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An Efficient Multi-User UWB Receiver for Distributed Medium Access in Ad Hoc and Sensor Networks

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***Abstract* — Large ad hoc and sensor networks require inexpensive, low power hardware. Impulse-based ultra wideband (I-UWB) is an attractive radio technology for such networks due to its simple hardware, low radiated power, and accurate ranging capability. This paper proposes a distributed medium access control (MAC) protocol for large I-UWB networks. The MAC protocol, pulse sense multiple access (PSMA), is similar to carrier sense multiple access (CSMA) in narrowband systems. At low pulse rates, PSMA provides a distributed multichannel MAC that significantly reduces collisions without increasing receiver complexity or network delay. A multi-user I-UWB receiver further improves performance with moderate hardware complexity.**

***Index Terms* — Ultra Wideband, Medium Access Control, Carrier Sense Multiple Access, Multi-User Receiver**

I. Introduction

Large ad hoc and sensor networks must manage a large number of inexpensive, low power nodes. Ultra wideband (UWB) is an attractive technology for such networks due to its high data rate, low radiated power, and accurate ranging capability. Two different UWB communications systems – impulse-based systems and multi-carrier systems – have been pursued recently. For low cost and low power applications, impulse UWB (I-UWB) has several advantages over multi-carrier systems including robustness to Rayleigh fading and simple, low power hardware.

Current medium access control (MAC) protocols for I-UWB include time division multiple access (TDMA), time hopping, or direct sequence UWB (DS-UWB) [1]-[3]. Since these protocols subdivide the channel into time slots or code channels, they are also called multichannel protocols. Each sub-channel's data rate is W/N, where W is the full channel data rate and N is the spreading rate or the number of time slots. Multichannel protocols increase network throughput by reducing collisions from hidden terminals and concurrently transmitting terminals. However, they require a more complex multichannel receiver or central timing control. Further, the reduced sub-channel bandwidth increases delay at low offered load [4].

These MAC protocols mainly target smaller networks, so they take a centralized approach. However, centralized MAC protocols become complex and inefficient for large networks. The central coordination increases complexity and overhead, and it also leads to a central point of failure. Therefore, large ad hoc and sensor networks implement distributed MACs, which generally realize random access and require the ability to detect a busy medium. I-UWB can detect a busy medium through pulse sense [5], which reliably detects I-UWB traffic just as carrier sense detects narrowband signals in a certain frequency band. The proposed I-UWB MAC operates similarly to carrier sense multiple access (CSMA) in narrowband systems, so it is called pulse sense multiple access (PSMA).

The low duty cycle of I-UWB allows a multichannel implementation of PSMA without centralized control and without modifications to a basic, single-channel I-UWB receiver. Even with the multipath delay spread, I-UWB signals contain a large amount of "dead time" between pulses at moderate pulse rates. The dead time allows several concurrent transmissions to be time-interleaved without incurring the delay penalty of other multichannel protocols. We propose a multi-user I-UWB receiver to receive time-interleaved transmissions concurrently, and it further improves performance with moderate hardware complexity. This paper examines the multichannel PSMA protocol and the multi-user I-UWB receiver.

II. MAC Protocol

Multichannel MACs increase throughput as compared to a single channel MAC, since concurrent transmissions on different channels do not collide. However, each sub-channel has a reduced data rate to incur a delay penalty at low offered load [4]. Further, multichannel MACs add complexity to a system. DS-UWB and time-hopping cannot separately detect sub-channel activity without first synchronizing and demodulating each signal. Frequency division multiple access (FDMA) requires modification to the front end, and TDMA requires centralized control.

Therefore, we propose to exploit the low duty cycle of I-UWB to allow concurrent transmissions without the above penalties. Even with the multipath delay spread, I-UWB contains a large amount of dead time between pulses at moderate pulse rates. This dead time is used to time-interleave additional sub-channels. Under PSMA, an I-UWB network maintains the full data rate for each sub-channel, so the network increases throughput without increasing delay. Further, for multichannel operation, a PSMA MAC requires neither centralized control nor modification to a single channel I-UWB receiver. Finally, PSMA maintains a random, distributed MAC approach.

PSMA is unslotted, so nodes may transmit any time they sense a free channel. If a node senses a busy channel, it attempts to retransmit after a random binary exponential backoff period. At low pulse repetition intervals (PRIs), it is probable that two concurrent transmissions (one is possibly from a hidden node) do not overlap in time at the receiver. The probability of overlap increases if more nodes transmit concurrently, but it also becomes increasingly less probable that additional nodes transmit concurrently.

PSMA provides multiple, time-interleaved channels by allowing concurrent transmissions of non-overlapping pulse trains. During an initial reception, the receiver may synchronize with (for a multi-user receiver) or ignore (for a single-user receiver) other concurrent, non-overlapping transmissions. For example, in Fig. 1, two nodes sense an idle channel at time T_0, so they simultaneously start transmitting at time T_1. The receiver detects the busy medium through pulse sense. Transmitter2 is closer, so its first pulse arrives at T_2, while Transmitter1's first pulse arrives at T_3. After some time, a single synchronization circuit detects the arrival time of the two pulse trains within each PRI. If both transmissions target a multi-user receiver, two clock recovery circuits track Transmitter2's pulse train starting at T_4 and Transmitter1's pulse train starting at T_5. A single-user receiver would track only Transmitter2's pulse train and ignore Transmitter1's pulse train, since Transmitter2's pulse train precedes Transmitter1's.

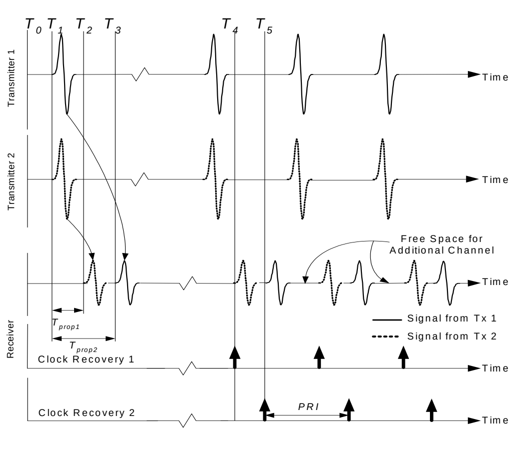

Fig. 1. Multichannel PSMA MAC operation.

III. Receiver Architecture

As an early work, we developed a frequency domain I-UWB receiver architecture with a pulse sense circuit [5], [6]. At the front end, a low-noise amplifier (LNA) feeds typical resonator filters realizing the second order transfer function $1/(s^2+(k\omega_o)^2)$. The filters capture in-band spectral components of the received signal, and the ADC bank samples these spectral components for demodulation. The main benefit of the receiver is that the ADCs operate at the pulse repetition rate, which is much lower than the Nyquist over-sampling rate to save power as well as circuit complexity. The receiver then performs signal processing in the frequency domain.

The pulse sense circuit shares the front-end with the receiver. When there is pulse activity at the pulse repetition frequency (PRF), the filters oscillate, and each energy detector receives a spectral component, f_i, which is an integer multiple of the PRF. Next, the outputs of the energy detectors are combined to detect the presence of I-UWB pulses, while rejecting narrowband signals.

Multi-user receivers, which can receive several channels concurrently, improve performance for multichannel MACs. TDMA is inherently multi-user but requires centralized control. A multi-user DS-UWB receiver requires separate correlators for each channel, and a multi-user FDMA receiver requires a separate front-end for each channel. Under PSMA, I-UWB can implement a multi-user receiver with much simpler hardware and no central control. The multi-user receiver in Fig. 2 only requires an additional clock recovery circuit for each channel. Since the pulses do not overlap, all channels share a single front end and decision block.

Here, we describe the clock recovery circuit, which has not been reviewed in earlier work. The circuit tracks the optimal point for correlation within a PRI under time variant and frequency selective channel conditions. Clock recovery starts after the initial synchronization, so we discuss the steady state response.

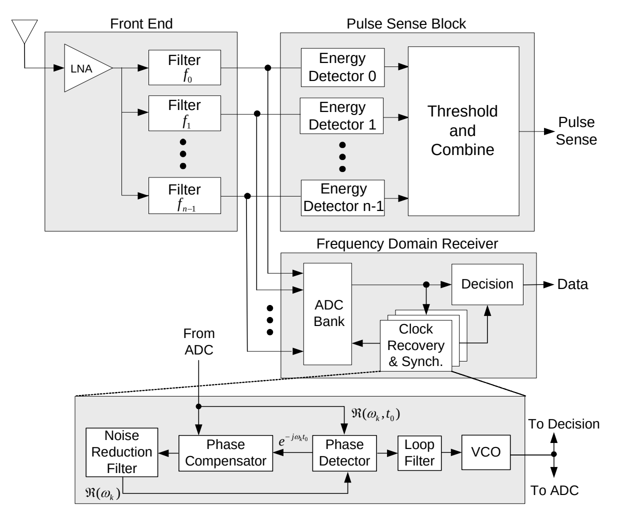

Fig. 2. Frequency domain UWB receiver with pulse sense capability and multiuser timing recovery.

The clock recovery scheme is based on a basic PLL architecture with two modifications. First, to handle time-variant channel conditions, the reference ($\Re(\omega_k)$ in Fig. 2) is updated according to channel conditions. In this process, the newly sampled signal is compensated for its phase error and fed into a noise reduction filter. Second, to handle the frequency selective channel, the circuit considers variations of signal-to-noise ratio (SNR) over the entire frequency band. The circuit tracks the reference phase with highest SNR among spectral components.

As shown in Fig. 2, the structure of the clock recovery circuit is similar to a time domain clock recovery circuit, but the basic difference is that the proposed circuit detects phase error from a sampled spectral component. This results from the time shift property of Fourier transform, which states that the amount of time shift is represented as a phase rotation in the frequency domain.

$$\Im\{f(t-t_0)\} = e^{-\omega t_0}F(\omega) \quad (1)$$

Thus, k^{th} harmonic spectral component of the received signal, $\Re(\omega_k, t_0)$, with time shift t_0, appears as

$$\Re(\omega_k, t_0) = e^{-\omega_k t_0}\Re(\omega_k), \quad (2)$$

where $\omega_k = k\omega_0$ with fundamental frequency ω_0, and $\Re(\omega_k)$ is the kth harmonic spectral component of the received signal under perfect synchronization.

From (2), a simple conjugate multiplication can detect phase error due to time shift as

$$\Re(\omega_k, t_0)\Re(\omega_k)' = e^{-\omega_k t_0}\Re(\omega_k)\Re(\omega_k)' = |\Re(\omega_k)|^2 e^{-\omega_k t_0} \quad (3)$$

Practical operation requires a narrow range of controlling phase, which allows a linear approximation of (3) as

$$|\Re(\omega_k)|^2 e^{-\omega_k t_0} = |\Re(\omega_k)|^2(\cos\omega_k t_0 - j\sin\omega_k t_0) \approx |\Re(\omega_k)|^2(1 - j\omega_k t_0) \quad (4)$$

There are two factors to consider in the performance of the clock recovery circuit. The first is the BER variation over phase error. The second is the phase error pdf, which is obtained from the transmitter characteristics. For example, Fig. 3 shows a BER variation plot at E_b/N_o = 9 dB normalized to the pulse width. The pulse shape mainly determines the BER variation.

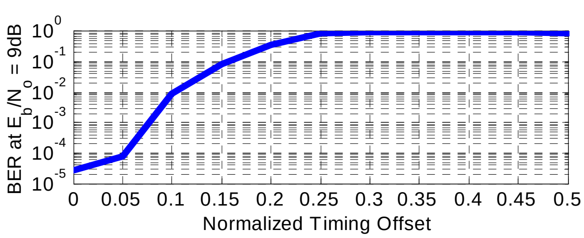

Fig. 3. BER variation $BER(\phi)$ at E_b/N_o = 9dB

Given results like Fig. 3 and a phase error pdf, one can calculate the nominal BER over the phase distribution as

$$BER = \int_{-\pi}^{\pi} BER(\phi)\, p(\phi)\, d\phi, \quad (5)$$

where $p(\phi)$ is a phase error pdf, which is mainly determined by the loop filter and inserted noise variation. Typical expected values of $p(\phi)$ should be less than 0.01.

IV. Simulation Results

To evaluate the performance of the multi-user I-UWB receiver with PSMA, we simulated the throughput vs. offered load using ns-2. We also compared the proposed system to PSMA with collision avoidance (PSMA/CA) and TDMA. PSMA/CA performs handshaking with request-to-send (RTS) and clear-to-send (CTS) packets, which can add significant overhead in an I-UWB network [8]. Table 1 describes the simulation environment.

TABLE 1
Simulation Environment

Topology	Grid of 225 stationary nodes. Maximum of 12 neighbors for any node.
Packet Format	4095 byte packets with packet format from [3]. The header is approximately 900 bits.
Traffic	Poisson traffic with a random source and a random destination.
Pulse Rate	1 Mpps and 100 Mpps. 1 bit per pulse.
Channel Model	CM4 channel model with 25 ns RMS delay spread [7]. No time-varying channel over a packet.
Receiver	No equalization. Capture occurs if SINR is > 10 dB.

First, we vary the number of users M from M=1 to M=8 for 1 Mpps under PSMA. We consider two transmissions to overlap if they occur within an RMS delay of each other. The 1000 ns PRI is much longer than the 25 ns RMS delay, so there is a low probability that two simultaneous transmissions overlap. Fig. 4 show shows the simulation results. As the multi-user receiver supports more users, performance improves but reaches a limit around M=4, since it is highly improbable that a node receives more than four simultaneous transmissions.

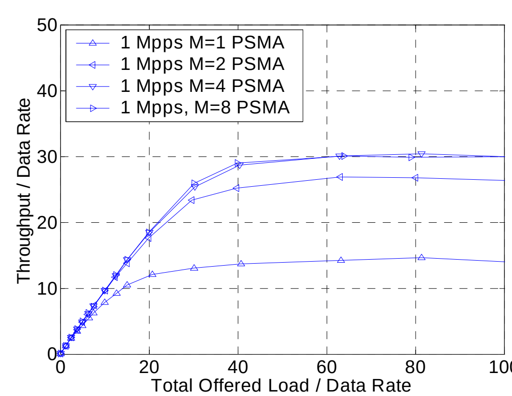

Fig. 4. Normalized offered load vs. throughput for PSMA

Fig. 5 compares the performance of PSMA to PSMA/CA and TDMA at 1 Mpps. The number of users is M=1 for the first two systems and M=8 for TDMA. From Fig. 5, the performance PSMA/CA is worse than the PSMA due to the handshaking packets, which increase overhead and prevent transmissions that may not result in collisions. For the M=8 TDMA system, we assume a central controller and scheduler. As shown in Fig. 5, the performance is worse than M=1 PSMA, since the sub-channel data rate is degraded. Further, the central control is undesirable.

Fig. 5 also shows that the benefits of PSMA diminish as the pulse rate increases. At 100 Mpps, PSMA results in a lower normalized throughput than that of PSMA/CA. The PRI is 10 ns at 100 Mpps, while the RMS delay spread is 25 ns, so simultaneous transmissions significantly overlap without equalization. The results are similar to a single channel narrowband system where simultaneous transmissions always overlap.

Disregarding propagation time, the average packet transmission delay D is defined as [4].

$$D = (G/S - 1) \times (N + \delta) + N \quad (6)$$

where N is the reduction in link bandwidth, δ is the average retransmission delay computed from the simulations, and $N+\delta$ is the normalized average delay between successive retransmissions. Fig. 6 compares the delay of a 1 Mpps PSMA system to a hypothetical 1 Mpps TDMA system that can achieve the same throughput at each M. Fig. 6 plots the PSMA delay with solid lines and the TDMA delay with dotted lines. Note that the TDMA MAC incurs longer delay for low offered load (i.e. when G/S is close to 1) as compared to the PSMA MAC. This is because each channel's bandwidth degrades by a factor of $1/N$, so it takes N times longer to transmit a packet on an empty channel. For the proposed PSMA MAC, N is always one since each successful transmission uses the full bandwidth.

V. Conclusion

We have proposed a PSMA MAC for I-UWB that permits distributed, random access for large ad hoc and sensor networks. In I-UWB, the probability of a collision depends on the PRI and the channel. Hence, it is important to treat I-UWB differently than narrowband systems, where simultaneous transmissions always result in collisions.

At low pulse rates, the low duty cycle of I-UWB reduces the probability of collisions similarly to a multichannel MAC. In contrast to multichannel MACs and handshaking schemes, the PSMA MAC improves performance without reducing link bandwidth, increasing delay, adding hardware complexity, or adding overhead. A multi-user I-UWB receiver further improves performance with moderate additional hardware, but the number of supported users and the network traffic profile limits the improvement. Collisions become more likely in I-UWB as the pulse rate increases, and I-UWB behaves more like a single channel narrowband system at high pulse rates.

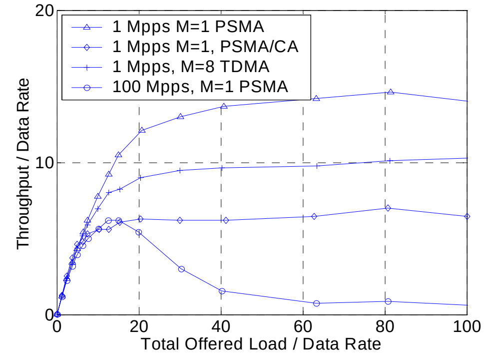

Fig. 5. Performance comparison of PSMA, PSMA/CA, and TDMA. Performance of PSMA at 100 Mpps.

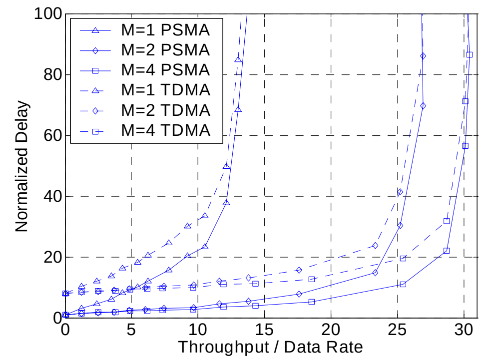

Fig. 6. Normalized delay vs throughput for PSMA and TDMA.

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