Discrete Signals with Special Correlation Properties

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Abstract. The methods of synthesis of discrete signals are analyzed with the special cross-correlation properties: m- sequences, signals of Legendre, Barker, Paley-Plotkin, Gold, small and large set of Kasami. Comparative researches of properties of the formed discrete signals are conducted. Separate direction develops in development of methods of forming of discrete signals, that is based on the use of algebraic and structural properties of circular shifts of group codes. It is shown that offered approach allows forming the great numbers of discrete sequences, ensemble and cross-correlation properties of that are set by the properties of the corresponding group controlled from distance, structural and cyclic.

Keywords. Discrete signals, cross-correlation and ensemble properties, group codes, circular shifts.

1 Introduction

The effective functioning of digital communication networks with providing plural access on the technology of code channel separation directly depends on ensemble, cross-correlation and structural properties of the formed discrete signals [1-3]. It is special it is important at the construction of perspective digital communication of fifth (5G) and sixth (6G) generation networks [4].

The perspective direction of researches is the development of methods of synthesis of discrete signals with the special correlation properties [5-30]. The values of lateral ejection of the function of correlation for such signals are determined by strict analytical correlations and directly related to structural and group properties of ensembles of discrete sequences [5-9]. In particular, such signals include [5–30]: m-sequences, Legendre, Barker, Paley-Plotkin, Gold signals, a small and large number of Kasami and many others. At the same time, the main disadvantage of such methods is the small power of the ensembles of the formed sequences. In this sense, the most promising methods are the synthesis of large ensembles of discrete signals with a multilevel auto- and cross-correlation function [16].

In this paper, the analysis and comparative studies of methods of synthesis of discrete signals with special correlation properties are carried out. Theoretically, synthesis methods based on the cross-section of circular shifts of the group code are justified, which allow forming a set of sequences with predetermined distance properties and algebraically construct large ensembles of discrete signals with a multilevel function of auto- and cross-correlation.

2 Analysis of the known methods of synthesis of discrete signals with the special correlation properties

The most development to date was got by the methods of synthesis of discrete signals, based on the use of recurrent transformations and corresponding linear and nonlinear recurrent sequences [5-30]. Procedures of forming of such sequences easily will be realized with the use of the simplest switch charts with shift registers.

Linear recurrent sequences are formed with the use of shift registers with linear feedback (LFSR) and at the corresponding choice of the function of feedback allow to provide the maximal period of the formed sequences [5-9]. In literature, such signals got the name of linear recurrent sequences of a maximal period (MLRS) or m- sequences. On their basis, many other classes of signals are formed: sequences of Legendre, Paley-Plotkin, a Barker signal and many other.

The results of a comparative analysis of some methods for synthesizing signals with special correlation properties are given in Table 1. The comparison was made according to the following indicators: the period length n and the power M of discrete signals, the maximum value of the lateral lobe module of the correlation function ρ.

The analysis showed that the lateral ejections of the correlation function of the considered signals take finite, previously known values, which allows them to be used at various stages of digital communication, including for channel synchronization and in radio-location. The main disadvantage is the small capacity of the ensembles of the formed sequences. For example, the number of MLRS, Legendre, Paley-Plotkin and other sequences is determined by the number of irreducible polynomials (Euler function), which determine the rule for the formation of sequences. Improved ensemble properties are possessed by Gold's sequences, small and large sets of Kasami sequences. The power of the ensembles of such signals is significantly increased. The lateral lobes of the correlation function ρ for these sequences are also increased, but with an increase in the length of the sequences n the loss in the correlation properties is insignificant. Therefore, the construction of large ensembles of discrete signals is a promising direction for further research.

Table 1. Ensemble and correlation characteristics of some discrete signals with special properties

Signal class	n	M	ρ
m-sequences	$2^m - 1$, $m \in Z^+$	$\varphi(2^m - 1)/2m$	$\rho = -\dfrac{1}{2^m - 1}$
Legendre Sequences	$n \le (p^m - 1)$, $p, m \in Z^+$	$M \le \varphi(p^m - 1)/2m$	$\rho = \dfrac{p^{m-1}}{n}$
Legendre sequences with $m = 2$, Barker signals	$p + 1$, $p = 3, 5, 7, 11, 13$	$\dfrac{p+1}{8}\dfrac{\varphi(p^2 - 1)}{\varphi(p-1)}$	$\rho = 1/p$
Legendre Sequences, $m = 2$	$p + 1$, $p \in Z^+$, $p \ne 3, 5, 7, 11, 13$	$\dfrac{p+1}{8}\dfrac{\varphi(p^2 - 1)}{\varphi(p-1)}$	$\rho = 1/\sqrt{p}$
Paley-Plotkin signals	p, $p \in Z^+$	p	$\rho = 1/p$
Gold signals	$2^m - 1$, $m = 2p + 1$, $p \in Z^+$	$2^m + 1$	$\rho = \dfrac{1 + 2^{(m+1)/2}}{2^m - 1}$
Gold signals	$2^m - 1$, $m = 2p$, $p \in Z^+$	$2^m + 1$	$\rho = \dfrac{1 + 2^{(m+2)/2}}{2^m - 1}$
Small set of Kasami	$2^m - 1$, $m = 2p$, $p \in Z^+$	$2^{m/2}$	$\rho = \dfrac{1 + 2^{m/2}}{2^m - 1}$
Large set of Kasami	$2^m - 1$, $m = 2p$, $p \in Z^+$	$2^{m/2}(2^{m/2} + 1)$	$\rho = \dfrac{1 + 2^{(m+2)/2}}{2^m - 1}$

The most important, in this sense, are methods based on the use of algebraic and structural properties of group codes. Thus, in [16, 29, 30], it was shown that the sub-orthogonal discrete signals, the three-level Gold signals are a special case of n-level discrete sequences formed by the section of cyclic orbits of a group binary code, and can be analytically formalized using the mathematical apparatus of the theory finite fields and, in particular, the theory of rings of polynomials.

3 Algebraic and structural properties of circular shifts of group codes

The proposed approach to the formation of discrete signals with a multilevel correlation function is based on the use of the algebraic and structural properties of cyclic orbits of group codes over finite fields, as well as the procedure for selecting the corresponding discrete sequences [8, 16]. Consider the algebraic structure of a finite field and the cyclic orbits contained in it. We will research the algebraic and structural properties of cyclic orbits of group codes to form discrete sequences with special properties.

We fix a finite field $GF(q)$, consider the vector space $GF^n(q)$ as a set of n - sequences of elements from $GF(q)$ with component-wise addition and multiplication by a scalar. A linear (n,k,d) code V is a subspace $GF^k(q)$ in space $GF^n(q)$, i.e. nonempty set of n-sequences (code words) over $GF(q)$, k is the dimension of a linear subspace, d is the minimum code distance (the minimum weight of a nonzero code word). A cyclic code is a special case of a subspace that has the additional property of cyclicity. Each vector from $GF^n(q)$ can be represented by a polynomial in a formal variable x of degree not higher than $n – 1$. The components of the vector are identified with the coefficients of the polynomial. The set of polynomials has the structure of a vector space, identical to the structure of the space $GF^n(q)$, as well as the structure of the ring of polynomials $GF(q)[x]/(x^n-1)$. In the ring of polynomials, the multiplication over polynomials is defined: $p_1(x)\cdot p_2(x)=R_{x^n-1}[p_1(x)\cdot p_2(x)]$, where $R_b[a]$ is the remainder of the polynomial a divided by the polynomial b. The cyclic shift on $\tau\in\{0,...,n-1\}$ elements in terms of polynomial algebra can be written as:

$$x^\tau\cdot p(x)=R_{x^n-1}\left[x^\tau\cdot p(x)\right]. \quad (1)$$

If the code words (n,k,d) of a code over $GF(q)$ are given in the form of polynomials, then code V is a subset of the ring $GF(q)[x]/(x^n-1)$. The code V is cyclic if, along with the code word $C(x)$ it also contains the polynomial $x\cdot C(x)$. The only nonzero given polynomial $g(x)$ of the smallest degree $r=n-k$ uniquely defines (n,k,d) the cyclic code over $GF(q)$ and is denoted by the generating polynomial, moreover $g(x)=\prod_i(x-\beta^i)$, where $\beta^i\in GF(q^m)$. It is connected with the check polynomial $h(x)$ by the relation $g(x)\cdot h(x)=x^n-1$, or, equivalently, $R_{x^n-1}[g(x)\cdot h(x)]=0$.

Consider the structure of a finite field $GF(q^m)$, as a set of polynomials of degree $\le m$ with coefficients from $GF(q)$, i.e. polynomial ring structure $GF(q)[x]/(x^m-1)$. This ring with modulo irreducible polynomial operations is an extended Galois field $GF(q^m)$. Such a field consists of a set of classes of conjugate elements $\alpha^{i(q^s)}$, $s=0,1,...,m_i-1$, where m_i is the smallest natural number, such that equality holds [8]:

$$iq^{m_i} = (i) \bmod \left(q^m - 1\right).$$

The algebraic structure of a finite Galois field is given in table 2. Each class of conjugate elements specifies (through the roots) the minimal polynomial $f_i(x)$. The product of all minimal polynomials $f_i(x)$ of a finite field $GF\left(q^m\right)$ defines the polynomial $(x^{q^m-1}-1)$, i.e. we have the equality:

$$(x^{q^m-1}-1) = \prod_{\forall i \in \{0,\ldots,q^m-1\}} f_i(x) = \prod_{\forall i \in \{0,\ldots,q^m-1\}} \left(x - \alpha^i\right),$$

where α is a primitive element of the field $GF(q^m)$, whence follows:

$$g(x) = LCM\left(\prod_j f_j(x)\right) = LCM\left(\prod_j \prod_{s=0}^{m_j} \left(x - \alpha^{j\left(q^s\right)}\right)\right),$$

$$h(x) = \frac{x^n - 1}{g(x)} = LCM\left(\prod_{i \neq j} f_i(x)\right) = LCM\left(\prod_{i \neq j} \prod_{s=0}^{m_i} \left(x - \alpha^{i\left(q^s\right)}\right)\right),$$

where LCM is least common multiples.

Table 2. Classes of adjoint elements and minimal polynomials

Adjoint elements					Minimal polynomials
α^0					$f_0(x) = (x - \alpha^0)$
α^1	α^q	α^{q^2}	...	α^{q^m}	$f_1(x) = f_q(x) = f_{q^2}(x) = \ldots = f_{q^m}(x) =$ $= (x-\alpha^1)\cdot(x-\alpha^q)\cdot(x-\alpha^{q^2})\cdot(x-\alpha^{q^m})$
...	...	...	...	...	...
α^i	α^{iq}	α^{iq^2}	...	α^{iq^m}	$f_i(x) = f_{iq}(x) = f_{iq^2}(x) = \ldots = f_{iq^m}(x) =$ $= (x-\alpha^i)\cdot(x-\alpha^{iq})\cdot(x-\alpha^{iq^2})\cdot(x-\alpha^{iq^m})$
...	...	...	...	...	...

Let us consider the structure of the group (n, k, d) code V over $GF(q)$ from the point of view of the cyclic properties of the sequences that form it. We will use the concept of *a cyclic orbit* V_ξ is a set of sequences with elements from $GF(q)$, equivalent to each other with respect to the cyclic shift operation, i.e. many such:

$$C_i=\left(c_0^i,c_1^i,...c_{n-1}^i\right),\ c_v^i\in GF(q)\ \text{and}\ C_j=\left(c_0^j,c_1^j,...c_{n-1}^j\right),\ c_v^j\in GF(q),$$

that equality holds:

$$\left(c_0^i,c_1^i,...c_{n-1}^i\right)=\left(c_{(\tau)\bmod(n)}^j,c_{(\tau+1)\bmod(n)}^j,...c_{(\tau+n-1)\bmod(n)}^j\right), \quad (2)$$

for any $\tau\in\{0,...,n-1\}$.

Expression (1) using (2) is expressed in terms of polynomial algebra:

$$p_i(x)=x^\tau\cdot p_j(x)=R_{x^n-1}\left[x^\tau\cdot p_j(x)\right],$$

$$p_i(x)=c_0^i+c_1^ix+...+c_{n-1}^ix^{n-1},\ p_j(x)=c_0^j+c_1^jx+...+c_{n-1}^jx^{n-1}.$$

Consider the set $W=GF^n(q)$ of all *n*- sequences with elements from $GF(q)$, which form the so-called "full code". The structure of a set is equivalent to a vector space $GF(q)$ with componential addition and multiplication by a scalar.

We divide the entire set W into subsets of orbits $V_0,V_1,\dots,V_L$, each of which contains a set of sequences equivalent to each other in relation to the cyclic shift operation. Thus, we obtain the decomposition of the vector space $GF(q)$ into sets of non-intersecting orbits (Fig. 1). In Fig. 1 $S_{i,j}\in GF^n(q), i=0,\dots,L, j=1,\dots,Z_i$ is schematically denoted by *n*- sequences as elements of the set W. All $S_{i,j}$ are grouped on the basis of equivalence in relation to the cyclic shift operation. Each group is a set V_i, all elements of the set V_i form *i* orbit of a set. W. It is also obvious that each sequence $S_{i,j}$ can be represented in the form (2) as some sequence C_L in the notations introduced above. The power of the set V_i (the number of elements of the *i* orbit of the set *W*) is equal to Z_i. Obviously, for a set *W* formed by *n*- sequences with elements from $GF^n(q)$, the power of the set V_i for an arbitrary $i=0,...,L$ does not exceed *n*, i.e. $Z_i\le n, i=0,...,L$, the number of nonzero orbits L is bounded below by the following value:

$$L\ge\frac{q^n-1}{n}. \quad (3)$$

Under the zero is understood the orbit V_0, consisting of one zero sequence S_{o,z_0} (a sequence consisting of only zero elements $GF(q)$), the corresponding number of sequences of the orbit $Z_0 = 1$.

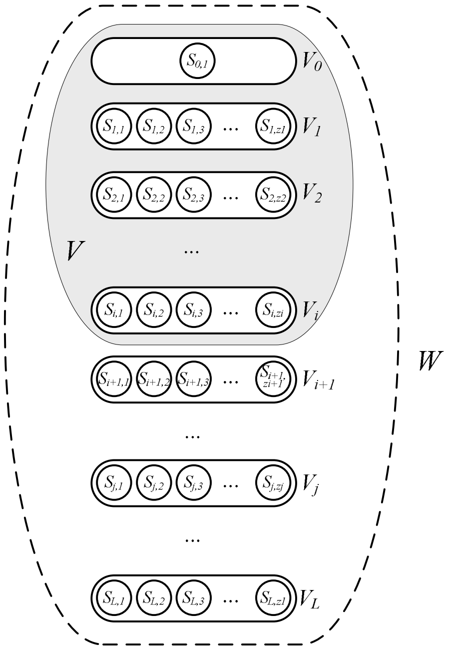

Fig. 1. A diagram of decomposition of vector space $GF^n(q)$ on the sets of not-intersecting circular shifts $V_i, i = 0,...,L$

Analyzing (2) we come to the conclusion that each orbit contains *n*- sequences with a fixed weight (the cyclic shift operation does not change the weight of the sequence). At the same time, the code *V* does not contain sequences of weight less than *d*. Strictly speaking, the weights of the sequences that form the code *V*, are determined solely by the weight spectrum of code *V*.

Suppose that the considered code *V* has a weight spectrum of the form:

$$A(w),\ w=0,\ldots,n,$$

where $A(w)$ is the number of code words of the *V* code with weight w.

It is obvious that for (n, k, d) code *V* the weight spectrum has the form:

$$\begin{cases} A(w) = 1,\ w = 0; \\ A(w) = 0,\ w = 1,\ldots,d-1; \\ A(w),\ w = d,\ldots,n, \end{cases} \tag{4}$$

i.e. nonzero components of the weight spectrum $A(w) \neq 0$ (except for one zero sequence $A(0) = 1$) are concentrated in the weight range $W = d,...,n$.

Taking into account the above considerations, the diagram for decomposing the vector space $GF^n(q)$ into sets of disjoint cyclic orbits $V_i, i = 0,...,L$ is represented as a diagram in Fig. 2.

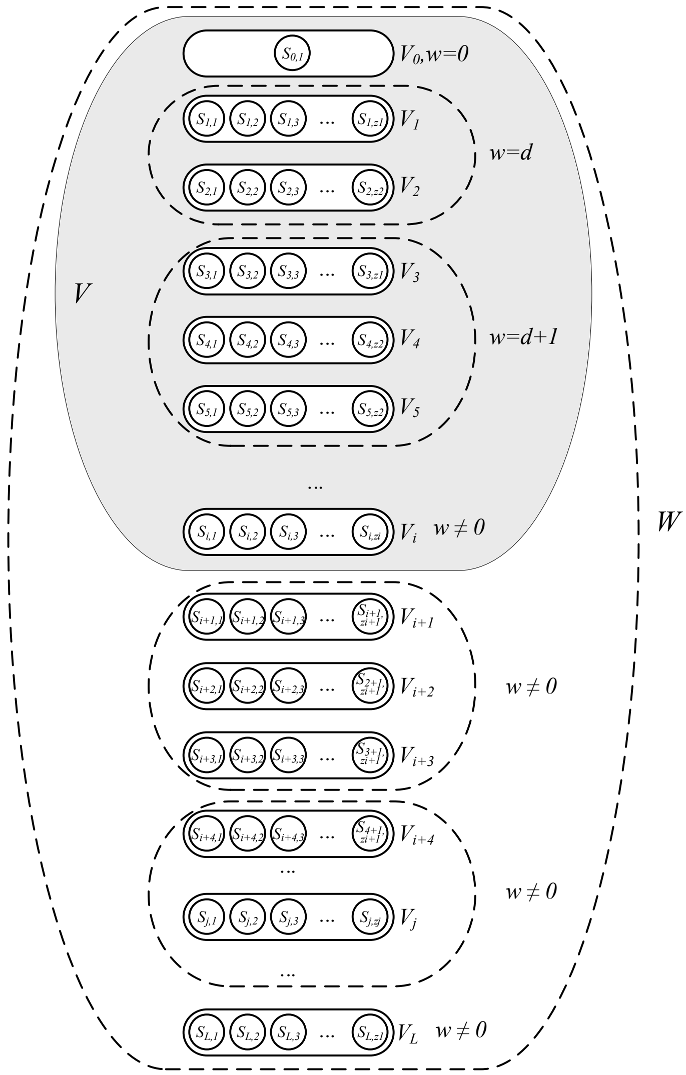

Fig. 2. The diagram of decomposition of vector space $GF^n(q)$ on the sets of not-intersecting circular shifts $V_i, i = 0,...,L$

Obviously, the «complete code» W is represented as a union of a finite number of disjoint orbit-sequences of fixed weight, equivalent to each other with respect to the cyclic shift operation. The code V as a subset of the space $GF^n(q)$ is the union of a finite number of orbits, and the weights of the sequences of the orbits are determined exclusively by the weight spectrum, i.e. relevant $w \neq 0$.

The number of orbits of a fixed weight is also determined by the weight spectrum of the code, i.e. the number of sequences in these orbits. Thus, the number of orbits of a weight $w \neq 0$ of a code V with a weight spectrum (4) is bounded below by an expression (by analogy with (3)):

$$L(w) \geq \frac{A(w)}{n}. \quad (5)$$

So, the group code is uniquely defined by the leaders (representatives) of its cyclic orbits.

4 Conclusions

The efficiency of functioning of digital communication systems with the provision of multiple access on the technology of code division of channels directly depends on ensemble, correlation and structural properties of used discrete signals. Promising in this sense are methods for the synthesis of discrete signals with special correlation properties, the magnitudes of lateral ejections of the correlation function of which are determined by strict analytical relations and are directly related to the structural properties of ensembles of discrete sequences.

The analysis of methods of synthesis of discrete signals with special correlation properties has shown that application of formed sequences allows providing the set level of noise immunity of communication The lateral ejections of function of correlation of discrete signals with the special properties take on final beforehand known values, that allows to use them on the different stages of digital communication At the same time, the main disadvantage of such methods is the low power of the ensembles of formed sequences. So, for example, the number of MLRS, sequences of Legendre, Paley-Plotkin of and other is determined by the number of irreducible polynomials that define the rule for the formation of sequences. The improved ensemble properties are possessed by sequences Golda, small and large set of sequences of Kasami. Their construction is based on the use of the developed mathematical vehicle of the theory of the finite fields and, in particular, the theory of polynomial rings, which allows us to connect the correlation properties of the formed sequences with the group and structural properties of signal ensembles. The most perspective in this sense are the methods of synthesis based on the cross-section of circular shifts of the group codes.

Research of cyclic properties of group codes and presentation of them through the combination of circular shifts allowed to ground the rule of forming of discrete signals as leaders of corresponding circular shifts. Due to the cross-section of circular shifts, it is possible to form a set of sequences, the ensemble and correlation properties of which are determined by the distance, structural and cyclic properties of the corresponding group codes. The further researches can be focused on using in some different other areas [31-34].

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