Mismatched Filters for Processing of Phase Manipulated Signals with Three-Valued Autocorrelation

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Abstract. **The phase manipulated signals, which autocorrelation functions resemble delta pulses, play a very important role for the radars, radio navigation networks and remote control systems as they provide the highest possible resolution of the received signals. Unfortunately, today known classes of such signals have small volumes, which often cannot ensure the necessary electromagnetic compatibility as well as high resistance in a hostile radio electronic environment. Accounting this situation in the paper a method for synthesis of mismatched filters, which effectively suppress the sidelobes of three-valued autocorrelations of phase manipulated signals, is substantiated.**

Keywords: signal with three-valued autocorrelation, synthesis of mismatched filter.

I. INTRODUCTION

Today a tremendous amount of autonomous devices is used practically in all spheres of industry, science, medicine, transportation, education and so on. As a result, the problems of ensuring: precise positioning, secure remote control and guidance, as well as electromagnetic compatibility of these devices, became a great importance [1], [2].

As known, a universal approach for solving of the above listed problems, is the exploitation of phase manipulated (PM) signals, which autocorrelation functions (ACFs) resemble delta pulses, as they provide the highest possible resolution of the received signals [3], [4]. Unfortunately, today known classes of such signals have small volumes, which often cannot ensure the necessary electromagnetic compatibility as well as high resistance in a hostile radio electronic environment. An effective approach for solving of this problem is the processing of received signals with mismatched filters (MMFs), which substitute the signals' ACFs with cross-correlation functions (CCFs), resembling delta pulses.

Accounting this situation in the paper a method for synthesis of MMFs, which process the PM signals with nearly uniform autocorrelation with small losses in the signal-to-noise ratio, is substantiated.

The paper is organized as follows. First, the basics of the signal processing in the receivers of the communication systems are recalled. After that the possibility the negative effects, caused by the multipath spread of the electromagnetic waves, to be minimized by simple transformations of PM signals' ACFs is substantiated. On this base infinite classes of PM signals, which can be processed effectively by the developed MMFs, are systematized. At the end, the applications of the proposed MMFs are analysed.

II. METHODOLOGY OF THE STUDY

Methodology of the study will be explained by the means of the so-called Barker codes (sequences, signals). Namely, the Barker signals can be presented mathematically by the following number sequence with length N:

$$\{\mu(k)\}_{k=0}^{N-1} = \{\mu(0), \mu(1), \dots, \mu(N-1)\}. \qquad (1)$$

The samples in the right side of (1) are integers $+1$ or -1, presenting the envelopes of the consecutive elementary phase pulses (or chips) with duration τ_{ch}, forming the Barker signal. Besides, N is the quantity of the chips. Due to this reason, the generation and the processing of the Barker signals can be realized by simple, reliable and cost-effective radio-electronic components. As a result, the Barker signals are widely used for positioning, sensing and remote control of small (miniature) autonomous devices.

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Here it should be recalled that the most often, the receivers in the communication systems are built as matched filters (MFs). They are digital filters with finite impulse response (FIR), which transfer functions (TFs) are a conjugate and mirror-reversed copy of the sent (expected) signal:

$$\{\mu^*(k)\}_{k=0}^{N-1} = \{\mu^*(0), \mu^*(1), \dots, \mu^*(N-1)\}. \qquad (2)$$

In (2) the symbol "*" stands for "complex conjugation". In cases of Barker signals, the complex conjugation does not change the samples in the both sides of (2).

As known, the result of signal processing by the respective MF is the ACF of the sent (received) signal:

$$P_{\mu\mu}(r) = \\ = \begin{cases} \sum_{k=0}^{N-1-\lceil r \rceil} \mu(k+\lceil r \rceil)\mu^*(k), -(N-1) \le r \le 0, \\ \sum_{k=0}^{N-1-r} \mu(k)\mu^*(k+r), \quad 0 \le r \le N-1. \end{cases} \qquad (3)$$

In (3) $P_{\mu\mu}(r)$ is the r-th sample of the ACF of the digital signal (1).

The wide exploitation of MFs can be explained by the fact that this type of signal processing maximizes the signal-to-noise ratio (SNR) in the presence of the so-called additive white Gaussian noise (AWGN), which meets most often in the practice.

In order to minimize the negative effects, caused by the multipath spread of the electromagnetic waves, the ACF of the sent signal have to resemble a delta pulse (i.e. to have a thumbtack form) [5], [6], [7]:

$$P_{\mu\mu}(r) = \begin{cases} E_s, r = 0, \\ 0, r \ne 0. \end{cases} \qquad (4)$$

In (4) E_s is the main peak (lobe) of the signal ACF:

$$E_s = \sum_{k=0}^{N-1} |\mu(k)|^2 = \sum_{k=0}^{N-1} \mu(k)\mu^*(k), \qquad (5)$$

which is the result of the coherent accumulation of the energies of all the chips (elementary phase pulses), forming the signal (1).

Here it should be noted that the Barker signals' ACFs are very similar to delta pulses as the lobes (samples) of their ACFs satisfy the conditions:

$$P_{\mu\mu}(r) = \begin{cases} N, r = 0, \\ 0, r \equiv 1 mod 2, \\ = \begin{cases} -1, N \equiv 3 mod 4, r \equiv 0 mod 2, \\ 1, N \equiv 1 mod 4, r \equiv 0 mod 2. \end{cases} \end{cases} \qquad (6)$$

The conditions (6) give reason the Barker signals' ACFs to be classified as three-valued autocorrelations as ACF lobes can take only three different values - $\{N, 0, -1\}$ or $\{N, 0, 1\}$.

Despite of the very small level of the sidelobes of the Barker signals' ACFs too often it is possible an ACF sidelobe of a powerful signal to mask the ACF main lobe of a weak signal, which could be much more important. It is accepted such situations to be called self-interferences (SIs). Due to this reason the methods for synthesis of MMFs, whish suppress (diminish) the sidelobes of the Barker signals' ACFs, have been intensively researched during the past fifty years. In fact, in Internet can be found many research articles as well as patents which present approaches for synthesis of such MMFs, but their inner structure is very complex [8], [9]. Due to this reason, the probability of their application for positioning, sensing and remote control in the sphere of miniature autonomous devices is small.

Accounting this situation, in the rest part of this section the possibility the ACF sidelobes of Barker signals to be suppressed effectively by simple (from implementation point of view) MMFs will be substantiated. More specifically, conditions (6) show that the Barker signals' ACFs have a very regular form, as their sidelobes are sequences, consisting of $N-1$ repeating patterns $\{1,0\}$ or $\{-1,0\}$. As a result, the non-zero sidelobes of each concrete ACF can be eliminated by subtraction of the ACF and its copy, shifted (delayed) at $r = 2$ time-clocks with duration τ_{ch}. This fact is explained on Fig. 1 by the means of the Barker signal with length $N = 11$:

$$\{\mu(k)\}_{k=0}^{10} = \{1,1,1,-1,-1,-1,1,-1,-1,1,-1\}. \qquad (7)$$

Here it should be pointed out the following facts.

First, the above processing of the Barker signals' ACFs can be easily realized by a digital filter with FIR, which TF is:

$$\{\xi(k)\}_{k=0}^{2} = \{-1,0,1\}. \qquad (8)$$

Second, the positive effect of usage of above MMF is the eliminating of all the ACF sidelobes with exception of the first and the last sidelobes. The negative effect is the significant increasing of the sidelobe at the position $r = 2$.

Third, if the processing of the Barker signals' ACFs is performed by two consecutively connected MMF with TFs (8), the peak-to-sidelobe ratio (PSR) increases two times. This approach is explained on Fig. 2, where Difference1 (D1) corresponds to Fig. 1c.

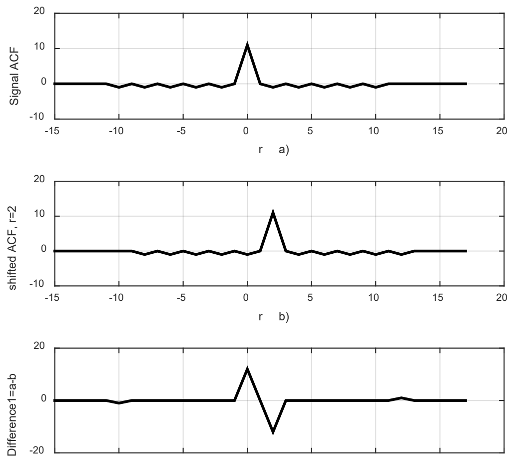

Fig. 1. ACF of the Barker signal (7) (a), its copy, shifted at $r = 2$ time-clocks (b) and the result of their subtraction (Difference1) (c).

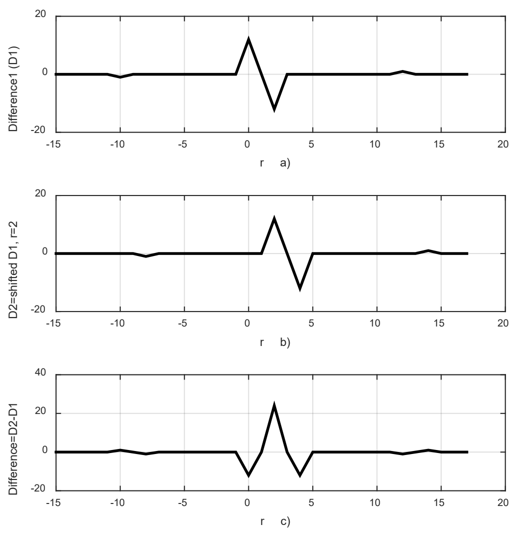

Fig. 2. The result of processing the ACF of the Barker signal (7) by two consecutively connected MMFs with TF (8).

Obviously, the last approach for processing the Barker signals' ACFs can be realized by one digital filter, which TF is the result of the convolution of TF (8) by itself:

$$\{\xi(k)\}_{k=0}^{4} = \{-1,0,2,0,-1\}. \qquad (9)$$

From all the above stated, the following conclusions ensue.

First, the MMFs with TFs (8) and (9) can be applied for processing of every three-valued ACF, which sidelobes are sequences, consisting of $N-1$ repeating patterns $\{a, b\}$, where a and b are arbitrary numbers.

Second, the only shortcoming (the significant increasing of the sidelobe at the position $r = 2$)) of the performance of the MMFs with TFs (8) and (9) could be easily avoided in communication systems, using many receivers at different positions (i.e. communication systems with spatial diversity). Due to this reason, the main obstacle for the practical implementation of the above MMFs is the small volume of the Barker signals' class. This problem will be studied in more detail in the next chapter of the paper.

III. RESULTS AND DISCUSSION

As known, a very effective approach for providing electromagnetic compatibility of all working simultaneously electronic devices as well as their resistance in a hostile radio electronic environment is the pseudo random change the emitted signals, using all volume of a large signal family. Accounting this fact as well as the small volume of the Barker signals' class, in sequel it will be substantiated the possibility the ACFs of two other classes of binary signals to be processed by simple MMFs, applying the method, developed in the previous chapter of the paper.

The first candidate in this way is the very large class of binary signals, which ACFs consist mostly of repeating patterns $\{1,0,-3,0\}$ or $\{-1,0,3,0\}$. In the sequel these PM signals will be called quasi Barker (QB) signals. Obviously, the TFs of MMFs for processing the QB signals' ACFs, should be:

$$\{\xi(k)\}_{k=0}^{4} = \{-1,0,0,0,1\}, \qquad (10)$$

$$\{\xi(k)\}_{k=0}^{8} = \{-1,0,0,0,2,0,0,0,-1\}. \qquad (11)$$

The reasonability of including the QB signals in the signal family, exploited by the communication devices, will be demonstrated by the means of the QB signal with length $N = 43$:

$$\begin{gathered}\{\mu(k)\}_{k=0}^{42} = \{-1,-1,1,-1,-1,1,1,-1,1,1,1 \\ -1,1,-1,-1,-1,-1,-1,1,-1,1,1,-1,-1, \\ -1,-1,1,-1,1,-1,-1,-1\ 1,1,-1,-1, \\ -1,1,1,-1,-1,-1,1,1\}.\end{gathered} \qquad (12)$$

The result of the processing the ACF of the QB signal (12) by the MMF with TF (10) is presented on Fig. 3.

Another promising approach for increasing the volume of the signal family, exploited by the communication devices, is the usage of the so-called complementary pairs (CPs). More specifically, according to the originating work [5] of M. Golay, every CP consists of two binary PM signals $\{\mu(i)\}_{i=0}^{N-1}$ and $\{\eta(i)\}_{i=0}^{N-1}$, chosen so that the sum of their ACFs to resemble a delta – pulse:

$$P_{\mu\mu}(r) + P_{\eta\eta}(r) = \begin{cases} 2N, r = 0, \\ 0, r \neq 0. \end{cases} \qquad (13)$$

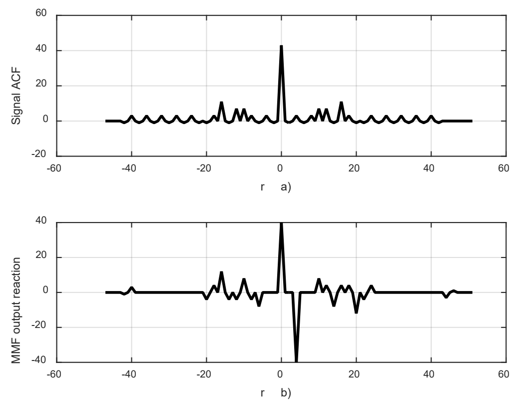

Fig. 3. The result of processing the ACF of the QB signal (12) by the MMF with TF (10).

Here it should be especially noted the following facts.

First, according to the analysis in [10], every CP can be implemented practically by the means of a single frequency channel, divided into two subchannels by quadrature phase manipulation (QPSK) or by two different types of polarization.

Second, M. Golay and R. Turin have developed recursive methods, which allow CPs of binary PM signals with infinite lengths to be synthesized, using any two basic (kernel, seed) CPs with lengths $N = 2, 10, 20, 26$ [5], [6], [7].

Third, according to the exploration, presented in our previous paper [11], it is possible once at an arbitrary step of the recursive procedure Barker or QB signal to be used. In such situations the results are quasi CPs (QCPs) [11], [12], which aggregated ACFs have very small relative quantity of non-zero sidelobes and they can be processed by simple (from the technical point of view) MMFs, applying the method, developed in the previous chapter of the paper.

The last fact will be clarified by the means of the Barker signal (7), which will be used as a QCP

$$\{\mu_1(k)\}_{k=0}^{10} = \{\eta_1(k)\}_{k=0}^{10} = \\ = \{1,1,1,-1,-1,-1,1,-1,-1,1,-1\}, \tag{14}$$

and the simplest non-trivial CP

$$\{\mu_2(k)\}_{k=0}^{1} = \{1,1\}, \{\eta_2(k)\}_{k=0}^{1} = \{1,-1\}\ . \tag{15}$$

On the base of the QCP (14) and CP (15) two different QCPs with length $N = 22$ can be obtained by the following methods:

$$\{\mu(k)\}_{k=0}^{21} = \\ = \{\mu_2(1).\mu_1(k)\}_{k=0}^{10} \odot \{\eta_2(1).\eta_1(k)\}_{k=0}^{10}, \\ \{\eta(k)\}_{k=0}^{21} = \\ \{\mu_2(2).\mu_1(k)\}_{k=0}^{10} \odot \{\eta_2(2).\eta_1(k)\}_{k=0}^{10}, \tag{16}$$

$$\{\mu(k)\}_{k=0}^{21} = \\ = \{\mu_2(1).\mu_1(k)\}_{k=0}^{10} \otimes \{\eta_2(1).\eta_1(k)\}_{k=0}^{10}, \\ \{\eta(k)\}_{k=0}^{21} = \\ \{\mu_2(2).\mu_1(k)\}_{k=0}^{10} \otimes \{\eta_2(2).\eta_1(k)\}_{k=0}^{10}. \tag{17}$$

In (16) and (17) the symbols "$\odot$" and "$\otimes$" denote "concatenation of the sequences" and "interleaving of the sequences" respectively.

The results of the processing the aggregated ACFs of the QCPs (16) and (17) by the MMFs with TFs

$$\{\xi(k)\}_{k=0}^{4} = \{-1,0,0,0,1\}, \tag{18}$$

$$\{\xi(k)\}_{k=0}^{2} = \{-1,0,1\}, \tag{19}$$

are presented on Fig. 4 and Fig. 5 respectively.

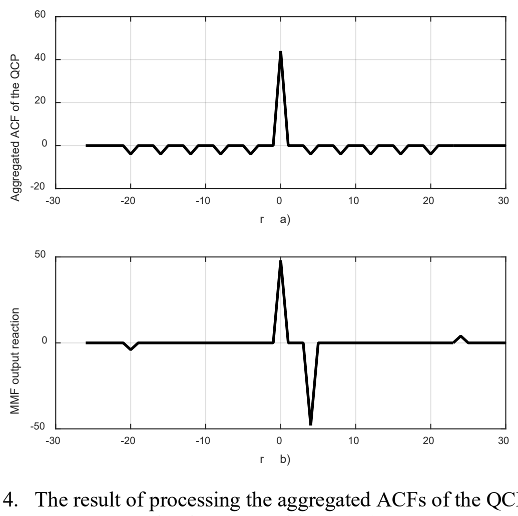

Fig. 4. The result of processing the aggregated ACFs of the QCPs (16) by the MMF with TF (18).

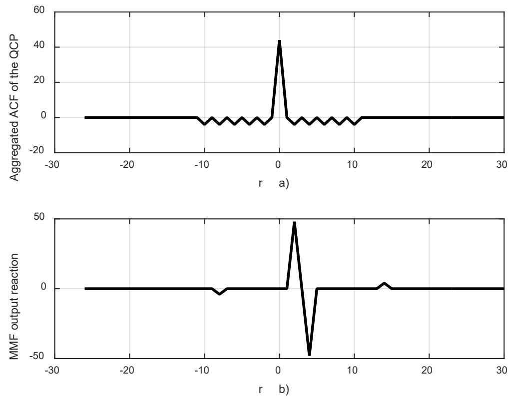

Fig. 5. The result of processing the aggregated ACFs of the QCPs (17) by the MMF with TF (19).

For completeness of the explanation, the results of the processing the aggregated ACFs of the QCPs (16) and (17) by the MMFs with TFs

$$\{\xi(k)\}_{k=0}^{8} = \{-1,0,0,0,2,0,0,0,-1\}, \tag{20}$$

$$\{\xi(k)\}_{k=0}^{4} = \{-1,0,2,0,-1\}, \tag{21}$$

are presented on Fig. 6 a, b respectively.

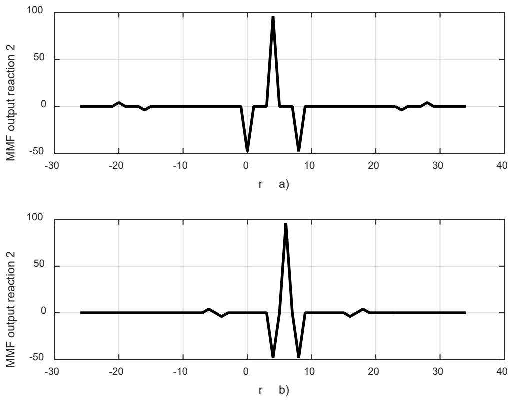

Fig. 6. The results of processing the aggregated ACFs of the QCPs (16) by the MMF with TF (20) (a) and the aggregated ACFs of the QCPs (17) by the MMF with TF (21) (b).

At the end of this chapter, the losses in the SNR, which may accompany the processing of the Barker and the QB signals as well as the QCPs by the MMFs, presented in the paper, will be analysed. In this connection, first of all it should be noted, that the above described MMFs act over the signal ACFs. As the main lobe of every ACF is the result of the coherent accumulation of the energies of all the chips (elementary phase pulses), forming the signal (see (5)), the SNR cannot be further improved by the means of a filter, matched to the ACF of the concrete signal (due to the limited space it is impossible here a rigorous proof of this fact to be presented). Hence, the losses in the SNR, caused by transformations of a signal ACF, are results of operand roundnesses, which may occur in the digital filters. As the TF samples of the MMFs, presented in the paper, are integers, it can be concluded that the losses in the SNR are very small or are completely missing.

IV. Conclusions

In the paper a method for synthesis of MMFs, which effectively suppress the sidelobes of signal ACFs, consisting of repeating patterns, is substantiated. The usage of the method allows the electromagnetic compatibility of all working simultaneously electronic devices as well as their resistance in a hostile radio electronic environment to be improved. The study, conducted in the paper, could be useful during the modernization of the extant or development of new radar sensor networks and remote control systems.

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