New Preamble Design for Reduced-Complexity Timing Acquisition in UWB Systems

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***Abstract*—Low-complexity rapid timing acquisition is one of the most pivotal challenges in ultra-wideband (UWB) wireless technology whose short duration pulse results in high resolution in time. In this paper, we propose a new preamble which can reduce the performance degradation caused by diminishing the operational complexity of the coarse timing acquisition. In the reduced-complexity acquisition algorithm, the received preamble is shortened by summing its elements group-by-group and correlated with the known PN sequence having reduced length to find the maximum output value of the correlators. This acquisition algorithm introduces performance deterioration since it loses the impulsive autocorrelation property of the PN sequence after summation. Therefore, we judiciously design a new preamble sequence whose slide correlator output function shows a distinct peak at zero delay and the symmetry even after summation. Simulation results demonstrate that the reduced-complexity acquisition algorithm exploiting the proposed preamble outperforms the algorithm using the PN sequence as the preamble, while the amount of computational reduction remains the same.**

Keywords-UWB; acquisition; synchronization; complexity reduciton; preamble design; doubly spread sequence

I. INTRODUCTION

Ultra-wideband (UWB) radio is a fast emerging technology exploiting huge "new bandwidth" (3.6-10.1 GHz) unleashed in its rulemaking proposal in 2002 by the Federal Communications Commission (FCC) in the United States [1], [2]. UWB systems utilize ultra-short time duration pulses, which have the extremely low power spectral density. This leads to uniquely attractive features: i) high data rates over short distances, ii) multipath mitigation, iii) low probability of intercept (LPI), iv) low power consumption, and v) low cost [3]. Therefore, UWB has invited rapidly growing research efforts in high-speed indoor short range wireless communication systems such as Wireless Personal Area Networks (WPAN) [4]. In this UWB system, one of the major challenges is the accurate and speedy synchronization. As UWB systems employ low-power ultra-short pulses (in the order of nanoseconds), timing requirements are stringent because even minor misalignments may result in lack of energy capture which renders symbol detection impossible. Moreover, narrow pulse widths imply that acquisition algorithms should employ high sampling rates and narrow search step sizes which could lead to significant operational complexity for acquiring timing. Accordingly design of acquisition schemes for UWB systems require reduced-complexity approaches.

In order to achieve low-complexity receiver, a way to reduce the total number of operations in the timing acquisition has been developed in [5]. In this preamble-assisted timing acquisition scheme, the new vector, which is computed by summing the output vector of the matched filter group-by-group, was correlated with the PN sequence with a reduced length by summation to find the maximum output correlation value. Then the fine acquisition was carried out by focusing on the element of the original vector corresponding to the maximum output value of the correlators. It was shown that this scheme can speed up the initial timing acquisition, alternatively, decrease the receiver sampling rate during the acquisition phase. However, the drawback of this technique is obviously the reduced performance since it loses the impulsive autocorrelation property of the preamble and suffers from the increased effects of white noise and interfering pulses after summation.

In this paper, we design a new preamble which can reduce the performance degradation caused by diminishing the operational complexity of the coarse timing acquisition as in [5]. Relying on the proposed preamble, the slide correlator output function shows a distinct peak at zero delay and symmetry although we downsize its length by summation. Compared with algorithms using the PN sequence as in [5], the reduced complexity acquisition algorithm using the proposed preamble exhibits the decreased degradation in timing acquisition performance under the same amount of the computational reduction in UWB multipath environment.

The rest of the paper is organized as follows. In Sec. II, we describe the system model. Then we explain the proposed DS sequence generation procedure and its property in Sec. III. Section IV shows the acquisition strategy considered in this work and its computational load reduction. Section V shows the simulation results by using the proposed preamble under UWB multipath environment and Sec. VI concludes the paper.

II. SYSTEM DESCRIPTION

The UWB signal chosen is the ultra-short pulse $w(t)$ whose power spectra meets the FCC spectral mask requirements as proposed in [6]. A single pulse having the effective pulse time width T_w. is transmitted within each frame with the time width T_f. In this paper, we only consider the timing acquisition phase using preambles.

The signal waveform $s(t)$ of the preamble is shown as

$$s(t) = \sum_{j=0}^{N_f-1} d_j w(t - jT_f) \tag{1}$$

where bi-phase (BPSK) modulated sequence $d_j \in \{-1,1\}$ represents each bit of the preamble and N_f is the number of frames in a preamble or the preamble length. The transmitted signal $x(t)$ is given by

$$x(t) = \sum_i s(t - iT_p) \tag{2}$$

where, T_p is the time width of a single preamble.

The channel impulse response is modeled by the well-known tapped delay line expression [7]:

$$h(t) = \sum_{l=0}^{L-1} \alpha_l \delta(t - \tau_l) \tag{3}$$

The channel coefficients, α_j, and the impulse response length, L, are modeled according to the model proposed in [7], which is a modification of the S-V model [8] for a UWB indoor environment. Then, in our analysis, the interference sources of the channel are additive white Gaussian noise (AWGN). We assume the channel is quasi-static while transmitting preamble sequences, i.e., the channel tap and delay coefficients do not change during the transmission of the preamble sequences.

The received signal can be expressed as

$$r(t) = \sum_{l=0}^{L-1} \alpha_l s(t - NT_P - \eta T_f - \varepsilon - \tau_{l,0}) + n(t) \tag{4}$$

where we define $\tau_0 \triangleq NT_P + \eta T_f + \varepsilon$ and $\tau_{l,0} \triangleq \tau_l - \tau_0$, with $0 \le \tau_{l,0} \le T_f$. The timing offset parameters $N \triangleq \lfloor \tau_0 / T_P \rfloor$, $0 \le \eta \le N_f - 1$, and $0 \le \varepsilon \le T_f$ denote the symbol-level acquisition, frame-level acquisition, and tracking offsets, respectively. The wide sense stationary process $n(t)$ accounts for AWGN. Timing acquisition amounts to estimating the frame-level offset η.

III. A New Preamble Design

A. Design Criteria

In practice, timing acquisition of UWB signals is based on the transmission of known preambles, which are followed by UWB data pulse sequences. The received signal is correlated with the known preamble for all possible time delays and then integrated for a fixed time duration, τ_D (a.k.a. the "dwell time"), in an integrate-and-dump (I & D) circuit and then compared to a predetermined threshold.

Therefore, the impulsive autocorrelation property of the preamble is crucial for the successful operation of the slide correlator [9]. Conventionally, the preamble has been designed to have an approximately two-valued (impulsive) autocorrelation function, i.e., a single positive peak at zero time delay and zero or near-zero values elsewhere.

We consider the variable length of the preamble as another important design criterion [9]. The longer preamble is desirable since its autocorrelation fuction has a higher correlation peak, which enables us to acquire timing in noise and multipath environments. However, as the length of the preamble lengthens, the complexity overhead increases. Thus, there arises tradeoff between the operational complexity and performance of timing acquisition.

B. Doubly Spread(DS) Sequence Generation

In this paper, we reduce the length of both the received signal and the known preamble by summation to diminish the operational complexity for acquiring timing. This undoubtedly results in the performance degradation due to the deformed autocorrelation function. Therefore, we aim to design a new preamble which maintains the impulsive and symmetric autocorrelation function even though we downsize its length.

The proposed DS sequence can be generated in following procedure.

At first, the initial sequence $\mathbf{I}_{N_I}$ is defined as

$$\mathbf{I}_{N_I} = [i_1 \quad i_2 \quad \cdots \quad i_{N_I}] \tag{5}$$

where N_I denotes the length of the initial sequence $\mathbf{I}_{N_I}$.

Next by using initial sequence $\mathbf{I}_{N_I}$, the symmetric sequence $\mathbf{S}_{N_S}$ is defined as follows

$$\begin{aligned} \mathbf{S}_{N_S} &= [s_1 \quad s_2 \quad \cdots \quad s_{N_S}] \\ &= \pm[\mathbf{I}_{N_I} \quad 1 \quad \mathit{fliplr}(\mathbf{I}_{N_I})] \\ &= \pm[i_1 \quad i_2 \quad \cdots \quad i_{N_I} \quad 1 \quad i_{N_I} \quad \cdots \quad i_2 \quad i_1] \end{aligned} \tag{6}$$

where N_S indicates the length of the symmetric sequence $\mathbf{S}_{N_S}$ and the function *fliplr*( ) the flipping operation of the input sequence horizontally. This symmetric structure guarantees the symmetry of the autocorrelation function of $\mathbf{S}_{N_S}$.

Finally, by *spreading* $\mathbf{S}_{N_S}$ by the spreading factor $S_f = N_S$, the doubly spread sequence $\mathbf{D}_{N_D}$ is defined as

$$\begin{aligned} \mathbf{D}_{N_D} &= [d_1 \quad d_2 \quad \cdots \quad d_{N_D}] \\ &= [s_1 \cdot \mathbf{S}_{N_S} \quad s_2 \cdot \mathbf{S}_{N_S} \quad \cdots \quad s_{N_S} \cdot \mathbf{S}_{N_S}] \end{aligned} \tag{7}$$

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where N_D represents the length of the doubly spread sequence $\mathbf{D}_{N_D}$. From (5), (6), and (7), we can obtain

$$N_S = 2 \cdot N_I + 1$$
$$N_D = S_f \cdot N_S = N_S^2 \quad (8)$$

which shows the relationship of N_I, N_S and N_D.

When the length of the received DS sequence is reduced by summation with the same reduction factor R_f as the spreading factor S_f, we can reconstruct the scaled symmetric sequence which has the impulsive and symmetric slide correlator output function.

We found some DS sequences which satisfy two design criteria, a distinct peak at zero delay and symmetry, even after summation and their corresponding initial sequences are displayed as follows

$$\mathbf{I}_2 = [-1 \quad -1]$$
$$\mathbf{I}_3 = [1 \quad 1 \quad -1]$$
$$\mathbf{I}_4 = [-1 \quad -1 \quad 1 \quad -1] \quad (9)$$
$$\mathbf{I}_5 = [1 \quad 1 \quad -1 \quad 1 \quad -1]$$

Fig. 1 shows an example of a DS sequence generation procedure. By using an initial sequence $\mathbf{I}_3 = [1 \quad 1 \quad -1]$, the symmetric sequence $\mathbf{S}_7$ is formed by (6) and the doubly spread sequence $\mathbf{D}_{49}$ is finally generated according to (7).

C. Slide-Correlator Output Function : Doubly Spread Sequence vs. PN Sequences

In this subsection, the slide-correlator output function (SCOF) of the DS sequence is compared with that of the PN sequence when their lengths are reduced. The length of the PN sequence is denoted as N_{PN}. The DS or PN sequence of length $N_D = N_{PN} = N_S^2$ is separated into N_S subsequences of the

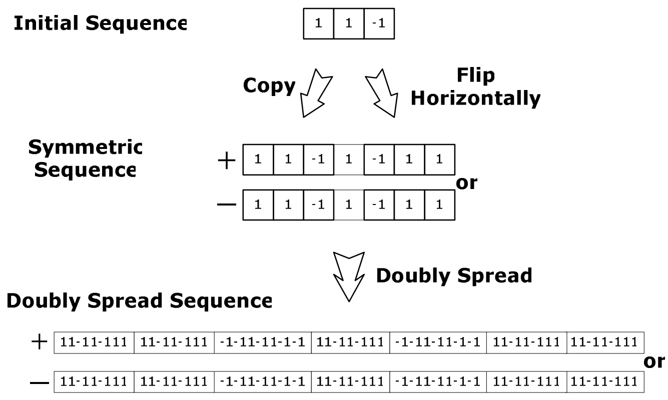

Figure 1. Doubly spread sequence generation (N_I = 3, N_S = 7, N_D = 49)

same length N_S and shortened by summing elements of each subsequence. This reduced sequence is correlated with the template sequence having reduced length by the 'separating and summing' method. We sweep the original sequences along repeating this correlating procedure and get the slide-correlator output function.

In Figs. 2 and 3, we plot the SCOFs of the DS sequence and the maximum-length shift-register sequence (M sequence) respectively. Length 49 and the reduction factor $R_f = 7$ are chosen for the sequences. In these figures, the horizontal line indicates the time delay between the received sequence and the template sequence both advancing and retarding. Zero delay indicates the correct position of timing. As shown in Fig.2, the SCOF of the proposed DS sequence of reduced length has a single distinct peak at zero delay and perfect symmetry. On the contrary, in Fig. 3 the SCOF of the conventional M sequence of reduced length has more output values close to the peak value without symmetry. As a result, compared with the algori-

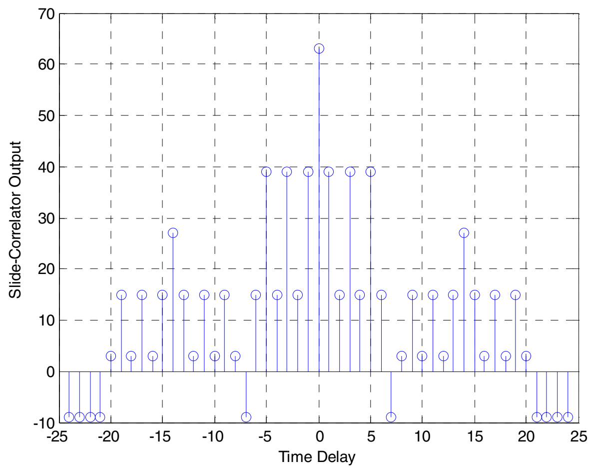

Figure 2. SCOF of the reduced DS sequence (N_D = 49 , R_f = 7)

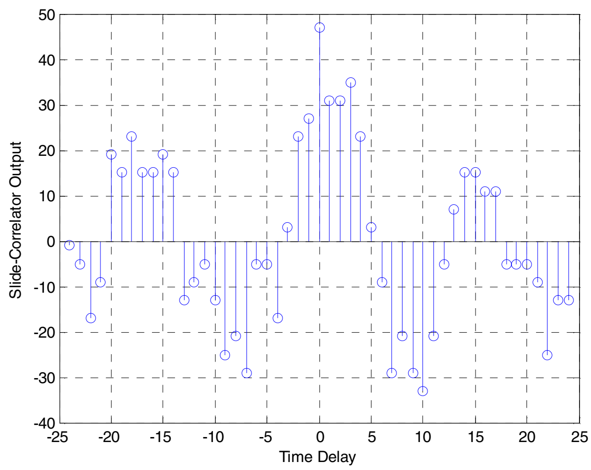

Figure 3. SCOF of the reduced M sequence (N_{PN} = 49 , R_f = 7)

thm using PN sequence, the better correlator output property of the proposed DS sequence can be a contribution to the better acquisition performance.

IV. ACQUISITION STRATEGY AND OPERATIONAL LOAD REDUCTION

A. Reduced Complexity Timing Acquisition using DS Sequence as the Preamble

We employ reduced complexity timing acquisition scheme using the received DS sequence of reduced length and the shortened template sequence as the integrator inputs. Except for this, all is the same as the general peak picking slide correlator method. We exploit the length- N_D DS sequence and the reduction factor $R_f = S_f = N_S$. 'Separating and summing' approach is used for the shortening of the DS sequence.

B. Operational Load Reduction

In this subsection, we analyze how much operational burden can be reduced when we shorten the length of the preamble. In case of the conventional scheme using length- N_D preamble, the number of addition N_A and that of multiplication N_M are shown as follows

$$N_A = (N_D - 1) \tag{10}$$

$$N_M = N_D \tag{11}$$

In the case of the acquisition scheme undergoing the shortening process by the reduction factor $R_f = S_f = N_S$, the number of addition $N_A^{'}$ and that of multiplication $N_M^{'}$ are calculated from Fig. 4 to obtain the following

$$\begin{aligned} N_A^{'} &= (N_S - 1)\cdot N_S + (N_S - 1) \\ &= (N_S^{\,2} - 1) \\ &= (N_D - 1) \end{aligned} \tag{12}$$

$$N_M^{'} = N_S = \sqrt{N_D} \tag{13}$$

From (11), (13), We can observe that the number of multi-

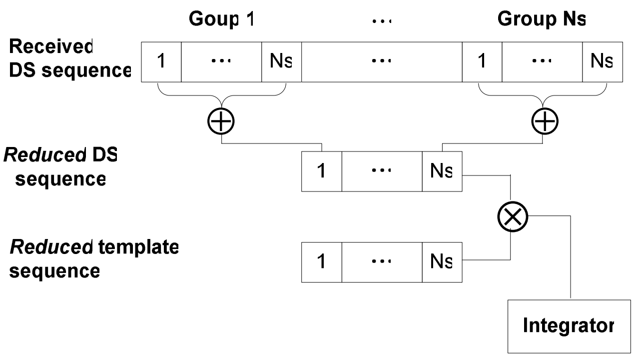

Figure 4. Correlating procedure of the reduced sequences

plication is reduced by the ratio of $1/\sqrt{N_D} = 1/N_S$. This is a contribution to the hardware complexity reduction since it requires more computational time for the the process of multiplication than that of addition. We define the ratio of the reduced number of multiplication to the original one as

$$\begin{aligned} r &= \left(N_M - N_M^{'}\right)/N_M \\ &= 1 - 1/\sqrt{N_D} \end{aligned} \tag{10}$$

In Fig. 5, we illustrate the ratio in (10) using the DS sequence of length 25, 49, 81, and 121. We can reduce the complexity of the multiplier at least by the ratio 0.8. It is also noticeable that the longer the length of a sequence, the more the operational complexity reduction.

V. SIMULATION IN UWB SYSTEM

A. Simulation Results

We verified the performance of the proposed acquisition algorithm with the DS sequence of length 49 and a pulse of width 2ns. Then we compared it with those of M sequence and Gold sequence of length 49. The frame time period chosen was 120ns, long enough to cover the delay spread since the energy leaking from one frame interferes with the next frame. We used BPSK modulation and a sixth of the frame duration for the search step size Δt to capture the dispersed pulse energy. For timing acquisition, we selected the peak among absolute correlation values.

We just declared that timing is acquired when the timing error between the correct position and the estimated position is within $T_f / 2$, i.e.,

$$\left|(\eta - \hat{\eta})T_f\right| \le T_f / 2 \tag{14}$$

where η is the actual start frame of the preamble, $\hat{\eta}$ is the estimated start frame of the preamble. We also measured the normalized mean square error (NMSE) defined as

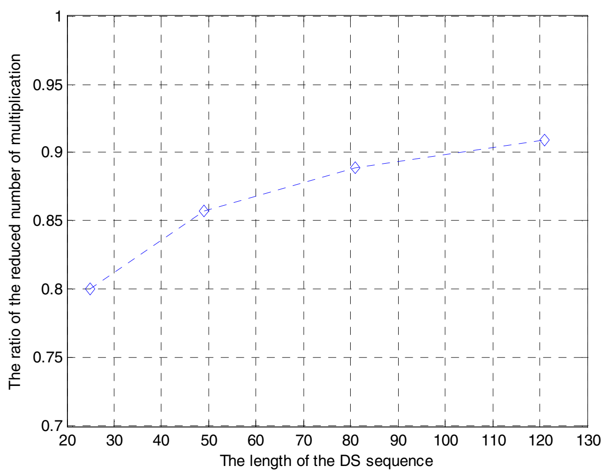

Figure 5. The ratio of the reduced number of multiplication to the number of original one

$$NMSE = E\left[\left|(\eta - \hat{\eta}) / N_f\right|^2\right]. \quad (15)$$

In Fig. 6 and Fig. 7, we used the doubly spread sequence of length $N_f = N_D = 49$ and the PN sequences of length $N_f = N_{PN} = 49$ with a reduction factor $R_f = 7$. In this case, we can reduce the number of multiplications by 1/7. When we detect timing without reducing the length of the preamble sequences, the algorithms using the proposed DS sequence and the PN sequences have a similar probability of detection. In the case of the reduced-complexity acquisition scheme, the algorithm exploiting the DS sequence however has a higher probability of detection than that using the PN sequences. In addition, the former has a lower NMSE value than the latter. It is obviously evident that the proposed DS sequence gives more benefits than the PN sequence for the timing acquisition when the corresponding complexity reduction acquisition algorithm is used.

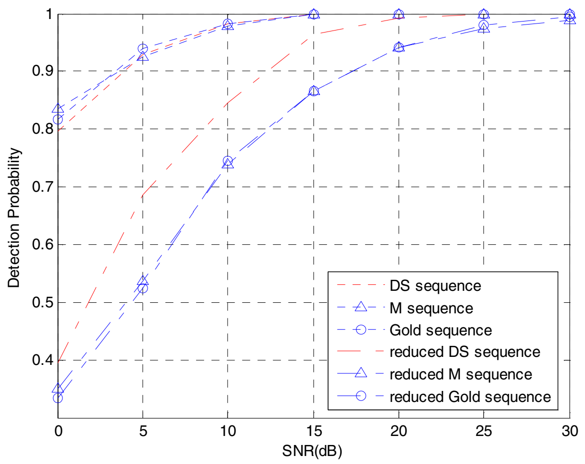

Figure 6. Detection probability ($N_f = N_D = N_{PN} = 49,\ R_f = 7$)

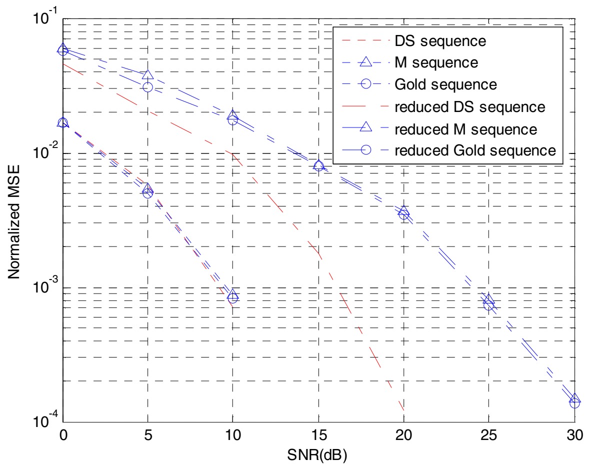

Figure 7. Normalized MSE ($N_f = N_D = N_{PN} = 49,\ R_f = 7$)

VI. CONCLUSION

In this paper, we have proposed the new preamble sequence efficient for the reduced operational complexity timing acquisition algorithm in UWB system. We showed that the proposed DS sequence kept the property of a single peak at zero delay and symmetry although its length is reduced by summation. As a result, we can reduce operational complexity and the sampling rate, simultaneously decreasing the performance degradation more than the case of using PN sequences as the preamble. Simulation results verified the decreased performance degradation by using the peak-picking slide-correlator method with the proposed DS sequence under the UWB multipath environment. The advantageous future work will be to apply the proposed preamble to the other search strategies.

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