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Improving Long PN-Code Acquisition in the Presence of Doppler Frequency Shifts

M. Borna[1*] and M. H. Madani [2]

1- PhD. Student, Communications Engineering Faculty, Malek Ashtar University of Technology, Tehran, Iran.
2- Associate Professor, Communications Engineering Faculty, Malek Ashtar University of Technology, Tehran, Iran.

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ABSTRACT

Wireless communication is the major form of connection nowadays. In most cases it exploits the benefits of the spread spectrum techniques to overcome channel introduced corruptions like Doppler residual frequency, noise, interference and jamming. These techniques also enhance the security and quality of the link. Using long spreading pseudo-noise codes provides further security for the link though its acquisition is challenging. In this paper we propose Enhanced Dual Folding method for acquiring long codes in high Doppler scenarios. Two main criteria of an acquisition algorithm i.e. probability of detection and mean acquisition time is theoretically and numerically obtained for the proposed method. The proposed method's performance is simulated for two Doppler residual frequencies and is compared with a similar technique of long code acquisition which confirms the success of the proposed method in tolerating high Doppler in comparison with the similar technique. The simulation results agree well with the theoretical equations.

KEYWORDS

DSSS, Long PN-code Acquisition, Doppler, Folding, Zero padding.

* Corresponding Author, Email: maryam.borna@gmail.com

1- INTRODUCTION

A widespread technique of connecting people in today's world is wireless communication. The channel for conveying wireless signals is the free space, which is always available for setting up connections, but the corruptions are also free to interfere with the communications as additive noise, fading, jamming, spoofing and eavesdropping. An efficient technique to overcome these issues is spread spectrum which increases the processing gain of the transmission link. Direct Sequence Spread Spectrum (DSSS) reaches this goal by multiplication of modulated data with a spreading code. Conventional spreading codes have short periods though can be acquired easily but are less secure against jamming and spoofing since reproducing the code is not that hard [1]. One way to enhance the security of the spreading codes is using long period codes that can be even longer than the message. Due to large uncertainty region of code phase offset between receiver and transmitter, acquisition methods for long Pseudo-Noise (PN) codes are different from those for short codes and the trade-off between detection and time is challenging [2, 3].

Long PN code acquisition methods mainly subside in two categories, searching in time or frequency domain for code phase offset and residual frequency. Although time domain approaches lost their attractiveness due to noticeable progress in digital processing boards, yet there are some new remarkable methods. The idea of two dimensional compressed correlator in [4, 5, 6] is a double dwell correlator which combines adjacent cells either of code phase offset or frequency hypotheses in a way that more energy is accumulated for each test. At the same time the search region is shrunk. However, as the compression rate increases there will be more Signal to Noise Ratio (SNR) loss.

There is a type of acquisition methods which estimate the initial states of the long code generating shift registers. This is done in [7, 8, 9] by iterative message passing algorithms in a similar manner to channel decoding with the use of parity check matrices and Tanner graphs. However, the application of these methods are limited to few types of PN codes like maximum length sequences and gold codes, where a Tanner graph can be developed.

Efficient methods of long code acquisition are based on hybrid search i.e. looking for the offset in serial and parallel manner at the same time. Parallel search is performed in frequency domain via Fast Fourier Transform (FFT). There are some effective methods in the literature for long code acquisition which precede one another in terms of acquisition time or detection probability. Generalized zero padding (GZP) is based on zero padding which pads zeros to the received signal before taking FFT, this makes the partial circular correlation by FFT-Inverse FFT (IFFT) process happening in the case of long code, resemble to linear correlation. In the proposed GZP in [10] the length of zeros padded to the received signal is optimized according to SNR. Although this method has a good detection performance, its parallel searching capability equals the length of padded zeros and the acquisition time is rather high. Based on zero padding (ZP) technique [10], in [11] a modified version is proposed which claims to have better mean acquisition time than ZP, while the detection probability drops only 1.5 dB. Anyhow its parallel searching capability is still low compared to folding methods. In [12] GZP method is applied by some alterations in padded zeros length. Besides Doppler residual frequency is compensated by simple FFT-shift operation. Also a jammer mitigation algorithm which uses the first derivative of the correlator’s output is appended to the acquisition algorithm. The performance is fair against Doppler and jamming but still not sufficient for long codes.

Averaging every certain numbers of samples of the received signal and local code increases the parallel searching capability that is proposed as Direct Averaging Method (DAM) [13]. This method is sensitive to code phase offset such that if the offset equals half the averaging length, maximum correlation peak decreases significantly. Overlap Averaging Method (OAM) treats this problem by adding shifted versions of the received signal and local code to themselves before averaging [14, 15]. Extended replica folding acquisition search technique (XFAST) reduces the uncertainty region of local code by folding several blocks of the code into one which obviously speeds up search process however this method is weak in low SNRs [16]. Dual Folding (DF) method is an enhancement to XFAST in which by folding both locally generated spreading code and received signal, the coherent integration (CI) time increases and detection improves [17]. By choosing appropriate parameters for DF, the detection performance can get close to GZP while having reasonable parallel searching capability and mean acquisition time.

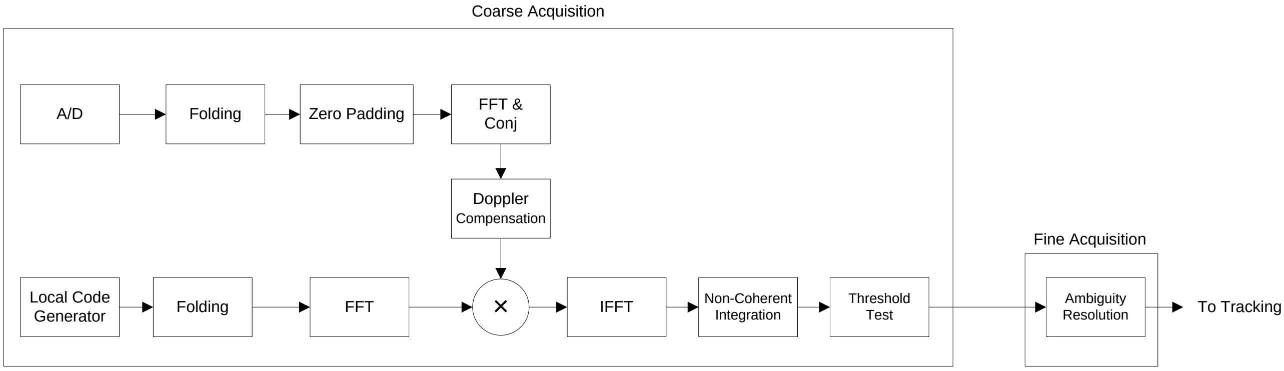

Fig. 1. Proposed long code acquisition algorithm

However increased CI time of DF allows more Doppler in every dwell, so in the case of high residual frequency, the enhancement provided by DF is rather repealed. Other approaches stemmed from mentioned methods trying to combine their best features are found in the literature [18, 19, 20].

For Doppler compensation, rather than conventional methods of shifting FFT output while processing with high sampling frequency, in [21, 22, 23] residual frequency cells were overlapped, folded or averaged so the search process for frequency offset is shortened. The method proposed in [21] is based on time and frequency folding technique, which can also be applied on averaging methods. In the paper, the proposed technique is compared against Double Block Zero Padding (DBZP) - pads a block of zeros to a block of received signal samples the same as ZP - for different FFT lengths and frequency steps up to 2400 Hz. In [24] an enhanced method for combination of Doppler hypotheses is proposed. However, in all of these papers parallel searching capability of code phase offset is still very low.

In this paper we propose a method that tolerates high Doppler while maintaining a good trade-off between parallel searching capability, detection performance and acquisition time. The performance remains close to above methods in low Doppler conditions. Next section describes the proposed method and its algorithm. Section 3 analyzes the proposed method theoretically in terms of detection probability and mean acquisition time. Section 4 provides simulation results and comparison. Section 5 concludes the paper.

2- METHOD DESCRIPTION

A- Signal Model

The k-th sample of In-phase and Quadrature phase components of the received digital baseband signal are as follows:

$$s_I[k] = Ad[k+\tau]c[k+\tau]\cos(\omega_D k\Delta t + \varphi) + n_I[k] \qquad (1)$$

$$s_Q[k] = Ad[k+\tau]c[k+\tau]\sin(\omega_D k\Delta t + \varphi) + n_Q[k] \qquad (2)$$

Where A is the signal amplitude, d is the modulated data bit $\in \{-1,+1\}$, τ is the code phase offset of the received signal, c is the spreading code's chip $\in \{-1,+1\}$, ω_D is the residual frequency in radians, Δt is the sampling period (the same as code period i.e. one sample per chip), φ is the unknown carrier phase offset and n_I and n_Q are in-phase and quadrature phase additive white Gaussian noises respectively with zero mean and variance σ^2, $\mathcal{N}(0,\sigma^2)$.

B- Enhanced Dual Folding Method

The proposed Enhanced Dual Folding (EDF) method focuses on long code acquisition detection performance in high Doppler conditions. The more Doppler compelled on the channel, the more detection performance deteriorates usually by a factor of $sinc^2(.)$ function including residual frequency in its argument [10, 15, 17]. Zero padding a signal helps taking longer Fourier transforms of a short signal, increasing frequency resolution of the spectrum, though no extra spectral information is added [19]. Use of shorter signal leads to shorter CI time which in turn diminishes adverse Doppler effect on detection performance, however decreasing CI weakens detection performance [26]. Hence a trade-off should be considered between resistance against Doppler and detection performance. Our proposed method improves DF method by applying GZP on it as shown in Fig. 1. The way a certain number of zeros is padded to the received folded signal is challenging, since it mustn't corrupt the autocorrelation properties of the folded signal. In other words, in the correlator's output of the proposed method there should still be the peak leading to the code phase offset. After checking different ways of embedding zeros to folded signal and their effect on correlation properties, following steps are proposed for the coarse and fine acquisition algorithms:

1. Received signal after mixer is down-converted to baseband then is sampled by analog-to-digital converter at the rate of spreading code, i.e. one sample per chip.
2. Take KN samples of the received signal and fold them into N samples, it's done by dividing KN samples into K blocks of N samples. Every resultant element is the sum of corresponding samples in all K blocks.
3. Choose the first $N-L$ samples of the folded samples and pad L zeros to it.
4. Take FFT and conjugate of N folded samples of previous step.
5. In the uncertainty region of locally generated code, take MN samples of the code and fold them into N samples, then shift the code $(M-K)N$ samples and fold next MN samples into N samples. Do this to the end of the ambiguity region.
6. Take FFT of the folded local code and multiply by the result of step 4 then IFFT.
7. Choose the first $L+1$ samples of the IFFT as the correlation result. If the maximum of that result passed a certain threshold then a coarse acquisition is declared and fine acquisition follows.
8. If the maximum correlation didn't pass the threshold, then the folded local code of step 5 is shifted L samples and the coarse acquisition restarts.

After the code is initially acquired, Index of maximum correlation shows the acquired folded block of the local code though there's ambiguity due to folding that should be resolved by the following fine acquisition algorithm:

9. Shift the unfolded local code by $(index\ of\ maximum\ correlation \times (M-K)N)$ samples and take N samples of the code then perform FFT.
10. Take $N/2$ samples of unfolded received signal, pad it with $N/2$ zeros and perform conjugate FFT.
11. Take IFFT; choose the first $N/2$ elements of the result. The maximum result passing the threshold gives in the code phase offset between received and local spreading code.
12. If no result passes the threshold, shift the local code of step 10 by $N/2$ samples and restart fine acquisition process.

3- PERFORMANCE ANALYSIS

Two main factors of evaluating an acquisition algorithm are the detection probability of true code phase offset and mean time spent in acquisition process. Here we analyze these items for the proposed algorithm so it can be compared with similar methods in the literature.

A- Detection Performance

Finding the true code phase offset involves correlation of the received signal with a code phase offset of τ and locally generated spreading code with offset of δ. Folded received signal, $s[l]$ will be:

$$s[l] = \sum_{k=0}^{K-1} s[l+kN] \tag{3}$$

where K is the folding number of the received signal. Every KN samples of the received signal is folded into N samples, where N is the length of FFT. Circular correlation of length N for In-phase received signal and local code is:

$$C_I[\delta] = \sum_{l=0}^{N-1} c[l+\delta] s_I[l] \tag{4}$$

Similar to DF, in proposed EDF, folding applies to both received signal and local code, such that after folding there are N samples of local code and received signal which will be correlated by FFT afterwards. Substitution of folded local code into eq. (4) yields:

$$C_I[\delta] = \sum_{l=0}^{N-1} \sum_{m=0}^{M-1} c[l+mN+\delta] \sum_{k=0}^{K-1} s_I[l+kN] \tag{5}$$

In which M is the folding number of the local code. As explained in the algorithm of proposed method, after folding, L zeros are padded to *N-L* folded samples of s_I and C_I changes to:

$$C_I[\delta-\tau] = \sum_{l=0}^{N-L-1}\sum_{m=0}^{M-1}\sum_{k=0}^{K-1} s_I[l+kN]c[l+mN+\delta]$$

$$= \sum_{l=0}^{N-L-1}\sum_{m=0}^{M-1}\sum_{k=0}^{K-1} Ad[\tau]c[l+kN+\tau]c[l+mN+\delta]\cos(\omega_D(l+kN)\Delta t+\varphi) + \sum_{l=0}^{N-L-1}\sum_{m=0}^{M-1}\sum_{k=0}^{K-1} n_I[l+kN]c[l+mN+\delta] \tag{6}$$

In most cases it can be assumed that data bit, $d[l+kN+\tau]$, is constant through the correlation so is replaced by $d[\tau]$. AWGN is independent of the spreading code so the noise term of (6), has the distribution of $\sim\mathcal{N}(0\,,\,\sigma^2(N-L)KM)$. There are two items in the first part of the correlation result of (6): self-noise and coherent integration [17]. CI item results from partially alignment of local code observation window and received signal when true hypothesis, H_1, holds. Similar to analysis of GZP in [10, 17], for EDF, the length of CI , n, is $KN-L$ so the mean value of CI part of the correlation, Γ_I , follows:

$$E_{\Gamma_I} = Ad[\tau]R_i(p)\sum_{l=0}^{KN-L}\cos(\omega_D l\Delta t+\acute{\varphi}) \tag{7}$$

Where p is the residual code phase offset and equals to $\delta-\tau-\lfloor\delta-\tau\rfloor$. $R_i(p)=\begin{cases}1-|p|\;,H_1\\0\quad\;\;,H_0\end{cases}$. $\acute{\varphi}$ is the phase of received signal at the first alignment with local code. The variance of Γ_I is $A^2G_i(p)n$ where $G_i(p)=\begin{cases}p^2\quad\quad\;\;,H_1\\(1-|p|)^2\;,H_0\end{cases}$. The CI item has a distribution of $\sim\mathcal{N}(E_{\Gamma_I}\,,\,\sigma^2{}_{\Gamma_I})$ [17]. Self-noise part is also modeled as a Gaussian random variable with zero mean, and the variance is similar to CI's but for the remaining samples; $KM(N-L)-n$. Considering the worst case, $p=0$, the self-noise has a distribution of $\sim\mathcal{N}(0\,,\,A^2[KM(N-L)-n])$ [17, 27].

The sum of three Gaussian random variables of AWGN, coherent integration and self-noise constitutes the correlation of in-phase received signal and local code. Replacing cosine function with sine in the mean value of the CI gives in the quadrature correlation results. The envelope of the correlation result is $\Psi=\sqrt{C_I^2+C_Q^2}$ which has Rice distribution [17] and the probability density function conditioned on p and H_i will be:

$$f_\Psi(x|\theta,H_i)=\frac{x}{\sigma_{H_i}^2}\exp\left\{-\frac{x^2+\mu_i^2}{2\sigma_{H_i}^2}\right\}I_0\left(\frac{x\mu_i}{\sigma_{H_i}^2}\right),\quad x\geq 0\,,i=0{,}1 \tag{8}$$

When observation window of the local code doesn't cover the received signal, the length of the CI, n, is zero and false hypothesis, H_0, holds. But when there's partial overlaying, true hypothesis, H_1, holds. I_0 is the zeroth order modified Bessel function of the first kind. μ_i^2 is the sum of squared means of in-phase and quadrature phase random variables and the variance is

$$\sigma_{H_i}^2=\sigma^2KM(N-L)+A^2G_i(p)n+A^2(KM(N-L)-n) \tag{9}$$

Detection probability of a single cell is achieved through Neyman-Pearson method, for a given false alarm probability, P_{fa}, the threshold can be derived from $P_{fa}=\int_{V_t}^{+\infty}f_\Psi(x|\theta,H_0)dx$ as $V_t=\sigma_{H_0}\sqrt{-2lnP_{fa}}$ [10]. And the detection probability will be:

$$P_d=Q_1(\frac{\mu_1}{\sigma_{H_1}},\frac{V_t}{\sigma_{H_1}}) \tag{10}$$

Where Q_1 is Marcum's Q function and

$$\mu_1^2=A^2(1-|p|)^2sinc^2\left(\frac{\omega_D}{2}\Delta t(KN-L)\right)n^2 \tag{11}$$

B- Mean Acquisition Time

Expected value of the time spent for acquiring a code (getting to desired detection probability) or mean acquisition time for a given false alarm, is a useful measure for performance comparison of acquisition techniques. The principals of calculating mean acquisition time of an acquisition algorithm is described in [28] for serial search of short codes, which is applicable to long codes as well and is formulated as:

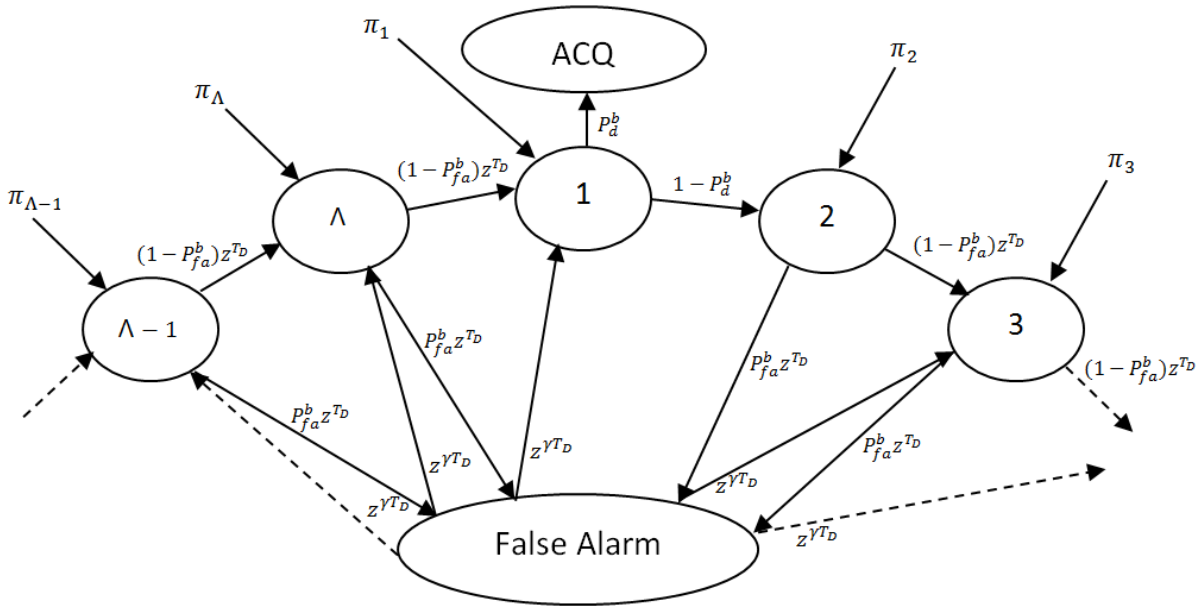

Fig. 2. A part of acquisition flow graph

$$E(T_{ACQ}) = \frac{T_D}{P_d^b}\left\{1 + (1+\gamma P_{fa}^b)(2-P_d^b)\frac{(\Lambda-1)}{2}\right\} \quad (12)$$

Where P_d^b and P_{fa}^b are detection and false alarm probability for the block of observation window respectively. T_D is the dwell time for searching an observation window. Λ is the number of observation windows in an uncertainty region of Θ code phases which is proportional to parallel searching capability of the algorithm that for EDF equals to $\frac{L+1}{N}[(M-K)N+1]$.

The flow graph diagram of the spent time through a typical acquisition is shown in Fig. 2. In EDF there's one state for true hypothesis of H_1 where $n = KN - L$ samples are covered by the observation window. The false alarm punishment of EDF is $\gamma = M$, since for checking the correctness of detected code phase, no folding is applied. The priori distribution of states is $\{\pi_i\}$ that is assumed as uniform one. Here we suppose there's no residual offset, $p = 0$ i.e. the sampling period is exactly the same as the chip period of the spreading code.

Consequently the mean acquisition time of EDF is obtained from (12) with following parameters:

$$\Lambda = \left\lceil \frac{\Theta}{(M-K)N+1} \times \frac{N}{L+1} \right\rceil \quad (13)$$

$$P_d^b = 1 - (1-P_{fa})^{L-1}(1 - P_{d|n=KN-L,p=0}) \quad (14)$$

$$P_{fa}^b = 1 - (1-P_{fa})^L \quad (15)$$

4- NUMERICAL RESULTS AND DISCUSSION

In this section, the proposed EDF method is simulated to be compared against theoretical results and DF method. The long spreading code is a maximal sequence produced by a 24-stage Linear Feedback Shift Register.

The sampling frequency is exactly the same as the chip rate i.e. 10.23 MHz and so the residual code phase offset is $p = 0$. False alarm probability is set as 10^{-5}.

The uncertainty region includes $\Theta = 10^7$ code phases and FFT length is 1024. Figure 3 shows the analytical and simulation results for the detection probability of long code coarse acquisition with EDF and DF methods when there's no Doppler. The folding numbers for these methods are $K = 16, M = 35$ which were chosen from [17] considering the achieved results in that paper. The length of zero padding in EDF is set as $L = \frac{N}{4}$ which yields the best trade-off between parallel searching and detection performance.

Since the CI length is decreased in EDF, in case of no Doppler, the performance is weaker than DF, however the difference is negligible. Figure 4 shows the EDF and DF method when there is a Doppler frequency of 1000 Hz, EDF is about 2dB better than DF. In figure 5 for frequency step of 1500Hz EDF is much better than DF.

As the Doppler increases to 2000 Hz, the success of the proposed EDF in tolerating higher Doppler is evident and performs about 2dB better than DF, Figure 6. The other criterion, mean acquisition time, is depicted in Figure 7 as a factor of T_D when there's Doppler of 1000 Hz. It shows that EDF spends less time than DF and settles faster. Figure 8 and figure 9 show mean acquisition time for frequency steps of 1500 and 2000Hz, since the probability of detection further improves, mean acquisition time of EDF is lower than DF. The proposed method is compared against DF in the sense of operations they perform in a single run of correlation. This parameter is denoted as MFLOPS (Mega Floating Point Operations)..

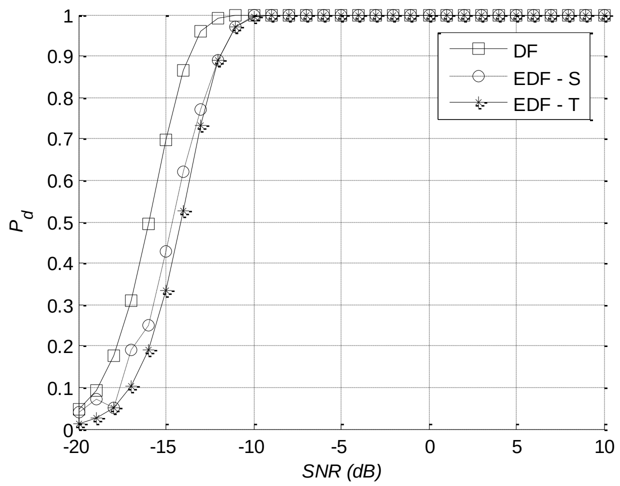

Fig. 3. Probability of detection for proposed method against Dual Folding, residual frequency is zero (T – Theory, S – Simulation).

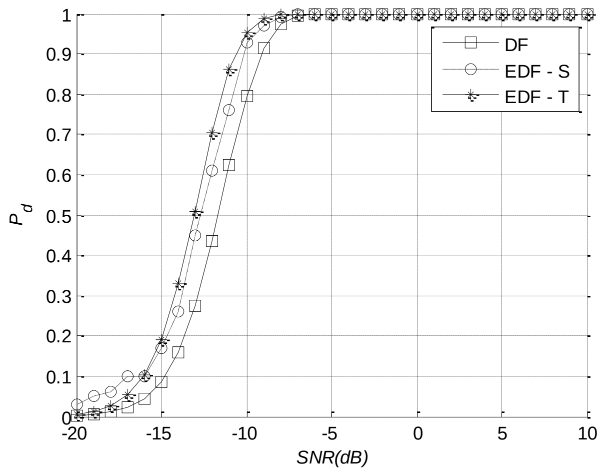

Fig. 4. Probability of detection for proposed method against Dual Folding, residual frequency is 1000 Hz (T – Theory, S – Simulation).

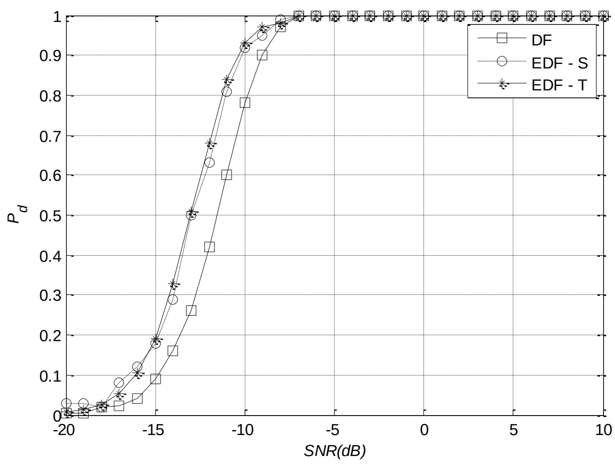

Fig. 5. Probability of detection for proposed method against Dual Folding, residual frequency is 1500 Hz (T – Theory, S – Simulation).

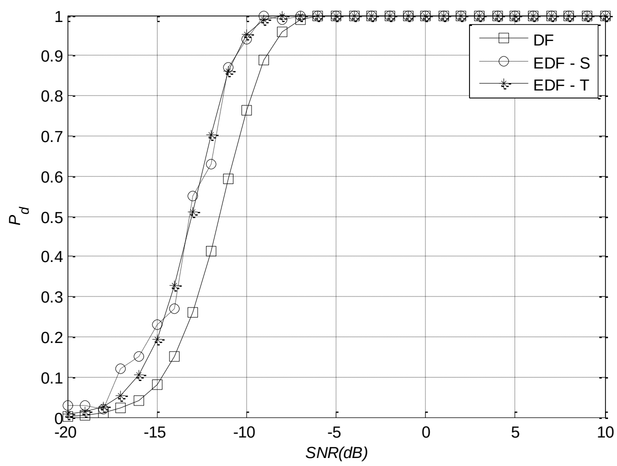

Fig. 6. Probability of detection for proposed method against Dual Folding, residual frequency is 2000 Hz (T – Theory, S – Simulation).

It has been obtained for each algorithm through the use of a toolbox for MATLAB software, named light speed[1]. For DF algorithm 830 MFLOPS is performed for searching the defined uncertainty region, while for EDF it's 1183 MFLOPSThe difference is small and negligible and it's due to different parallel searching capability of the two algorithms.

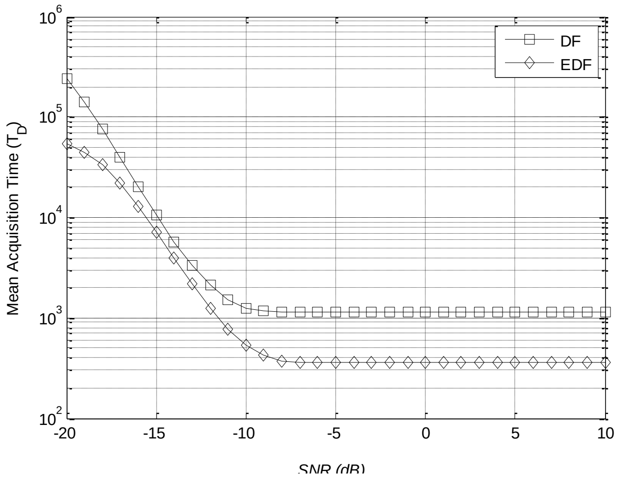

Fig. 7. Mean Acquisition Time of proposed method against Dual Folding, residual frequency is 1000 Hz.

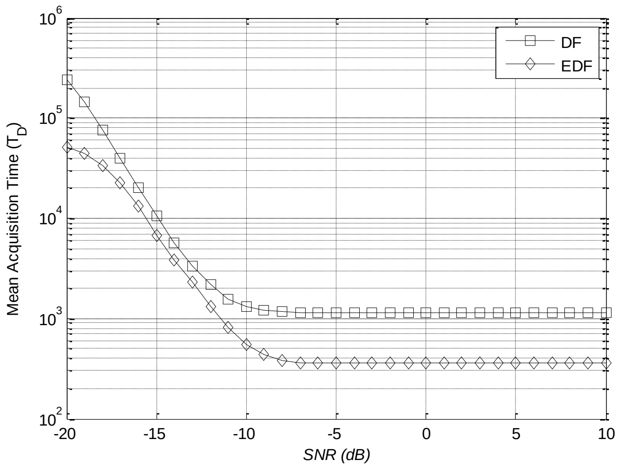

Fig. 8. Mean Acquisition Time of proposed method against Dual Folding, residual frequency is 1500 Hz.

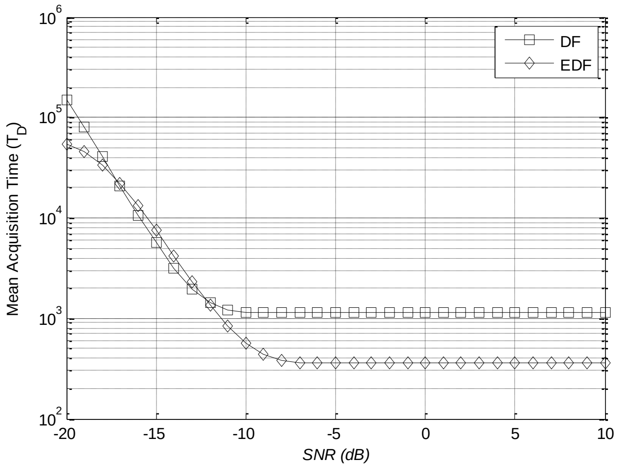

Fig. 9. Mean Acquisition Time of proposed method against Dual Folding, residual frequency is 2000 Hz.

5- CONCLUSION

In this paper Enhanced Dual Folding method is proposed for the acquisition of long spreading codes in a direct sequence spread spectrum system. The focus is on the performance in high Doppler environments. The algorithm of the proposed method is declared and its performance is analyzed theoretically in terms of detection probability and mean acquisition time. Also this method is simulated in no Doppler and high Doppler of 2 kHz and compared against Dual Folding method. The results show the success of EDF over DF in tolerating higher residual frequency of Doppler. Also the simulation results agree well with theoretical expressions. Regarding mean acquisition time, EDF is faster than DF. Therefore EDF is better for high Doppler conditions at the cost of less parallel searching capability than DF. Since it has better mean acquisition time than DF, this can't be counted as a deficiency.

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