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POLYPHASE SEQUENCES ANALYSIS WITH GOOD MERIT FACTOR AND CORRELATION PROPERTIES

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Abstract

Polyphase sequences such as P*n* (*n* = 1, 2, 3, 4, x), Frank, Golomb, the Chu with large Merit factor and correlation properties are helpful in applications like RADAR, SONAR, channel estimation and communications. The Correlation function of a given sequence expressed by integrated sidelobe level (ISL). The ISL related metrics minimized by improving the performance parameters Merit Factor (MF) and Modified Merit Factor (MMF). In this paper, the merit factors are compared with all sequences for the usual case and considering the Weights (ones and zeros throughout the sequence length) from 10^2 to $10^{3\sim4}$. The observation is made for four consecutive even, and odd square integer lengths say 16^2, 17^2, 18^2, and 19^2. The Px sequence exhibits the best merit factor among all Polyphase sequences. P2 sequence existed only for even square integer length when no weights applied. P1, Px, Frank sequences shows the good MMFs among all Polyphase sequences. For the possible lengths, the Elapsed time is more for MF than MMF except at four consecutive even and odd square integer lengths.

Keywords: Autocorrelation level, Integrated sidelobe level, Merit factor, Modified merit factor, Polyphase sequences.

1. Introduction

The former sequences such as maximum length sequences (*M*-sequences) are a family of binary signals that are particularly well suited for the practical implementation of a such a pseudo-noise radar, Binary sequences (alphabet is ± 1), Ternary sequences (it is 0, ± 1) replaced with Polyphase sequences from many years in the field of radar applications [1, 2]. These Polyphase sequences derived from the Analog signals chirp or step-chirp, which stores the phase properties, can be processed and implemented digitally. As commented by Skolnik [3], the performance of the Polyphase sequences in spread spectrum applications compared based on range tolerance, time delay such as autocorrelation by correlation measurement Based on studies by Frank [4], the first Polyphase sequence in Radar applications reported is known as Frank sequence. Permuting the phases of the Frank sequence a new class of Polyphase sequences obtained is P1and P2 sequences with the inclusion of phases [5].

As explained by Rapajic and Kennedy [6], lengths $N = M^2$ from $M = 3$ to 20 only except P2 sequence merit factor values for P1, P3, P4, Px, Frank, Golomb, and the Chu found. In that, Px exhibit the maximum merit factor. P1, Frank has the same merit factor values. P3, P4, Golomb, and the Chu have the same merit factor, and modified merit factor values are for lengths. Frank [4] investigated Frank sequences and found that it is identical to the P1 sequence. Roberts et al. [7] and Stoica et al. [8] found that Modified Merit Factor values for Golomb Sequence when weights applied.

The objective of this paper is to compare the performance parameters known as Merit Factor and Modified Merit Factor of Polyphase sequences P1, P2, P3, P4, Px, Frank, Golomb, and Chu that are existing for square integer length ($N = M^2$). In Figs. 1 and 2 the Merit Factors and Modified Merit Factors are shown For Lengths $N = 10^2$, 16^2, 17^2, 18^2, 19^2, 32^2, 100^2 respectively. The correlation plots of all Polyphase sequences for the lengths 10^2, 10^3 and 10^4 are shown in Figs .3 (a) to (c) respectively. Correlation plots for even and odd square integer lengths are shown in Figs. 3 (d) to (f). Both MF and MMF values for even and odd square integer length (16^2, 17^2, 18^2, and 19^2) studied along with correlation levels. The Merit Factor (MF) and Modified Merit Factor (MMF) impact with respect to sequence length compared with Elapsed Time (τ) shown in Fig.4.

2. Polyphase Sequences

The Polyphase sequences named Frank, Golomb, Chu, P1, P2, P3, P4, Px possibly exist for square integer length $N = M^2$ (where N is sequence Length, M is an integer) having elements $Sn= (S_1, S_2, S_3, \ldots S_N)$. These Polyphase sequences can be defined as follows. $S(Mn+k+1)$ and $S(k+1)$ are defined P1, P2, Px, Frank and P3, P4, Golomb, Chu respectively that are denoted by $f(n)$. As commented by Roberts et al. [7] and Stoica et al. [8], the Golomb and Frank sequences are compared with P1, P2, P3, P4, Px, Frank and Chu sequences. All the sequences have existed for square integer length. The sequences with equal merit factor exhibit the same correlation. Sequences with large merit factor values have the lower sidelobes in correlation plots. Even though correlation levels are identical but the way in which, the sequence representation differs from one another. The Performance parameters analysis, i.e., Merit Factor (MF) and Modified Merit Factor (MMFs) values and plotting the correlation levels shown in Fig. A-1. The description outlined in Appendix A.

2.1. P1, P2, Px sequences

These sequences defined as $S(Mn+k+1) = e^{i\varphi n,k}$ for $0 \leq k \leq M$ and $0 \leq n \leq M$, here the phase elements of the sequences can be defined as shown below.

$$\phi_{n,k} = -(\pi/M)(M - 2n - 1)(nM + k) \tag{1}$$

$$\phi_{n,k} = +(\pi/M)(M - 2n - 1)((M - 1)/2 - k) \tag{2}$$

$$\phi_{n,k} = (\pi/M)[(M - 1)/(2 - k)](M - 2n - 1) \tag{3}$$

$$\phi_{n,k} = (\pi/M)[(M - 2)/(2 - k)](M - 2n - 1) \tag{4}$$

Equations (1) and (2) are the phase elements of P1, P2 sequences respectively. Phase elements in Eq. (3) and (4) of the Px sequence of M even and odd integers.

2.2. P3, P4 sequences

The polyphase sequence elements Sn for $n = 1 \ldots. N$ of a positive integer length M for P3 and P4 sequence [9] defined as $S(k+1) = e^{i\varphi k+1}$ here $0 \leq k \leq M$.

$$\phi_{k+1} = \pi k^2 \tag{5}$$

$$\phi_{k+1} = \pi(k - N)k \tag{6}$$

Equations (5) and (6) are phase elements of P3 and P4 sequences respectively. The mathematical equation of these two sequences exhibits the identical MFs and correlation levels.

2.3. Golomb sequence

The Golomb sequence [10] of Polyphase sequence elements Sn for $n = 1 \ldots.$, N of a definite integer length M defined as $S(k+1) = e^{i\varphi k+1}$ here $0 \leq k \leq M$. the phase elements can be defined as:

$$\phi_{k+1} = \pi(k + 1)k \tag{7}$$

Another way of Golomb sequence [11] can be denoted as $g(n)$ of length N for a positive integer.

$$g(n) = e^{j\pi(n-1)n/N} \tag{8}$$

Equations (7) and (8) shows the Golomb sequence $g(n)$ for $n = 1 \ldots N$. these two mathematical representations bring out the same response.

2.4. Frank sequence

These sequences can be defined as $S(Mn+k+1) = e^{i\varphi k+1}$ for $0 \leq k \leq M$ and $0 \leq n \leq M$, here the phase elements of the sequence can be defined as:

$$\phi_{k+1} = 2\pi nk/M \tag{9}$$

As presented by Antweiler and Bomer [12], another way of Frank sequence can be denoted as $f(n)$ of length N is given by:

$$f(Mn+k+1) = e^{j2\pi nk/M,}k, n = 0,1,\ldots.,M-1 \quad (10)$$

Equations (9) and (10) demonstrates the $f(n)$ for $n = 1\ldots N$. these two draw out a similar result.

2.5. Chu sequence

The Chu sequence [12], phase elements Sn for $n = 1\ldots N$ of a positive integer length N as $S(k+1) = e^{i\phi k+1}$ here $0 \leq k \leq M$.

$$\phi_{k+1} = \pi(k+2q)k \quad (11)$$

$$\phi_{k+1} = \pi(k+1+2q)k \quad (12)$$

Equations (11) and (12) are the phase elements of the Chu sequence for even and odd integers respectively.

3. Performance Parameters

The elements of the Polyphase sequence $Sn = S_1, S_2, S_3\ldots.S_N$ that exist for square integer Length ($N = M^2$). Some parameters that define the ability for improving the characteristics of a Radio Detection and Ranging (RADAR) system. These are Merit Factor (MF), Modified Merit Factor (MMF) increasing in nature defines the performance improvement, and some are integrated sidelobe level decreasing in nature also defines the same. The sequences with good correlation properties and Merit Factor (MF) values helped in RADAR and Sound Navigation and Ranging (SONAR) applications.

3.1. Correlation function and correlation level

The autocorrelation $r = \rho$ (S) of a sequence $Sn = (S_1, S_2, S_3\ldots.S_N)$ is a sequence length of 2K-1 defined as ρ (S) = $v(s, s)$ the main lobe c_k, of the autocorrelation c, is given by $c_k = s\, s^T$ and complex conjugates and transpose denoted by $(.)^T$ denotes the complex conjugate, conjugate transpose for scalars and vectors, matrices respectively.

$$c_k = \sum_{n=k+1}^{N} s_n\, s_{n-k}^T = s_{-k}^T, k = 0,\ldots..N-1 \quad (13)$$

$$CorrelationLevel = 20\, log_{10}\left|\frac{c_k}{c_0}\right|, k = 1,\ldots\ldots.,N-1 \quad (14)$$

Equation (13) is the autocorrelation function and Eq. (14) defines the correlation level in dB, in Eq. (13) the correlation function is shown.

3.2. Integrated sidelobe level (ISL) and weighted integrated sidelobe level (WISL)

The integrated sidelobe level from Eq. (13) is defined as follows:

$$ISL = \sum_{k=1}^{N-1}|c_k|^2, k = 1,\ldots.,N-1 \quad (15)$$

Equation (15) defines that $c_0, c_1, c_2 \ldots.c_{N\text{-}1}$ square modulus.

$$WISL = \sum_{k=1}^{N-1} w_k|c_k|^2 w_k \geq 0, k = 1,\ldots.,N-1 \quad (16)$$

From Eq. (16), the Integrated Sidelobe Level (ISL) can be obtained by substituting $w_e = 1$. For considering the correlation lags to a region of interest for example $c_1 \ldots c_{41}$ and $c_{66} \ldots c_{72}$, i.e., by making some are zeros and some are ones is known as Weighted Integrated Sidelobe Level (WISL).

$$w_k = \begin{cases} 0, k \in (26,69) \cup (80,99) \\ 1, k \in (1,25) \cup (70,79) \end{cases} \tag{17}$$

These weights applied for improving Merit Factor (MF) and minimizing the desired correlation level [8]. The weights in Eq. (17) are defined to length 100 only. The arrangement length is taken over 100 then common complex grouping components that exist in succession as it is taken over for Modified Merit Factor (MMF) computation.

3.3. Merit factor and modified merit factor

As according to Gabidulin et al. [11], the merit factor is an important measure of the collective smallness of the aperiodic autocorrelations of a sequence length N.

$$MeritFactor = \frac{|c_0|^2}{\sum_{\substack{k=-(N-1) \\ k\neq 0}}^{N-1} |c_k|^2} = \frac{N^2}{2ISL} \tag{18}$$

Equation (18) shows the Merit Factor and correlation levels in the denominator consider all except at $k = 0$.

$$ModifiedMeritFactor = \frac{|c_0|^2}{2\sum_{k=1}^{N-1} w_k |c_k|^2} = \frac{N^2}{2WISL} \tag{19}$$

From Eq. (18), multiplication by 2 in denominator shows the symmetry of the correlation function with respect to zero.

3.4. Correlation level, MF and MMF calculation procedure

Plotting the correlation level and calculation of merit factor and modified merit factor is shown in Fig. A-1 as outlined in Appendix A. The correlation plots sequence length vs. correlation Level in (dB) shown in Fig. 1. The merit factor values for 10^2, 10^3, and 10^4, for even and odd consecutive even and odd integers are shown in Tables 1 and 3. From Table 1 P1, Frank sequences exhibit the same merit factor and P3, P4 and Chu exhibit identical values. For 10^2 lengths, P2 is minimum and Px is maximum values obtained. For 10^3 P2 is third highest MF value next to the P1 and Frank sequence. As explained by Roberts et al. [7], Table 2 shows the MMF values compared for all Polyphase sequences such that, Px exhibits the maximum merit factor value and P1, Frank next maximum merit factor value to the Px sequence.

From Table 2 when $N = 10^4$ length P1, P2, Px, and Frank exhibit maximum. P3, P4, Golomb, and Chu exhibit minimum value. Tables 3 and 4 show the Merit Factors (MFs) and Modified Merit Factors (MMFs) for four even and odd consecutive square integers. Px sequence is only the sequence that never shows an impact on even and odd integer square lengths. It is always high enough among all sequences. Tables 3 and 4 are the Merit Factor (MF) and Modified Merit Factor (MMF) calculations for four even and odd consecutive square integers starting from 16 to 19.

From Table 3, it is observed that Merit Factor (MF) improvement happened in all sequences except P2. Because P2 is the only sequence that exists for even square integer length. Among all sequences, Px only exhibits the good merit factor. In

Table 1, elapsed time (τ) is more for 10^4 when compared with 10^2 and 10^3. From Tables 1 and 2 the average elapsed time for Modified Merit Factor (MMF) is 11.432 seconds less when compared with MF elapsed time (τ). The reason behind this has we filled with a sequence with weights, i.e., some with zeros and ones instead of calculating complex sequence elements. However, it is different even and odd consecutive square integer case. For MF values in Table 3 took less than 1.000 seconds for 16 to 19 square integer lengths. However, for MMF case in Table 4 it is less than 1.500 seconds. It makes very less difference in elapsed time (τ) form 10^2 to 16^2.

Table 1. MF values for $N = 10^2, 10^3, 10^4$.

	Merit factor		
Length	$N = 10^2$	$N = 10^3$	$N = 10^4$
τ	1.922 s	2.091 s	14.216 s
P1	23.099	78.145	246.385
P2	18.722	75.041	244.924
P3	15.873	50.316	157.096
P4	15.873	50.316	157.096
Px	25.124	79.241	246.877
Golomb	15.873	50.316	157.096
Frank	23.099	78.145	246.385 [7]
Chu	15.873	50.316	157.096

Table 2. MMF values for the weights in Eq. (17) for $N= 10^2, 10^3, 10^4$.

	Modified merit factor		
Length	$N = 10^2$	$N = 10^3$	$N = 10^4$
τ	1.274 s	1.413 s	8.745 s
P1	50.069	306.747	4.958×10^3
P2	42.865	306.173	4.958×10^3
P3	32.545	157.251	2.171×10^3
P4	32.545	157.251	2.171×10^3
Px	53.146	306.939	4.958×10^3
Golomb	32.545 [8]	157.251	2.171×10^3
Frank	50.069	306.747	4.958×10^3
Chu	32.545	157.251	2.171×10^3

Table 3. MF values for $N = 16^2, 17^2, 18^2, 19^2$.

	Merit factor			
Length	$N = 16^2$	$N = 17^2$	$N = 18^2$	$N = 19^2$
τ	0.986 s	0.982 s	0.989 s	0.973 s
P1	38.230	41.077	43.246	46.054
P2	34.067	7.781	39.226	8.319
P3	25.235	26.800	28.366	29.932
P4	25.235	26.800	28.366	29.932
Px	39.875	42.701	44.792	47.578
Golomb	25.235	26.800	28.366	29.932
Frank	38.230	41.077	43.246	46.054
Chu	25.235	26.800	28.366	29.932

Table 4. MMF values with weights in Eq. (17) for $N = 16^2, 17^2, 18^2, 19^2$.

	Modified merit factor			
Length	$N = 16^2$	$N = 17^2$	$N = 18^2$	$N = 19^2$
τ	1.280 s	1.270 s	1.300 s	1.311 s
P1	105.791	127.521	153.904	171.221
P2	102.648	65.497	148.406	65.244
P3	61.349	67.061	71.426	75.578
P4	61.349	67.061	71.426	75.578
Px	106.896	128.604	155.847	173.207
Golomb	61.349	67.061	71.427	75.578
Frank	105.791	127.521	153.904	171.221
Chu	61.349	67.061	71.426	75.578

4. Results and Discussion

Figures 1 and 2 the MF and MMF values are shown for N = 10, 16, 17, 18, 19, 32, 100 square integer length. Figure 2 the MMF values are obtained with weights using Eq. (17) in which, for lengths above N = 100 the correlation levels considered according to sequence only. From Fig. 1 it is observed that at two points the MF value is too less with reference to all sequences because of P2 sequence exhibit less MF value at 17^2 and 19^2 values.

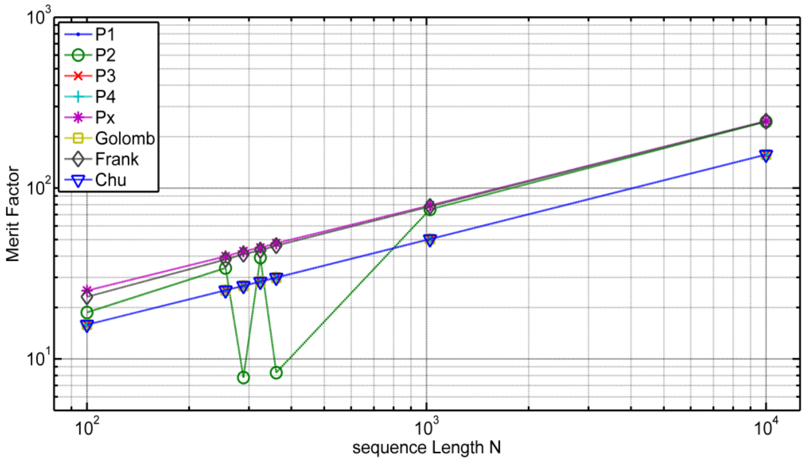


Fig. 1. Merit factor vs. sequence length from $N = 10^2$ to 100^2.

Px and Frank exhibit best merit factor values and almost the same for the length $N = 10^3$ and above. Similarly, in Fig. 2, the MMF values are increasing linearly except P2 sequence. However, the P2 sequence in Fig. 2 does not have too low values as that of P2 sequence in Fig. 1 for $N = 17^2$ and 19^2.

The correlation plots are shown in Fig. 3 using Eq. (14). From Figs. 3(a) to (c) the overlapping of correlation for P3, P4, Golomb and Chu sequences indicates that these sequences have same merit factor (MF) values for lengths $N = 10^2$, 10^3, 10^4 lengths respectively. Similarly, the Frank and P1 correlation levels overlapped. Among all the sequences Px and P2 are non-identical. Moreover, the P2 sequence exhibits a distinct correlation level as shown in Figs. 3(e) to (g)) because it exists for even square integer length only.

Px exhibits the best merit factor next to the Frank and P1 sequence for all lengths considered, which shown in Table 1. From Figs. 3 (d) to (f) are correlation plots for lengths N = 16^2 and 18^2 indicates that P2 sequence does not make the significant difference with the remaining sequences.

Figure 4 indicates that elapsed time of MF is more than elapsed time of MMF at N = 10^2, 10^3 and 10^4 except at four consecutive even and odd square integer length 16^2, 17^2, 18^2, 19^2. The elapsed calculation procedure explained in *Appendix A*.

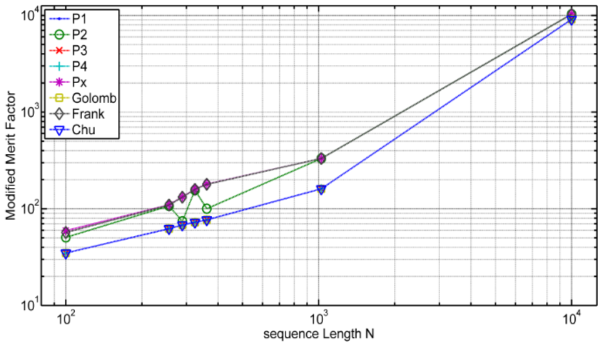
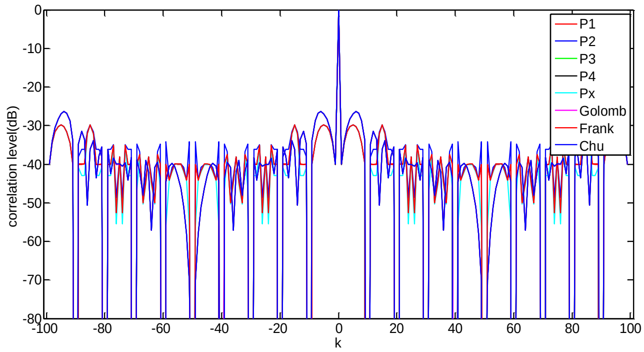
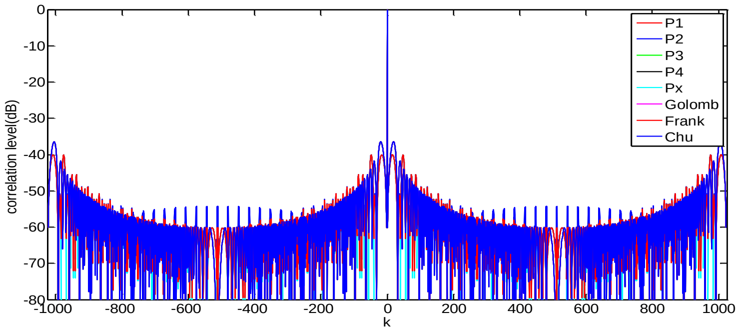


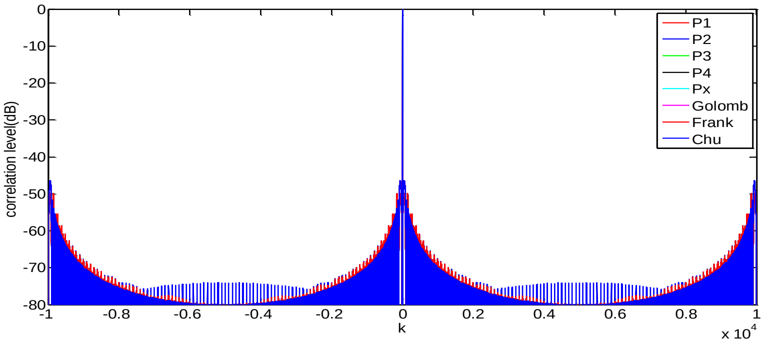
Fig. 2. Modified merit factor vs. sequence length from N=10^2 to 100^2.



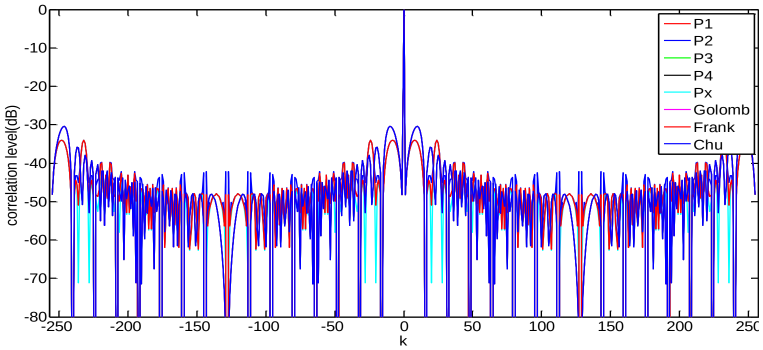
(a) Correlation level of P1, P2, P3, P4, Px, Golomb, Frank, Chu for N = 10^2.



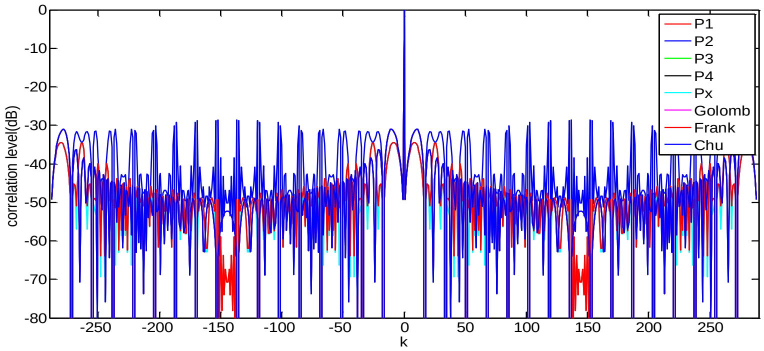
(b) Correlation level of P1, P2, P3, P4, Px, Golomb, Frank, Chu N = 10^3.



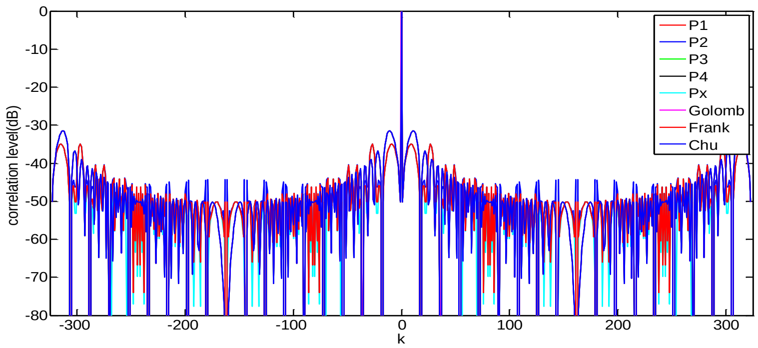
(c) Correlation level of P1, P2, P3, P4, Px, Golomb, Frank, Chu for $N = 10^4$.



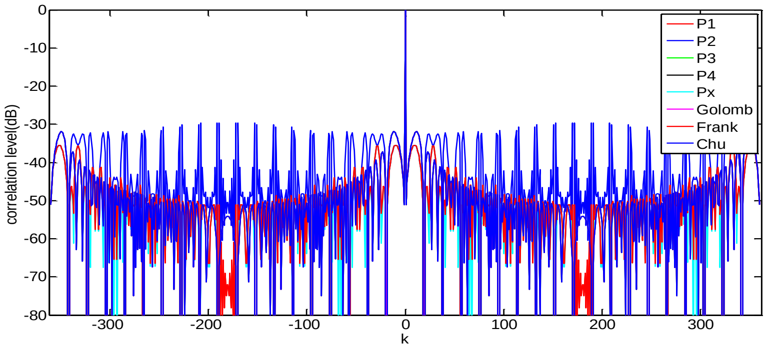
(d) Correlation level of P1, P2, P3, P4, Px, Golomb, Frank, Chu for $N = 16^2$.



(e) Correlation level of P1, P2, P3, P4, Px, Golomb, Frank, Chu for $N = 17^2$.



(f) Correlation level of P1, P2, P3, P4, Px, Golomb, Frank, Chu for $N = 18^2$.



(g) Correlation level of P1, P2, P3, P4, Px, Golomb, Frank, Chu for $N = 19^2$.

Fig. 3. Correlation levels of polyphase sequences of different lengths.

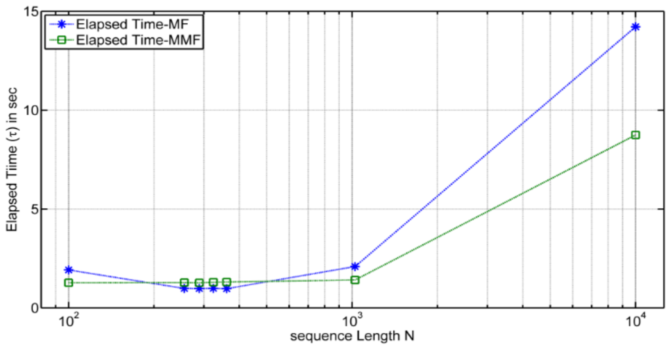


Fig. 4. Sequence length vs. elapsed time.

5. Conclusions

The effect of Polyphase sequences have been made for Square integer Lengths from 10^2 to 10^4 for both standard case and weights applied case. Some concluding observations from the examination given below:

- An average of more than cent percentage of improvement in merit factor from normal ISL to WISL. (P1, Frank), (P3, P4, Golomb, Chu), exhibits the same merit factor values for all the sequence lengths. Whereas P2 and Px only the sequence show different values.
- The ascending order of the merit factor of the sequences is (P3, P4, Golomb, Chu) < P2 < (P1, Frank) < Px for all lengths in both cases.
- Px sequence gives the maximum merit factor and (P3, P4, Golomb, Chu) gives minimum among all sequences.
- Less elapsed time (τ) difference from 10^2 to 10^3 and substantial difference from 10^3 and above lengths, i.e., 10^4.
- P2 exists for even numbered square integer lengths only in MFs calculation. But not when weights applied (not too large deviation in MMFs occurred when weights used).

- If the length of a sequence is outside the limits of weighted defined (for example 0 to 100 only), then correlation lags are considered as it is for the lengths greater than weights defined.
- A Cyclic algorithmic approach, which works based on SVD (Singular Value Decomposition) for improving the MFs for the same sequence length.
- If Elapsed Time is not considerate, then the above-said approach gives the good MFs works on the covariance matrix.

Nomenclatures

f(n)	Frank sequence, Eq. (5)
g(n)	Golomb sequence, Eq. (4)
k	Limit of positive integer (0 to N-1)
M	Positive integer, $N = M^2$
N	Sequence length
Pn	Sequences, *n*=1, 2, 3, 4, *x*
q	Integer Chu sequence Eqs. (11) and (12)
S_n	Polyphase sequence elements, $n = 1, 2, \ldots, N$

Greek Symbols

τ	Elapsed time, second
$\rho(s)$	Autocorrelation function
$\varphi_{n,k}$	Phase elements, rad

Abbreviations

ISL	Integrated Sidelobe Level
MF	Merit Factor
MMF	Modified Merit Factor
WISL	Weighted Integrated Sidelobe Level

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Appendix A

Representation and Figures of Design Charts

A computer code, for plotting the correlation level, Merit Factors (MFs) and Modified Merit Factors (MMFs) of different sequence Lengths. This programme describes the performance parameters presented in Section 3.

The Personal Computer (PC) program can fill two primary needs: firstly, computing the correlation Levels of Polyphase Sequences (PPS) and secondly, by calculating Merit Factors (MFs), Modified Merit Factor (MMFs) for sequence lengths mentioned in Tables 1 to 4.

Programme Structure and Description of Subroutines

MATLAB 2014a language used for calculation of Merit Factor (MF), Modified Merit Factor (MMF), and correlation plots. Firstly, an integer is read to a variable *M*. squaring the *M* value and assigned to variable *N*. length of a sequence is read on to the variable *K* and loop starts from $k = 0$ to *K*, i.e., reaching on to the maximum length of the sequence. In the same subroutine, all Polyphase sequences (P1, P2, P3, P4, Px, Golomb, Frank, Chu) Performance measures, i.e., Integrated Side-lobe Level (ISL), Weighted Integrated Sidelobe Level (WISL), Merit Factors (MFs), Modified Merit Factors (MMFs) and Correlation Level are calculated. ISL and WISL are the intermediate results obtained for calculating the MFs and MMFs from Eqs. (18) and (19). Each Polyphase sequence is taken as function. It takes N as input and computes all parameters like ISL, WISL, etc.

At “A” correlation plots are obtained, i.e., sequence length vs. correlation level in Eq. (14). At “B” MFs and MMFs are plotted using the “log log” command in MATLAB. The τ calculated by using “tic and toc” one at the beginning another at the end of the program. It enables to display total elapsed time in the command window. Each sequence MFs and MMFs Calculation wrote in the same subroutine for comparing all the sequences at a time. The flow chart for MFs, MMFs and correlation plots is continued in the next page.

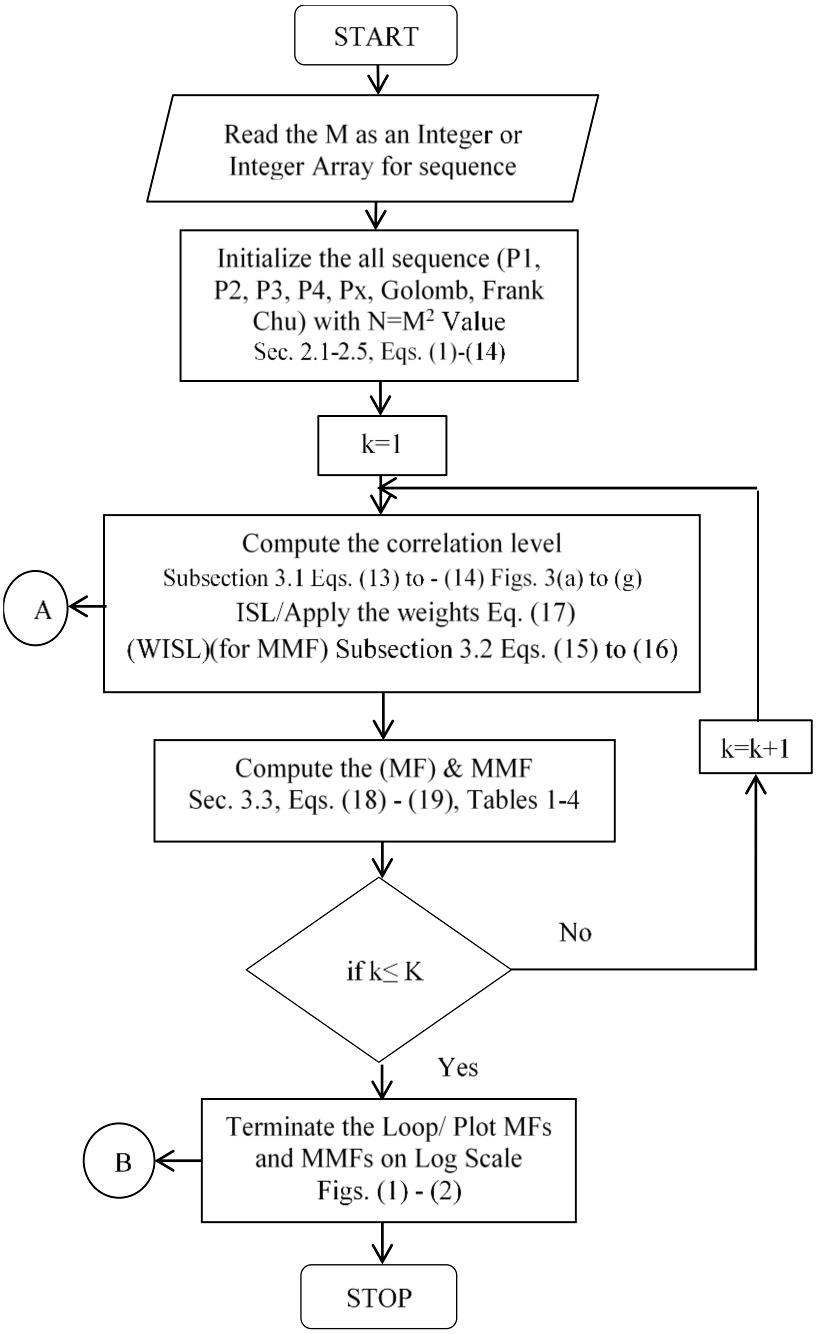

Fig. A-1. Flow chart for MFs, MMFs and correlation plots.