Distributed MAC Protocols for UWB Ad Hoc and Sensor Networks

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Abstract — **Large ad hoc and sensor networks impose stringent constraints on cost and energy efficiency. Impulse-based ultra wideband (I-UWB) is an attractive radio technology, and we have developed four medium access control (MAC) protocols to support I-UWB radios in such networks. The four MAC protocols are multichannel ALOHA (M-ALOHA), multichannel pulse sense multiple access (M-PSMA), PSMA with collision avoidance (PSMA/CA), and busy signal multiple access (BSMA). These MAC protocols permit random, distributed medium access with no central point of failure. This paper characterizes the energy efficiency, throughput, and delay of the four protocols. The results suggest appropriate application scenarios for each of the protocols.**

Index Terms — **Ad hoc and sensor networks, busy signal, medium access control, pulse sense, ultra wideband**

I. Introduction

Ad hoc and sensor networks demand low cost and power dissipation, and the radio and medium access control (MAC) protocol heavily influence cost and energy efficiency.

For ad hoc and sensor networks, the impulse-based UWB (I-UWB) approach of IEEE 802.15.4a is particularly attractive due to its resilience to harmful multipath effects, simple transceiver circuitry, accurate ranging ability, flexibility, and low transmission power. I-UWB systems communicate with a train of pulses that have a pulse width on the order of hundreds of picoseconds and a bandwidth on the order of gigahertz. The pulse repetition interval (PRI) is generally much longer than the pulse width. We have implemented in CMOS a low-power, low-cost I-UWB transceiver targeted for ad hoc and sensor networks [1]-[4].

Centralized MAC protocols for I-UWB are well developed [5]-[7], but they target cellular and small personal area networks. Central coordination increases complexity and overhead in large networks, and it also leads to a central point of failure. Instead of centralized protocols, ad hoc and sensor networks generally implement random, distributed MAC protocols that scale to large networks [8].

We have developed four different distributed MAC protocols for I-UWB: multichannel ALOHA (M-ALOHA), multichannel pulse sense multiple access (M-PSMA), PSMA with collision avoidance (PSMA/CA), and busy signal multiple access (BSMA). None of the protocols significantly complicates hardware, adds control traffic overhead, or has a central point of failure. The protocols behave differently than their narrowband counterparts, so we characterize them according to their energy efficiency, throughput, and delay.

II. Distributed MAC Protocols for I-UWB

A. M-ALOHA

ALOHA is a basic distributed MAC protocol. A node may transmit a data packet anytime, unless it is busy with another packet. If the data transmission succeeds, the target node responds with an acknowledgment (ACK) packet. Otherwise, the source node waits a random period of time to retransmit the data. ALOHA performs well under light traffic but poorly under heavy traffic.

In narrowband systems, signals are continuous in time, so two simultaneous transmissions always interfere with each other at a receiver within range of both transmissions. For a non-continuous I-UWB signal with low duty cycle, such concurrent transmissions do not necessarily interfere with each other. 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. The time-interleaved pulse trains effectively occupy different channels. Hence, in an I-UWB network, ALOHA acts as a multichannel MAC protocol. Our multichannel ALOHA (M-ALOHA) protocol increases throughput as compared to a single channel protocol, because concurrent transmissions on different channels do not necessarily collide.

In narrowband systems, the method of dividing the channel adds complexity and decreases the sub-channel data rate. Code division introduces baseband complexity and decreases the sub-channel data rate by the spreading factor. Frequency division adds front-end complexity and reduces the sub-channel data rate by the number of bands. Time division requires centralized control and decreases the sub-channel data rate by the number of time slots. In contrast, M-ALOHA requires neither centralized control nor modification to our basic I-UWB receiver. It also maintains the full data rate on each sub-channel.

Multi-user receivers, which can receive on M channels concurrently, improve performance for multichannel MAC protocols. Under M-ALOHA, an I-UWB system only requires additional clock recovery circuits for each channel. Because any decodable pulses must not overlap, all channels can time-share a single front-end and baseband circuitry.

When two nodes transmit concurrently in M-ALOHA, it is probable that the two pulses do not overlap in time at the receiver. The receiver may synchronize with (for a multi-user receiver) or ignore (for a single-user receiver) the second transmission. In Fig. 1, two source nodes receive a packet from the upper layers at time T_0, so they both start transmitting at time T_1. When the transmissions arrive, the destination receiver starts to acquire the incoming transmissions. Transmitter2 is closer, so its first pulse arrives at T_2, and Transmitter1's first pulse arrives at T_3. After some time, the single synchronization circuit in the receiver detects the arrival time of the two pulse trains within each PRI. A multi-user receiver would use two clock recovery circuits to 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.

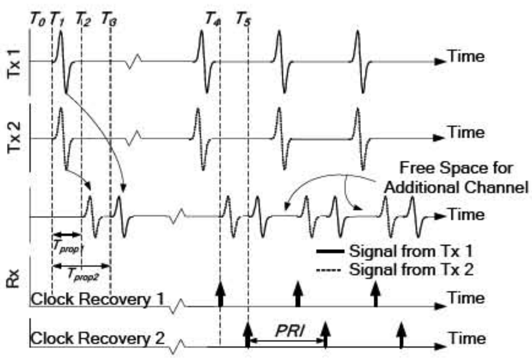

Fig. 1. Multichannel I-UWB Operation.

B. M-PSMA

In narrowband systems, carrier sense multiple access (CSMA) improves on ALOHA by requiring a node to listen to the status of the medium before transmitting. Carrier sense is also known as clear channel assessment (CCA). CCA performs two important roles in a MAC protocol: one is to detect an incoming packet, and the other is to ensure that the channel is free before transmitting.

Because an I-UWB signal has no carrier, I-UWB systems use a CCA technique known as pulse sense. Pulse sense quickly and reliably detects I-UWB pulses, just as carrier sense detects narrowband signals [6]. In I-UWB networks, multichannel PSMA (M-PSMA) improves over M-ALOHA by adding pulse sense. M-PSMA allows time-interleaving of concurrent transmissions, but it prohibits nodes from transmitting if they sense a busy medium.

In M-PSMA, packets may collide if two nodes sense a free medium close in time to each other or if a hidden terminal condition exists. Even then, a collision will only occur if the transmissions also overlap in time within a PRI at the receiver. The multiple, time-interleaved channels reduce the probability of collisions.

C. PSMA/CA

Narrowband systems mitigate hidden terminal conditions via handshaking packets. Time-duplexed collision avoidance (CA) packets communicate a transmitter's request-to-send (RTS) and a receiver's clear-to-send (CTS) status to all nodes within range. In an I-UWB system, PSMA can also be augmented with collision avoidance. The handshaking packets prevent most concurrent transmissions, so PSMA/CA is not considered a multi-channel protocol. In addition, the handshaking packets may add significant overhead due to the long acquisition time of I-UWB [8].

D. BSMA

PSMA/CA could be more efficient if it provided feedback *during* data transmission. In BSMA, the destination node and the neighbors of the source node supply such concurrent feedback with a busy signal to reduce overhead, increase throughput, and more efficiently manage collisions.

The busy signal provides two services: (i) to prevent nodes within radio range of the destination node from initiating a transmission and (ii) to inform the source node of a successful (or unsuccessful) transmission. The busy signal prevents hidden terminals and also eliminates control packets such as RTS, CTS, and ACK. In I-UWB, this is a significant advantage due to the long acquisition overhead. Further, the busy signal immediately alerts the source node to a corrupted packet, thus reducing the energy wasted on transmitting a corrupt packet. Several varieties of BSMA exist, and we use wireless collision detect (WCD) [9].

I-UWB systems implement BSMA by time-interleaving the busy signal with the data signal at the pulse level as shown in Fig. 2 [10]. At the packet level, the fine-grained half-duplex appears to be full duplex.

Narrowband BSMA systems duplex the data signal and busy tone via two frequency bands. A distributed network has no base station to translate between the bands, so each node must operate in either band, depending if it is a source node or a destination node. Fig. 3 shows that this approach requires two transceivers in a narrowband system, which increases hardware cost and power dissipation. For I-UWB, both the data signal and the busy signal are in the same band, so they can share a single transceiver as in Fig. 4.

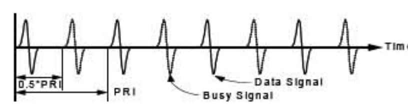

Fig. 2. Fine-Grained Time Division Half Duplex with I-UWB

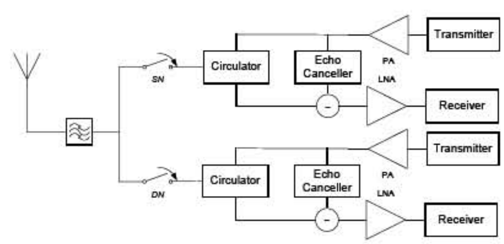

Fig. 3. Architecture for Frequency Domain Division Full Duplex

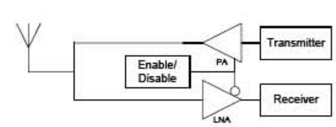

Fig. 4. Fine-Grained Time Domain Half Duplex with I-UWB

III. Simulation Results

Our previous work verified the physical layer feasibility of the proposed protocols [3],[4],[10]. We now characterize the network performance in terms of throughput, delay, and energy efficiency. The throughput is defined as sum of the rates (bps) of traffic that the Physical Layer offers to the MAC Layer of each destination node. The delay is defined as the average time period that a successful packet spends between the source MAC Layer and destination MAC Layer. The energy efficiency is defined as the energy expended for a successful transmission divided by the total energy expended for all transmitted and received packets, including dropped packets and collisions. These quantities are plotted against the offered load, which is defined as the sum of the rates (bps) of traffic that the Network Layer offers to the Link Layer over all nodes.

The I-UWB Physical Layer, channel model, and MAC protocols are implemented as custom blocks in ns-2. A two-dimensional square holds 225 stationary nodes in random positions. The radio ranges limit each node to a maximum of 12 neighbors. Nodes transmit a packet, formatted according to 802.5.3a [7], to a random destination following a Poisson distribution. The link data rate is 1 Mbps and one pulse corresponds to one bit, i.e., no spreading. The channel model is a slow-fading version of the 802.15.3a CM4 model with a 25 ns RMS delay spread [11], and the receiver behaves according to our previous physical layer characterizations [3],[4],[10].

First, Fig. 5 compares the throughput of the four protocols at 1 Mbps. We include a centralized time division multiple access (TDMA) MAC protocol as a baseline. The number of users supported by the single-user receivers is $M = 1$ for all systems except a TDMA system with 8 slots, which is inherently $M = 8$. The TDMA system has an omniscient central controller with perfect scheduling. In actual ad hoc and sensor networks, the centralized control and single point of failure for TDMA would be undesirable.

The M-PSMA system outperforms TDMA, BSMA, and PSMA/CA because it allows channel interleaving; and it outperforms M-ALOHA because it checks for a busy medium before transmitting. Next, BSMA achieves nearly the throughput of centralized TDMA, because it avoids most collisions and efficiently handles the rest. Next, PSMA/CA performs worse than BSMA due to the handshaking packets, which increase overhead. PSMA/CA performs worse than M-PSMA because it prevents transmissions that may not result in collisions. M-ALOHA performs similarly to PSMA/CA at low offered loads, but it is unstable at high offered loads.

Fig. 6 shows the throughput of M-ALOHA and M-PSMA as the number of users supported by a multi-user receiver increases from $M = 1$ user to $M = 16$ users at 1 Mbps. Two transmissions overlap if the multipath interference decreases the link budget below the safety margin. M-PSMA achieves a higher throughput than M-ALOHA, and M-PSMA is more stable at high offered loads. As a receiver supports more users, performance improves for both protocols but reaches a limit around $M = 4$ users for M-PSMA and $M = 8$ users for

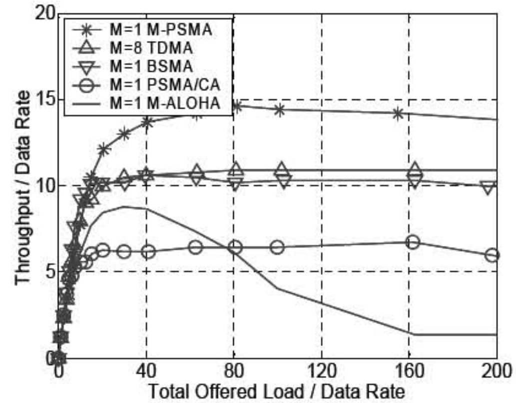

Fig. 5: Throughput for M-PSMA, PSMA/CA, M-ALOHA, BSMA, and TDMA

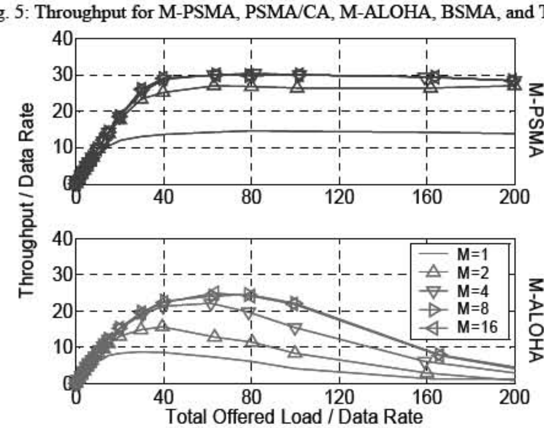

Fig. 6 Throughput for M-PSMA and M-ALOHA with Multi-User Receivers

M-ALOHA. This is because it is highly improbable that a node under M-PSMA receives more than four simultaneous transmissions from a maximum of 12 neighbors. A node under M-ALOHA may receive more simultaneous transmissions because nodes do not check for a busy medium before transmitting.

Fig. 7 compares the delay of a 1 Mbps M-PSMA system to a hypothetical 1 Mbps TDMA system that can achieve the same throughput at each M. Note that the TDMA MAC incurs longer delay at low offered load as compared to the M-PSMA MAC. This is because each channel's bandwidth degrades by a factor of $1/N$ under TDMA, where N is the number of time slots. Therefore, it takes N times longer to transmit a packet on an empty channel. For the proposed M-PSMA MAC, N is always one since each successful transmission uses the full bandwidth.

Fig. 8 compares the energy efficiency of the protocols. BSMA attains the highest energy efficiency among the distributed protocols. It outperforms PSMA/CA because the RTS packets may directly collide with data packets. The RTS packets may also indirectly cause collisions by interfering with control packets. BSMA outperforms M-ALOHA and M-PSMA because neither M-ALOHA nor M-PSMA has a mechanism to detect or avoid collisions. The PSMA/CA system attains the second best energy efficiency, because the handshaking packets avoid most collisions.

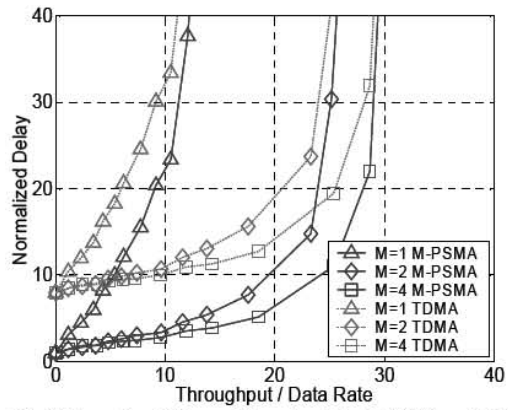

Fig. 7: Normalized Delay vs Throughput for M-PSMA and TDMA.

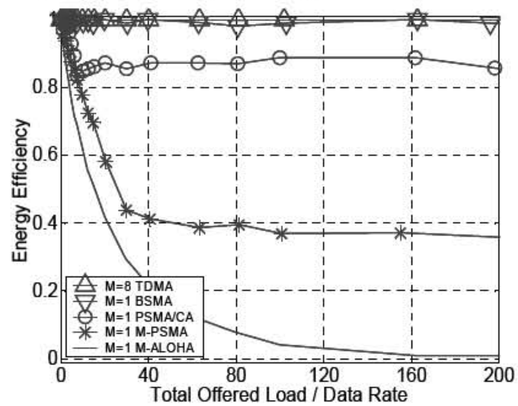

Fig. 8: Energy efficiency for M-PSMA, PSMA/CA, M-ALOHA, BSMA, TDMA.

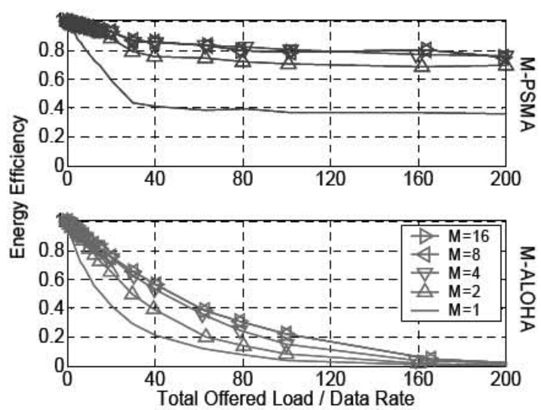

Fig. 9: Energy efficiency for M-PSMA and M-ALOHA with multi-user receivers

The M-PSMA system performs poorly in terms of energy efficiency, because it has no mechanism to avoid collisions. M-ALOHA has the worst energy efficiency, because it does not even check for channel activity before transmitting.

Finally, we evaluate the energy efficiency of M-PSMA and M-ALOHA for multi-user receivers. Fig. 9 varies the number of users from M = 1 to M = 16. M-PSMA outperforms M-ALOHA, which approaches 0% energy efficiency as the offered load increases. Again, energy efficiency reaches a limit around M = 4 for M-PSMA and M = 8 for M-ALOHA. Regardless of the number of receivers, the energy efficiency of M-PSMA and M-ALOHA is still worse than either PSMA/CA or BSMA.

IV. Conclusion

I-UWB is a particularly attractive radio for ad hoc and sensor networks. We have proposed four different distributed MAC protocols for I-UWB that are suitable for ad hoc and sensor networks: M-ALOHA, M-PSMA, PSMA/CA, and BSMA. None of the protocols significantly complicates hardware, adds control traffic overhead, or has a central point of failure. However, the protocols do not necessarily behave as they would in narrowband systems.

M-ALOHA the simplest protocol, and it is suitable only for networks with an expected offered load much less than the data rate. In general, BSMA is the most energy efficient distributed MAC protocol for I-UWB, so it is appropriate for energy-sensitive sensor networks with offered loads that approach or surpass the link data rate. I-UWB is well-suited for BSMA because it can implement BSMA with a single receiver to save hardware complexity and power as compared to a narrowband system. In terms of throughput and delay, M-PSMA outperforms all other protocols. It is relatively energy efficient as compared to M-ALOHA, and it attains a much higher throughput than PSMA/CA. A multi-user receiver further improves throughput and energy efficiency at the cost of moderate additional hardware complexity. PSMA/CA is not as efficient as BSMA, nor does it achieve the throughput of M-PSMA.

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