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Reduction of Side-lobe Levels for the Optimum Binary Codes Using the Mismatched Optimum Integrated Side-lobe Level Filter

Weaam Talaat Ali

College of Engineering, Diyala University, Diyala, Iraq

***Corresponding Author's E-mail:** wface2010@yahoo.com*

Abstract

Pulse compression is a technique that transmits a long coded pulse and processes the received echo to get a short pulse, but simultaneously, at the receiver side yields side-lobes around the main-lobe that permits the clutter to pass through it, and mask the desired target signal This work illustrates the performance of reduction of the Side-lobe Levels, which mask the desired target signal and make difficult to detect the target as a result of binary codes generating by genetic algorithm with length up to 128 bits, with use the minimum peak side-lobes as criteria for generation codes. Then, for further reduction of side-lobes, the mismatched optimum integrated side-lobe level filter is used with and without Additive White Gaussian Noise. When the mismatched filter is used without noise, then the reduction of side-lobe level has the improvement of peak side-lobe level value on the average (4-15) dB, and for integrated side-lobe level value on the average (5-17) dB, which depends on the code length while it is accompanied by, signal to noise ratio loss level in range (0.2-1.4) dB. On other hand, when the mismatched filter is used with noise, the signal to noise ratio loss level is in range (0.2-1.4) dB.

Keywords: *Mismatched optimum integrated side-lobe level filter (ISL) filter, Autocorrelation Function (ACF), Genetic algorithm (GA.), Signal to Noise Ratio Loss (SNR_L).*

1. Introduction

The use of high energy (long pulses duration) permit high detection range and the time-compressing of a received radar signal permitted an increase in the range resolution capability of radar. In that way the radar will utilize a long pulse to achieve large radiated energy, but simultaneously it will be obtain the range resolution of a short pulse. Pulse compression can be accomplished by employing frequency or phase modulation to widen the signal bandwidth.Then using a matched filter (also called a pulse compression filter) or any other mismatched filter on reception to compress the pulse [1].Phase coding can be divided into two types: binary phase coding and polyphase coding. The term “range sidelobes” was used first to describe the lobes in both sides of a mainlobe of the compressed time function of a received binary phase-coded signal. The term sidelobe is generalized to describe the time function of any pulse compression waveform.Optimal binary codes are binary sequences whose peak side-lobes of the aperiodic autocorrelation function is the minimum possible for a given code length. Codes whose autocorrelation function or zero-Doppler response exhibit low side-lobes are desirable for pulse compression radars because the clutter rejection is satisfied when

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the pulse compression waveforms have low side-lobes (by maximizing signal to clutter or noise ratio) [2].By exhaustive computer search program, Lindner [3] found all binary sequences up to length 40 with minimum PSL. Cohen et al. [4] extended those results to length 48. Boehmer [5] has developed an analytical technique for generating good binary pulse compression codes.

In this paper, the sequences generated by genetic algorithm up to length 128 is optimum, to suppress these side-lobes, the amplitude response of the matched filter is reshaped by another filter (optimum mismatched ISL filter) to yield lower side-lobes (to reduce the clutter (unwanted signals) as a result) at the expense of some signal-to-noise ratio loss at the output of the mismatched filters.

2. Allomorphic Forms of Binary Phase Codes

All Each binary code can be represented in any one of fourAllomorphic Forms [6], all of which have the same correlation characteristics. If $\boldsymbol{R_a(n)}$refers to ACF of sequence$\boldsymbol{a_k}$, these three codes have ACF equal to$\boldsymbol{R_a(n)}$:

Inverse-amplitude or complement:

$$\{\boldsymbol{b_k}\}\ ,\qquad \boldsymbol{b_k = -a_k}\ ,\qquad \boldsymbol{0 \le\ k\ \le (N-1)} \tag{1}$$

Inverse-time or reverse:

$$\{\boldsymbol{c_k}\}\ ,\qquad \boldsymbol{c_k = a_{N-K-1}}\ ,\qquad \boldsymbol{0 \le\ k\ \le (N-1)} \tag{2}$$

Complement of reverse:

$$\{\boldsymbol{d_k}\}\ ,\qquad \boldsymbol{d_k = -a_{N-K-1}}\ ,\quad \boldsymbol{0 \le\ k\ \le (N-1)} \tag{3}$$

Then,

$$\boldsymbol{R_a(n) = R_b(n) = R_c(n) = R_d(n) = \forall n} \tag{4}$$

For example, the following 7-bit Barker codes all have the same autocorrelation peak value and the same peak side-lobe magnitude:

7-bit Barker codes	Inverse-amplitude or complement	Inverse-time or reverse	Complement of reverse
1110010	0001101	1011000	0100111

Now it is worthy to say that in any literature when the number of codes of certain length is given, it represents the code itself (first form) without its other three Allomorphic forms. For symmetrical codes, the code and its inverse are identical.

3. Generating Binary Codes by GA.

The output of the matched filter is the ACF of the input signal (without any Doppler shift frequencies and considering noise). So, a good criterion on the optimum binary phase code is that its autocorrelation has side-lobes as minimum as possible. So, this section, discussed GA; there are several methods to find optimum codes with low side-lobes level. As there is 2^Ndifferent, state for code with N bits, consider all of possible states are very time consuming and even for some code lengths impossible. So, for long length codes, optimization and local methods are used instead of exhaustive search [7].

So, in GA an initial population included stochastic N-element codes is generated, then in each step, two parent codes is selected (by using roulette wheel selection) and two new codes which is belonged to new population is produces by using crossover and mutation operations. If each of these new codes has desired MPS, it will be member of desired final optimum population. The fitness function of this genetic algorithm is MPS. The procedure is defined in two steps:

1ststep: entire set of codes can presented by a subset then calculates the side-lobe of these codes and eliminate the Allomorphic Forms of them, each binary code can be represented in any one of four Allomorphic Forms. If any of calculated values are larger than desired MPS, then these codes are deleted from search space, else, at 2ndstep if one code has side-lobes smaller than desired MPS, it will be an optimum code. Figure (1) shows flowchart of GA to generate Binary Codes.

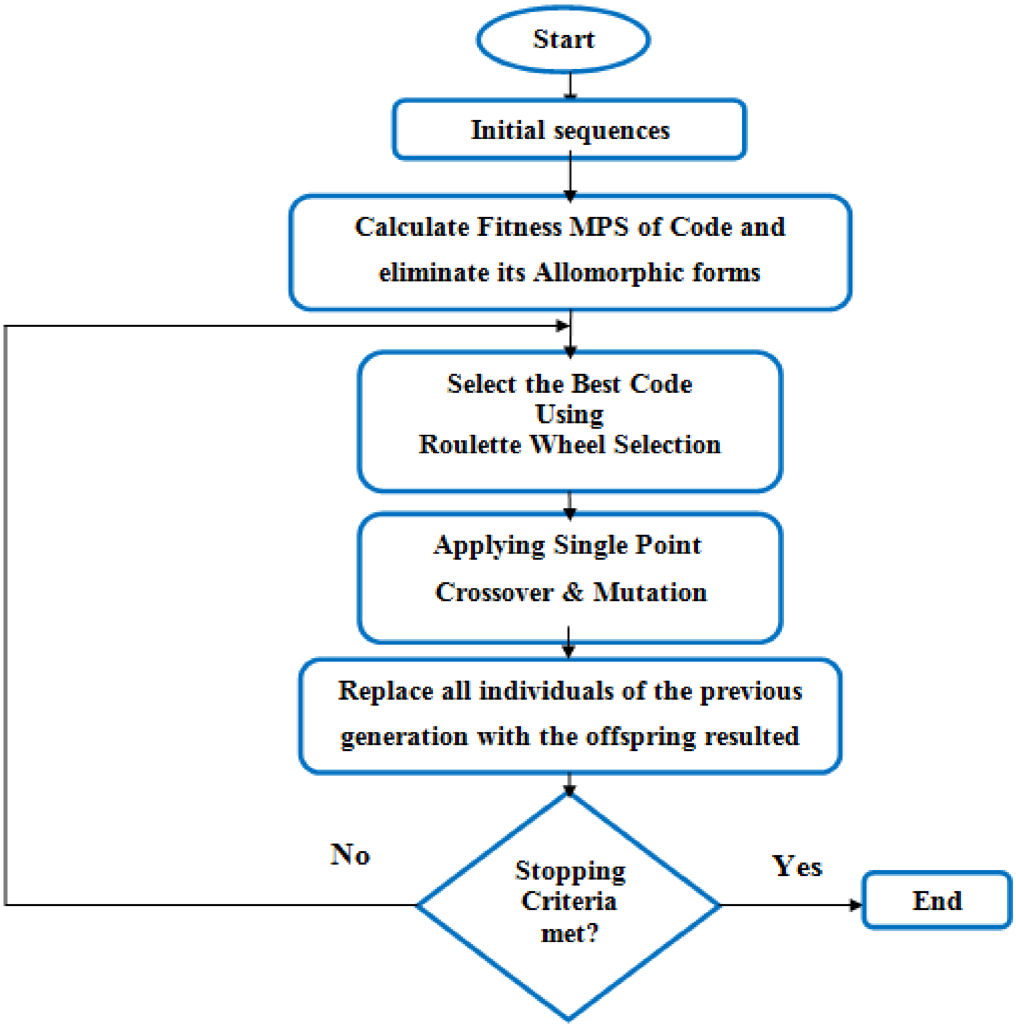

Figure 1: A flow chart of Genetic algorithm to generate Binary Codes.

4. Mismatched Filter for Binary Phase-coded Signals (Optimal Integrated Side-lobe Level (ISL) Filter)

An optimal integrated side-lobe level (ISL) filter, or Wiener filter, is a filter used tominimize the total energy in the range side-lobes [8].Optimal ISL filter is such a Finite-Duration Impulse Response (FIR) filter that it can be expressed as a matrix operation:

Let $c = [c(0), c(1), c(2),...., c(N-1)]$

and,

$$h = [h(0), h(1), h(2),...., h(P-1)]$$

where the row vector „c" of length N represents the known code and the row vector „h" of length P contains the unknown filter coefficients, respectively. The filter coefficients are real and the filter length P can be longer than the code length N, i.e., $P \geq N$. When this is the case, the code vector is zero-padded to match the length of the filter. For the sake of simplification, if N is even then P is even too, and when N is odd then P is odd too. Thus, P-N is always even, since (P-N)/2 is an integer denoted as z. Now, Z is defined as an all-zero code of length z used to create a zero-padded signal code of length $P = N + 2z$ given by matrix [9]:

$$x = [Z \quad c \quad Z] \tag{5}$$

The aperiodic cross correlation output at tap m, due to the zero-padded input code, is given by [8]:

$$y(m) = \sum_{r=0}^{P-1} x(r)\,h(r-m) \qquad m = -(P-1),....., (P-1) \tag{6}$$

where vectors, x and h, are defined to be zero for taps less than zero or greater than (P-1). Equation (2) can be represented in matrix form as [9]:

$$y = h\,X \tag{7}$$

where X is the (P) by (2P-1) Hankel matrix of the zero-padded code vector x, and y is the crosscorrelation vector of length (2P-1). The Hankel matrix X is defined as [10]:

$$X = \begin{bmatrix} 0 & \dots & 0 & x(0) & x(1) & \dots & x(P-1) \\ \vdots & 0 & x(0) & x(1) & \dots & x(P-1) & 0 \\ 0 & x(0) & x(1) & \dots & x(P-1) & 0 & \vdots \\ x(0) & x(1) & \cdots & x(P-1) & 0 & \dots & 0 \end{bmatrix} \tag{8}$$

and the crosscorrelation vector y is defined as :

$$y = [y(-(P-1))......y(0)......y(P-1)] \tag{9}$$

In calculating the total power in the side-lobes, the main peak y(0) term must be subtracted out. Therefore, the total power in the side-lobes is given by:

$$E = \sum_{m=-(P-1)}^{(P-1)} y^2(m)\; f^2(m) - y^2(0)\; f^2(0) \tag{10}$$

In minimizing E, the trivial solution, h(r) = 0 where $r \in [0, \ldots, (P-1)]$ must be disallowed, so a constraining equation, defining the peak as constant, is used, as follows:

$$\sum_{r=0}^{P-1} x(r)\,h(r) - N = 0 \tag{11}$$

5. The Performance of Side-lobe Suppression Techniques:

The following measures are often used to quantify the performance of range side-lobe suppression techniques. These measures are as in the following [11]:

5.1 Signal Side-lobe Level:

Signal Side-lobe Level, a measure of the largest side-lobe power as compared with the main-lobe power of the signal, is defined as [9]:

$$SSL = 10\log_{10}\left[\frac{\text{peak sidelobe power}}{\text{total mainlobe power}}\right] \tag{12}$$

5.2 Integrated Side-lobe Level:

Integrated Side-lobe Level, a measure of the energy distributed in the side-lobes as compared with the main-lobe power, is defined as [9]:

$$ISL = 10\log_{10}\left[\frac{\text{power integrated over sidelobes}}{\text{total mainlobe power}}\right] \tag{13}$$

5.3 Mismatch Loss:

SNR_L is expressed in decibels as the ratio of the peak output value of the mismatched filter$y_{peak,mismatched}$, relative to the peak output value of the matched filter $y_{peak,matched}$, as follows[9]:

$$SNR_L = -20\log_{10}\left[\frac{y_{\mathbf{peak,mismatched}}}{y_{\mathbf{peak,matched}}}\right] \tag{14}$$

where the coefficients of both filters have been normalized for unity noise gain, such that:

$$\sqrt{\sum_{r=0}^{P-1}[h(r)]^2} = 1 \tag{15}$$

Or,

$$SNR_L = -20\log_{10}\left[\frac{y_{\mathbf{peak,mismatched}}}{N}\right] \tag{16}$$

where N is the code length, and the coefficients of the mismatched filter are normalized to yield the same noise output power as the matched filter, when the input is only white noise. Thus, the normalization requires that [11]:

$$h\,h^T = x\,x^T \tag{17}$$

whereh^T is the transpose of h vector.

6. Simulation and Results

6.1 Binary Codes Generating by GA.

The criterion for chosen optimum codes is Minimum Peak Side-lobes (MPS) for each sequence for a certain length and according to the flow chart in Figure (1). From simulation an 128 codes were obtained and in Table (1) a samples of these codes are presented. In this Table, the codes are stated after excluding all Allomorphic forms of codes during generation, and SSL, ISL exhibited in this Table according to Eqs. (12) and (13) respectively for each code.

Table 1: Samples of Optimum Binary Codes Resulted by GA.

Code Length	MPS	Sequence	SSL [dB]	ISL [dB]
3	1	110	-9.5424	-6.5321
8	2	10010111	-12.0411	-6.0206
9	2	011010111	-13.0642	-5.2827
13	1	1111100110101	-22.2788	-11.4871
14	2	01010010000011	-16.9019	-7.1247
15	2	001100000101011	-17.5012	-6.8942
24	3	011001001010111111100011	-18.0617	-9.0309
25	2	1001001010100000011100111	-21.9382	-8.5140
36	3	001100110001010010100000100000111110	-21.5836	-8.3845
42	3	000100010001000111101110000111010010110 100	-22.9225	-9.4115
49	4	000010010101010111110110001111001111001 0001101111	-21.7627	-5.4788
57	4	٠٠٠٠١٠٠١٠٠١١٠١٠٠٠١٠١٠١٠٠٠١١١٠١١٠١٠١١٠٠ ٠١٠٠٠١١١١٠٠٠١١٠١١١١	-23.0763	-6.4962
64	4	010000000100100001010001011101001111001 1 0001100100011011111000010	-24.0823	-7.2250
77	4	110010110000110101110001001010001110111 0010010101000011111101110110111111 0100	-25.6886	-7.4117
80	4	110011100100000111100100011011001100001 1 0 ١ ١٠١١١ ١١ ١ ١٠٠١ ٠٠١٠ ٠١٠٠ ١١١٠١١٠١ ٠١٠١ ١١١ ١٠١٠	-26.0206	-7.9588
90	5	110011001001101101100001111100001110101 0010001 ٠٠٠١٠ ١١٠١١٠١٠١ ١٠١١١١١٠١٠١٠٠٠٠١٠٠٠٠١٠٠٠٠١٠٠٠١	-25.1054	-7.5681
100	5	110111111010010010000 ١٠ ١٠١ ١١١١١١١١ ٠ ١٠١٠٠١٠١٠١٠ ٠٠٠ ٠٠١١١١١١٠٠٠٠٠١١١٠٠١٠ ٠ ١١ ٠١٠١٠١ ١ ٠١١٠٠١١٠ ١ ٠٠١ ٠٠١١١١ ١١١٠	-26.0205	-7.5746

In figure (2) shows the comparison between two codes with the same length 25-bits, but different sequence. The first normalized code is [0001001010100000011100110] with SSL equal to -13.9794 and the ISL equal to -3.2459 ,while the second normalized code is [1001001010100000011100111] which is the optimum code that resulted from GA as shown in table (1) with SSL equal to -21.9382 and ISL equal to -8.5140. So; it is shown that the good a periodic ACF for the two sequences is the second code because it has minimum peak side-lobes.

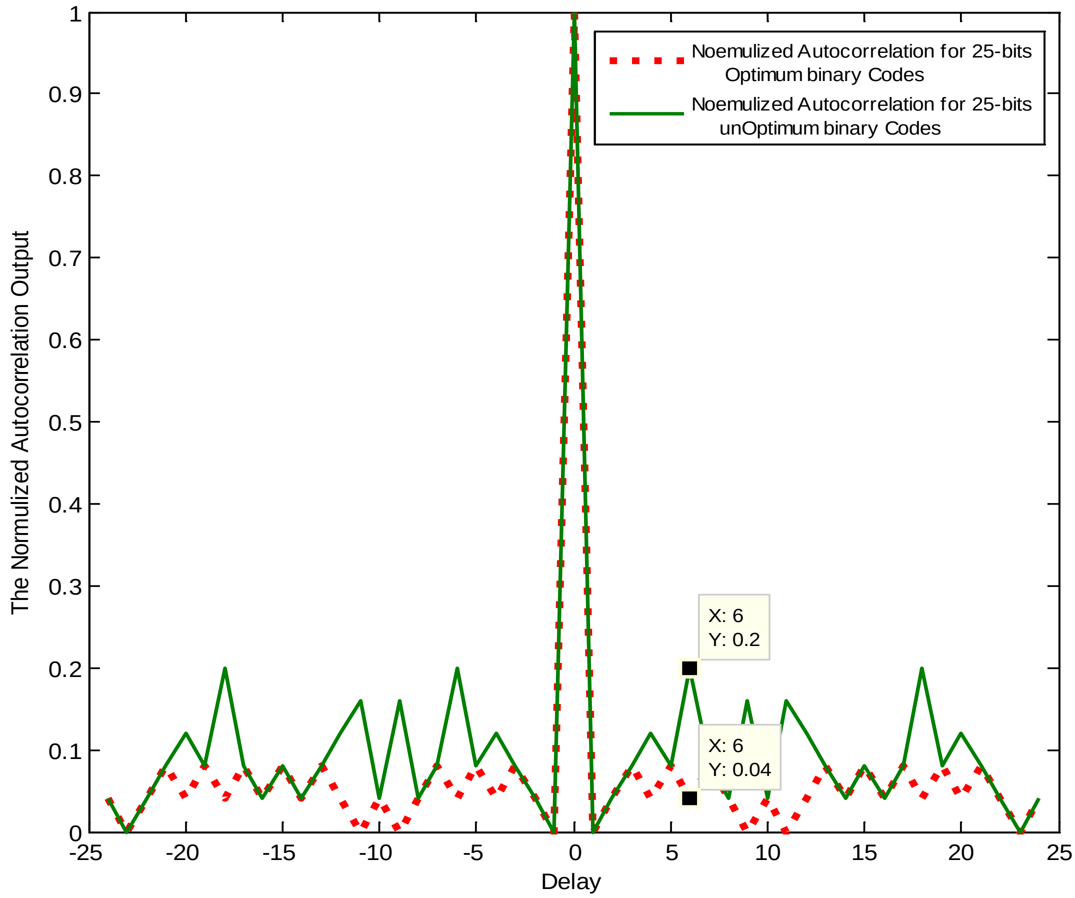

Figure 2: The Normalized Autocorrelation of N=25-bit optimum and unoptimum binary code.

6.2 Optimal ISL Filter for Binary Phase Codes with and without AWGN:

In this section, examples on the free noise effect are introduced. In order to test the chosen codes under the same conditions, the filter length (P) is considered to be (three times of the code length)-elements in all sections below.

In Table (2) some codes chosen from Table (1) as shown entered as input to the optimum ISL filter and the results of SSL, ISL, SNRL is presented in this Table without noise, a sample of codes is chosen, autocorrelation and crosscorrelation figures are shown below for the code to illustrate the degradation in side-lobe level.

Table 2: Output of Optimum Mismatch (ISL) Filter for Some Codes Chosen from Table (1) without AWGN.

Code Length (N)	SSL [dB]	ISL [dB]	SNR_L [dB]
8	-22.4002	-11.3719	0.9559
13	-38.4708	-30.0332	0.2044
14	-22.8184	-14.3810	1.1303
25	-34.0231	-24.7305	0.6507
36	-26.8280	-17.3354	0.7141
49	-25.3547	-13.0081	1.3757
57	-28.9602	-15.0764	1.0487
80	-33.8248	-19.0666	0.8029
90	-33.3529	-18.6424	0.9679
100	-33.9169	-18.5852	0.9739

By comparing the results of Table (2) with the results of Table (1), an improvement in values of SSL, ISL is found with disadvantage of SNR_L due to mismatch optimum (ISL) filter when the noise is free, The reduction of side-lobe level has the improvement of SSL value on the average (4-15) dB, and for ISL value on the average (5-17) dB, Which are depend on the code length while it is accompanied by, SNR_L in range (0.2-1.4) dB. Figures below illustrate the plotting of code N=13 (for example), as output of matched filter and (optimum ISL) mismatched filter.

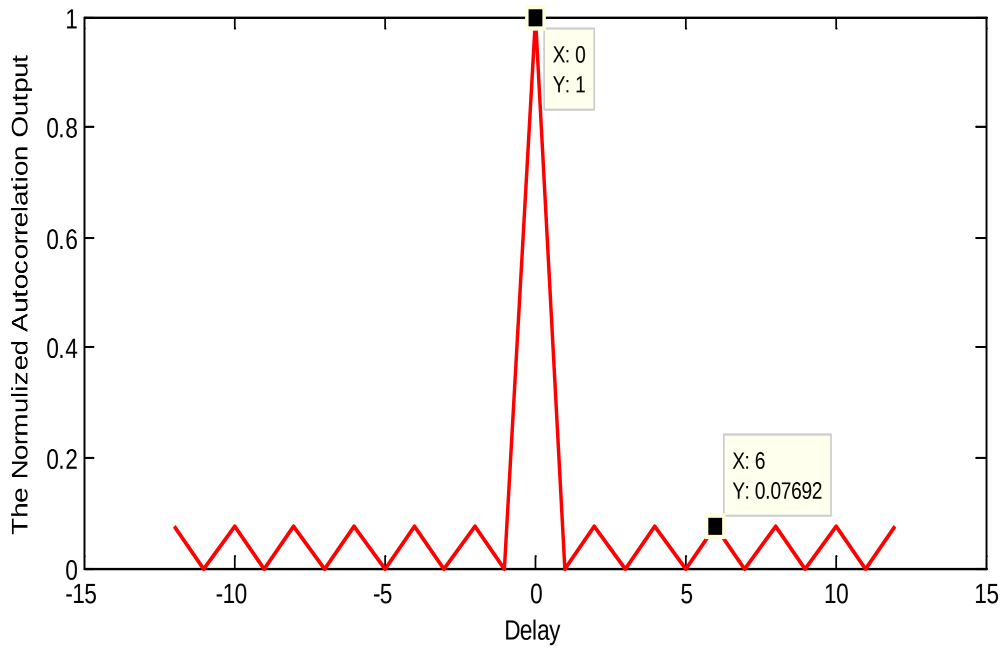

Figure 3: The Normalized Autocorrelation of the optimal ISL filter when it is applied to N=13-bit binary code without Noise.

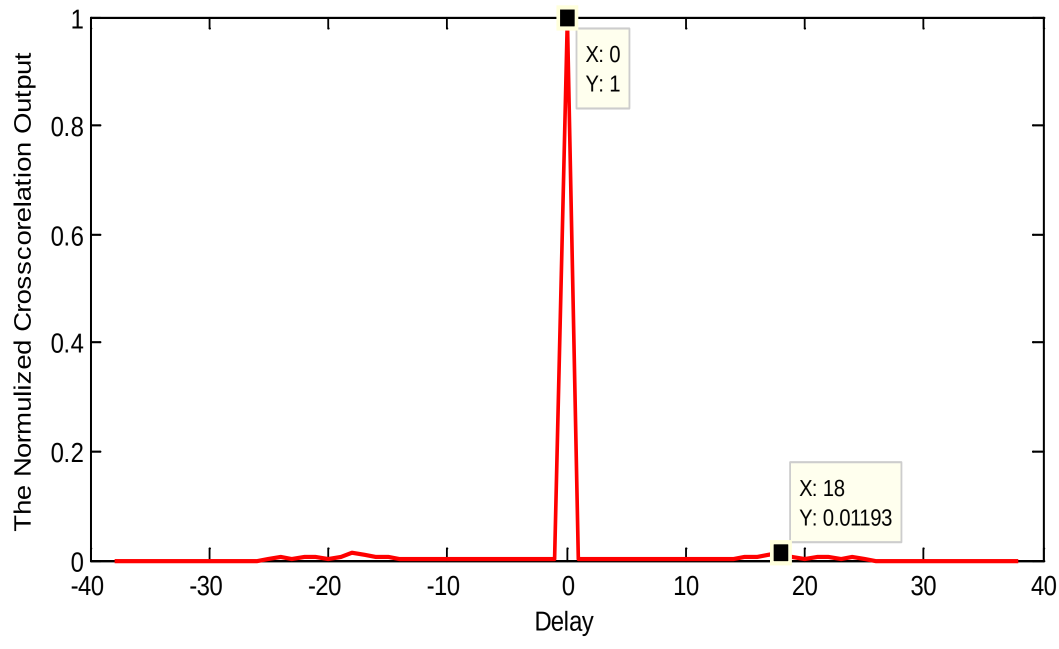

Figure 4: The Normalized Crosscorrelation of the optimal ISL filter when it is applied to N=13-bit binary code without noise.

Figure (5) shows the SSL-versus-P (P-filter length) behaviors of the optimal ISL filter when it is applied to five different binary phase codes with SNR_i equal to 7dB. While, Figure (6) show the ISL-versus-P behaviors of the optimal ISL filter when it is applied to five different binary phase codes with SNR_i equal to 7dB. Moreover, Figure (7) shows SNR_L -versus-P behaviors of the optimal ISL filter when it is applied to five different binary phase codes with SNR_i equal to 7dB.

Figure (8) shows SSL-versus- SNR_i behavior, Figure (9) shows ISL-versus- SNR_i behavior and Figures (10) shows SNR_L -versus- SNR_i behavior of the optimal ISL filter when it is applied to five different binary phase codes with different SNR_i.

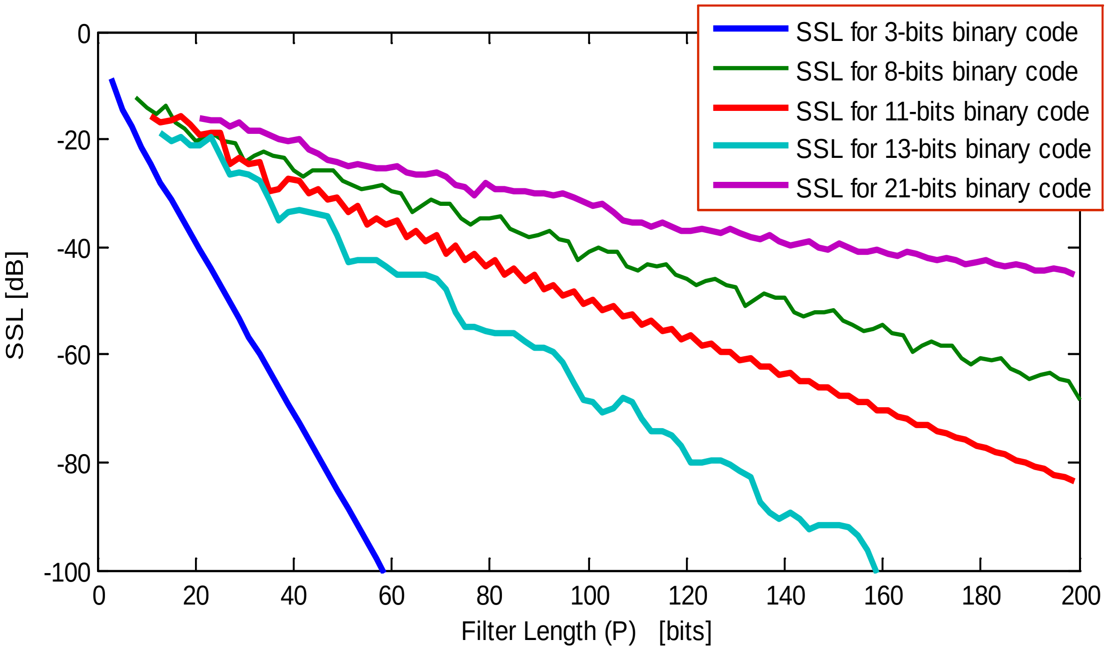

Figure 5: SSL-versus-P behavior of the optimal ISL filter when it is applied to five different codes with SNR_i =7dB.

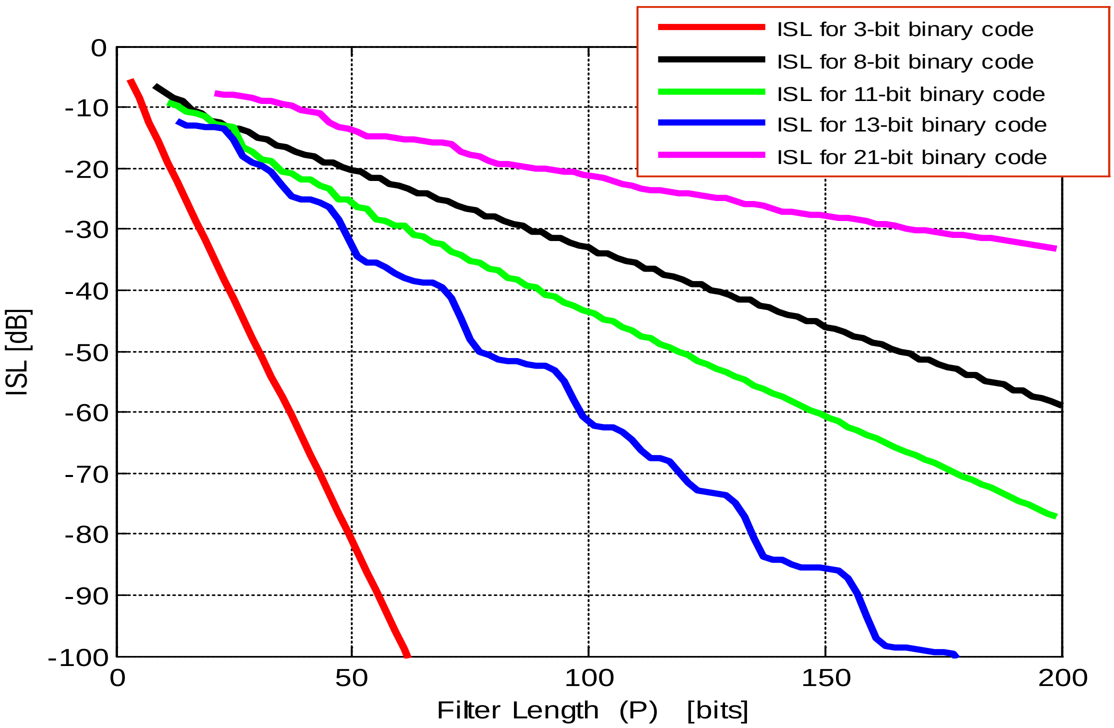

Figure 6: ISL-versus-P behavior of the optimal ISL filter when it is applied to five different codes with SNR_i= 7dB.

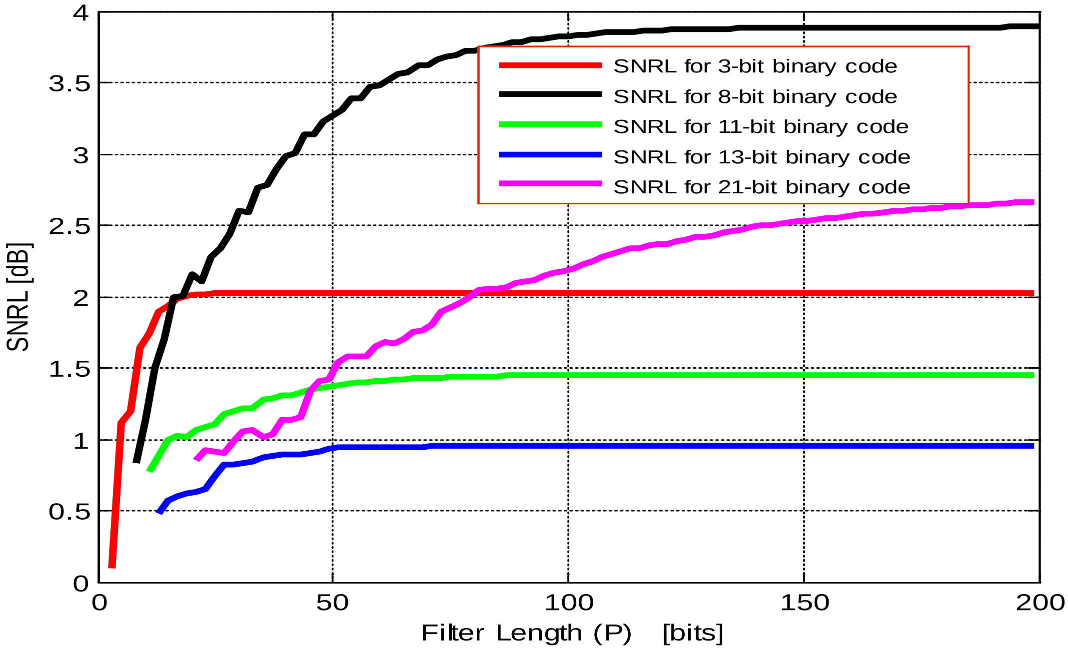

Figure 7: SNR_L--versus-P behavior of the optimal ISL filter when it is applied to five different codes with SNR_i= 7dB.

From the previous figures (5), (6) and (7), it is believed that SSL, ISL improve when the filter length is increase, but SNR_L increases as disadvantage.

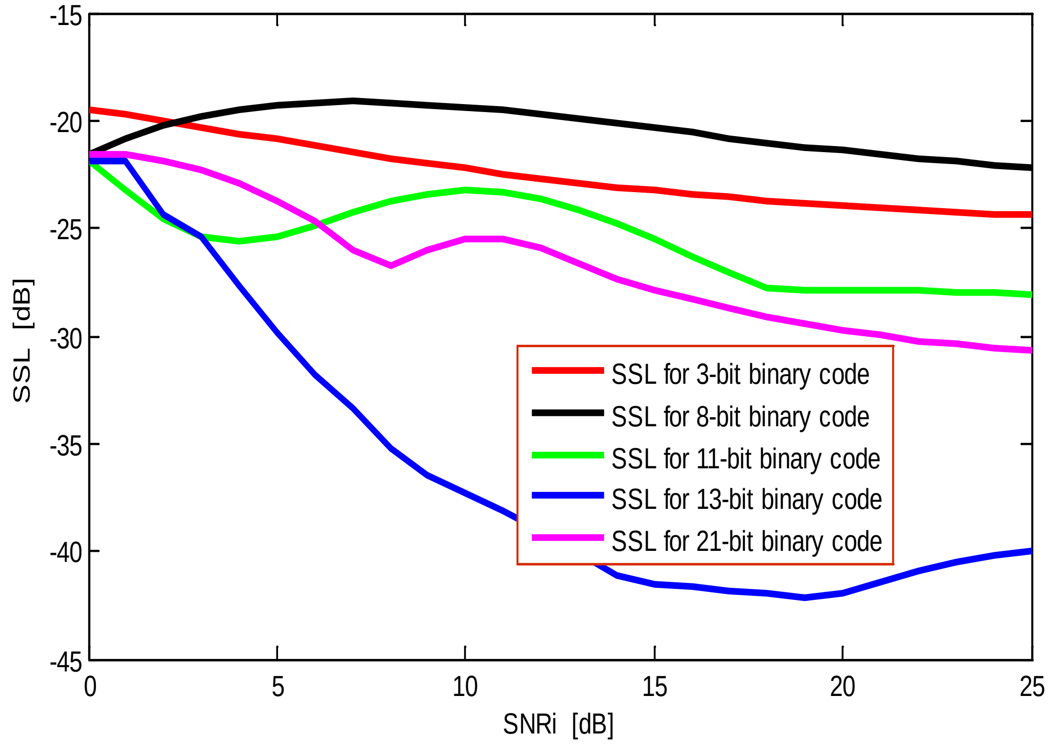

Figure 8: SSL-versus- *SNRi* behavior of the optimal ISL filter when it is applied to five different codes with different *SNRi*

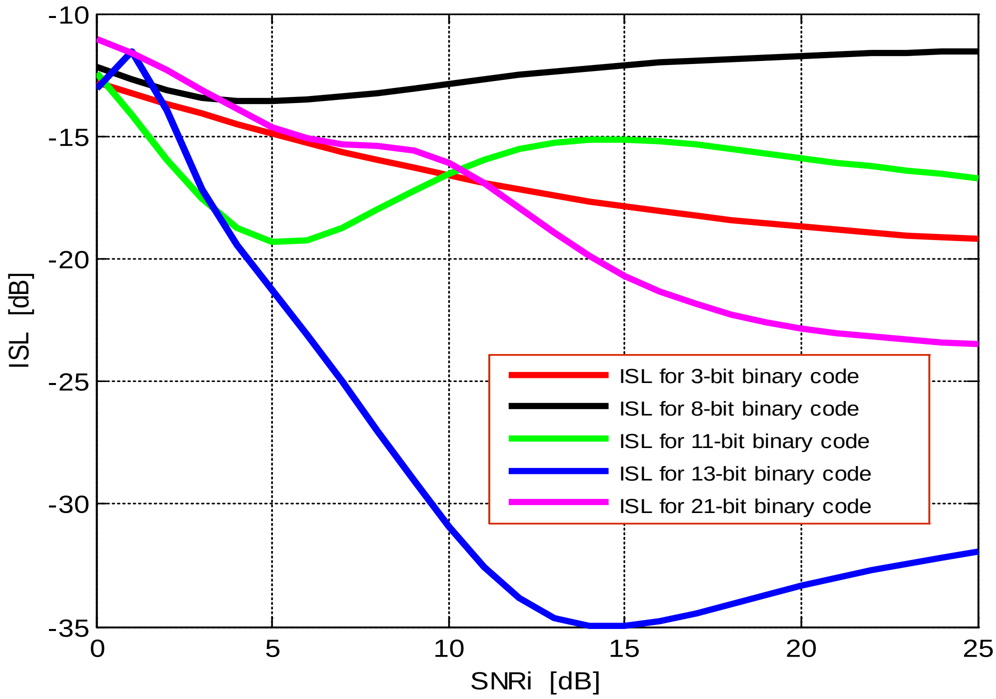

Figure 9:ISL-versus- *SNRi* behavior of the optimal ISL filter when it is applied to five different codes with different *SNRi*

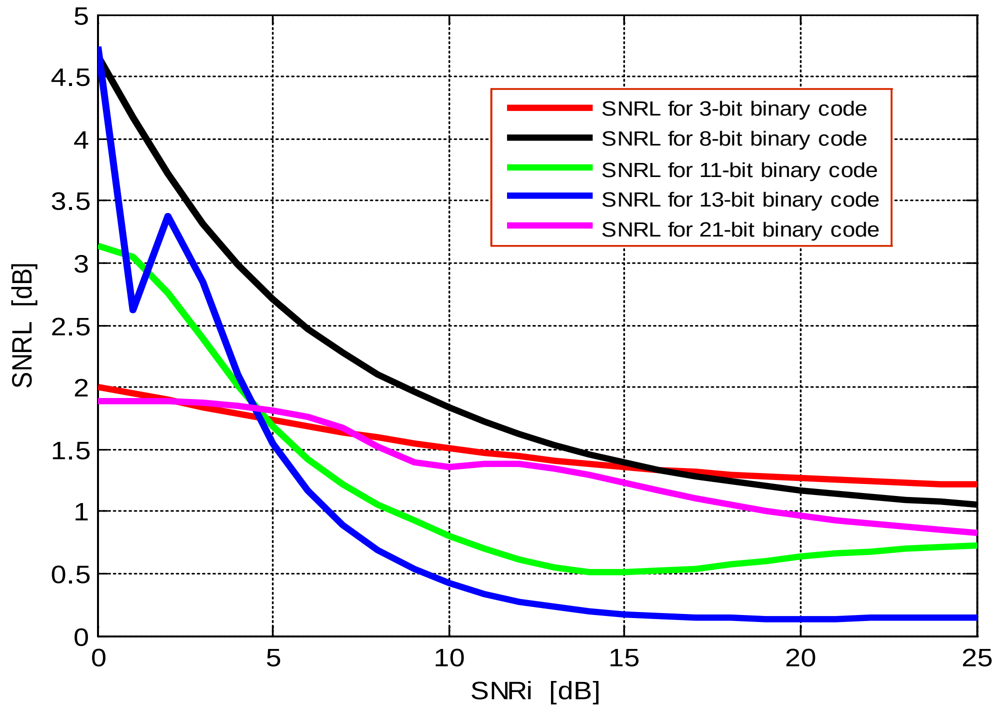

Figure 10:SNR_L-versus- SNR_i behavior of the optimal ISL filter when it is applied to five different *codes with different SNRi*

From the previous figures (7), (8) and (9), it is believed that when the *SNRi* increases the SSL, ISL has a small improvement at the same time the SNR_L decreases very large (the range of SNR_L is (0.2-1.4) dB), which are depend on the code length. So, the best result of SNR_L is up to 5dB of *SNRi*. The range of SNR_L is (0.2-1.4) dB.

Conclusion

The followings summarize the main important points that are noted from the work.

1. The limitation of the upper limit is related to the time processing, the range of code length from (2-128) bits, of the optimum codes that generated by the programmed GA.
2. When the code length is increased, MPS is also increases. As a result, the value of SSL is also increased.
3. By increasing in the number of generations yields the quality of solution improves also.
4. The processing of optimum codes by mismatch optimum ISL filter for further reduction in SSL value is obtained:
   - When the filter length is increase, The SSL, ISL improves very well, but SNRL increases as disadvantage.
   - As advantage, when the *SNRi* increases the SSL, ISL has a small improvement at the same time the SNR_L decreases very large.

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