A New Synchronization Scheme Exploiting Mean Energy Profile in UWB Non-coherent Receiver

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Abstract—We introduce a new synchronization scheme to improve the synchronization performance in a ultra-wideband (UWB) non-coherent energy collection receiver. Our proposed scheme exploits the mean normalized energy profile, which is known at the receiver, to acquire synchronization. The synchronization process is performed through comparing the energy collected from the received signal with the mean normalized energy profile and correcting the timing error. The synchronization performance is investigated in terms of the normalized mean squared synchronization error (NMSSE) in IEEE 802.15.3a UWB indoor channel environment. Through simulation results, we show that the proposed scheme enhances the synchronization performance.

I. INTRODUCTION

Since the Federal Communications Commission (FCC) issued a Report and Order in February 2002 commercializing Ultra-Wideband (UWB) systems with a given spectral mask requirement for both indoor and outdoor applications, UWB systems have attracted increasing interest owing to the possibility of low-complexity, low-power, and low-cost devices.

One of the advantages of UWB impulse radio communication systems is its capability to resolve individual multi-path components, which provide multi-path diversity that can be exploited to enhance the performance by efficiently capturing the energy from all these multi-path components. Although a RAKE structure can be used to collect the energy from the multi-path components, a large number of RAKE fingers are required, which will lead to significant increase in the hardware complexity because multi-path acquisition, tracking, and channel estimation are needed.

Recently, studies have been performed on non-coherent energy collection receivers, which are low-complexity receivers [1] - [4]. A bit synchronization process in an energy collection receiver, which can minimize the complexity of the receiver using a short preamble, is introduced in [3]. To acquire the start time of a bit, the receiver simply collects the energy of the received preamble signal in the integration windows, which are located at equal distance during a bit interval, and regards the start time of the integration window of the maximum energy as the synchronization time. The synchronization performance of the scheme proposed in [3] is improved in [4] by judiciously designing the amplitude and length of the pulse in preambles. However, in both [3] and [4], the time accuracy of synchronization cannot exceed the ambiguity within the synchronization range that depends on the number of integrators. It is these findings that have motivated our research into a synchronization scheme based on the non-coherent energy collection receiver.

In this paper, we introduce a new synchronization scheme based on a non-coherent energy collection receiver to improve the synchronization performance. The proposed scheme exploits the mean normalized energy profile, which is obtained by averaging the normalized energy of UWB channels and is known at the receiver. The synchronization process is performed through comparing the energy collected from the received signal with the mean normalized energy profile and correcting the timing error. The synchronization performance of the proposed scheme is verified in the IEEE 802.15.3a channel environment.

II. SYSTEM MODEL

For data transmission, binary pulse position modulation (B-PPM) is used as the modulation scheme, in which a bit interval is divided into two time slots to represent the two different symbols. However, it can be readily extended to M-ary modulation. The transmitted signal is expressed as

\[
s(t) = \sum_{i=-\infty}^{\infty} s_i(t) = \sum_{i=-\infty}^{\infty} \sqrt{E_b} p(t - iT_b - b(i)T_s),
\]

where \( p(t) \) \( (\int_{-\infty}^{\infty} p^2(t)dt = 1) \) is the short-duration transmitted UWB pulse of width \( T_p \), \( E_b \) refers to the bit energy, \( T_b = 2T_s \) denotes a bit interval, and \( b(i) \in \{0, 1\} \) represents the \( i \)-th data bit. Although the multi-user scheme is not considered here for simplicity, it can be additionally adapted using the time hopping (TH) approach.

The channel for a pulsed UWB system can be modeled as a discrete linear filter [5] whose impulse response is represented as

\[
h(t) = \sum_{l=0}^{L-1} \alpha_l \delta(t - \tau_l).
\]

In (2), \( L \) is the total number of resolvable paths, \( \alpha_l \) denotes the gain for the \( l \)-th path, \( \tau_l \) represents the arrival time of the
l-th path relative to the first path \((l = 0 \text{ and } \tau_0 = 0)\), and the \(\delta(t)\) refers to the Dirac delta function.

After passing through the multi-path channel described by (2), the transmitted signal \(s(t)\) given by (1) is received in the receiver as

\[
r(t) = s(t) * h(t) + n(t)
\]

\[
= \sum_{i=-\infty}^{\infty} \sum_{l=0}^{L-1} \alpha_l \sqrt{E_b p(t - iT_b - b(i)T_s - \tau_l)} + n(t),
\]

(3)

where \(*\) denotes the convolution and \(n(t)\) is the additive Gaussian noise with zero mean and variance of \(\sigma^2\).

The receiver structure is presented in Fig. 1. After passing through a band pass filter, the received signal is fed into the square-law device and integrator. Then, detection is performed through the decision device using sampling values of the integrator output. Since the receiver structure is based on a non-coherent energy collection receiver, it does not require a template signal generator and timing-control block; thus, the low-complexity nature of the receiver can be maintained.

III. SYNCHRONIZATION PROCESS

Let us define \(g(t) = p(t) * h(t)\) and the mean normalized energy which is collected from the first arrival time of the channel \(\tau_0\) to time \(t\) as

\[
E_{\text{mean}}(t) = E\{E_{\text{nor}}(t)\},
\]

(4)

where

\[
E_{\text{nor}}(t) = \frac{\int_{\tau_0}^{t} g^2(\tau)d\tau}{\int_{\tau_0 - T_p}^{\tau_0 + T_p} g^2(\tau)d\tau}, \quad \tau_0 \leq t \leq \tau_{L-1} + T_p,
\]

(5)

and \(E\{\cdot\}\) denotes the expectation operation. It is assumed that the mean normalized energy profile is known at the receiver.

Figure 2 shows the mean normalized energy profiles that were obtained by averaging 1000 realizations of CM1 through CM4 in the IEEE 802.15.3a channel environment [7], respectively. It is noted that the mean normalized energy profiles are very similar from CM2 through CM4, except for CM1, which is the only channel model in line of sight (LOS). It is these findings that have motivated us to propose a new synchronization scheme exploiting the mean normalized energy profile of the channels in a UWB non-coherent receiver.

To explain the basic concept of our proposed synchronization scheme, we first consider the case of no energy loss and no additive noise in the channel. We assume that synchronization is made using a preamble of symbol '0', and that the signaling rate is such that the received signal energy of a particular bit is contained within one pulse repetition interval so that there is no inter-symbol interference (ISI). Thus we can focus on a particular bit, \(i = 0\), and (3) is rewritten as \(r(t) = \sqrt{E_b g(t)}\). Then, the integration window has an output value of

\[
E_r = \int_{t_{\text{start}}}^{t_{\text{start}} + T_p} r^2(t)dt = E_b \int_{t_{\text{start}}}^{t_{\text{start}} + T_p} g^2(t)dt,
\]

(6)

where \(t_{\text{start}}\) refers to the start position of the integration window. Figure 3 is presented to better understand the synchronization process. As shown in Fig. 3, there are two types of received signal energy collection depending on whether the start position of the integration window is on the right side (RS) of a bit start position, as shown in Fig. 3-(a), or on the left side (LS) of a bit start position, as shown in Fig. 3-(b). These two types of received signal energy collection cause the problem that the receiver does not know whether energy has been collected by RS type or by LS type. However, just for now, let us assume that receiver knows the type of received signal energy collection. Using the collected energy, \(E_r\), and the mean normalized energy profile known at the receiver, the estimated synchronization time can be obtained as

\[
\hat{t}_{\text{sync}} = \begin{cases} 
  t_{\text{start}} - t_{\text{RS}}, & \text{for RS} \\
  t_{\text{start}} - t_{\text{LS}} + T_s, & \text{for LS}
\end{cases}
\]

(7)

where \(t_{\text{RS}}\) and \(t_{\text{LS}}\) satisfy \(E_{\text{mean}}(t_{\text{RS}}) = 1 - E_r/E_b\) and \(E_{\text{mean}}(t_{\text{LS}}) = E_r/E_b\), respectively.

However, there practically exists the difference between \(E_{\text{mean}}(t)\) and \(E_{\text{nor}}(t)\) of the realized channel, which results in the synchronization error. To investigate the synchronization error, the normalized mean squared synchronization error (NMSSE) according to the collected energy, \(E_r\), in the IEEE 802.15.3a channel models is shown in Fig. 4. It is defined as

\[
\text{NMSSE}(\hat{t}_{\text{sync}}) = E\{(\hat{t}_{\text{sync}} - t_{\text{sync}})^2\}/T_s^2,
\]

(8)

where \(t_{\text{sync}}\) denotes the start time of a bit. It is noted that the NMSSE is reduced as the collected energy decreases and is very small especially at the energy close to zero. Therefore, to acquire more accurate synchronization, the integration window...
requires to collect the low energy, at which the NMSSE is small.

As previously mentioned, if we use the only one integration window to collect the energy from the received signal, the receiver does not know whether energy has been collected by RS type or by LS type. Besides, the possibility is small that the only one integration window collects low energy because the time region of low energy is small, as shown in Fig. 2. Therefore, we use several integration windows to solve these two problems. If $N_{\text{int}}$ integration windows are used, the start time of the $n$-th integration window is $t_n = t_{\text{start}} + (n - 1)T_s/(N_{\text{int}} - 1)$ for $n = 1, 2, \ldots, N_{\text{int}}$. The $n$-th integration window has an output value of

$$E_r^{(n)} = \int_{t_n}^{t_n + T_s} r^2(t) dt = E_b \int_{t_n}^{t_n + T_s} g^2(t) dt. \quad (9)$$

Among $N_{\text{int}}$ collected energies, the minimum one is selected to acquire synchronization since it has the smallest NMSSE. The problem about whether energy has been collected by RS type or by LS type can be solved by comparing the selected energy for synchronization process with the energy of its neighbors since $E_r^{(n)}$ decreases for RS type as $n$ increases while $E_r^{(n)}$ increases for LS type as $n$ increases. Even if we used $N_{\text{int}}$ integration windows for convenience of analysis, we can use one integrator in the practical implementation by sampling the output value of the integrator at the instance of $T_s/2(N_{\text{int}} - 1)$ from $t_{\text{start}}$ to $t_{\text{start}} + T_b$ and obtaining the needed values through computation with sampling values.

Until now, we have not considered the energy loss and additive noise in the channel, but they should be included in practical channel environment. In the case that there exist the energy loss and additive noise in the channel, (3) is rewritten as $r(t) = \sqrt{E_b} g(t) + n(t)$, and (9) can also be modified as

$$E_r^{(n)} = \int_{t_n}^{t_n + T_s} r^2(t) dt = E_b \int_{t_n}^{t_n + T_s} g^2(t) dt + \int_{t_n}^{t_n + T_s} n^2(t) dt + 2 \sqrt{E_b} \int_{t_n}^{t_n + T_s} g(t)n(t) dt. \quad (10)$$

In (10), the first term is no longer same as that of (6) because of the energy loss in the channel, and the second term and the third term are due to the additive noise.

To remove the effect of the energy loss and noise in the channel, we define four integration windows of length $T_s/2$, as shown in Fig. 5. One of four integration regions should be a noise-only region if we design the preamble structure so that $T_s > T_p + \tau_{L-1}$. Using the fact that the energy obtained from a noise-only region is the minimum among four collected energies, we can acquire the estimated noise variance as

$$\hat{\sigma}^2 = E_{i^*} / (T_s/2), \quad (11)$$

where $i^* = \arg \min E_i$ and

$$E_i = \int_{t_{\text{start}} + iT_s/2}^{t_{\text{start}} + (i-1)T_s/2} r^2(t) dt, \quad i = 1, 2, 3, 4. \quad (12)$$

The total energy $E_t$ is obtained by summing the output values
of the four integration windows as

\[ E_t = E_1 + E_2 + E_3 + E_4 \]

\[ = E_b \int_{t_{\text{start}}}^{t_{\text{start}}+T_b} g^2(t)dt + \int_{t_{\text{start}}}^{t_{\text{start}}+T_b} n^2(t)dt \]

\[ + 2\sqrt{E_b} \int_{t_{\text{start}}}^{t_{\text{start}}+T_b} g(t)n(t)dt. \]

(13)

Conditioned upon the channel, let us take the expected value of (10) and (13) as follows:

\[ \mathbb{E}\{E_t(n)\} = \mathbb{E}\left[ E_b \int_{t_n}^{t_n+T_s} g^2(t)dt + E_n \right] \]

(14)

and

\[ \mathbb{E}\{E_t\} = \mathbb{E}\left[ E_b \int_{t_{\text{start}}}^{t_{\text{start}}+T_b} g^2(t)dt + 2E_n \right] \]

\[ = \mathbb{E}\left[ E_b \int_{t_{\text{start}}}^{t_{\text{start}}+T_b} g^2(t)dt + 2E_n, \right] \]

(15)

where

\[ E_n = \mathbb{E}\left\{ \int_{t_n}^{t_n+T_s} n^2(t)dt \right\} = T_s \sigma^2. \]

(16)

Using the estimated noise variance in (11) to remove the energy due to noise in (14) and (15), we can obtain the normalized energy of the received signal as

\[ E_{r,nor}^{(n)} = \frac{\mathbb{E}\{E_t(n)\} - T_s \sigma^2}{\mathbb{E}\{E_t\} - 2T_s \sigma^2} \approx \frac{\int_{t_n}^{t_n+T_s} g^2(t)dt}{\int_{t_{\text{start}}}^{t_{\text{start}}+T_b} g^2(t)dt}. \]

(17)

To reduce the synchronization error, we use the minimum value among \( N_{\text{int}} \) collected energies because the NMSSE becomes smaller as the collected energy decreases, as shown in Fig. 4. Letting \( \hat{E}_{r,nor} = E_{r,nor}^{(n^*)} \) where \( n^* = \arg\min_n E_{r,nor}^{(n)} \) and comparing it with the mean normalized energy profile known at the receiver, we can obtain the estimated synchronization time as

\[ t_{\text{sync}} = \begin{cases} t_{n^*} - t_{RS}, & \text{for RS}, \\ t_{n^*} - t_{LS} + T_s, & \text{for LS}, \end{cases} \]

(18)

where \( t_{RS} \) and \( t_{LS} \) satisfy \( E_{\text{mean}}(t_{RS}) = 1 - \hat{E}_{r,nor} \) and \( E_{\text{mean}}(t_{LS}) = \hat{E}_{r,nor} \), respectively.

IV. SIMULATION RESULTS

In this section, we investigate the synchronization performance of our proposed scheme in terms of NMSSE, which was defined in (8). For comparison, the performance of conventional scheme [3] is also provided. Since the synchronization performance depends on the number of integration windows, \( N_{\text{int}} \), both in our proposed scheme and in the conventional scheme [3], the simulation results for the different \( N_{\text{int}} \) values will be shown. In the simulation, we used the UWB pulse with a pulse duration \( T_p = 1\,\text{ns} \) acquired from [6]. The simulation has been performed in the IEEE 802.15.3a channel models [7], CM1 through CM4. The mean normalized energy profiles in the CM1 through CM4 are obtained by averaging the normalized energy profiles of 1000 realizations of each channel model. The number of preamble used for synchronization, \( N_p \), was 10 bits.
The signal to noise ratio (SNR) is defined as

\[
SNR = \frac{E_b}{N_0} \times \frac{R_d}{B_w} 
\]  

where \( N_0 \) is the one-side noise power spectral density, \( R_d = 1/T_b \) is the data rate, and \( B_w \) is the signal bandwidth. Figure 6 shows the NMSSE versus SNR for \( N_{int} = 4, 8, 12 \) in the CM2. One bit duration, \( T_b \), was set to 150 ns. Our proposed scheme shows the better performance that the conventional scheme [3] for all cases, \( N_{int} = 4, 8, \) and 12. It is confirmed that not only does the NMSSE of our proposed scheme converge to the error floor more rapidly than that of conventional scheme, but the error floor of our proposed scheme is also lower than that of the conventional scheme [3]. Figure 7 and 8 show NMSSE versus SNR in the CM3 and CM4, respectively. \( T_b \) was set to 220 ns for the CM3 and 450 ns for the CM4. In both CM3 and CM4, the performances of our proposed scheme are also better than those of the conventional scheme. To investigate the performance of our proposed scheme in a channel environment, where the normalized energy profiles of the realized channels change radically, we performed a simulation in CM1+CM2, which is the channel environment newly made by mixing CM1 and CM2. The simulation result is shown in Fig. 9. Even if a greater difference between the mean normalized energy profile and the normalized energy profile of the realized channel led to the performance degradation, it is verified that our proposed scheme still enhances performance in a harsh channel environment.

V. CONCLUSION

We have developed a new synchronization scheme to improve the synchronization performance in a UWB non-coherent energy collection receiver. Our proposed scheme acquires the synchronization by comparing energy collected from the received signal with the mean normalized energy profile known at the receiver and correcting the timing error. We have shown through the simulation results that our proposed scheme guarantees more accurate synchronization than the conventional scheme proposed in [3]. However, the additional hardware complexity of our new synchronization scheme should be considered since it incurs substantial hardware overhead for the storage of the energy profile and for necessary computations. In addition, the accuracy reported in the paper is meaningful for limited operating environments in that our claim that the mean normalized energy profile has the small variance is based on four UWB channels. Hence, it is required to show the performance considering a common energy profile and see the performance when the channel realization belongs respectively to the different channel models.

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