ENERGY-EFFICIENT AND MUI-FREE SYNCHRONIZATION FOR UWB BASED WSNS

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ABSTRACT

Synchronization is a challenging task in ultra wideband (UWB) communications, and becomes more difficult in UWB based wireless sensor networks (WSNs) in the presence of multi-user interference (MUI). For such a system, we develop a synchronization scheme including a novel design of transmitted reference (TR) signal model to avoid MUI and an energy-efficient synchronization algorithm. The synchronization signal of cluster-head is designed to be TR symbols with normal reference pulse and the interfering signal of common neighbour nodes is designed to be TR symbols with alternant anti-polar reference pulse, thus the MUI-free operation is obtained. Furthermore, the synchronization algorithm employs sample mean and energy detection relying on the periodicity in the mean of synchronization signal. Theoretic analysis and simulative results prove that the proposed scheme is both reliable and scalable.

I. INTRODUCTION

Due to recent advancement of micro-electro-mechanical systems (MEMS), embedded systems and self-organized networking, wireless sensor networks (WSNs) have been utilized in various applications, such as industrial monitoring, environmental surveillance, logistics management, healthcare and asset tracking [1, 2, 3, 4]. Impulse radio (IR) ultra wideband (UWB) has been testified to possess following unique features: low complexity and low cost, resistance to severe multipath, good time domain resolution and localization capability [5, 6]. All these characteristics make UWB ideal candidate for physical layer radio transmission technology (RTT) of WSNs, so research and usage of UWB based WSNs have been emerged and become attractive [7, 8, 9].

Synchronization is the most important technology for WSNs [10, 11]. Firstly, the sensed data with time stamps is essential for localization in most applications; secondly, combining and processing information from multiple nodes need accurate synchronization for data fusion of WSNs; thirdly, routing and network cooperation assume synchronization of nodes. However, synchronization is particularly challenging with UWB transmission for WSNs. Low-duty cycle and low power of UWB make the search space of acquisition very large [12]. Extremely narrow pulses require precise synchronization to the nanosecond level. Moreover, multi-user interference (MUI) limits synchronization performance greatly when many asynchronous nodes are to be synchronized. Hence, synchronization has received so much emphasis in UWB based WSNs research [13, 14, 15, 16, 17]. Timing with dirty templates (TDT) is a recently proposed acquisition algorithm [14], but blind TDT is available only for single-user links and performance degrades markedly in the presence of MUI even with data-aided TDT. Synchronized aggregate template (SAT) receiver is a more attractive one for its blind low-complexity timing estimation which is resilient to MUI and inter-symbol interference (ISI) [13], nevertheless its intermittent transmission of nonzero mean symbols requires large amounts of data. In this paper, we exploit transmitted reference (TR) signal to establish our own synchronization scheme for UWB based WSNs. TR signal is adopted because it possesses intrinsic nonzero-mean reference pulse waveform. Furthermore, TR system meets the unique requirement of WSNs by offering simplicity and low transmission power.

The rest of the paper is organized as follows. In Section II, the novel design of TR signal model to avoid MUI is introduced. The proposed synchronization algorithm relying on mean statistical operation and energy detection of reference pulse waveform is presented in Section III. The simulative results are given in Section IV and the conclusions are drawn in Section V.

II. SIGNAL MODEL

A cluster with K nodes in a UWB based WSN is considered here. The transmitted signal is TR waveform with antipodal modulation, which can be expressed as:

$$s(t)=\sum_{i=-\infty}^{\infty}\left[s_{Rf}\left(t-iT_s\right)+d_i s_{Tr}\left(t-iT_s\right)\right] \qquad (1)$$

with

$$s_{Rf}\left(t\right)=\sum_{j=0}^{N_s-1} w\left(t-jT_f-c_jT_c\right) \qquad (2)$$

$$s_{Tr}\left(t\right)=\sum_{j=0}^{N_s-1} w\left(t-jT_f-\left(c_j+m\right)T_c\right) \qquad (3)$$

where $w(t)$ is the unit-energy monocycle pulse and T_s is the duration of a symbol. Each symbol has N_s frames and T_f is the frame duration. For simplicity but without loss of generality, data sequence d_i is an independent, identically distributed binary sequence taking ± 1 values equiprobably. Each frame contains two monocycle pulses: the first one is a reference and the second, mT_c seconds later, is a pulse modulated by sequence d_i. In symbol-level, they are represented as $s_{Rf}(t)$ and $s_{Tr}(t)$, respectively. The time hopping (TH) sequence $\left\{c_j\right\}_{j=0}^{N_s-1}\in\left[0,N_c-1\right]$ shifts the pulse pair to user-specific position which enables multiple access.

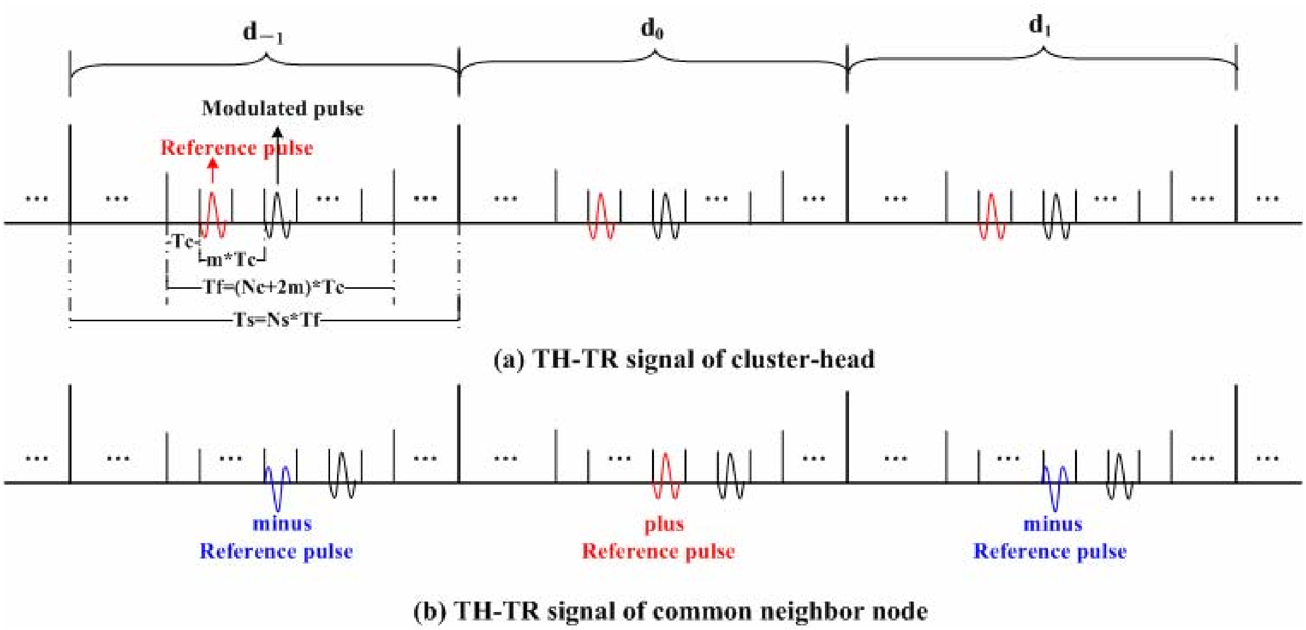

Figure 1: TH-TR signal structure with proposed synchronization scheme.

In this TH-TR system, the pulse pair interval mT_c should be greater than or equal to the multipath delay spread T_{mds} to ensure that there is no interference between reference pulse and data pulse. The frame duration T_f satisfies $T_f \geq (N_c + 2m)T_c$ so that no inter-frame interference exists.

Clustering topology of WSNs minimizes energy usage and enhances system lifetime by distributing the load to all the nodes. Besides having the burden of fusing data from nodes in the cluster to obtain an aggregate signal and transmitting this aggregate signal, high-energy cluster-heads undertake the task of synchronizing neighbors in order to form clusters in WSNs.

In our case, we propose a feasible signal model to solve the performance-limiting problem caused by MUI. The 1st node, as the cluster-head, transmits TH-TR symbols with normal reference pulse, while the k^{th} node $(k = 2,3,\cdots,K)$, as common neighbor node, transmits symbols with alternant anti-polar reference pulse. The TH-TR signal structures of the cluster-head and common neighbor nodes are illustrated in Fig. 1. The transmitted waveform of the 1st node is:

$$s^{(1)}(t) = \sum_{i=-\infty}^{\infty}\left[s_{Rf}^{(1)}(t-iT_s) + d_i^{(1)} s_{Tr}^{(1)}(t-iT_s)\right] \quad (4)$$

And the transmitted waveform of the k^{th} node is:

$$s^{(k)}(t) = \sum_{i=-\infty}^{\infty}\left[(-1)^i s_{Rf}^{(k)}(t-iT_s) + d_i^{(k)} s_{Tr}^{(k)}(t-iT_s)\right] \quad k = 2,3,\cdots,K \quad (5)$$

The data bit stream for all nodes has zero mean: $\mathrm{E}[d_i]=0 \ \forall i$. Thus, the mean of the 1st node transmitted signal is:

$$\mathrm{E}\left[s^{(1)}(t)\right] = \mathrm{E}\left[\sum_{i=-\infty}^{\infty} s_{Rf}^{(1)}(t-iT_s)\right] \quad (6)$$

while the mean of the k^{th} node $(k = 2,3,\cdots,K)$ transmitted signal is $\mathrm{E}\left[s^{(k)}(t)\right] = 0$. Accordingly, intrinsic reference pulse in TH-TR symbol produces the nonzero mean property of the synchronization signal. On the contrary, alternant anti-polar reference pulse makes interfering signals zero mean.

The propagation multipath channel is modeled as a tapped delay line with impulse response:

$$h(t) = \sum_{l=0}^{L} \alpha_l \delta(t - \tau_l) \quad (7)$$

path gains $\{\alpha_l\}_{l=0}^{L}$ and delays $\{\tau_l\}_{l=0}^{L}$ are assumed invariant over a block of symbols.

For a receiving node, aiming at getting synchronization signal of the 1st node, the signals of other nodes are presented as MUI $\gamma(t)$. The received signal can be written as:

$$\begin{aligned} r(t) &= \sum_{k=1}^{K} s^{(k)}(t) * h(t) + \eta(t) \\ &= s^{(1)}(t) * h(t) + \sum_{k=2}^{K} s^{(k)}(t) * h(t) + \eta(t) \\ &= r^{(1)}(t) + \gamma(t) + \eta(t) \\ &= \sum_{i=-\infty}^{\infty}\left[r_{Rf}^{(1)}(t-iT_s-\tau_0^{(1)}) + d_i^{(1)} r_{Tr}^{(1)}(t-iT_s-\tau_0^{(1)})\right] + \gamma(t) + \eta(t) \end{aligned} \quad (8)$$

in which $r_{Rf}(t) = \sum_{l=0}^{L}\alpha_l s_{Rf}(t-\tau_{0,l})$ and $r_{Tr}(t) = \sum_{l=0}^{L}\alpha_l s_{Tr}(t-\tau_{0,l})$. τ_0 is the propagation delay, or equivalently, the first path arrival time, and $\{\tau_{0,l}\}_{l=0}^{L}$ are multipath delays relative to the first

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path. $\eta(t)$ is additive white Gaussian noise (AWGN) with power spectral density $N_0/2$.

III. Synchronization Algorithm

Based on the proposed signal model presented in Section II, the mean of the received signal is:

$$\begin{aligned}
\mathrm{E}\left[r(t)\right] &= \sum_{i=-\infty}^{\infty} r_{Rf}^{(1)}\left(t-iT_s-\tau_0^{(1)}\right) \\
&= \sum_{i=-\infty}^{\infty}\sum_{l=0}^{L^{(1)}} \alpha_l^{(1)} s_{Rf}^{(1)}\left(t-iT_s-\tau_0^{(1)}-\tau_{0,l}^{(1)}\right) \\
&= \sum_{i=-\infty}^{\infty}\sum_{j=0}^{N_s-1}\sum_{l=0}^{L^{(1)}} \alpha_l^{(1)} w\left(t-iT_s-jT_f-c_j^{(1)}T_c-\tau_0^{(1)}-\tau_{0,l}^{(1)}\right) \\
&= \sum_{i=-\infty}^{\infty}\sum_{j=0}^{N_s-1} v\left(t-iT_s-jT_f-c_j^{(1)}T_c-\tau_0^{(1)}\right) \\
&= \sum_{i=-\infty}^{\infty}\sum_{j=0}^{N_s-1} v\left(t-iT_s-\tau_{Rf,j}^{(1)}\right) \qquad (9)
\end{aligned}$$

which shows $\mathrm{E}\left[r(t)\right]$ is periodic with period T_s. A circularly shifted (by $\tau_0^{(1)}$) copy of $r_{Rf}^{(1)}(t)$ is contained in $\mathrm{E}\left[r(t)\right]$. MUI $\gamma(t)$ and AWGN $\eta(t)$ in (8) have $\mathrm{E}\left[\gamma(t)\right]=0$ and $\mathrm{E}\left[\eta(t)\right]=0$. $v(t)$ denotes the pulse waveform influenced by the multipath channel and $\left\{\tau_{Rf,j}^{(1)}\right\}_{j=0}^{N_s-1}$ are the exact positions of pulse waveforms in each shifted copy of $r_{Rf}^{(1)}(t)$.

In order to estimate $\tau_0^{(1)}$, we propose a synchronization algorithm based on mean statistic of $r(t)$ and energy detection of reference pulse waveform of the 1st node (the cluster-head). $\tau_0^{(1)}$ is assumed to be uniform distributed over $[0,T_s)$ without loss of generality [15]. We define the energy detection synchronization function with $\tau\in[0,T_s)$:

$$E_{r_{Rf}^{(1)}}(\tau)=\sum_{j=0}^{N_s-1}\left(\int_0^{T_{window}}\left|\mathrm{E}\left[r\left(t-jT_f-c_j^{(1)}T_c-\tau\right)\right]\right|^2 dt\right) \qquad (10)$$

where T_{window} is the integration window equal to T_{mds}. When $\tau=\tau_0^{(1)}$, we have

$$\begin{aligned}
E_{r_{Rf}^{(1)}}\left(\tau_0^{(1)}\right) &= \sum_{j=0}^{N_s-1}\left(\int_0^{T_{window}}\left|\mathrm{E}\left[r\left(t-jT_f-c_j^{(1)}T_c-\tau_0^{(1)}\right)\right]\right|^2 dt\right) \\
&= \sum_{j=0}^{N_s-1}\left(\int_0^{T_{window}}\left|\mathrm{E}\left[r\left(t-\tau_{Rf,j}^{(1)}\right)\right]\right|^2 dt\right) \\
&= \sum_{j=0}^{N_s-1}\left(\int_{\tau_{Rf,j}^{(1)}}^{\tau_{Rf,j}^{(1)}+T_{window}}\left|\mathrm{E}\left[r(t)\right]\right|^2 dt\right) \qquad (11)
\end{aligned}$$

Because $r_{Rf}^{(1)}(t)=0$ for $t\notin\left[\tau_{Rf,j}^{(1)},\tau_{Rf,j}^{(1)}+T_{mds}\right]$ with $j=0,1,\cdots,N_s-1$, $E_{r_{Rf}^{(1)}}\left(\tau_0^{(1)}\right)$ is the unique maximum by extracting the complete energy of $r_{Rf}^{(1)}(t)$, i.e., all N_s reference pulses are captured.

A period of $\mathrm{E}\left[r(t)\right]$ in (9) can be estimated in practice by using sample mean across N symbol-long segments of $r(t)$:

$$\bar{r}(t)=\frac{1}{N}\sum_{n=0}^{N-1} r(t+nT_s) \qquad t\in[0,T_s] \qquad (12)$$

Replacing ensemble mean in (10) with sample mean, the synchronization algorithm can be described as:

$$\hat{\tau}_0^{(1)}=\arg\max_{\tau\in[0,T_s)} E_{r_{Rf}^{(1)}}(\tau),$$

$$E_{r_{Rf}^{(1)}}(\tau)=\sum_{j=0}^{N_s-1}\left(\int_0^{T_{window}}\left|\bar{r}\left(\left(t-jT_f-c_j^{(1)}T_c-\tau\right)_{\bmod T_s}\right)\right|^2 dt\right) \qquad (13)$$

since the duration of $\bar{r}(t)$ is T_s, the modulus operation ($\bmod T_s$) is performed.

Furthermore, the goal of synchronization shifts from estimating the exact $\tau_0^{(1)}$ to estimating n_0T_c, which satisfies $\left|n_0T_c-\tau_0^{(1)}\right| < T_c$. Synchronization algorithm can be re-written as:

$$\hat{n}_0=\arg\max_{nT_c\in[0,T_s)} E_{r_{Rf}^{(1)}}(nT_c),$$

$$E_{r_{Rf}^{(1)}}(nT_c)=\sum_{j=0}^{N_s-1}\left(\int_0^{T_{window}}\left|\bar{r}\left(\left(t-jT_f-c_j^{(1)}T_c-nT_c\right)_{\bmod T_s}\right)\right|^2 dt\right) \qquad (14)$$

With the chip resolution T_c, n_0 is in the range of integer $n\in[0,T_s/T_c)$, consequently, only $(N_c+2m)N_s$ candidate offsets will be detected when $T_f=(N_c+2m)T_c$. Combined with low-complexity energy detection, the proposed synchronization algorithm provides further rapid and energy-efficient synchronization.

IV. Simulation Performance

The performance of the proposed synchronization scheme for UWB based WSNs has been investigated in Saleh-Valenzuela CM1 channel [18]. 100 channel realizations have been considered. For TH-TR signal we choose $T_c=1ns$, $m=40$ and $T_f=80ns$. The TH code is Gold code with $N_c=32$. Each symbol consists of $N_s=15$ frames. The monocycle pulse is modeled as a second derivative Gaussian waveform. The number of node K is [1 5 10]. In multi-user scenarios, the interfering nodes transmit signals with the same Eb/N0 as the signal of the cluster-head.

In order to show the MUI-free capability of proposed synchronization scheme, the correct probability of synchronization as a function of Eb/N0 for the averaging size $N=100$ is plotted in Fig. 2. Line set A are results without proposed synchronization scheme and Line set B are with proposed synchronization scheme. In Line set A, the correct estimation probabilities for $K=5$ and $K=10$ are less than 20% no matter what the value of Eb/N0 is, while the correct estimation probability for $K=1$ can be above 60% when Eb/N0 is higher than 10dB. It is clear that the performance is poor in the presence of MUI. However, in Line set B, the correct estimation probabilities for $K=5$ and $K=10$ are almost the same as that for $K=1$. Evidently, a reliable MUI-free timing estimation is provided in our synchronization scheme.

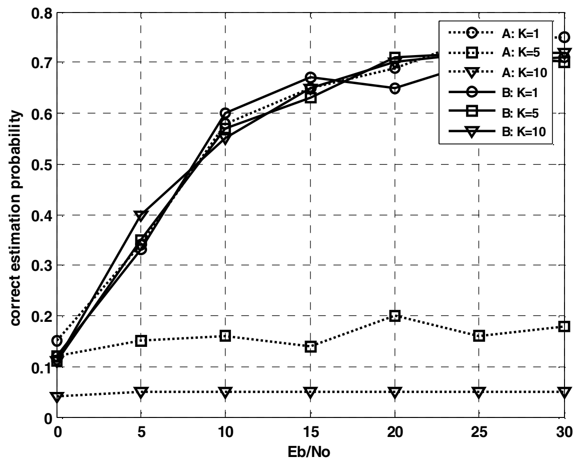

Figure 2: Correct estimation probability with & without proposed synchronization scheme.

Correspondingly, the normalized mean square error (MSE) of synchronization is plotted in Fig. 3. Compared with Line set A, Line set B for $K=5$ and $K=10$ have obvious improvement. The normalized MSE for $K=5$ and $K=10$ in Line set A are always above 1, while those in Line set B is lower than 10^{-2} when Eb/N0 is 10dB. Simultaneously, an error floor is observed. That's because the low-complexity requirement of synchronization is achieved at the price of low time resolution T_c. The error floor can be alleviated by further tracking.

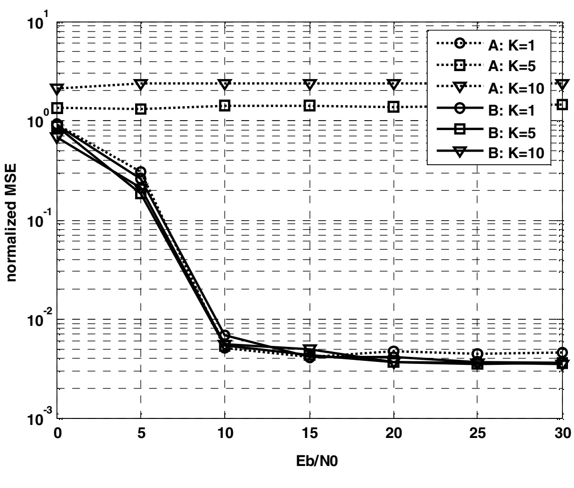

Figure 3: Normalized MSE with & without proposed synchronization scheme.

Fig. 4 and Fig. 5 show the performance with proposed synchronization scheme for various values of the averaging size N in (12) when $K=10$. As N increases, the correct estimation probability improves monotonically and the normalized MSE reaches the error floor at lower value of Eb/N0. When Eb/N0 is 20dB, the correct estimation probability with $N=100$ is 70% and the correct estimation probability with $N=16$ is about 57%. The normalized MSE with $N=100$ reaches the error floor when Eb/N0 is 10dB, while the normalized MSE with $N=16$ reaches the error floor when Eb/N0 is 20dB. The normalized MSE performance with $N=100$ in Fig. 5 is consistent with Fig. 3.

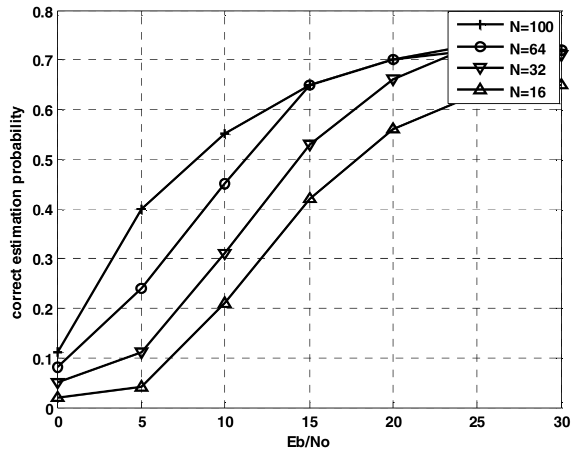

Figure 4: Correct estimation probability with proposed synchronization scheme when $K=10$.

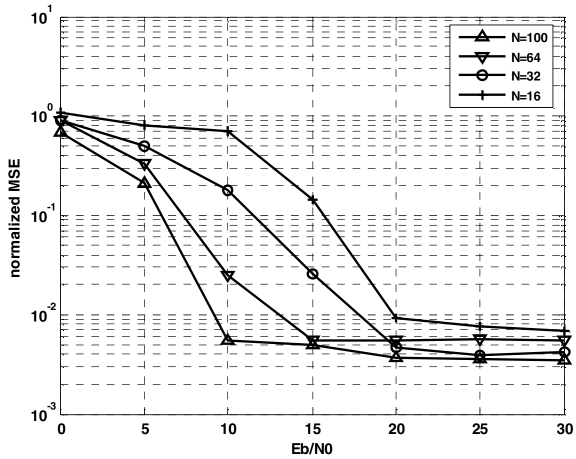

Figure 5: Normalized MSE with proposed synchronization scheme when $K=10$.

V. CONCLUSION

This paper presented a synchronization scheme for UWB based WSNs. A novel of TR signal model is designed at the node transmitter and a synchronization algorithm is proposed at the node receiver. In brief, cluster-head broadcasts synchronization signal with normal reference pulse in each symbol, while common neighbour nodes transmit symbols with alternant anti-polar reference pulse. As a result, no matter how many communicating nodes are in the network, there is no MUI existing in the mean of received signal. Furthermore, due to the nonzero mean property of received broadcasting signal and periodicity in its mean, the synchronization algorithm employs sample mean and energy detection. Theoretic analysis and simulative results demonstrate that the synchronization scheme takes full advantage of signal structure to make a tradeoff between complexity and reliability, providing scalability through changing the averaging size.

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