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Research on An Improved PMF-FFT Fast PN Code Acquisition Algorithm

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ABSTRACT

To solve the problem of the large Doppler frequency offset in the LEO communication system, this paper studies a rapid PN code acquisition method based on the PMF-FFT architecture, which searches the phase and frequency offset and at the same time reduces the acquisition time. It presents an improved method equivalent to windowing function and uses windowing process to overcome the attenuation of related peak envelope caused by partial matched filters.

Keywords: Doppler Frequency Offset; Rapid PN Code Acquisition Algorithm; PMF-FFT; Windowing

1. Introduction

Doppler frequency offset, which makes it very difficult for the receiver to seize the signals. Ordinary one-dimensional search cannot meet the requirements of the rapid PN code acquisition, and thus two-dimensional search method is being gotten more attention. M. Sust has proposed a fast acquisition concept in the audio CDMA system [1]. In the paper, he analyzed the method of using FFT compensation method to solve the problem of large offset acquisition in the system, and the capture structure he used was the prototype of PMF-FFT algorithm. G.J.Povey, who first proposed this kind of algorithm which was based on [1] and made an efficient study and analysis [2-4], has gotten significant conclusions, making great contributions to the later development of the algorithm.

Reference [3] describes a non-coherent rapid acquisition system under the Doppler frequency offset. For the first time, it gives the PMF-FFT acquisition model and analyzes the probability of false alarm and detection probability characteristic in the Gaussian channel. S. M. Spangenherg proposed the windowing process of the FFT input to reduce the Scalloping Loss. This paper focuses on windowing approaches and then improves the structure of windows, improving the acquisition performance of the algorithm. It also presents a structure equivalent to windowing function, simplifying the implementation. For some low-pass attenuation of the matched filters, the window approach is also introduced.

2. Acquisition Algorithm Models Based on the PMF-FFT Structures

2.1. Acquisition Theory

M. Sust etal first used the FFT compensation, increasing the search range greatly in the frequency fields, which is equal to the parallel searches. Then G.J.Povey developed this method, systematically analyzed the acquisition algorithm of the FFT auxiliary digital matched filters, and showed the model based on both the digital part of the matcher filters and the FFT, shown in **Figure 1**. Here MX = KN, N is the length of PN code, while K is the sampling factor.

Supposing the sampling interval $T_s = T_c/K$, the initial phase is φ, the sampling signal after the down-conversion is

$$\tilde{x}(n) = \sqrt{PT_s}\,\frac{\sin(\pi f_d T_s)}{\pi f_d T_s} c(n-L) e^{-j(2\pi f_d n T_s + \varphi)} \quad (1)$$

When PN code obtains full synchronization,

$$\tilde{Y}(k, f_d) = \sqrt{PMXT_s}\,\frac{\sin(\pi f_d XT_s)}{\pi f_d XT_s}\,\frac{\sin[\pi M(f_d XT_s - k/M)]}{M\sin[\pi(f_d XT_s - k/M)]} e^{-j\varphi'} \quad (2)$$

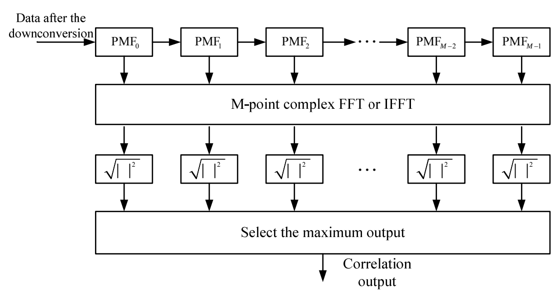

Figure 1. Capture model based on PMF-FFT[1].

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Normalize (2), the normalized frequency response of the FFT output of the k-th point

$$G_{\text{PMF-FFT}}(k, f_d) = \frac{\sin(\pi f_d X T_s)}{\pi f_d X T_s} \frac{\sin[\pi M(f_d X T_s - k/M)]}{M \sin[\pi(f_d X T_s - k/M)]} e^{j\Psi(k, f_d)} \tag{3}$$

$\Psi(k, f_d)$ is the phase characteristic of the PMF-FFT.

It is shown in **Figure 1** that the input which is compared with the preset threshold is the maximum output value of the k-th FFT point. That is, for a fixed variable f_d, comparing these values of $|G_{\text{PMF-FFT}}(k, f_d)|$, then we can get the related gains in the acquisition system.

$$\begin{aligned} A(f_d) &= \max\left\{|G_{\text{PMF-FFT}}(k, f_d)|\right\} \quad (k = 0,1,2 \cdots M-1) \\ &= \left| G_{\text{PMF-FFT}}\left(\left\lfloor NT_c f_d + \frac{1}{2} \right\rfloor, f_d \right) \right| \quad (0 \le f_d \le \frac{M}{NT_c}) \end{aligned} \tag{4}$$

$\lfloor \bullet \rfloor$ means to get the integral results downward.

2.2. FFT Compensation Characteristic

Equation (4) can be divided into two parts, and the normalized contribution of the partial matched filter of (4) is

$$G_{\text{PMF}}(f_d) = \frac{\sin(X f_d T_s / 2)}{X f_d T_s / 2} e^{-\frac{j(X-1) f_d T_s}{2}} \tag{5}$$

And the contribution that the FFT makes to the related normalized is

$$G_{\text{FFT}}(k, f_d) = A_{\text{FFT}}(k, f_d) e^{j\Psi_{\text{FFT}}(k, f_d)} \tag{6}$$

$A_{\text{FFT}}(k, f_d)$ is the amplitude response, and $\Psi_{\text{FFT}}(k, f_d)$ is the phase response.

For the moment, partial influence of the matched filters is not considered, and the following properties can be deprived from (6):

1) Panning features

Change the form of (6), then

$$G_{\text{FFT}}(k+1, f_d) = G_{\text{FFT}}(k, f_d - \frac{1}{NT_c}) \tag{7}$$

Equation (7) indicates that the frequency response of the kth FFT point is actually a $1/NT_c$ units right shift of the (k-1)th FFT point's frequency response.

So the synchronization system based on the PMF-FFT structure in **Figure 1**, can be extended M times in frequency searching range, which is $[0, M/(NT_c)]$. Therefore the simultaneous capture algorithm based on the PMF-FFT structure is not sensitive to the Doppler frequency offset, and the system is still able to complete the simultaneous capture successfully.

2) Period feature

Because the FFT compensation factor W_M^{km} is a rotation factor with a period of M, and is reflected as a periodic function in frequency domain in (6), with the period of $M/(NT_c)$. According to (6), it can be obtained:

$$G_{\text{FFT}}(k, f_d + \frac{M}{NT_c}) = G_{\text{FFT}}(k, f_d) \tag{8}$$

3) Ax symmetric feature

It can be found that $|G_{\text{FFT}}(k, f_d)|$ is an ax symmetric function of f_d, and on the axis of $k/(NT_c)$. Make simple algebraic simplification to (6), then

$$G_{\text{FFT}}(k, -f_d + \frac{k}{NT_c}) = G_{\text{FFT}}^*(k, f_d + \frac{k}{NT_c}) \tag{9}$$

That is

$$\left| G_{\text{FFT}}(k, -f_d + \frac{k}{NT_c}) \right| = \left| G_{\text{FFT}}(k, f_d + \frac{k}{NT_c}) \right| \tag{10}$$

4) Dual feature

Now consider the negative frequency, there is

$$G_{\text{FFT}}(k, -f_d) = G_{\text{FFT}}^*(M-k, f_d) \tag{11}$$

When $f_d \in [-\frac{k}{2NT_c}, -\frac{k-1}{2NT_c}]$, the capture system can still work effectively, and produces the maximum related output on the $(M\text{-}k)$ FFT.

3. Scalloping Loss

The associated gain of each FFT point is similar to sinc(x) function. At the crossover point, the associated gain output appears on the trough, presenting the phenomenon of the Scalloping Loss. Reference [4] proposes two solutions, storage zeros and windowing, and makes a thorough analysis to the former one. This paper focuses on the study and improvement of the windowing method. The main idea of this method is to increase the width of the main lobe and increase the FFT peak output intersection of the two adjacent points, in order to reduce the loss.

Now the window function is adapted to the united form

$$w(m) = \begin{cases} \dfrac{1}{1+\beta}\left[1 - \beta\cos\left(\dfrac{2\pi m}{M}\right)\right], & 0 \le m \le M-1 \\ 0 & \textit{others} \end{cases} \tag{12}$$

The related gain is

$$G'_{\text{FFT}}(k, f_d) = \left[A_{\text{FFT}}(k, f_d) + \frac{\beta}{2} A_{\text{FFT}}(k, f_d - \frac{1}{NT_c}) + \frac{\beta}{2} A_{\text{FFT}}(k, f_d + \frac{1}{NT_c}) \right] e^{j\Psi_{\text{FFT}}(k, f_d)} \tag{13}$$

Considering the panning features of the FFT compensation, we can change the form of (13). That is

$$G'_{\mathrm{FFT}}(k, f_{\mathrm{d}}) = G_{\mathrm{FFT}}(k, f_{\mathrm{d}}) - \frac{\beta}{2} G_{\mathrm{FFT}}(k-1, f_{\mathrm{d}}) - \frac{\beta}{2} G_{\mathrm{FFT}}(k+1, f_{\mathrm{d}}) \tag{14}$$

Thus the weighted sum of three consecutive FFT points according to (14) can get the same effect as windowing and the structure is simpler. In **Figure 2**, there is the comparison of the realization between windowing and equivalent windowing. It can be seen that the weighted sum of the FFT output is equal to the windowing process of the FFT input. They share the same improving properties.

4. The Low-pass Decay of PMF

As to the discussion about the FFT compensation features before, it is supposed to be all-pass without the influence of FFT. But actually PMF is a limited FIR with the length of X and all the coefficients are one.

In fact, G_{FFT} (k,f_{d}) is the related gain envelop of the PMF-FFT. When there is a large Doppler frequency offset, the attenuation of the PMF greatly influences the peak of related gain. This paper uses the same method as the windowed FFT input to perform the windowing process to the sampled data entering the FFT, increasing the width of the main lobe envelop in order to improve the decay when the frequency is large, shown in **Figure 3**.

5. The Improved Structure of the Algorithm

Thus, this paper makes a detailed analysis of the acquisition structure based on PMF-FFT, and discusses two methods to overcome the Scalloping Loss. After comparison, adding zeros by windowing turns to be easier and more effective. Therefore, this paper introduces windowing and its equivalent method into the acquisition system. For the influence on the related gain in the system which is made by the low-pass characteristic of some matched filters, this paper presents two effective solutions, which are adaptive threshold method and windowing. These two methods can be combined in order to improve the ability of acquiring PN code in large frequency offset.

The improved PMF-FFT structure is shown in **Figure 4**.

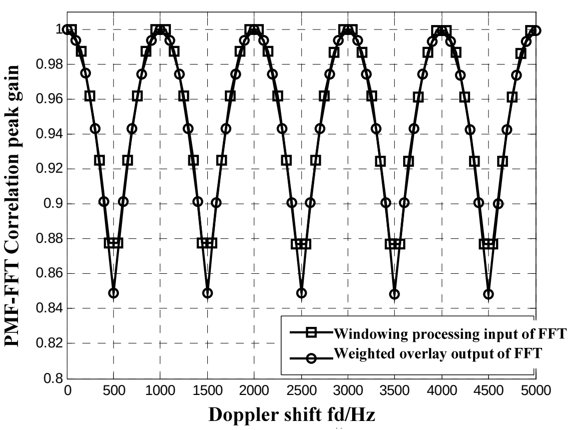

Figure 2. Simulation of equivalent window function method.

6. Algorithm Evaluation

Considering the non-coherent detection system, the amplitude statistical variables of M-point FFT output are identically distributed.

In the acquisition system in **Figure 4**, the statistical variables *R* that is compared with the threshold is the maximum value of *M*-point FFT output. Now the false probability is

$$P_{\mathrm{FA}} = 1 - \prod_{k=0}^{M-1}(1 - P_{\mathrm{FA}}(k)) = 1 - \left(1 - \exp\left(-\frac{\mathrm{c}}{2}\right)\right)^{M} \tag{15}$$

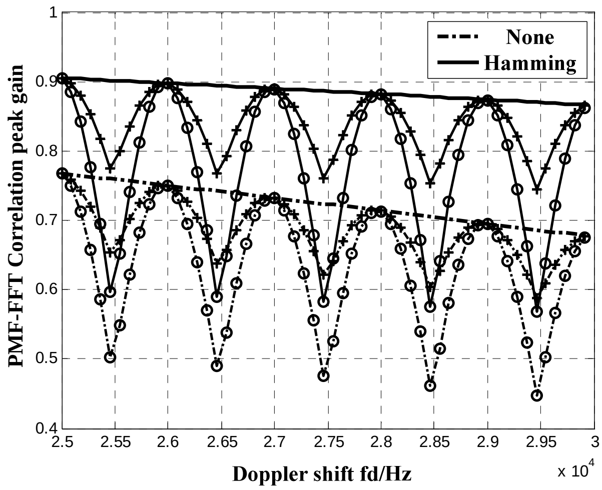

Figure 3. Effect of Amplitude-frequency response of PMF.

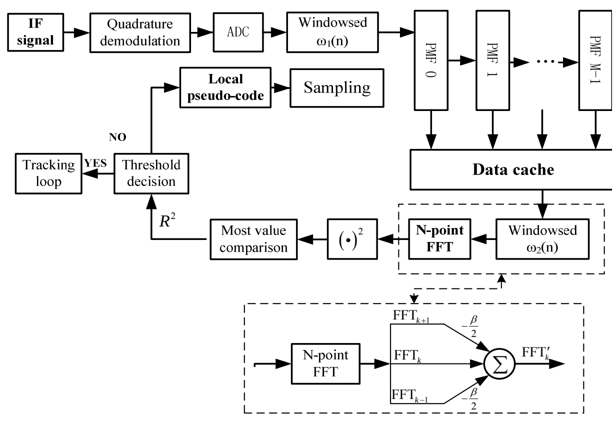

Figure 4. Block diagram of captures structure of Improved PMF-FFT.

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From (15), not only the threshold, but the number of FFT points has connection with false alarm probability. And the probability increases with the increasing values of *M*. Therefore, the number of the chosen FFT points in actual system is limited, and the false probability and the searching range of the frequency offset are in contradiction.

For the PMF-FFT capture system the detecting probability [4, 5] is

$$P_D(k) = Q\left(\sqrt{2N \bullet SNR_{in}}\left|G'_{\text{PMF-FFT}}(k, f_d)\right|, \sqrt{c}\right) \quad (16)$$

Suppose the preset threshold c=30, at this time PFA = 3.92×10^{-5}, the information rate R_b=1kpbs, the period of the PN code N=10240, the input SNR SNR_{in} = -25 dB. The relation between the detecting probability and the Doppler offset before and after the improvement is shown in **Figure 5**.

From **Figure 5**, the PMF-FFT algorithm expands the right detecting probability in the frequency domain. And the probability is bigger after windowing process than before. So the windowing method improves the detecting probability of the PN code acquisition.

This paper uses the single stay acquisition decision, so the average acquisition time is

$$\overline{T}_{\text{Acq}} = \frac{2 + (2 - P_D)(q-1)(1 + kP_{FA})}{2P_D}\tau_d \quad (17)$$

Here q is the number of code offset units to be searched, q=KN; τ_d is single stay time. The stay time will be T_s by using parallel matched filters, but it is at the cost of huge hardware resource. So it is the serial way that is chosen in this design and the stay time is XT_s; k is the number of decisions approving the happening of false alarm. So false alarm penalty time is $k\tau_d$. If k = 10, the relation between PMF-FFT algorithm and the Doppler frequency offset before and after the improvement is shown in **Figure 6**. **Figure 7** shows the connection of algorithm and the input SNR before and after improvement.

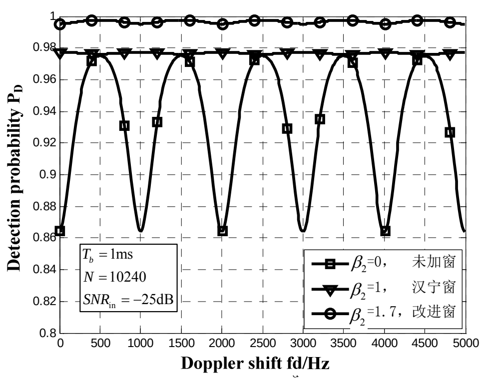

Figure 5. Relationships between probability of detection of improved algorithm and Doppler shift.

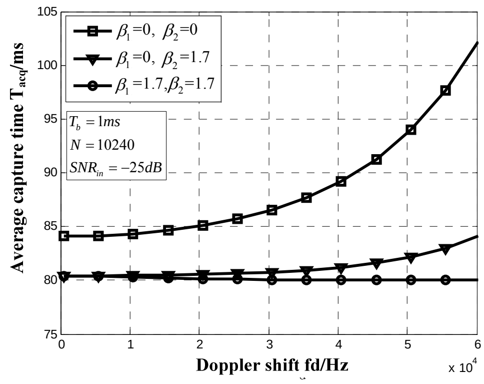

Figure 6. Average capture time of original and improved algorithm under Doppler shift.

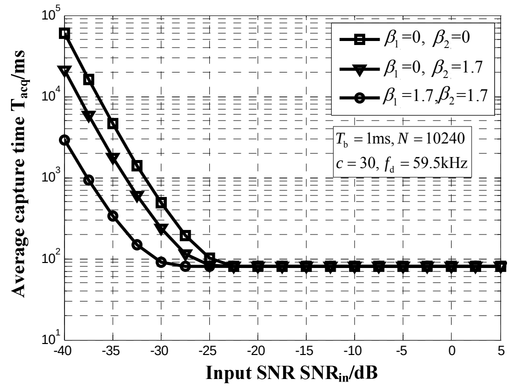

Figure 7. Average capture time of original and improved algorithm under different SNR.

7. Conclusions

This paper analyses basic theory of the PMF-FFT PN code acquisition algorithm. For the Scalloping Loss, it focuses on the windowing function method and improves the structure, reducing the influence of the Scalloping Loss. What is more, it proposes an equivalent method equipped with easier structure. For the loss brought by PMF fixed low-pass properties, it chooses the windowing process to the received data. Theoretical analysis results show that, after windowing twice, the algorithm improves detecting probability and reduces average acquisition time compared with the original one, improving the capacity of resisting disturbance.

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