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FEATURES OF MULTIPLICATIVE COMPLEMENTARY SIGNAL CONSTRUCTIONS BASED ON GENERALIZED BINARY BARKER SEQUENCES

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Abstract—*Radio and signal processing systems often use spread-spectrum and pulse compression techniques combined with the matched filtering approach as the main signal processing scheme. Among different signals that have been designed for these techniques, Golay complementary sequences are well known signal constructions, which are additive complementary sequences in terms of the nature of their signal processing. The similar multiplicative complementary sequences, which based on generalized binary Barker sequences, also exist. Spectral and detection features of generalized binary Barker sequences and Golay complementary sequences, their comparative analysis are given in the article.*

Index Terms—Generalized binary Barker sequences; Golay complementary sequences; pulse compression technique; signal processing; spectral characteristics; signal detection.

I. INTRODUCTION

Generalized binary Barker sequences are a kind of sequences, which can be synthesized by deterministic regular generation rules [1]. These sequences are characterized by regular structures of sequences and their aperiodic autocorrelation function. They also contain all known Barker sequences of lengths $N \leq 13$ as particular cases. Unfortunately, these sequences have large values of sidelobes in the autocorrelation function, which restricts their direct use in spread-spectrum and pulse compression techniques. However, generalized binary Barker sequences form systems of multiplicative complementary signal-code constructions, which are characterized by rejection of sidelobes during their joint signal processing [2], and therefore they can be used in radio systems using a modulation technique that is typical for Golay complementary sequences [3].

The article contains extended results of the research [4] and focuses on spectral and detection features of multiplicative complementary signal constructions, which based on generalized binary Barker sequences, and a comparative analysis of these features with the case of Golay complementary sequences.

II. ANALYSIS OF PUBLICATIONS

A number of publications were devoted to the methodology of synthesis, analysis and signal processing of generalized binary Barker sequences. They were first proposed in [1]. Generation rules for them and their structures were described in detail in [5]. Correlation properties of generalized binary Barker sequences, including complete mathematical expressions for aperiodic autocorrelation function, were synthesized and analyzed in [6]. Aspects of the use of this kind of sequences in DSSS technique were described in [7], [8]. A synthesis of multiplicative complementary signal-code constructions, which based on generalized binary Barker sequences, a theoretical continuity of these signal constructions and known Barker binary sequences, which based on a statistical model of correlated signal components and their clusterization, were systematically shown in [2].

In view of the considered research results and publications, the article deals with some characteristics (spectral and detection) in the context of signal processing of generalized binary Barker sequences and their multiplicative complementary structures.

It should also be noted that described in the article kind of signals and signal processing are connected with spread-spectrum and pulse compression techniques, which boil down to a signal generation and processing in a wider bandwidth than in the case of using of more simple signals. Typically, these techniques use electric and radio signals in radar technologies [9], telecommunications [10], and navigation systems [11], however ultrasonic applications have been also designed, e.g., the prototype of an airborne ultrasonic array that combines pulse compression techniques with positioning algorithms in order to achieve accurate determination of the position of the reflectors placed in front of the array [12], and the method of evaluation of position and velocity measurement for a moving object by pulse compression using ultrasound [13]. The pulse compression techniques and related signals as probing signals have been also applied in the field of

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automation and motion control, e.g., to monitoring of a nonlinear model for the longitudinal motion of a Boeing-747 [14] and in the model of real-time monitoring of a closed-loop nonlinear GTM aircraft (NASA generic transport model) [15]. A matched filtering is the main signal processing method for the pulse compression technique and it is realized in signal processing equipment by means of a matched filters [16], [17].

III. PROBLEM STATEMENT

The accuracy of signal detection of a signal in the pulse compression technique depends on sidelobes in the signal after matched filtering and their absolute peak sidelobe level (PSL), therefore, must be as low as possible.

In the case of a signal in spread-spectrum radio system, which based on a binary sequence $a_i \in \{\pm 1\}$ ($i = \overline{1, N}$, N – the length of sequence), the signal $Z(t)$ after matched filtering reproduces the autocorrelation function $R(\mu) = \sum_{j=1+\mu}^{N} a_j a_{j-\mu}$, $\mu = \overline{0, (N-1)}$, of this sequence:

$$Z(t) = \\ = \sum_{i=-N+1}^{N-1} R(|i|)\left[H\left(t-(N+i)\tau\right)-H\left(t-(N+1+i)\tau\right)\right],$$

where $H(x)$ – the Heaviside step function.

In view of the above, sidelobes of autocorrelation function of a sequence a_i defines sidelobes in the signal $Z(t)$ after matched filtering and $\max\{|R(\mu \mid \mu \neq 0)|\} = \text{PSL}$ also must be as low as possible.

A synthesis of sequences with low values of aperiodic autocorrelation PSL is still a theoretical problem in general.

This problem boils down to the fact that the systematic deterministic methods for synthesis of such signals for the case of an arbitrary length of sequence are unknown, and the complexity of this problem is associated with an algorithmic undecidability of arbitrary algebraic Diophantine equations (Hilbert's Tenth Problem) [18].

However, there are well known binary and non-binary sequences and their combinations with low sidelobes or equivalent sidelobes of autocorrelation function. An overview of known binary sequences with low autocorrelation PSL for their maximum lengths N was given in [4], [19].

There are also known non-binary sequences, which have low values of PSL or its equivalent, e.g., ternary pulse compression sequences that consist of elements $a_i \in \{0, \pm 1\}$ [20], polyphase pulse compression sequences [21]. Binary sequences and their combinations are the most suitable in radio systems due to their binary structure. Among binary combinations, which give equivalent low sidelobe level of autocorrelation function, the Golay complementary sequences (complementary codes) and related complementary code keying (CCK) scheme are well known and used type of signal constructions [3].

The aim of the article is to research and compare particular features, namely, spectral and detection ones of additive (based on Golay complementary sequences) and multiplicative (based on generalized binary Barker sequences) complementary signal constructions.

IV. GOLAY COMPLEMENTARY SEQUENCES AND GENERALIZED BINARY BARKER SEQUENCES AS ADDITIVE AND MULTIPLICATIVE COMPLEMENTARY SIGNAL CONSTRUCTIONS, RESPECTIVELY

The binary Golay complementary sequence pair consists of two sequences $a_i \in \{\pm 1\}$ and $b_i \in \{\pm 1\}$, $i = \overline{1, N}$, $N = 2^n 10^k 26^m$, n, k, m are non-negative integers, with a property that the result of adding of sidelobes of their autocorrelation functions is equal to zero [3].

An example of such sequences for $N = 2^3 10^0 26^0 = 8$ are a = {-1;-1;-1; 1; 1; 1;-1; 1}; b = {-1;-1;-1; 1;-1; -1; 1;-1} [4].

Golay complementary sequences are additive complementary sequences due to features of their signal processing, namely, a total rejection of sidelobes of autocorrelation function in the process of adding of results of matching filtering. In [1], [2] were proposed and described signal constructions that based on generalized binary Barker sequences, which have the similar technical effect to Golay complementary sequences (low resultant values of sidelobes after joint signal processing) in a multiplicative sense. Described in the article multiplicative complementary signal constructions may consist of $K \geq 2$ binary sequences of different lengths and provide a signal after multiplication of results of matched filtering with a central main lobe equals to a result of multiplication of all lengths of sequences, which are part of a system of mentioned K binary sequences, and a normalized maximum absolute sidelobe level equals to $1/N_K$, where N_K is the maximum length of sequence in a the system of sequences [2], [4].

An example of such sequences at $K = 2$ are $a = \{1;-1;-1\}$ ($N_1 = 3$) and $b = \{1;-1; 1; 1; -1; 1; 1; 1; 1;-1;-1;-1\}$ ($N_2 = 12$) [4]. If $K = 3$, the sequence $c = \{1;-1; 1; 1;-1; 1; 1; 1;-1; 1; 1; 1; 1; -1; 1; 1; 1;-1; 1; 1; 1\text{-}1;-1;-1\}$ ($N_3 = 24$) is also a part of the system of multiplicative complementary signal construction based on generalized binary Barker sequences. If $K = 4$, the sequence $d = \{1; -1; 1; 1;-1; 1; 1; 1;-1; 1; 1; 1;-1; 1; 1; 1;-1; 1; 1; 1;-1; 1; 1; 1; 1;-1; 1; 1; 1;-1; 1; 1; 1;-1; 1; 1; 1;-1; 1; 1; 1; -1; 1; 1; 1;-1;-1;-1\}$ ($N_4 = 48$) is also a part of one, etc. in accordance with generation rules in [2].

V. Spectral and Detection Features of Generalized Binary Barker Sequences as Multiplicative Signal Constructions

In this section are presented simulation results, which focused on spectral and detection features of generalized binary Barker sequences and their comparison with such features of Golay complementary sequences. Sequences *a* and *b* from Section IV were used for simulation of signal processing in the case of Golay complementary sequences and in the case of generalized binary Barker sequences. The case of analysis of structures of mentioned signal constructions without the impact of noise was described in detail in [4] and the case with the impact of noise is considered in this article more detail.

Simulation conditions are as follows:

1) input signals at the input of signal processing exist within the time range $t \in [24, 48]$ μs;

2) there is the Gaussian noise at the input of signal processing; values of signal to noise ratio ($\mathrm{SNR_{in}}$) are in the range –10...30 dB for each component of signal construction.

The first point of the presented results is the spectral characteristics of considered signal constructions (without noise). Spectral characteristics of considered Golay complementary sequences (duration of the element of a sequence is 3 μs), which were evaluated by the fast Fourier transform in a logarithmic scale (dB), are shown in Fig. 1 (the maximum values are normalized and equal to 0 dB). Spectral characteristics of considered generalized binary Barker sequences (duration of the element of a sequence is 8 μs and 2 μs for the sequences *a* and *b*, respectively) are shown in Fig. 2.

Analysis of spectral characteristics shows that Golay complementary sequences in a pair have the same bandwidth of the main spectrum lobe ($\Delta f_0 \approx 0.333$ MHz) and almost the same peak-to-average ratio of spectral components $-M$ (20.3…21.2 dB in the bandwidth 1 MHz).

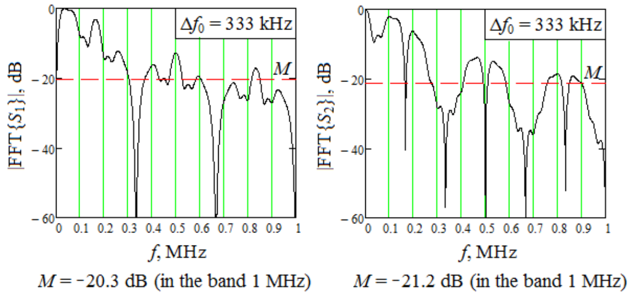

Fig. 1. Spectral characteristics of considered Golay complementary sequences (on the left – sequence *a*, on the right – sequence *b*)

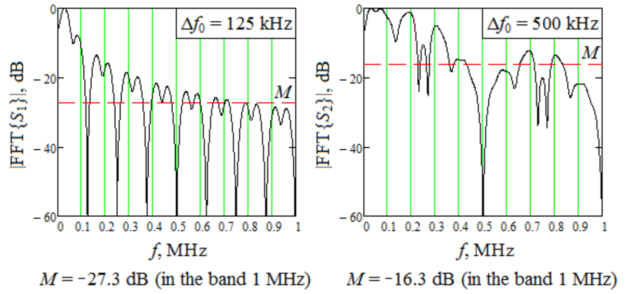

Fig. 2. Spectral characteristics of considered generalized binary Barker sequences (on the left – sequence *a*, on the right – sequence *b*)

In contrast with Golay complementary sequences, generalized binary Barker sequences have significantly different values of the main spectrum lobe (the difference is 4 times: $\Delta f_0 = 0.125$ MHz for the sequence *a*, and $\Delta f_0 = 0.5$ MHz for the sequence *b*) and significantly different values of the peak-to-average ratio of spectral components $-M$ (the difference is 11 dB: 27.3 dB for the sequence *a*, and 16.3 dB for the sequence *b*).

Thus, generalized binary Barker sequences are characterized by a greater imbalance of spectral characteristics between sequences in a system than Golay complementary sequences. These spectral features may define design features of a physical layer of a radio system and specifics of used modulation scheme and signal processing (e.g., selection of reference signals etc.).

The second point of the presented results is the detection features of considered signal constructions. There are two cases of simulation results are presented below: at signal to noise ratio (for signal and noise power) for each component of signal construction at the input of signal processing scheme $\mathrm{SNR_{in}} = 30$ dB and $\mathrm{SNR_{in}} = -10$ dB, which are bounds of studied range of the value $\mathrm{SNR_{in}}$.

In Figure 3 are shown input signals with noise $a(t) + \eta(t)$ and $b(t) + \eta(t)$ for considered Golay complementary sequence pair at $\mathrm{SNR_{in}} = 30$ dB.

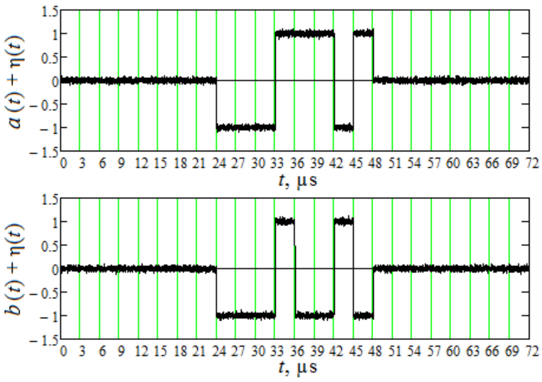

Fig. 3. Input signals based on Golay complementary sequences ($N = 8$) at $SNR_{in} = 30$ dB

An output signal $Z(t)$ after signal processing, which based on matched filtering and adding of its results, and its parameters (SNR_{SL} and SNR_{ML}, in dB, are signal to noise ratios in sidelobes and in the main central lobe, respectively; $G_{SL} = SNR_{SL} – SNR_{in}$ and $G_{ML} = SNR_{ML} – SNR_{in}$, in dB, are processing gains in sidelobes and in the main central lobe, respectively) for considered Golay complementary sequences at $SNR_{in} = 30$ dB is shown in Fig. 4.

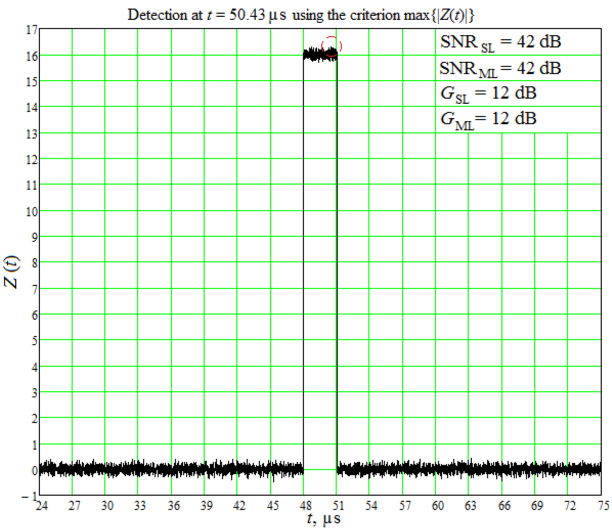

Fig. 4. Output signal after signal processing for input signals based on Golay complementary sequences ($N = 8$) at $SNR_{in} = 30$ dB

In Figure 5 are shown input signals with noise $a(t) + \eta(t)$ and $b(t) + \eta(t)$ for considered generalized binary Barker sequences at $SNR_{in} = 30$ dB. An output signal $Z(t)$ after signal processing, which based on matched filtering and multiplication of its results (described in detail in [2]), and its parameters (SNR_{SL}, SNR_{ML}, G_{SL}, G_{ML}) for considered generalized binary Barker sequences at $SNR_{in} = 30$ dB is shown in Fig. 6. Note that non-zero sidelobes of $Z(t)$ are accounted for as a part of noise in SNR_{SL} for a correctness of the comparison with Golay complementary sequences.

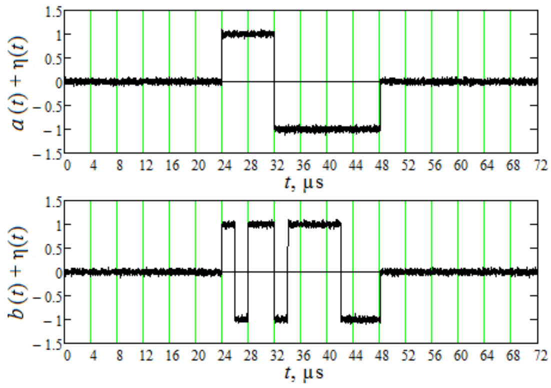

Fig. 5. Input signals based on generalized binary Barker sequences ($N_1 = 3$; $N_2 = 12$) at $SNR_{in} = 30$ dB

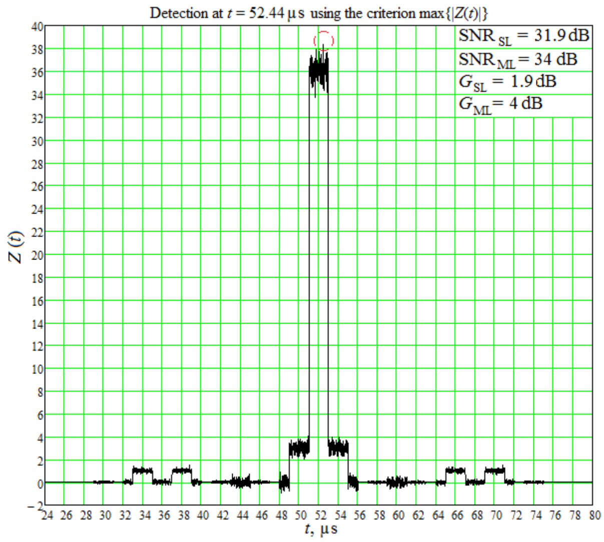

Fig. 6. Output signal after signal processing for input signals based on generalized binary Barker sequences ($N_1 = 3$; $N_2 = 12$) at $SNR_{in} = 30$ dB

In Figure 7 are shown input signals with noise $a(t) + \eta(t)$ and $b(t) + \eta(t)$ for considered Golay complementary sequence pair at $SNR_{in} = –10$ dB.

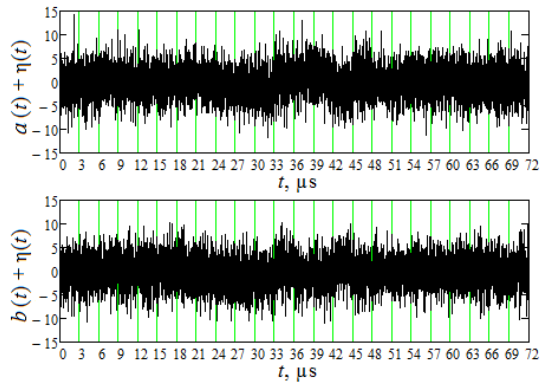

Fig. 7. Input signals based on Golay complementary sequences ($N = 8$) at $SNR_{in} = –10$ dB

An output signal $Z(t)$ after signal processing and its parameters (SNR_{SL}, SNR_{ML}, G_{SL}, G_{ML}) for considered Golay complementary sequences at $SNR_{in} = –10$ dB is shown in Fig. 8.

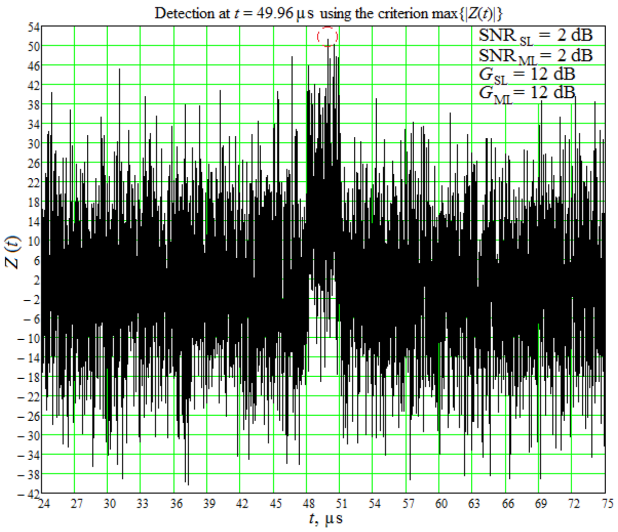

Fig. 8. Output signal after signal processing for input signals based on Golay complementary sequences ($N = 8$) at $SNR_{in} = -10$ dB

In Figure 9 are shown input signals with noise $a(t) + \eta(t)$ and $b(t) + \eta(t)$ for considered generalized binary Barker sequences at $SNR_{in} = -10$ dB.

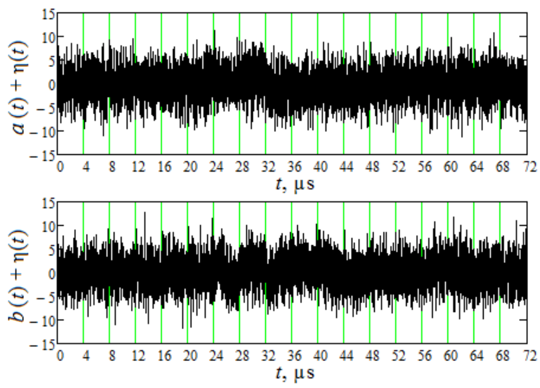

Fig. 9. Input signals based on generalized binary Barker sequences ($N_1 = 3$; $N_2 = 12$) at $SNR_{in} = -10$ dB

An output signal $Z(t)$ after signal processing and its parameters (SNR_{SL}, SNR_{ML}, G_{SL}, G_{ML}) for considered generalized binary Barker sequences at $SNR_{in} = -10$ dB is shown in Fig. 10 (non-zero sidelobes of $Z(t)$ are also accounted for as a part of noise in SNR_{SL} for a correctness of the comparison with Golay complementary sequences).

Note that in Fig. 4, Fig. 6, Fig. 8 and Fig. 10 a detection using the criterion $\max\{|Z(t)|\}$ was observed in the main lobe. It is a particular cases at $SNR_{in} = -10$ dB and, of course, a probability to register a detection in sidelobes (an error of the first genus) in Fig. 8 and Fig. 10 is a very large in a general case in different simulations.

Analysis of results of signal processing shows that at very large (30 dB) and at very small (–10 dB) values of SNR_{in} Golay complementary sequences are better than generalized binary Barker sequences.

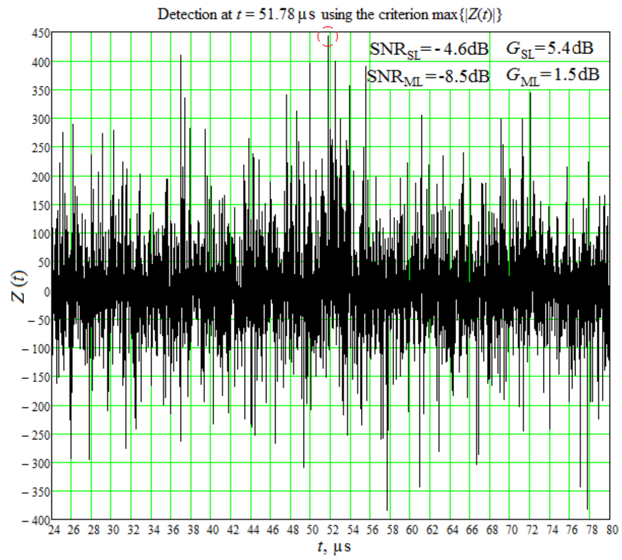

Fig. 10. Output signal after signal processing for input signals based on generalized binary Barker sequences ($N_1 = 3$; $N_2 = 12$) at $SNR_{in} = -10$ dB

However, within this range at medium values of SNR_{in} generalized binary Barker sequences are able to provide larger values of G_{SL}, e.g., at $SNR_{in} = 14$ dB [4].

Dependences of efficiency of signal processing in sidelobes and in the main lobe, which is estimated by the parameters SNR_{SL}, SNR_{ML}, G_{SL}, G_{ML}, on the value of SNR_{in} for considered Golay complementary sequences and generalized binary Barker sequences are shown in Fig. 11 and Fig. 12.

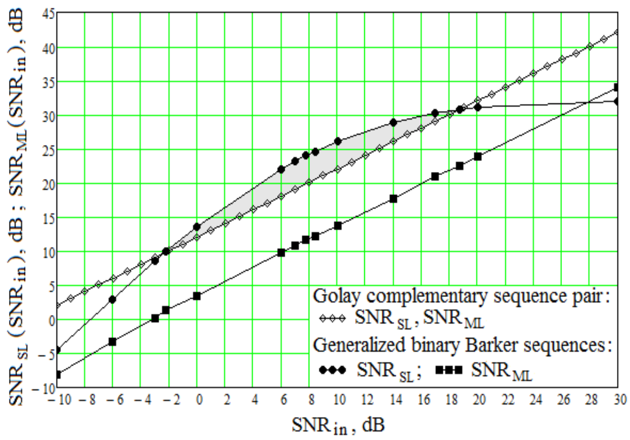

Fig. 11. Dependences of SNR_{SL} and SNR_{ML} on SNR_{in} for considered Golay complementary sequences and generalized binary Barker sequences

The range of values of SNR_{in}, where generalized binary Barker sequences provide better efficiency by the criterion of larger values of SNR_{SL} and G_{SL} than Golay complementary sequences (less noise in sidelobes and less number of errors of the first genus), are marked in Fig. 11 and Fig. 12 as contrast zones.

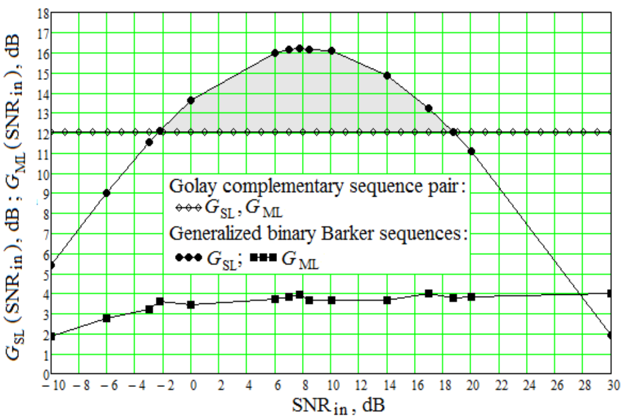

Fig. 12. Dependences of G_{SL} and G_{ML} on SNR_{in} for considered Golay complementary sequences and generalized binary Barker sequences

Note that a better efficiency (using the criterion G_{SL}) in the range $SNR_{in} = -2.2\ldots19$ dB of generalized binary Barker sequences in comparison with Golay complementary sequences is also observed in conditions of almost the same total bandwidth (667 kHz and 625 kHz for Golay complementary sequences and generalized binary Barker sequences, respectively), 33.3 % less value of a duration of the main lobe (3 µs and 2 µs for Golay complementary sequences and generalized binary Barker sequences, respectively), which provides less measurement uncertainly for a time (in synchronization systems) or for a distance (in radar and navigation systems). At the same time, Golay complementary sequences provides better efficiency by the criterion of larger values of SNR_{ML} and G_{ML} than generalized binary Barker sequences (less noise in the main lobe and less number of errors of the second genus).

VI. CONCLUSIONS

Spectral and detection features of multiplicative complementary signal constructions based on generalized binary Barker sequences and their comparison with Golay complementary sequences were studied in the article.

Results of comparative analysis allow to state features and conclusions, which are as follows.

Advantages of generalized binary Barker sequences in comparison with Golay complementary sequences (values are indicated for considered in the article parameters of analyzed signal constructions):

1) the total bandwidth estimated by the criterion Δf_0 is 6.3 % less (667 kHz and 625 kHz for Golay complementary sequences and binary Barker sequences, respectively);

2) the measurement uncertainly for a time (e.g., in synchronization systems) and for a distance (e.g., in radar and navigation systems) is 33.3 % less (3 µs and 2 µs for Golay complementary sequences and generalized binary Barker sequences, respectively);

3) in contrast with Golay complementary sequences, generalized binary Barker sequences provide larger values of the processing gain in sidelobes G_{SL} in the range $SNR_{in} = -2.2\ldots19$ dB (4.1 dB greater at $SNR_{in} = 7.8$ dB, as a maximum value of G_{SL}); it causes less noise in sidelobes and less number of errors of the first genus in the case of the use of generalized binary Barker sequences.

At the same time, the main disadvantage of generalized binary Barker sequences in comparison with Golay complementary sequences is that the processing gain in the main central lobe G_{ML} is less (8..10 dB less). It causes more noise in the main lobe and greater number of errors of the second genus in the case of the use of generalized binary Barker sequences in radio and signal processing systems.

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О. Г. Голубничий. Особливості мультиплікативно комплементарних сигнальних конструкцій на основі узагальнених бінарних послідовностей Баркера

Радіотехнічні системи та системи обробки сигналів часто використовують широкосмугові сигнали та узгоджену фільтрацію для їх обробки. Комплементарні коди Голея є добре відомими сигнально-кодовими конструкціями серед різних типів широкосмугових сигналів. Вони є адитивно комплементарними сигналами з точки зору їх обробки. Також існують подібні до них мультиплікативно комплементарні сигнали на основі узагальнених бінарних послідовностей Баркера. У статті проаналізовано особливості виявлення та спектральні характеристики цих типів сигналів.

Показано, що доцільність використання того чи іншого типу сигнальних конструкцій із зазначених залежить від сигнально-завадового стану на вході системи обробки сигналів.
Ключові слова: узагальнені бінарні послідовності Баркера; комплементарні коди Голея; узгоджена фільтрація; обробка сигналів; спектральні характеристики; виявлення сигналів.

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А. Г. Голубничий. Особенности мультипликативно комплементарных сигнальных конструкций на основе обобщённых бинарных последовательностей Баркера

Радиотехнические системы и системы обработки сигналов часто используют шумоподобные сигналы и согласованную фильтрацию для их обработки. Комплементарные коды Голея являются хорошо известными сигнально-кодовыми конструкциями среди разных типов шумоподобных сигналов. Они являются аддитивно комплементарными сигналами с точки зрения их обработки. Также существуют подобные им мультипликативно комплементарные сигналы на основе обобщённых бинарных последовательностей Баркера. В статье проанализированы особенности обнаружения и спектральные характеристики этих типов сигналов. Показано, что целесообразность использования того или иного типа сигнальных конструкций из указанных зависит от сигнально-помеховой обстановки на входе системы обработки сигналов.
Ключевые слова: обобщённые бинарные последовательности Баркера; комплементарные коды Голея; согласованная фильтрация; обработка сигналов; спектральные характеристики; обнаружение сигналов.

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