ADAPTIVE SYNCHRONIZATION FOR NON-COHERENT UWB RECEIVERS

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ABSTRACT

Ultra-wideband (UWB) radio transmits data using sub-nanosecond pulses with a very low duty-cycle. It is a promising candidate for short-range communications in dense multipath environments. However, UWB systems have to cope with great design challenges, including difficulties on synchronization, template signal design, and multipath energy combining. The UWB differential scheme with a non-coherent receiver offers a way to solve these problems, but may experience performance degradation due to inadequate synchronization knowledge. In this paper a novel adaptive synchronization algorithm for UWB non-coherent receivers is proposed, which adaptively improves on partial synchronization information until frame-level synchronization is achieved. The algorithm requires only tens of symbol durations, which is orders of magnitude less than that of the coherent receiver. Performance enhancement is observed through both theoretical analysis and simulations.

1. INTRODUCTION

UWB radio is a promising candidate for short-range communications in dense multipath environments. A popular UWB signaling scheme is proposed in [1], which transmits sub-nanosecond pulses once per frame, with N_f frames per symbol (representing one bit). The frame duration is usually much larger than the pulse width, resulting in a very low pulse duty-cycle and the transmission power as low as tens of micro-watts. Techniques such as pseudo-random time-hopping (PRTH) help to obtain a noise-like power spectral density (PSD) of the UWB signal, offering the possibility to coexist with narrow-band systems. Extremely narrow pulses prevent a significant overlap of signals from different paths, resulting in a multipath fading much lighter than that of the narrow-band system. Resolvability of multipath components also leads to the potential for multipath energy combining, which is important for power-limited UWB systems.

Many of the approaches in the literature adopt a coherent receiver, which correlates the received signal with a template signal. This receiver, however, has to cope with great design challenges [2]. First, to correlate the received signal with the template signal, the receiver needs to achieve a pulse-level synchronization accuracy at the order of tens of picoseconds [3]. Thus, despite of some fast synchronization algorithms [4] [5], the whole synchronization process is still long. Secondly, precise template signal design is required to maximize the signal-noise-ratio (SNR), which is difficult due to distortions on the pulse shape during its transmission. Finally, multipath energy combining requires "rake" receiving of resolvable multipath components with enough branches [6], incurring a great receiver complexity.

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The differential scheme [7] with a non-coherent receiver overcomes some of the problems just mentioned. Differential pulse amplitude modulation is employed in this scheme, where pulse polarities in one symbol are inverted only when the -1 is transmitted. At the receive end, the received signal is delayed for a symbol duration and correlated with itself. Only symbol-level synchronization is needed for the differential receiver, which can be achieved within only a few symbol durations. No template signal is needed since the received signal itself acts as the template signal, and multipath energy can be combined automatically during the auto-correlation process.

However, great performance degradation may exist for the differential receiver. In UWB radio, each frame of the received signal is composed of two parts: the *signal region (SR)* where the pulse and its multipath components are present, and the *noise-only region (NOR)*. When only partial (symbol-level) synchronization is achieved, the differential receiver can not tell the SR apart from the NOR. Thus, the NOR included in the integration will corrupt the integrator output and degrade the performance. In [7], the necessity of choosing an integration time (in each frame) less than the frame duration T_f to exclude the NOR is argued, but no algorithm is proposed to achieve the required synchronization.

In this paper, a novel adaptive synchronization algorithm is proposed for non-coherent receivers, which could quickly achieve frame-level synchronization through adaptively searching for the SR during each frame. The whole searching process requires only tens of symbol durations, which is much shorter than the acquisition process of the coherent receiver, and the receiver complexity remains low. It is worth mentioning that this algorithm can also be applied to the non-coherent receiver of the transmitted-reference scheme [8], which differentially modulates the pulse amplitude employing a pilot signal. The transmitted-reference scheme has a 3dB energy loss compared with the differential scheme because of its usage of pilot signals, but it delays the signal for a shorter distance, which is easier for circuit implementation.

We will start with an introduction to the UWB differential scheme and its autocorrelation receiver in Section 2, and then describe the adaptive synchronization algorithm in Section 3. Simulation results are given in Section 4, followed by the conclusion in Section 5.

2. DIFFERENTIAL SCHEME

2.1. Signaling Scheme

The UWB differential scheme [7] employs binary signaling. Pulses are transmitted once per *frame* with a frame duration T_f much larger than the pulse width T_p; N_f frames are used to transmit one bit and constitute one *symbol*, resulting in a symbol length $T_s = N_f T_f$ and a bit rate of $1/T_s$. Typical values for N_f range between 10 and 100. Pseudo-random time-hopping (PRTH) is applied to shift the pulse position during each frame. Notice that direct sequence (DS) spreading can also be applied to modulate the pulse polarity during each frame, but is not considered here for simplicity. Thus, pulse polarities remain the same during each symbol, but will change in the next symbol if a -1 is transmitted. The transmitted signal of the differential scheme can be expressed as:

$$s(t) = \sum_{i=0}^{\infty} \sum_{j=0}^{N_f-1} L_i \sqrt{E_p} p\left(t - (iN_f + j)T_f - c_j T_c\right), \quad (1)$$

where $L_i = \pm 1$ modulating the pulse polarity, c_j is the PRTH code, T_c is the chip duration (unit hopping distance), E_p is the transmitted pulse energy, and $p(t)$ is the normalized pulse. Note that c_j needs to repeat at the symbol rate $1/T_s$. This is to guarantee the pulse position match when pulses are delayed by one symbol duration to correlate with those in the preceding symbol. The i^{th} transmitted bit is $\frac{1}{2}|L_i - L_{i-1}|$.

2.2. Differential Receiver

A differential receiver has been originally proposed in [7], but is slightly different from the scheme presented here. In [7], it is assumed that the SR position during each frame is known to the receiver, i.e., frame-level synchronization has been achieved, so the integration region can be directly narrowed down to the SR. However, what we discuss here is a general differential receiver without synchronization knowledge at the beginning.

Let us consider the channel and the received signal at first. Ignoring for simplicity distortions on the transmitted pulse and the slow time-varying effect, the UWB multipath channel can be modelled as a linear filter with impulse response as:

$$h(t) = \sum_{l=1}^{N_{path}} \alpha_l \delta(t - \tau_l) \quad (2)$$

where N_{path} is the number of resolvable paths and τ_l is the delay of path l. The delay spread T_m has the value of $\tau_{N_{path}} - \tau_1$. Since $T_f \gg T_m \gg T_p$ can be assumed in this paper as on the UWB literature, the inter-frame-interference (IFI) and inter-symbol-interference (ISI) can be ignored. The received signal can then be expressed as:

$$\begin{aligned} r(t) &= s(t) * h(t) + n(t) \\ &= \sum_{i=0}^{\infty} \sum_{j=0}^{N_f-1} \sum_{l=1}^{N_{path}} L_i \alpha_l \sqrt{E_p} \cdot \\ &\quad p\left(t - (iN_f + j)T_f - c_j T_c - \tau_l\right) + n(t), \quad (3) \end{aligned}$$

where $n(t)$ is the additive white Gaussian noise (AWGN) with power spectral density N_0.

The received signal will first be passed through an ideal bandpass filter (BPF) with one-sided bandwidth W and center frequency f_0, where W is the bandwidth of the UWB signal. The resultant noise term $\hat{n}(t)$ is non-white Gaussian and has an auto-correlation function:

$$R_{\hat{n}\hat{n}}(\tau) = W N_0 \frac{\sin(\pi W \tau)}{\pi W \tau} \cos(2\pi f_0 \tau). \quad (4)$$

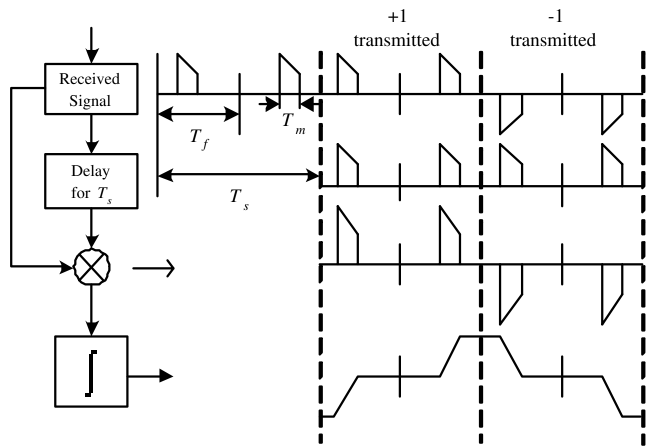

Fig. 1. Differential receiver ($N_f = 2$)

The filtered signal is then delayed for a symbol duration T_s and correlated with itself. The correlator is shown in Fig. 1, where the noise effect is ignored. For convenience, we set N_f to be only 2 in this figure. As seen in Fig. 1, when the received signal is delayed for T_s, all its multipath components are delayed for the same value and their energies are automatically combined. Every frame will contribute to the integrator output, which goes up when $+1$ is transmitted or down when -1 is transmitted until it reaches the end of a symbol. Notice that when continuous +1s or -1s are transmitted, there is no turning point in the integrator output to show the symbol boundary. Thus, the data sequence needs to be scrambled at the transmit end to avoid long sequences of 1s or -1s.

Since the symbol boundary is unknown at the beginning, we need to sample the integrator output twice per frame to achieve symbol level synchronization. The sampled values are compared to find the highest absolute one, which corresponds to the coarse symbol boundary. It can be proved that when

$$T_f/2 > (c_{N_f-1} - c_0)T_c > 0 \quad (5)$$

and the SNR is not very low, the inaccuracy of symbol-level synchronization can be controlled within T_f. A PRTH code satisfying (5) is easy to find through computer search. It is noted that symbol-level synchronization can be achieved within only a few symbol durations, which is orders of magnitude shorter than the acquisition process of the coherent receiver.

Once symbol-level synchronization is achieved, the sampling rate can be decreased to be once per symbol. Assuming that the estimated start point of symbol i is at $\hat{\zeta}_i$, the sampled output of this symbol can be written as:

$$S_i = \int_{\hat{\zeta}_i}^{\hat{\zeta}_i + T_s} \hat{r}(t)\hat{r}(t - T_s)dt \quad (6)$$

where $\hat{r}(t)$ is the signal from the BPF output.

2.3. Performance Analysis

To get an explicit expression for the bit error rate (BER) performance, we digitize the receiver output with a sampling rate of W to get uncorrelated Gaussian noise at the sampling points. We derived the BER performance of the sampled differential receiver over the non-ISI multipath channel as:

$$P_e = Q\left(\sqrt{\frac{N_f\left(\sum_{l=1}^{N_{path}}\alpha_l^2\bar{E}_p\right)^2}{N_0^2WT_f+2N_0\left(\sum_{l=1}^{N_{path}}\alpha_l^2\bar{E}_p\right)}}\right) \quad (7)$$

where $\bar{E}_p$ is the pulse energy (after sampling), N_0 is the power spectral density level of the white Gaussian noise in (3).

As we can see from (7), the combination of multipath energy helps to improve the BER performance. However, increasing the frame duration T_f, when the other parameters are fixed, results in an increasing NOR length, which will degrade the performance. Excluding the NOR in each frame needs frame-level synchronization knowledge, i.e., the position (start and end points) of the SR during each frame, which is not initially available. This motivates us to propose the adaptive synchronization algorithm to seek frame-level synchronization. The algorithm is described in the following section.

3. ADAPTIVE DIFFERENTIAL RECEIVER

To exclude the NOR, we need to reduce the integration time in each symbol to be much less than T_s. Since each symbol is composed of N_f frames, the new integration region would also be composed of N_f sections, which are discontinuous and denoted as "*sub-integration-windows (SIWs)*". Each frame has a SIW, and each SIW has a same width T_w at one iteration, which is smaller than T_f. Assuming that the exact start point of symbol i is at ζ_i and is known to us, the integrator output can then be expressed as:

$$S'_i = \sum_{j=0}^{N_f-1}\int_{\zeta_i+jT_f+c_jT_c}^{\zeta_i+jT_f+c_jT_c+T_w}\hat{r}(t)\hat{r}(t-T_s)dt. \quad (8)$$

where $\zeta_i + jT_f + c_jT_c$ is the position of the line-of-sight signal (start point of the SR) in the $(j+1)^{th}$ frame of symbol i. When $T_w = T_m$, the NOR in each frame is completely excluded from the integration.

However, since we only have symbol-level synchronization with an inaccuracy smaller than T_f (see Section 2), we can not determine the exact value of ζ. What we have is only an estimate $\hat{\zeta}_i$ with

$$|\zeta_i - \hat{\zeta}_i| \le T_f. \quad (9)$$

Thus, the integration in (8) can not be implemented without more accurate synchronization knowledge.

Our adaptive synchronization algorithm is designed to solve this problem. Instead of trying to determine the SIW according to the SR position in each frame, however, the algorithm fixes the SIW in each step and shifts it to find the SR. We assume $T_f \gg T_m \gg T_p$ as on the UWB literature, and that we know an upper-bound on T_m, denoted as $\bar{T}_m$. Let $Q = \lfloor T_f/\bar{T}_m \rfloor$, we have $Q \gg 1$. The algorithms can be implemented in multiple steps:

Step 1. This step achieves symbol-level synchronization, which has been discussed in Section 2. The symbol-level synchronization inaccuracy is at most T_f.

Step 2. This step splits the continuous integration region over a whole symbol into N_f SIWs, each with a width $U = T_f/M$, where $2 \le M \le Q/4$. Thus, the total integration time is reduced to N_fT_f/M in this step. The SIW is shifted to search for the SR during each frame.

From (9) we know that the uncertain region in Step 2 has a length of $2T_f$. We set the searching step size to be $\Delta = U/2 = T_f/(2M)$. Thus, altogether $2T_f/\Delta - 1 = 4M-1$ times of search are needed. Assuming that the search starts from the $(i+1)^{th}$ symbol, at the k^{th} ($1 \le k \le 4M-1$) search, the integrator output is:

$$\hat{S}_{i+k} = \sum_{j=0}^{N_f-1}\int_{\bar{\zeta}_{i,j,k}}^{\bar{\zeta}_{i,j,k}+U}\hat{r}(t)\hat{r}(t-T_s)dt \quad (10)$$

with

$$\bar{\zeta}_{i,j,k} = \hat{\zeta}_{i+k} + jT_f + c_jT_c - T_f + (k-1)\Delta, \quad (11)$$

where $\hat{\zeta}_{i+k} = \hat{\zeta}_i + kT_s$ is the estimated start place of the $(i+k)^{th}$ symbol.

Since each search need one symbol duration, altogether $(4M-1)$ symbols are needed for Step 2, and $(4M-1)$ output values are acquired. Only the correct integration region contains all the SRs in a symbol, and would produce the highest value at the integrator output if no noise effect is considered. Thus, the output values can be compared to find the highest absolute one, which is believed to be associated with the desired integration region composed of N_f SIWs. However, since noise exists, the detection may have errors, whose rate is denoted as the detection error rate (DER).

Notice that when an incorrect integration region is searched, some of its SIWs may contain signals from the preceding or the following frame, especially when the SIW width U is large (the highest value of U is $T_f/2$). Such interference from the neighboring frame, although occurs with low probability, will inevitably increase the DER. Thus, to achieve a greater reliability we can choose a small U, corresponding to a large M. The price paid is that the total searching time is increased.

Step q ($q \ge 3$). Assuming that in Step $q-1$, the SIW width is U_{q-1}; the corresponding searching step size is $\Delta_{q-1} = U_{q-1}/2$; and the achieved integration region is:

$$I(m) = \bigcup_{j=0}^{N_f-1}[P_{m,j}, P_{m,j}+U_{q-1}]$$

where m is the symbol index.

In Step q, the new SIW width is set to be $U_q = U_{q-1}/2$. The new searching step size Δ_q is decided by the relationship of U_{q-1} and $\bar{T}_m$: when $U_{q-1} \ge 4\bar{T}_m$, we set $\Delta_q = \Delta_{q-1}/2$; when $3\bar{T}_m \le U_{q-1} < 4\bar{T}_m$, $\Delta_q = \Delta_{q-1}/3$; while when $U_{q-1} < 3\bar{T}_m$, the searching process stops. Thus, the final frame-level synchronization accuracy could reach $1.5\bar{T}_m$ to $3\bar{T}_m$.

Now let us take a look at how to narrow down the integration region in Step q. Take the situation where $U_{q-1} > 4\bar{T}_m$ as an example, and assume that we start from symbol $m+1$. Altogether $U_{q-1}/\Delta_q - 1 = 3$ times of search are needed. The integrator output of the the n^{th} ($n \le 3$) search is:

$$\bar{S}_{m+n} = \sum_{j=0}^{N_f-1}\int_{P_{m,j}+nT_s+(n-1)\Delta_q}^{P_{m,j}+nT_s+(n-1)\Delta_q+U_q}\hat{r}(t)\hat{r}(t-T_s)dt \quad (12)$$

Again, the output values are compared to find the highest absolute one, which corresponds to the new integration region. And this step is repeated until the condition $U_{q-1} < 3\bar{T}_m$ is met.

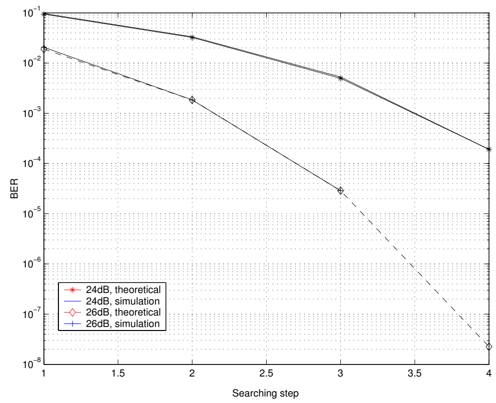

Fig. 2. BER performance v.s. searching step

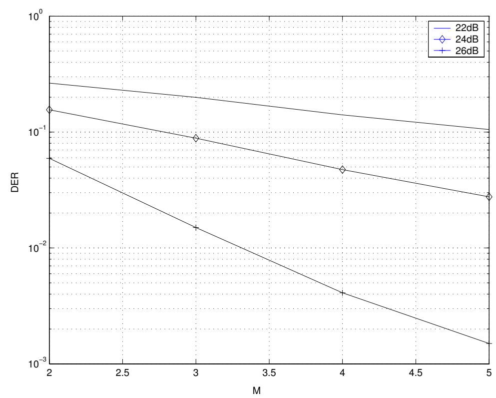

Fig. 3. DER performance v.s. M (in Step 2)

4. RESULTS

Fig. 2 compares analytical and simulation results of the BER performance with respect to the searching step, at $E_b/N_0 = 24dB$ and $26dB$. Parameters employed in the simulation are: $T_p = 0.7ns$, $T_m = 8ns$, $T_f = 100ns$, $N_f = 20$. The SIW length corresponding to Step 1 to 4 is: $100ns$, $50ns$, $25ns$, $12.5ns$, respectively. Simulation results prove the validity of (7), and the claim that excluding the noise-only region could greatly enhance the performance.

Fig. 3 gives DERs of Step 2 with respect to different values of M, at $E_b/N_0 = 22dB$, $24dB$, $26dB$, respectively. Detection error occurs when an incorrect integration region produces a higher absolute value at the integrator output than the correct integration region. Notice that when M decreases, i.e., the SIW width $\Delta = T_f/M$ increases, more signal power in neighboring frames would be incorporated into the incorrect integration region, and the DER would increase, as shown in Fig. 3. For later steps, we expect the DER to be lower since the integration region becomes smaller. Figure 3 also shows a decreasing DER with respect to an increasing E_b/N_0, which agrees with our intuition.

From Section 3, it is easy to see that the total searching process of this algorithm requires only tens of symbol durations, which is comparable to the symbol-level synchronization time, and much shorter than the synchronization process of the coherent receiver. The final SIW width could reach $1.5\bar{T}_m$ to $3\bar{T}_m$, which is much smaller than its original length T_f. Since no additional component is employed to implement the algorithm, the receiver complexity remains at a reasonably low level.

5. CONCLUSIONS

The non-coherent differential receiver has advantages over the coherent receiver on ease of synchronization, circumventing template signal design, and the capability of automatic multipath energy combining. Consequently, it has a much lower complexity than the coherent receiver. However, performance degradation exists for the differential receiver due to the corruption of the noise-only region, which can not be distinguished from the desired signal region when synchronization knowledge is inadequate. A novel adaptive synchronization algorithm for non-coherent receivers is proposed in this paper, which could adaptively narrow down the integration region to achieve frame-level synchronization and exclude the noise-only region. The synchronization can be achieved within only tens of symbol durations, and the receiver complexity is kept at a reasonable low level. Performance enhancement is shown through both theoretical analysis and simulations.

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