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A New Acquisition Structure with Frequency Offset Estimation For Impulse Radio Ultra Wide Band Signal

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Abstract: The influence of clock frequency offset between transmitter and receiver of IR UWB (Impulse Radio Ultra Wide Band) system is talked about in this study. Firstly, this study highlight the fact that clock frequency offset in UWB system will decrease the performance of the coherent receiver and then the necessity of frequency offset estimation before acquisition step is stated. To improve the acquisition failure situation caused by frequency offset, a new acquisition structure with frequency offset estimation, as well as a new method to estimate frequency offset, is proposed. The scheme employs the characteristics of the symmetry and linearity of correlation to approximate the frequency offset in a range of searching area and has good accuracy. As the simulation results reveal, the proposed acquisition structure with frequency offset estimation outperforms the traditional acquisition system and the acquisition failure caused by frequency offset is improved greatly.

Key words: UWB impulse radio, acquisition, frequency offset estimation, matching correlation

INTRODUCTION

In the baseband-based UWB impulse radio, every information-bearing symbol is repeatedly transmitted over a large number of frames with one pulse per frame, in order to provide adequate symbol energy while maintaining low power density. Such a transmission structure entails a two-stage estimation task: one is the large-scale frame-level acquisition to identify when the first frame in each symbol starts and the other is the small-scale pulse-level tracking to find where a pulse is located within a frame.

The traditional UWB acquisition detects the peak of correlation between receive signal and matching template (Blazquez *et al*., 2003). The study of acquisition algorithm for UWB systems has drawn more and more attention, especially, the searching strategy aiming at fast and accurate acquisition. Several classic acquisition algorithms are proposed. Searching strategies are proposed based on Markov chains such as Truly-Random-Search, Random Permutation Search and look-and-jump-by-K-bins Search and etc., (Homier and Scholtz, 2002). Iinatti applied CLPDI scheme in multipaths for TH UWB system. In this scheme, the output of a matched filter, whose impulse response is a time reversed replica of the spreading code, is integrated over successive time intervals (Iinatti and Latva-Aho, 2001). Some acquisition schemes attempt to solve the large search space problem by employing a two-stage acquisition strategy (Gezici *et al*., 2003; Reggiani and Maggio, 2003; Aedudodla and Vijayakumaran, 2005; Corazza, 1996). The basic principle behind all these schemes is that the first stage performs a coarse search and identifies the true phase of the received signal to be in a smaller subset of the search space. The second stage then proceeds to search in this smaller subset and identifies the true phase. An optimum serial searching strategy based on TH-UWB in a multipath environment is introduced (Vijayakumaran and Wong, 2004) and a nonconsecutive searching in a frequency selective fading channel is presented (Shin and Lee, 2001). A variable step acquisition algorithm aims to improve the accuracy and mean acquisition time is discussed in our previous work (Zhang *et al*., 2008).

However, UWB extremely narrow impulse and multipath increase the challenging problem for UWB acquisition. The classical tracking circuit can achieve satisfying performance based on the condition as follows: coarse acquisition will provide an accurate estimation for symbol or frame synchronization. But in dense multipath environment, influenced by Doppler shift, clock frequency offset and clock jitter between transmitter and receiver, it is less likely to acquire the ideal estimation for acquisition with data-aided UWB receiver. Furthermore the probability of accurate tracking based on the wrong

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acquisition result will be decreased. To sum up, performance of acquisition and tracking UWB impulse will be influenced by clock jitter and frequency bias and yields large tracking error. Scholtz indicates only one tenth impulse width synchronization error will decrease the system output to zero (Scholtz, 1993).

Among the different factors that deteriorate synchronization performance, frequency offset is the most important one. Frequency offset describes the frequency error between transmitter and receiver; it depreciates tracking precision and acquisition performance as well. However, the study of frequency offset has drawn little attention to date and has been usually bypassed by adjusting phase at the tracking stage (Ibrahim and Buehrer, 2006; Khalesehosseini and Nielsen, 2006). The method adjusts the synchronization time frequently, but it has failed to remove the offset error. Furthermore, the problem that acquisition error will be introduced by frequency offset, cannot be solved. There are several frequency offset algorithms designed for OFDM systems. An estimation scheme based on cyclostationary in OFDM system is introduced (Tian *et al*., 2002) and another Maximum likelihood estimation method based on GLRT is proposed in (Tian and Giannakis, 2007). These above algorithms are less likely to be implemented in IR UWB system owing to complex architecture. Thus, more studies about frequency offset estimation are essential for IR-UWB acquisition system.

This study investigates the necessity of frequency offset estimation before acquisition for IR-UWB system. Furthermore a new acquisition structure with frequency offset estimation, as well as a new method to estimate frequency offset, is proposed. The estimation method using symmetry and linearity of matching correlation to find the optimum offset estimation in a given search-frequency scope. The proposed acquisition system has the advantages of simple architecture and accurate precision.

ANALYSIS OF FREQUENCY OFFSET ESTIMATION

The transmitted signal in IR UWB system is

$$s(t) = \sum_{j=-\infty}^{\infty} a_j g_T(t - jT_s)$$

where, g_T is the pulse generator at transmitter.

After the frequency selective faded channel, the signal can be described as tapped delay line module,

$$r(t) = s(t) * h(t) + \eta_c(t) = \sum_{j=-\infty}^{\infty} a_j \sum_{n=1}^{N\max} \mu_n g_T(t - jT_s - \tau_n) + \eta_c(t) \quad (1)$$

where, h(t) = $h(t) = \sum_{n=1}^{N\max} \mu_n \delta(t - \tau_n)$, μ_n, τ_n, N_{max} are expressed as channel gain, impulse arriving time and number of multipath. The received signal r(t) correlate with matching filter g_R, with frequency offset f_c and phase offsetθ considered.

$$g_R(t) = g_T(t) e^{j2\pi f_c t} \quad (2)$$

$$x(t) = r(t) * g_R(t) = e^{j\theta}\left(\sum_{j=-\infty}^{\infty} a_j \sum_{n=1}^{N\max} \mu_n g_T(t - jT_s - \tau_n)\right) * (g_T(t) e^{j2\pi f_c t}) + v(n) \quad (3)$$

Without frequency offset in the system, matching correlation output reaches the maximum at $t = jT_s + \tau_n$. Otherwise, frequency offset $e^{j2\pi f_c t}$ disturbs the correlation. This can also be shown in simulation results as in Fig.1, the correlation output with and without frequency offset is compared. Simulation environment is setup as follows, Gaussian 2nd derivative is adopted as UWB signal, impulse width T_p = 2ns, sampling rate f_s = 50GHz, frame cycle T_s = 30ns. IEEE_UWB indoor channel model CM1 is adopted to describe the multipath model. The correlation without frequency offset and with relative frequency offset 1.0001 are shown in Fig. 1a and b respectively. f_1 and f_2 are expressed as the clock frequency for transmitter and receiver and the relative frequency offset is described as $f_c = f_1/f_2$. To enhance comparison, the output energy of a and b is accumulated in c and d, respectively and correlation envelope is generated by adding the multipath energy in each time bin. Ideal correlation curve should have symmetry and linearity such as Fig. 1c; while, irregular change arises because of frequency offset, such as in d.

Above analysis reveals, the correlation will be influenced by frequency offset between transmitter and receiver badly. However, the correlation must be utilized by peak detection during the classic acquisition stage. The first multipath exceeding the preset detection threshold is the coarse acquisition position. The probability of missing the right place increases with lack of the correlation caused by existence of frequency offset. The comparison of acquisition bias with and without frequency offset is shown in Fig. 2, where, SNR changes from -24 to 10 dB. MSE (Mean Squared Error) is used to evaluate the acquisition bias between the actual and ideal acquisition position.

$$MSE = \frac{1}{N} \sum_{i=1}^{N} |x_i - \hat{x}_i|^2 \quad (4)$$

where, x is the actual acquisition position and $\hat{x}$ is the ideal synchronized position. N is the number of times of performing acquisition operation. Increasing SNR lowers the acquisition bias, which in turn improves acquisition precision with smaller influence of noise. The

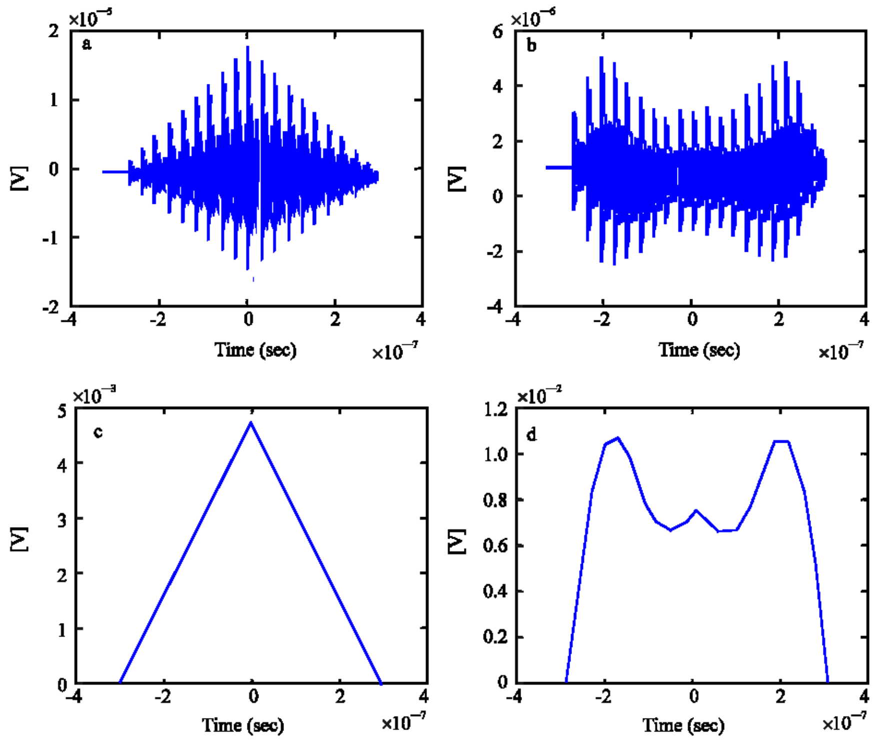

Fig. 1: Comparison of correlation curve with and without frequency offset

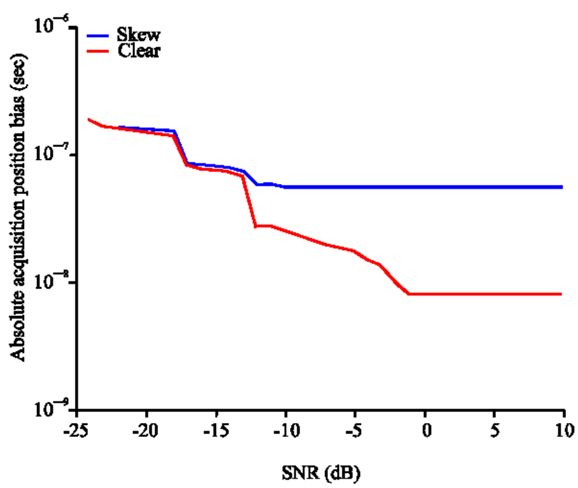

Fig. 2: Comparison of acquisition bias with and without frequency offset

two curves are stable around 0 dB; the acquisition bias without frequency offset falls in ns-level, while the acquisition bias with frequency offset is around dozens of ns. Because only small phases could be compensated at the tracking stage, i.e., within the half of one frame cycle (Scholtz, 1993), acquisition bias with dozens of ns exceeds scope of the tracking. Therefore, the acquisition with frequency offset failed.

ACQUISITION SYSTEM WITH FREQUENCY OFFSET ESTIMATION MODEL

As stated earlier, matching filter correlation will be influenced by frequency offset leads to synchronization failure. Therefore, frequency offset should be estimated before acquisition in the UWB system module and receiver clock will be adjusted according to the offset estimation. A new acquisition system with frequency offset estimation model is introduced in this study and the clock offset estimation will be implemented by the following algorithm.

Frequency offset estimation algorithm: The proposed algorithm is to evaluate the quality of correlation based on linearity and symmetry detection results and includes two parts, i.e., linearity and symmetry detection. Linearity detection aims to examine whether the correlation increases before maximum and decreases after maximum at a fixed slope. A unit distance step is preset at first and the amplitude function for correlation output is expressed as A. The sequence position for maximum amplitude is defined as I_{max}. Then, the linearity detection result for the i-th detection process L_i should meet 5.

$$\begin{cases} L_i = \left|L_{1i} - N \times L_{2i}\right| \\ L_{1i} = \left|A(I_{max}) - A(I_{max} - N \times step)\right|_i, \ N = 2,3,4L \\ L_{2i} = \left|A(I_{max}) - A(I_{max} - step)\right|_i \end{cases} \tag{5}$$

The linearity detection process is described in Fig. 3a. Obviously, L_i is smaller and linearity is better. When, there is ideal linearity in correlation, L_i equals zero. Practically, the best linearity should be attainted at the least value of L.

Symmetry detection aims to confirm whether the correlation distributed symmetrically before and after peak. The symmetry detection result can be expressed as C and then the i-th symmetry result C_i should meet the following equation.

$$\begin{cases} C_i = |C_{1i} - C_{2i}| \\ C_{1i} = A(I_{max} - step)_i \\ C_{2i} = A(I_{max} + step)_i \end{cases} \tag{6}$$

The symmetry detection process will be expressed in Fig. 3b. Obviously, the best symmetry should be acquired at the minimum of C. Especially the ideal symmetry can be obtained when C equals zero.

The quality of linearity and symmetry is considered thoroughly, i.e.,

$$Y_i = L_i + C_i \tag{7}$$

The correlation output is approximated capable of the best symmetry and linearity at the minimum of Y.

The receiver clock frequency increments with Δf each time, thus the correlation detection results are yielded for I times. Finally, the minimum detection result is selected from these results and the frequency stepping times i is obtained accordingly. Assume the min(Y) is gained at $i = I_{min}$, the frequency offset is estimated as follows:

$$\hat{f}_s = I_{min} \times \Delta f \tag{8}$$

Acquisition system with offset estimation: The proposed frequency offset estimation algorithm is based on characteristics of symmetry and linearity (Fig. 4).

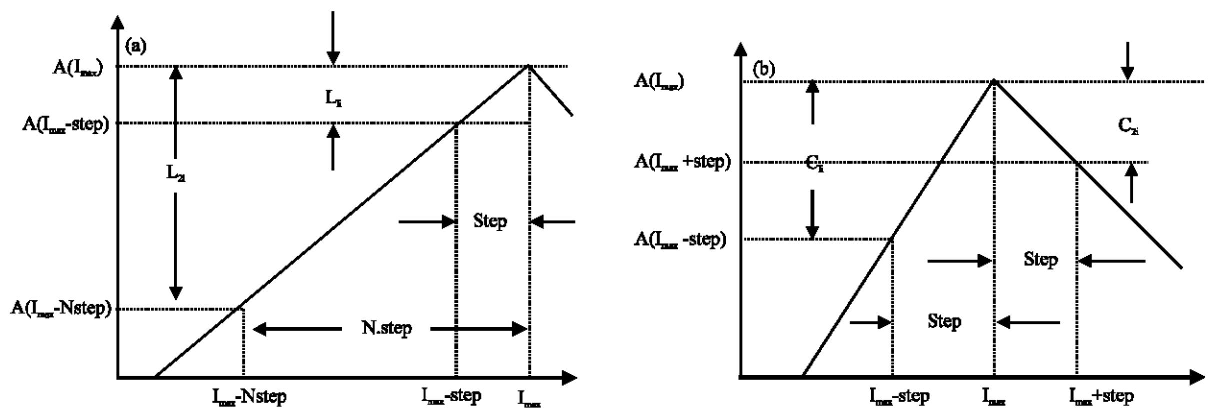

Fig. 3: Correlation detection sketch (a) linear detection process and (b) symmetry detection process

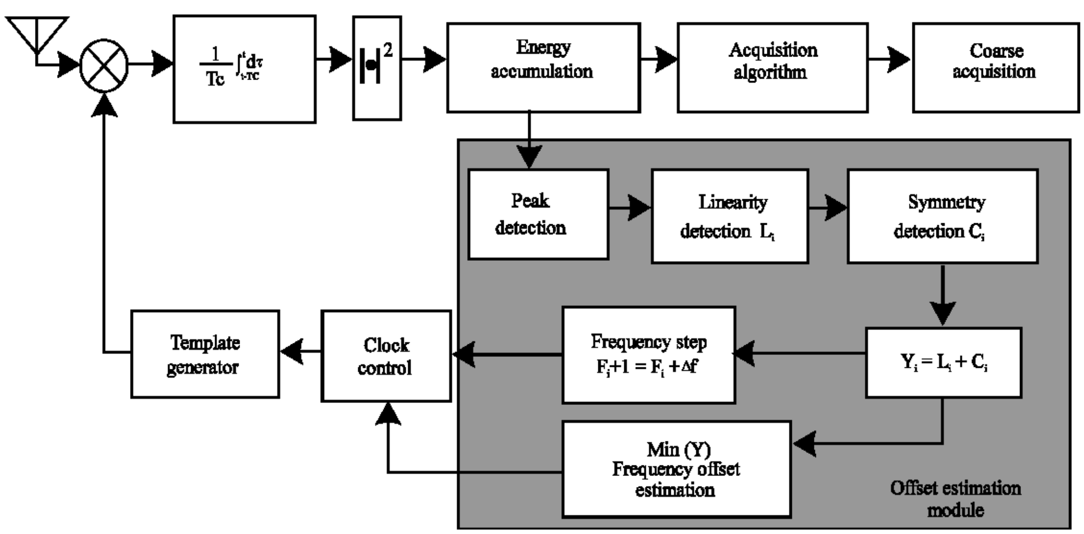

Fig. 4: Framework of frequency offset estimate system

The proposed system works in two different stages, i.e., offset estimation stage and acquisition stage, separately. At the offset estimation stage, firstly, transmitter sends a leader sequence with simple structure, which launches sequence template for I times. Once the leader sequence reaches the receiver, the frequency offset estimation module is started and the acquisition process is implemented for I times. Thus the offset estimation is obtained. Eventually, the receiver clock is adjusted accordingly, i.e., receiver clock will be locked into an updated fixed frequency, which ensures the same clock frequency with the transmitter and then stops the offset estimation stage.

At the acquisition stage, a coarse synchronization result is obtained. The detailed acquisition process can be referred to our previous work (Zhang *et al.*, 2008).

Frequency offset estimation process will be specific introduced. The matching template is correlated with receiving signal; then correlation output is squared and the energy is collected. In energy accumulation module, time is divided into small time bins and energy in each time bin is accumulated. This discrete correlation output can simplify the performance analysis and simulation for multipath channel system and can be prepared for frequency offset estimation. The output of energy accumulation module executes the peak detection and the first turning point is recorded. Using the turning point correlation value; linearity detection and symmetry detection are executed sequentially to determine whether the chosen correlation is good or not. L_i and C_i, result obtained from Linearity and Symmetry detection, are recorded. With Δf as the frequency step, new frequency for next matching is $F_{i+1} = F_i+\Delta f$, which adjusts local clock accordingly. Pulse shape generator controlled by clock control unit is combined with template sequence to generate matching template. Min(Y) is the module to find the minimum of Y_i, which represents the best linearity and symmetry. Then frequency offset is estimated by i according to 8.

PERFORMANCE ANALYSIS

The simulation conditions are setup as follows, Gaussian 2nd derivative is adopted as UWB signal, impulse width T_p = 2ns, sampling rate f_s = 50GHz, frame cycle T_s = 30ns. IEEE_UWB indoor channel model CM1 is adopted to describe the multipath model. The actual relative frequency offset is 1.0003 between transmitter and receiver, changing relative frequency offset from 1 to 1.0007 with 10^{-4} as the step to get the corresponding correlation curves in Fig. 5a-h. Obviously, Fig. 5d has the best linearity and symmetry and relative frequency offset under this condition is the same as the actual one, i.e., 1.0003. Fig. 5c-d are lack of linearity but their amplitude are close to Fig. 5d. The other plots are worse because of lack of symmetry and linearity and lower amplitude of correlation.

The proposed frequency offset estimation algorithm is evaluated with SNR changing from -20 to 10 dB, as shown in Fig. 6. The bias between the actual relative frequency offset and estimated one is measured by MSE,

$$MSE = \frac{1}{N}\sum_{i=1}^{N}\left|f_i - \hat{f}_i\right|^2 \qquad (9)$$

where, f is the actual frequency offset and is the frequency offset estimated by proposed algorithm;

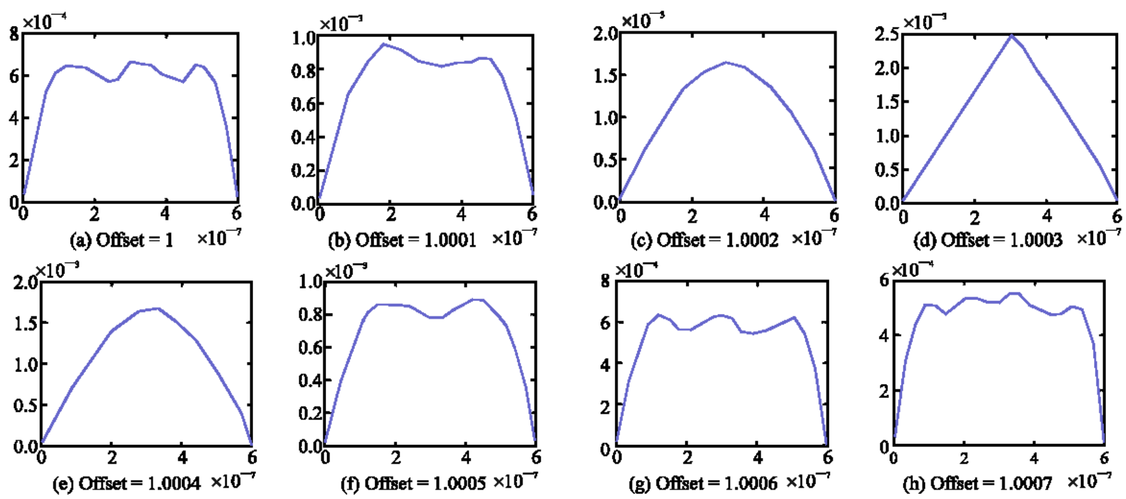

Fig. 5: The comparison of correlation curve with relative frequency offset changing from 1 to 1.0007 (actual relative frequency offset 1.0003)

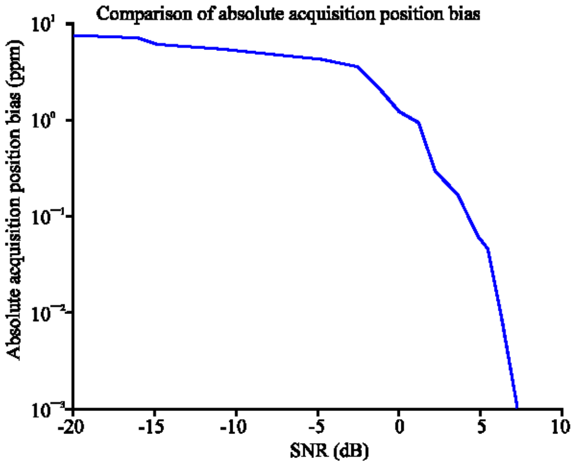

Fig. 6: MSE performance of frequency offset estimation algorithm

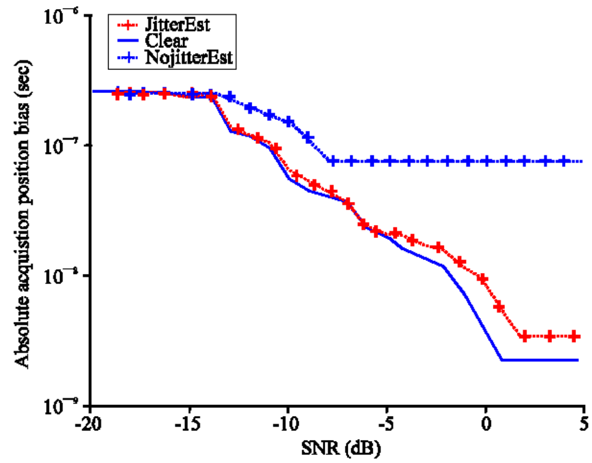

Fig. 7: The acquisition result comparison between with and without frequency offset

N is the number of operations. The maximum bias of the relative frequency offset is less than 10 ppm (part per million) within SNR range from -20 to 10 dB. With the SNR increasing, bias is decreasing and is reduced to 0 around 6 dB.

With same simulation conditions as above, the acquisition performances with and without estimation of frequency offset are compared in Fig. 7. Blue and red dotted line expressed the acquisition bias of traditional acquisition system and proposed system, respectively. And the ideal acquisition bias with no frequency offset between transmitter and receiver is described as blue solid line. From the simulation results, the acquisition with offset estimation outperforms traditional acquisition and is close to the ideal acquisition curve without clock offset. The two curves are stable around 0 dB; the acquisition bias without frequency offset falls in ns-level, while the acquisition bias with frequency offset is around dozens of ns, which indicates a poor acquisition. Above all, acquisition precision is improved by frequency offset estimation algorithm and is close to the ideal synchronized acquisition precision.

CONCLUSIONS

The necessity that frequency offset should be estimated before acquisition stage in IR UWB system is analyzed. Frequency offset will lead to acquisition failure, because acquisition result is out of the tracking range. The proposed frequency offset algorithm based on correlated receiving has simple architecture. In simulations, the poor acquisition performance under clock frequency offset circumstance is greatly improved by proposed acquisition system with offset estimation algorithm. And the offset estimation bias is no more than 0.001 ppm at higher SNR. However, the actual physical implementation of the proposed scheme is desired.

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