERIVATIVE, GENERATING FUNCTION.*

1. Introduction

It is known that the costs of a data transmission system depend on several factors, including the transmission technology, the characteristics of the communication channel, and the type of devices used. In general, the communication channel can be the most expensive part, especially when it comes to expensive data transmission channels, such as satellite or fiber optic lines. Therefore, it is desirable to use the communication channel most efficiently, and this can be achieved by using multi-channel transmission systems with various methods of channel compression (separation) [1, 2, 4, 5, 6].

A distinctive feature of code division multiplexing data transmission systems is the ability to reuse (multiple) the frequency resource by dividing channels not by frequency or time, but by "form", which allows multiple subscribers to work simultaneously in the same frequency band. Such a system uses pseudo-random sequences (PRS) with specified correlation properties. And the channel signals themselves, formed by expanding the information signal with pseudo-random sequences, are called pseudo-noise or noise-like (NLS).

Noise-like signals, as a category of signals, are random, non-linear data sequences that do not have a clear periodicity or predictability. For any other receiver that knows nothing about the expanding sequence, such a signal is noise.

It should be noted that the information itself can be introduced into the wideband signal in several ways. For example, a narrowband signal is multiplied by a pseudo-random sequence with period T, consisting of N bits of duration τ_0 each. In this case, the NLS base is numerically equal to the number of PRS elements. [1, 2, 5, 6].

2. Theoretical preconditions

Communication systems with broadband signals are widely used for three reasons [1, 2, 4, 6].

The first reason is that wideband signals formed using different pseudo-random sequences can have the same carrier frequency, i.e. be transmitted in the same band.

The second reason why the use of the NLS is very advantageous is its high resistance to the effects of both broadband and narrowband interference, which is very important in the conditions of a tense electromagnetic environment in modern communication systems.

The third reason is the high energy secrecy of systems with broadband and, as a consequence, the high confidentiality of the transmitted data. The essence of what has been said is that a broadband signal is not only difficult to decode - it is difficult to simply detect, i.e. to identify the very fact of the subscriber station's operation.

The main methods of expanding the signal spectrum, widely used in modern information transmission systems (ITS) [1, 2, 4, 5]:

1. Frequency - hopping spread spectrum, FHSS. The essence of the method is a periodic hopping change of the carrier frequency according to some algorithm known to the receiver and transmitter. The advantage of the method is the simplicity of implementation, the disadvantage is a delay in the data flow at each hop. The method is used in Bluetooth.
2. Direct sequence spread spectrum, DSSS. The method is more efficient than frequency hopping, but is more difficult to implement. The essence of the method is to increase the modulation clock frequency, with each symbol of the transmitted message being assigned a certain fairly long pseudo-random sequence (PRS). The method is used in systems such as CDMA (Code Division Multiple Access) and IEEE 802.11 (Wi-Fi) standard systems;
3. Chirp spread spectrum, CSS. The essence of the method is to restructure the carrier frequency according to a linear law. The method is used in radar, in some radio modems, LoRaWAN networks.

Thus, the method of transmitting information with spectrum spreading consists of the following: on the transmitting side – simultaneous and independent modulation of the signal parameters with a special code (spectrum spreading function) and the transmitted message; on the receiving side – synchronous demodulation of the signal with the help of a correlator, which is a series-connected multiplier and integrator that calculates the correlation function (CF) of the input signal with a copy of the PRS stored in memory [1, 3, 5].

It is known that for the correct processing of input signals, the receiving and transmitting devices must work synchronously and in phase. Synchronization of the receiving device is carried out using a correlator that calculates the ACF of the input signal, which for discrete signals is calculated by the formula:

$$\boldsymbol{R_u(n) = \sum_{j=-\infty}^{\infty} u_j\, u_{j-n}}, \tag{1}$$

where *n* is an integer, positive, negative or zero.

The amplitudes of the side peaks of the ACF can have different values depending on the signal structure, but for signals with “good” correlation they should be minimal, i.e. significantly less than the amplitude of the central peak. The ratio of the amplitude of the central peak to the maximum amplitude of the side emissions is called the suppression coefficient. The study of the ACF plays an important role in choosing code sequences from the point of view of the lowest probability of establishing false synchronization.

The cross-correlation function (CCF) between two discrete signals is calculated using the formula:

$$\boldsymbol{R_{uv}(n) = \sum_{j=-\infty}^{\infty} u_j\, v_{j-n}}. \tag{2}$$

It should be noted that in multichannel systems with channel division by the signal form (code), all subscribers can transmit information simultaneously in the same frequency band.

The consequence of this is the occurrence of multiple access interference, i.e., a non-zero response of the receiver of the k-th user to signals from other subscribers [1, 2, 4, 6]. Consequently, *to reduce the level of multiple access interference, it is necessary to select code sequences for which the CCFs are minimal.*

Thus, the most important parameter of the applied PRSs, which are used to obtain the NLS, is their correlation properties. Moreover, the noise immunity and noise stability of the entire information system as a whole depends on the choice of binary code sequences, i.e. on their correlation properties. In addition, the code sequence must be well balanced, i.e. the number of bipolar symbols in it must be approximately the same. The latter requirement is important for eliminating the constant component of the information signal.

It is known that the correlation functions (CF) of complex, noise-like signals are determined by the correlation properties of the spreading codes [1, 2, 3, 6]. Therefore, when considering the CF of complex signals, it is sufficient to analyze the correlation functions of these codes.

Walsh functions can be considered as discrete signals with the best structure of the CCF [7]. Walsh functions (J. Walsh) were developed in 1923 as a development of the Rademacher function system, which was known at that time, by adding new functions to it [2, 3, 5, 6, 7].

Walsh functions are formed from Rademacher functions using the following relationship:

$$\boldsymbol{wal_0(\theta) \equiv 1, wal_n(\theta) = \prod_{k=1}^{m}[rad_k(\theta)]^{n_k}}, \quad (3)$$

where n is the Walsh function number, n_k is the value (0 or 1) of the k -th digit of the Walsh function number n, written as an m-digit binary Gray code. From this it is easy to see that the number of functions in the Walsh system is equal to $N = 2^m$, where m is an integer.

Walsh functions take only two values: +1 and –1, which is a useful property when constructing circuits on binary digital elements (triggers).

Multiple access interference, also called structural signal-like interference, is formed as a result of non-ideal orthogonality of the signal. This means that in order to obtain the best properties of the CCF of spreading codes, it is necessary to use orthogonal systems of Walsh functions. The orthogonal system, which is most often used in multichannel code division systems, is the Walsh-Hadamard system (matrix) of order $N = 2^k$, k is an integer, which is determined by the recursive rule:

$$W_{2N} = \begin{bmatrix} W_N & W_N \\ W_N & -W_N \end{bmatrix}, \quad (6)$$

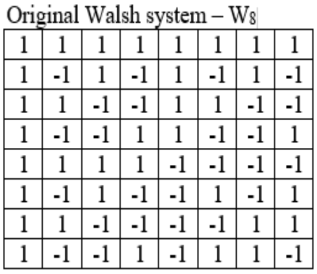
where W_N is the Walsh-Hadamard matrix of order N, assuming $W_1 = +1$, or in the signed form $W_1 = +$.

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

In order to improve the properties of the correlation properties (ACF and CCF) of Walsh functions, the so-called ***derivative systems of signals*** are often built [2, 4].

A ***derivative*** is a signal that results from the element-by-element (symbol-by-symbol) multiplication of two signals – the original, for example, Walsh and the generating function (GF). A system composed of derivative signals is called a derivative. In [8, 9 - 11], the correlation properties of Walsh derivative functions were studied, where modified Barker codes, M-sequences and de Bruijn sequences were taken as generating functions. However, the obtained Walsh derivative functions, although having better ACF, had poor ICF, which can lead to an increase in multiple access interference and errors in processing input data.

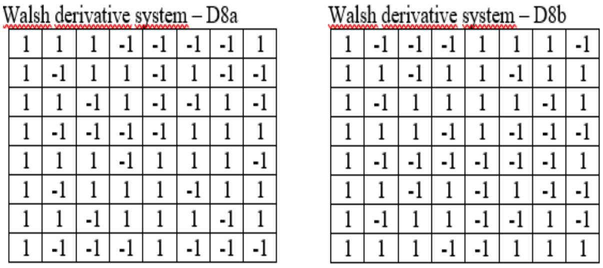
In order to reduce the level of multiple access interference, we will consider a method for constructing derivative signal systems, when the Walsh system is also used as the original signal system (Fig. 1), where each line is a code sequence of the corresponding BSPK signal, and the generating functions are pseudo-random sequences **PRS1: 1 1 1 -1 -1 -1 -1 1** and **PRS2: 1 -1 -1 -1 1 1 1 -1.**



Original Walsh system – W8

1	1	1	1	1	1	1	1
1	-1	1	-1	1	-1	1	-1
1	1	-1	-1	1	1	-1	-1
1	-1	-1	1	1	-1	-1	1
1	1	1	1	-1	-1	-1	-1
1	-1	1	-1	-1	1	-1	1
1	1	-1	-1	-1	-1	1	1
1	-1	-1	1	-1	1	1	-1

Fig.1 The original Walsh-Hadamard function system



Walsh derivative system – D8a

1	1	1	-1	-1	-1	-1	1
1	-1	1	1	-1	1	-1	-1
1	1	-1	1	-1	-1	1	-1
1	-1	-1	-1	-1	1	1	1
1	1	1	-1	1	1	1	-1
1	-1	1	1	1	-1	1	1
1	1	-1	1	1	1	-1	1
1	-1	-1	-1	1	-1	-1	-1

a)

Walsh derivative system – D8b

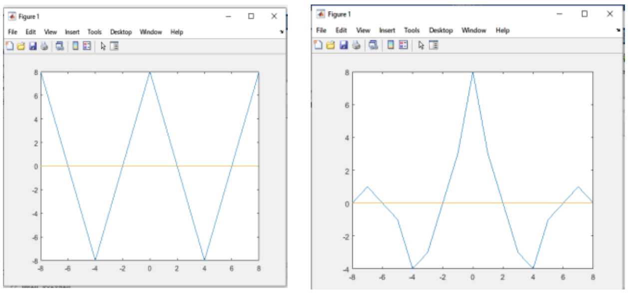
1	-1	-1	-1	1	1	1	-1
1	1	-1	1	1	-1	1	1
1	-1	1	1	1	1	-1	1
1	1	1	-1	1	-1	-1	-1
1	-1	-1	-1	-1	-1	-1	1
1	1	-1	1	-1	1	-1	-1
1	-1	1	1	-1	-1	1	-1
1	1	1	-1	-1	1	1	1

b)

Fig. 2. Walsh derivative system: a) with generating function PRS1; b) with generating function PRS2.

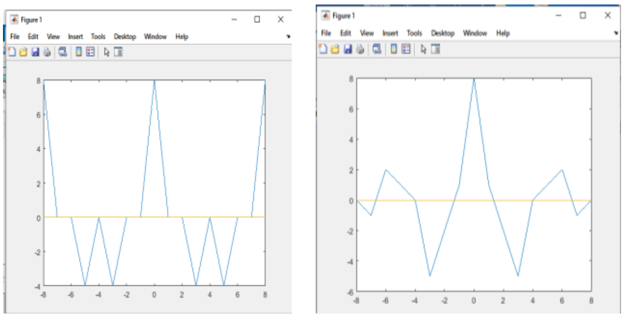
3. *Experimental data*

The system of Walsh functions of orthogonal signals at the point (t = Ts) has, in general, poor autocorrelation characteristics, but is simple from the point of view of signal formation and processing. Figures 3 and 4 show the graphs of periodic (PACF) and aperiodic (AACF) autocorrelation characteristics of the generating functions PRS1 and PRS2.



a) b)

Fig. 3 PACF (a) and AACF (b) of the generating function PRS1

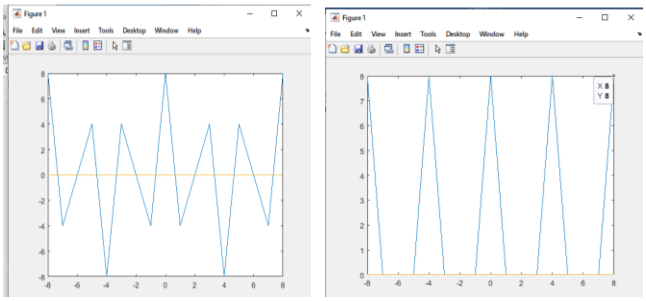


a) b)

Fig. 4 PACF (a) and AACF (b) of the generating function PRS2

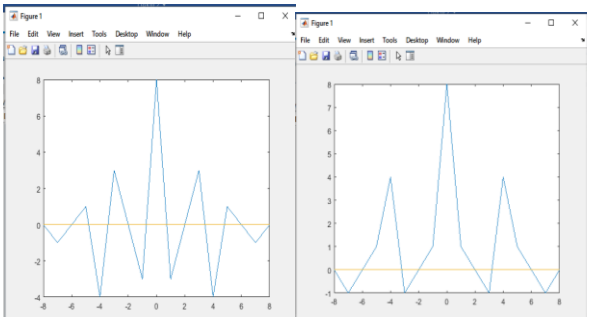
As can be seen from Fig. 3 and Fig. 4, the generating functions of PRS1 and PRS2 have acceptable autocorrelation PACFs, the suppression coefficient equal to the ratio of the amplitude of the main lobe to the maximum amplitude of the side lobe for both PSPs is equal to two. The AACFs are slightly different: the suppression coefficient for the first PSP is 2, for the second – 1.6.

Let us consider what form the autocorrelation characteristics of the ***derivatives*** of the Walsh functions will have (Fig. 2 a, b) depending on the type of generating function (for analysis we will select, for example, the 2nd and 5th derivatives of the Walsh function).



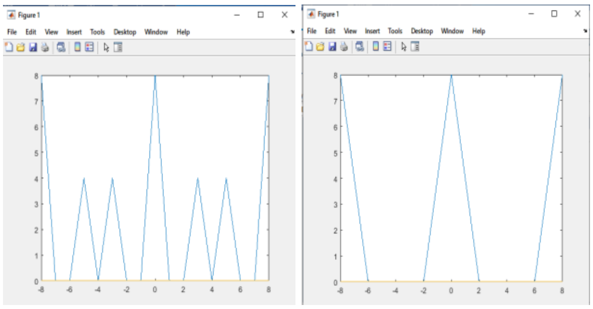
a) b)

Fig. 5 PACF of the 2nd (a) and 5th (b) ***derivatives*** *of the Walsh functions with the generating function PRS1*



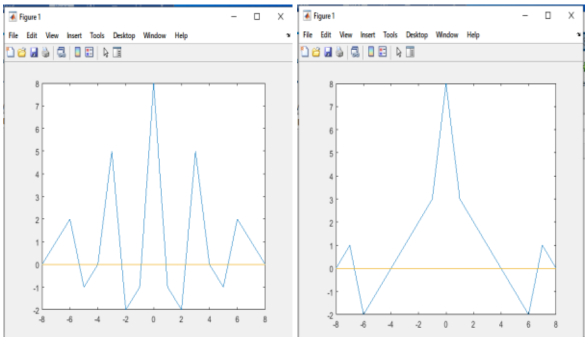
a) b)

Fig. 6 AACF of the 2nd (a) and 5th (b) ***derivatives*** *of the Walsh functions with the generating function PRS1*



a) b)

Fig. 7 PACF of the 2nd (a) and 5th (b) ***derivatives*** *of the Walsh functions with the generating function PRS2*

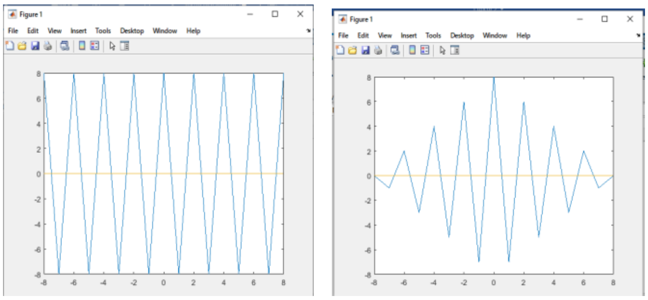


a) b)

Fig. 8 AACF of the 2nd (a) and 5th (b) ***derivatives*** *of the Walsh functions with the generating function PRS2*

From Fig.5 - Fig.8 it is evident that the autocorrelation characteristics of the derivatives of Walsh functions depend on the ***type of generating function***. The autocorrelation characteristics of the derivatives of Walsh functions with the generating function PSP2 have somewhat better characteristics.

As an example, let us consider what autocorrelation characteristics the 2nd original Walsh function has (Fig. 9).

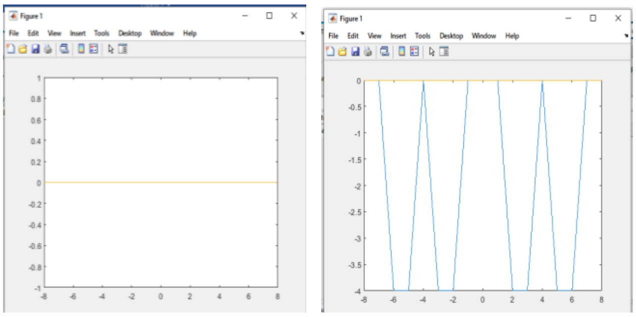


a) b)

Fig. 9 PACF (a) and AACF (b) of the 2nd ***original*** *Walsh function*

As can be seen from Fig. 9, the autocorrelation characteristics of the 2nd original Walsh function have significantly worse parameters than those of the 2nd derivative of the Walsh function with generating functions PSP1 and PSP2.

Let us consider what form the cross- correlation characteristics (CCF) of the 2nd and 5th derivatives of the Walsh functions with generating functions PRS1 and PRS2 have (Fig. 10).



a) b)

Fig.10. VCF of the 2nd and 5th ***derivatives*** *of the Walsh functions: a) – PRS1; b) – PRS2*

As can be seen from the graphs of the VCF (Fig. 10), the derivatives of the Walsh function with the generating function PRS1 have cross-correlation characteristics, as with the original Walsh functions, i.e. they are equal to zero. ***Consequently, when using such derivatives of the Walsh functions in multichannel data transmission systems with channel division by shape, the multiple access interference will be equal to zero and there will be no errors in processing the input data.***

4. Conclusion

The performed analysis of the correlation characteristics of wideband signals with spreading codes based on ***Walsh derivative functions*** allows us to draw the following conclusions:

1. The correlation characteristics of Walsh functions that are orthonormal have good cross-correlation functions - the cross-correlation function between two different Walsh functions is zero. However, these functions have such properties only at a point (at zero shift). In real conditions, especially with multipath propagation, orthogonality is violated and the cross-correlation function of these functions is nonzero. This leads to an increase in the level of interference of multiple access and to errors in the separation of signals (channels).
2. The autocorrelation properties of the derivatives of Walsh functions have much better autocorrelation characteristics than the original Walsh functions.
3. Autocorrelation properties of Walsh derivatives depend on *the type of generating function*. Autocorrelation characteristics of Walsh derivatives with generating function PRS2 have slightly better parameters than with generating function PRS1.

4. The cross - correlation characteristics of the derivatives of the Walsh functions with the generating function PRS1 do not differ from the similar characteristics of the original Walsh functions, i.e. they are equal to zero. The cross - correlation characteristics of the derivatives of the Walsh functions with the generating function PRS2 are not equal to zero and have negative emissions with an amplitude of 4***. Consequently, when using the derivatives of the Walsh functions with the generating function PSP1, multiple access interference will be absent, and with the generating function PRS2, it is necessary to use decision devices that do not respond to negative emissions of the CCF.***

5. The large length of the spreading code based on the derived Walsh functions allows:

- spreading the signal energy over the spectrum,
- increasing the noise immunity of the system,
- providing good protection against unauthorized access,
- improving electromagnetic compatibility with neighboring radio systems.

The results can be used in the development of broadband communication systems and information transmission systems with protection from unauthorized access.

5. References

1. Л.Е. Варакин, *Системы связи с шумоподобными сигналами*. (М.: Радио и связь, 1985).
2. М.И. Мазурков, *Системы широкополосной радиосвязи*. (О.: Наука и техника, 2009).
3. W. Solomon, Golomb and Guang, Gong. *Signal Design for Good Correlation*. (Cambridge University Press, 2005).
4. К. Феер, *Беспроводная цифровая связь, методы модуляции и расширения спектра. Перевод с англ. / Под ред. В.И.Журавлева* (М.: Радио и связь, 2000).
5. В.Е. Гантмахер, Н.Е. Быстров, Д.В. Чеботарев, *Шумоподобные сигналы. Анализ, синтез, обработка (*СПб.: Наука и Техника, 2005).
6. В.П. Ипатов, *Широкополосные системы и кодовое разделение сигналов. Принципы и приложения*: Пер. с англ. (М.: Техносфера. 2007).
7. М.С. Беспалов, В.А. Скляренко, *Функции Уолша и их приложения*. (Владимир; Изд-во ВлГУ, 2012).
8. Gh. Sorochin, T. Sestacova. *Comparative analysis of composite Barker codes and composite Walsh functions***.** (Austria//Österreichisches Multiscience Journal №38/2021, pp.72-78).
9. T. Sestacova, Gh. Sorochin. *Comparative analysis of pseudorandom sequences using modified Barker codes and M – sequences of the same length.* (International Scientific Journal „Mathematical Modeling”, Vol. 4 (2020), Issue 2, pp. 45-50).
10. Gh. Sorochin, T. Șestacova, V. Jdanov, *Analysis of the correlation properties of direct and inverse composite Walsh functions.* (*Engineering. Technologies. Education. Security 2021*: proc. of the IX Intern. scient. conf., Borovets, June 07-10, 2021. Bulgaria, 2021, vol. 2, pp. 83-87).
11. Gh Sorochin, T. Șestacova, V. Jdanov, *Improvement of signal quality in CDMA systems on the basis of analysis of correlation properties of pseudo-random sequences,* (*International Scientific Journal "Industry 4.0"*, year VI, Issue 5/2021, pp. 177-181).