

A Medium Access Control Protocol for UWB Sensor Networks with QoS Support

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Abstract—Ultra-wideband (UWB) is a physical (PHY) layer technology that promises high transmission rates, as well as high resistance to noise and multipath effects. However, the impulse-based nature of UWB, coupled with its low transmission power, makes it difficult to enable efficient detection of the signals. Consequently, conventional carrier-sensing based MAC protocols cannot be used with a UWB PHY.

In this paper, we propose *SASW-CR* - a Slotted Aloha MAC protocol for UWB networks with Sliding contention Window and Cooperative Retransmissions, which provides QoS support without the use of carrier sensing. *SASW-CR* utilizes the slotted-Aloha technique to avoid carrier sensing and reduce packet collisions. In addition, it makes use of differentiated contention windows to provide varying classes of QoS for different traffic classes. A cooperative retransmission technique is also introduced to improve the overall traffic throughput and reduce end-to-end delay. The efficacy of our protocol is demonstrated through simulations.

I. INTRODUCTION

Ultra-Wideband (UWB) [1] is an enabling physical (PHY) layer technology for the transmission of data bits using very narrow duration pulses, resulting in extremely large transmission bandwidths [2]. According to the Federal Communications Commission (FCC) [3], a UWB device is defined to be one whereby the fractional bandwidth is at least 20%, or occupies at least 500 MHz of the spectrum. As UWB is able to provide high data rates for short-to-medium ranges, it is a viable technology for use in Wireless Sensor Networks (WSNs), which can be deployed for a multitude of applications such as healthcare monitoring, tracking and surveillance. In these networks, multiple sensor nodes are deployed within a terrain to sense physical data from the environment, and then transmit these data back to one or more sinks for real-time processing.

While UWB promises high transmission rates, as well as high resistance to noise and multipath effects, it also has its limitations. The impulse-based nature of UWB, coupled with its low transmission power, makes it difficult to enable efficient detection of UWB signals. As such, conventional carrier-sensing based medium access control (MAC) protocols cannot be used with a UWB PHY. In order to exploit the advantages and overcome the limitations of UWB, special considerations must be given to the design of the UWB MAC layer protocol [4].

We consider the design of a UWB MAC protocol which is able to provide differentiated Quality of Service (QoS) for

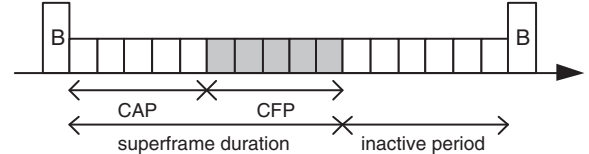


Fig. 1. Contention window (CW) of IEEE 802.11e.

traffic flows of different classes. In large-scale sensor networks (such as those that are deployed for healthcare monitoring), data of multiple modalities (voice, video, temperature, etc) may be collected by the sensors. These sensed data may be of different priorities; for example, multimedia traffic may have higher priority than pressure data as the former provides more detailed information at the sink. Hence, high priority data should be granted better QoS than low priority data, in terms of throughput and delay.

In this paper, we propose *SASW-CR*, a Slotted-Aloha MAC protocol for UWB networks with sliding contention window and cooperative retransmissions, which provides QoS support without the use of carrier sensing. *SASW-CR* utilizes slotted-Aloha to avoid carrier sensing and reduce packet collisions. In addition, it makes use of differentiated contention windows to provide varying classes of QoS for different traffic classes. A cooperative retransmission technique is also introduced to improve the overall traffic throughput and reduce the end-to-end delay.

The rest of the paper is organized as follows. Section II provides insights on how differentiated contention windows and cooperative retransmissions can be used to provide QoS support and improve network throughput respectively. Protocol details of *SASW-CR* and its analytical framework are presented in Section III and Section IV respectively. In Section V, we evaluate and discuss the performance of *SASW-CR* using extensive simulations. We conclude this work in Section VI.

II. STUDY OF EXISTING MAC PROTOCOL FOR WIRELESS NETWORKS

A. IEEE 802.15.4 MAC

The IEEE 802.15.4 standard for LR-WPANs (Low-Rate Wireless Personal Area Networks) [5] uses CSMA/CA for medium access. It adopts a superframe structure (Figure 1) whereby each superframe consists of a beacon and a number

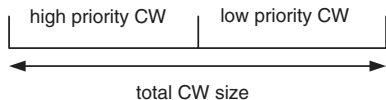


Fig. 2. Contention window (CW) of IEEE 802.11e.

of time slots. The size of the superframe is periodically broadcasted by a central coordinator (sink).

Each superframe is divided into a superframe duration and an inactive period. The former part can be further divided into contention access period (CAP) and contention free period (CFP). Both data packets and control messages can be sent during the CAP. The central coordinator uses control messages to pre-allocate time slots within the CFP to sensor node; hence no collisions occur during the CFP.

Although IEEE 802.15.4 provides a simple way for synchronization among sensor nodes using the superframe structure, it is not suitable for UWB WSNs as it uses carrier sensing for contention resolution.

B. IEEE 802.11e MAC: EDCA for QoS support

IEEE 802.11e is the standard protocol which provides QoS support for WLAN (Wireless Local Area Network) [6]. It uses a DCF (Distributed Coordination Function) for medium access control among multiple wireless nodes. The DCF also employs CSMA/CA and a backoff mechanism for contention resolution within a contention window.

In order to provide QoS support, IEEE 802.11e employs an Enhanced Distributed Channel Access (EDCA) which assigns Traffic Classes (TC) to different types of traffic. For example, text data can be assigned to low priority class and video traffic can be assigned to high priority class.

With EDCA, traffic belonging to different priority classes are assigned different contention window sizes. The contention window for high priority traffic precedes the contention window for low priority traffic (see Figure 2). As the backoff period for high priority packets is smaller than that of low priority packets, the former experiences less waiting time before being transmitted. Consequently, high priority traffic is able to achieve higher average throughput and less average delay than low priority traffic.

Although IEEE 802.11e can provide QoS support using differentiated contention windows for different traffic classes, it has its limitations. Contention between high and low priority traffic may happen as the contention windows belonging to a particular class of traffic at one node may overlap with another traffic class at another node. The transmission of low priority traffic may be delayed infinitely by the other high priority traffic and vice versa. Starvation may also occur when the number of high priority nodes is much greater than the number of low priority nodes, or vice versa. In addition, IEEE 802.11e is not suitable for UWB WSN as it requires the use of carrier sensing.

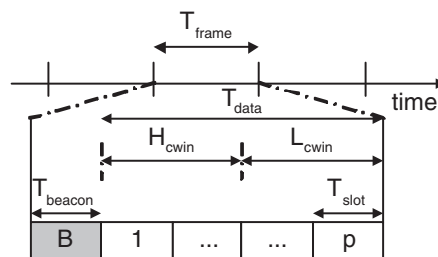


Fig. 3. Slotted-Aloha with TH-UWB

C. Cooperative retransmission in WSNs

By overhearing and buffering packets that are transmitted by its neighbors, a node can potentially help to retransmit an originally failed transmission to its destination. In [7], a cooperative retransmission scheme is used to improve the overall traffic throughput and reduce packet delays for WSN with bursty channels. The authors consider a single-hop network with n nodes located around a centralized sink. A TDMA approach is adopted whereby a MAC frame consists of n time slots and each node is assigned one unique fixed time slot. In each assigned slot, a node transmits either zero or one packet and performs overhearing during the rest of the time slots. The node which successfully overhears the packet will store it in an overhearing buffer. The packet is removed from the overhearing buffer when the node overhears the corresponding ACK that is transmitted by the sink. However, if no ACK is received, the node may choose to retransmit a packet from the overhearing buffer if it does not have its own packet to transmit. If the retransmission succeeds, the original sender will refrain from retransmitting the same packet. Through this cooperative retransmission approach, the overall traffic throughput shows an improvement of 16% to 43%.

Our proposed MAC protocol for UWB WSN combines the frame structure of IEEE 802.15.4 with the differentiated contention window in IEEE 802.11e to provide QoS support. In addition, it utilizes a cooperative retransmission technique to improve overall throughput and reduce packet delays.

III. SASW-CR: PROTOCOL DESCRIPTION

In this section, we describe the protocol details of SASW-CR - a Slotted-Aloha medium access control protocol with Sliding contention Window and Cooperative Retransmissions to achieve network QoS. We first present the network and traffic models, followed by the two main mechanisms of SASW-CR: (i) Sliding Disjoint Contention Window; and (ii) Cooperative Retransmission.

A. Network Model

We consider a generic wireless sensor network comprising of a number of sensor nodes N connected to a centralized sink via a single hop connection. The underlying PHY layer used by the entire network is Time-Hopping Ultra-Wideband (TH-UWB), whereby each signal is transmitted over several

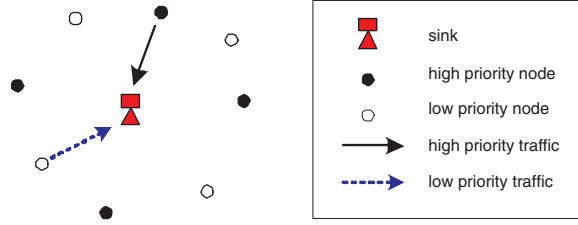


Fig. 4. Network Topology

symbols, and each of these symbols comprise of a burst of extremely short pulses.

Due to the impulse nature of TH-UWB, carrier sensing is not feasible. Hence, we make use of Slotted-Aloha as the MAC protocol with TH-UWB incorporated into the frame structure [8]. In the simplified frame structure as shown in Figure 3, a beacon B of length T_{beacon} precedes each MAC frame and is used for various purposes such as synchronization or transmission of control packets from the sink to the sensor nodes. A frame also comprises of p Time-Hopping (TH) slots, each of length T_{slot} . A node selects only *one* out of the p possible TH slots within each T_{frame} to transmit its data. Here, it should be noted that p is not a fixed value, but is dependent on the number of active nodes in the previous time epoch; this will be discussed in further detail in Section III-C. Each data packet (and its corresponding ACK) is assumed to be transmitted within T_{slot} . A packet collision (and subsequently packet loss) arises whenever one or more packets are transmitted to the sink using the same TH slot. Packet losses may also arise due to radio propagation impairments.

B. Traffic Model and QoS Provisioning

We assume that all the N nodes in the network can be classified as high priority or low priority nodes, depending on the data traffic that they generate. Figure 4 shows a network topology whereby the different classes of nodes in the network are transmitting data of different traffic classes to the centralized sink.

Generally, QoS can be provisioned in two ways: (i) guaranteed QoS; and (ii) soft QoS. In guaranteed QoS, a specific traffic class (usually the one with a higher priority) is provided with specific performance guarantee. For instance, the delay incurred for high priority traffic should always be less than a certain threshold. However, in wireless network where the channel is transient and time-varying, it may be more feasible to provide soft QoS, whereby relatively better service is provided to a particular traffic class over another without any guarantee on the qualitative performance. For instance, in soft QoS, the delay incurred for high priority traffic should always be lesser than that incurred by low priority traffic.

In this work, our proposed UWB MAC protocol aims to provide soft QoS support in the following ways:

- Maximize the total traffic throughput.
- High priority traffic should incur smaller average delays than low priority traffic.

Algorithm 1 State Selection

Require: N_H - number of active high priority nodes

N_L - number of active low priority nodes

N_a - total number of active nodes

R - minimum proportion of resources to be allocated to each traffic class

Ensure: State S

if $N_H < R \times N_a$ **||** $N_L < R \times N_a$ **then**

$S = SP$

else

$S = TP$

end if

return

- High priority traffic should achieve larger average throughput than low priority traffic.
- No starvation should occur in any class of traffic.

C. Sliding Disjoint Contention Windows

To segregate contention between the two different traffic classes and prevent starvation of either class, the T_{data} portion of the frame structure of slotted-Aloha with TH-UWB (as shown in Figure 3) is further divided into two **disjoint** components: (i) the high priority contention window H_{cwin} ; and (ii) the low priority contention window L_{cwin} . High priority nodes uniformly-randomly select one slot within H_{cwin} to transmit data, while low priority nodes in the network select from L_{cwin} to transmit data.

Recall that p is the total number of TH slots within each MAC frame. We further denote the number of TH slots within H_{cwin} and L_{cwin} as $|H_{cwin}|$ and $|L_{cwin}|$ respectively, where $|H_{cwin}| + |L_{cwin}| = p$. Let the number of active nodes (as seen by the sink) within the previous time epoch be N_a ; the number of *active* high priority nodes and low priority nodes within the previous time epoch are given by N_H and N_L respectively, where $N_a = N_H + N_L$. The value of p is adaptively adjusted according to $p = \frac{N_a}{2}$. The corresponding values of p , $|H_{cwin}|$ and $|L_{cwin}|$ are broadcasted by the sink to the sensor nodes during T_{beacon} after each update.

Each node may be in only one of two states at any one time: (i) Starvation Prevention (SP) - to actively prevent starvation of any traffic class; or (ii) Traffic Prioritization (TP) - to sacrifice low priority traffic in order to improve the QoS of higher priority traffic. The state that each node is in, is determined by the proportion of *active* high and low priority nodes that are in the network in the previous time epoch. If either class of traffic dominates the other, i.e. $N_L \gg N_H$ or $N_H \gg N_L$, the traffic class with more nodes is likely to cause the other class to starve. Hence, if either $N_H < R \times N_a$ or $N_L < R \times N_a$, where R is a fixed threshold ($0 < R < 1$), the nodes in the network enter the SP mode; otherwise, the nodes enter the TP mode. The value of R used determines the minimum proportion of resources (TH slots) that each class of traffic should be allocated, and also helps to prevent starvation. Algorithm 1 summarizes the state selection procedure of SASW-CR.

Algorithm 2 Traffic Prioritization

Require: T_{total} - total throughput at sink
 T_L - throughput of low priority traffic
 R - minimum proportion of resources to be allocated to each traffic class

if $T_L < R \times T_{total}$ **then**
 $|L_{cwin}| = |L_{cwin}| + \alpha$
 $|H_{cwin}| = p - |L_{cwin}|$
else
 $|L_{cwin}| = |L_{cwin}| - \alpha$
 $|H_{cwin}| = p - |L_{cwin}|$
end if
return

1) *Starvation Prevention (SP)*: When nodes enter the SP state, one class of nodes is much less than the other, and starvation is likely to occur. The values of $|H_{cwin}|$ and $|L_{cwin}|$ are set to $\frac{N_H}{2}$ and $\frac{N_L}{2}$ respectively. The number of TH slots that are allocated to each traffic class is proportional to the number of nodes that are in each class, to provide some form of fairness in the network. In addition, at least one TH slot is allocated to each class, in order to prevent starvation.

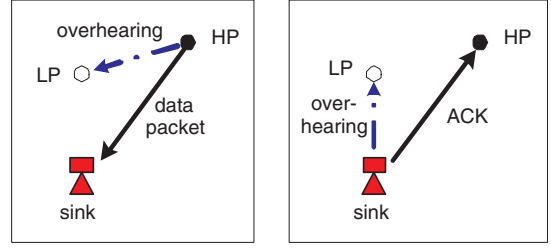
2) *Traffic Prioritization (TP)*: In the TP state, the number of active high and low priority nodes are similar. As starvation is unlikely to occur under this circumstance, the network attempts to improve the QoS of the higher priority traffic class by allocating more TH slots to H_{cwin} . Consequently, there is less contention among the high priority traffic, leading to better throughput and delay performance, as compared to low priority traffic.

We let T_{total} denote the total throughput received at the sink during the last time epoch. The throughput contributed by high and low priority traffic are T_H and T_L respectively, where $T_H + T_L = T_{total}$. Whenever $T_L < R \times T_{total}$, more TH slots will be allocated to L_{cwin} to prevent starvation of the low priority traffic class. Conversely, more TH slots will be allocated to H_{cwin} to improve the QoS of the high priority traffic class. The number of TH slots that are shifted from H_{cwin} to L_{cwin} (or vice versa) is denoted by α . The value of α determines the aggressiveness of the adaptation and is a function of p . The TP algorithm is summarized in Algorithm 2.

D. Cooperative Retransmission

As the contention windows of the two different traffic classes H_{cwin} and L_{cwin} are disjoint within each MAC frame, high priority nodes will be in idle state when low priority nodes are transmitting, and vice versa. SASW-CR makes use of overhearing and cooperative retransmissions to improve the QoS of the higher priority traffic class.

Each node i in the network maintains two buffers (or queues): (i) data queue, which stores data packets generated by i ; and (ii) overhearing buffer, which stores data packets belonging to another traffic class, that are successfully overheard by i . During each MAC frame, node i may transmit a



(a) LP node overhears data packet. (b) LP node overhears ACK packet.

Fig. 5. Overhearing behavior without cooperative retransmission.

data packet from either its data queue or overhearing buffer, depending on its current *mode*:

1) *Selfish Mode*: Node i will always transmit its own packet from the data queue if the queue is not empty. When the data queue of node i is empty, it will then randomly select a packet from its overhearing buffer to transmit.

2) *Selfless Mode*: Node i will always select a packet from the overhearing buffer to transmit (if the buffer is not empty), instead of transmitting from its own data queue. When the overhearing buffer is empty, node i will then transmit its packet from the data queue.

A high priority node is always in selfish mode and will cooperatively retransmit only when its data queue is empty. In contrast, a low priority node may be in either of the two modes. During the Starvation Prevention (SP) state, the low priority node is in selfish mode; during the Traffic Prioritization (TP) state, the low priority node is in selfless mode.

It is assumed that all the ACK packets corresponding to each data packet can be received correctly by all the nodes in the network (since they are all one hop away from the sink). Hence, all copies of an arbitrary data packet P_n (in the data queue of the source node and overhearing buffers of all the nodes that have overheard P_n) will be deleted when the sink has received P_n .

Figure 5 illustrates the overhearing behavior between a high priority node (HP), a low priority node (LP) and the sink, when cooperative retransmission is not required. In Figure 5(a), HP transmits its data packet to the sink. LP, which is currently idle, overhears the data packet and stores it in its overhearing buffer. Upon successful reception of the data packet, the sink sends an ACK to HP, which subsequently deletes the data packet from its data queue. Since LP is also able to overhear the ACK, it knows that the data packet has been successfully received by the sink and thus, LP also deletes the data packet from its overhearing buffer.

Figure 6 illustrates the overhearing behavior between HP, LP and the sink when cooperative retransmission is triggered. At time t_1 , the high priority node HP transmits packet P_1 to the sink during H_{cwin} . Due to radio propagation impairments, the sink is unable to receive P_1 ; however, the low priority node LP is able to overhear P_1 , and stores it in its overhearing buffer. At time t_2 (during L_{cwin}), LP selflessly retransmits P_1 on behalf of HP (since P_1 is of a higher priority and no ACK has

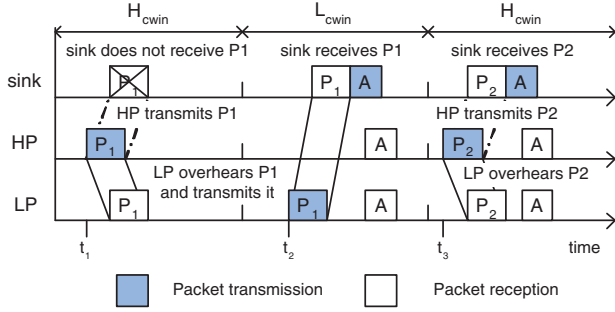


Fig. 6. Overhearing behavior with cooperative retransmission.

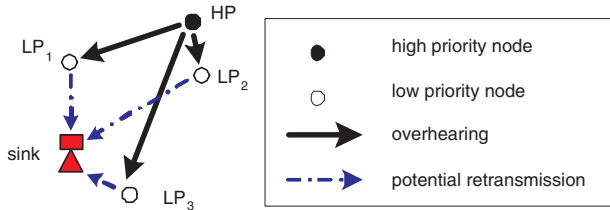


Fig. 7. Cooperative retransmission with more than 1 relay.

been transmitted for P_1 from the sink yet). Upon successful reception of P_1 from LP, the sink transmits an ACK, which is received by both HP and LP. Both HP and LP then delete P_1 from the data queue and overhearing buffer, respectively. Hence, at time t_3 , HP needs not retransmit P_1 and can proceed on to send the next packet P_2 from its data queue. Due to the cooperative retransmission by LP, the delay of P_1 is reduced by $t_3 - t_2$.

In a generic network, the transmission of a single data packet may be overheard by more than one neighboring node. Figure 7 illustrates a network whereby the transmission of a data packet by a high priority node HP may be overheard by 3 low priority nodes LP_1 , LP_2 and LP_3 which are of varying distances to the sink. If the data packet that is transmitted by HP does not reach the sink successfully, LP_1 , LP_2 and LP_3 become the potential relays to cooperatively retransmit the overheard packet to the sink. However, it is inefficient to have all LP_1 , LP_2 and LP_3 retransmitting the same data packet to the sink on behalf of HP, as this may increase packet collisions as well as unnecessarily deteriorate the throughput performance of low priority data.

Instead of using an election algorithm, which is expensive as it requires inter-nodal communications, to select a relay node to retransmit the packet to the sink, SASW-CR makes use of a simple, distributed mechanism to select the best relay using distance information of the nodes, which is easily available with an UWB PHY.

We first note that the successful reception of any packet from a source node i in a wireless channel is inherently dependent on the signal strength of the packet at the receiver

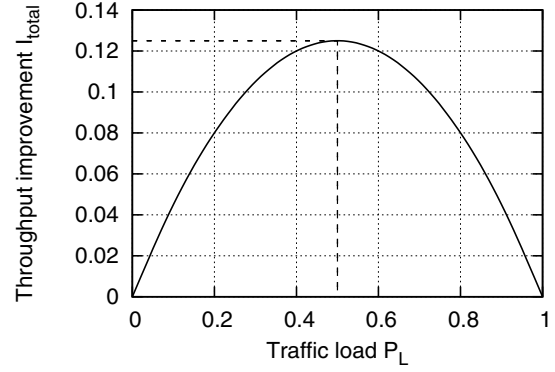


Fig. 8. Throughput improvement with $P_s = 0.5$.

node j , which is given by:

$$P_{ij} = \frac{k \cdot P_{init}}{d_{ij}^2} \quad (1)$$

where P_{init} is the transmission power of i ; d_{ij} is the distance between i and j ; and k is a constant.

Typically, a higher signal strength denotes a higher probability of successful packet reception at the receiver. Hence, upon overhearing a data packet from an arbitrary source node i , node j will estimate P_{ij} as well as P_{js} using known distance information, where P_{js} denotes the received signal strength of a packet that is being transmitted from node j to sink S . It is assumed that each node has complete location information of all the nodes in the one-hop network, and is hence able to calculate the respective signal strengths of all the nodes to itself and to the sink. The node with the highest value of $P_{ij} + P_{js}$ will select itself as the relay. However, if the selected relay fails to overhear the transmitted data packet, then the data packet will not be retransmitted.

IV. ANALYSIS

In this section, we analyze the theoretical performance of SASW-CR using cooperative retransmission, in terms of throughput improvement.

We consider a network with n high priority nodes and n low priority nodes. The network is evenly distributed such that every high priority node has a distinct low priority node as a best relay node, and vice versa. Each MAC frame has $p = n$ TH slots, divided equally among H_{cwin} and L_{cwin} such that $|H_{cwin}| = |L_{cwin}| = \frac{p}{2}$. Since each node chooses a slot uniform-randomly from either H_{cwin} or L_{cwin} (depending on the node priority), on the average, each TH slot is shared by two nodes. We denote the (normalized) traffic load as P_L (where $0 \leq P_L \leq 1$); the probability that each node has a new packet to transmit in each MAC frame is P_L .

We refer to the communication channel between an arbitrary source node i and the sink S as the **direct channel**. The communication channel between i and its best relay j is known as the **overhearing channel**. A channel is in state **G** (Good) if packets that are transmitted in the channel are always received

correctly by the receiver; otherwise, the channel is in state **B** (Bad). We assume that all overhearing channels are always in state **G** such that the best relay will always overhear the data packet. In addition, each direct channel is independently in state **G** with probability P_s ($0 \leq P_s \leq 1$).

The **improvement** on high priority traffic throughput is achieved by successfully relaying high priority packets which have failed to be received by the sink. The improvement of high priority traffic throughput per MAC frame is:

$$I_H = n \times P_L \times (1 - P_s) \times P_s \quad (2)$$

The **loss** on low priority traffic throughput is due to low priority nodes relaying high priority traffic at the expense of low priority traffic. The loss of low priority traffic throughput per MAC frame is:

$$Loss_L = I_H \times P_L \quad (3)$$

In addition, since low priority traffic may also be relayed by high priority nodes when high priority nodes do not have packets to transmit, the improvement of low priority traffic per MAC frame is given by:

$$I_L = n \times P_L \times (1 - P_s) \times (1 - P_L) \times P_s \quad (4)$$

Hence, the overall loss of low priority traffic per MAC frame is given by:

$$Loss_L(total) = Loss_L - I_L \quad (5)$$

The overall improvement is achieved by a node successfully relaying packets for other nodes, without suppressing its own packets. The overall improvement per MAC frame is:

$$\begin{aligned} I_{total} &= I_H - Loss_L(total) \\ &= 2n \times P_L \times (1 - P_s) \times (1 - P_L) \times P_s \end{aligned} \quad (6)$$

Figure 8 illustrates how the overall throughput improvement I_{total} varies with different traffic loads P_L , when $P_s = 0.5$. The greatest improvement on overall throughput occurs when the traffic load is 50%.

V. PERFORMANCE EVALUATION

We evaluate the performance of SASW-CR in Qualnet 4.0 [9], a commercially available network simulation tool and compare it with EDCA, which is used by IEEE 802.11e for QoS support, using the same underlying slotted-Aloha MAC structure and UWB physical channel. As EDCA is used with carrier sensing in the IEEE 802.11e standard, for the purpose of comparison, we implement EDCA with instantaneous carrier sensing (denoted as EDCA*) in our simulations, noting however that carrier sensing would typically take a much longer time in practical scenarios.

The network size is fixed at $N = 32$ sensor nodes (sources) and 1 centralized sink. Two classes of traffic, viz. high priority and low priority classes, are generated at the sensor nodes. The number of nodes that generate low priority data N_L is increased from 1 to 31; the corresponding number of nodes that generate high priority data $N_H = N - N_L$ is decreased

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Transmission Power P	-14.32 dBm
Channel Frequency f	4 GHz
Center Frequency f_c	4492.8 MHz
Channel Bandwidth B	499.2 MHz
Packet Rate (pkts/s)	200
Packet Size (B)	46
Time Epoch (s)	1
R	0.3
α	1

from 31 to 1. In addition, the communication channel between the sensor nodes and the centralized sink is also set to have a 50% link error rate; while the channel among the sensor nodes experiences a link error rate of 10%. The time epoch used in our simulations has a duration of 1 second. This means that the sink will collect information of the active nodes in the network and update the size of p every 1 second. The various parameters used in our simulations are summarized in Table I.

A. Throughput Performance

Figure 9 illustrates the throughput performance of the network when EDCA and SASW-CR are being used. As the number of low priority nodes N_L increases, the number of high priority data packets that are being generated decreases correspondingly. Consequently, the number of high priority data packets that are received by the sink also decreases for both EDCA and SASW-CR, as shown in Figure 9(a). In Figure 9(b), it can be seen that the throughput contributed by the low priority data increases with increasing N_L , since there is now more low priority data packets being generated in the network. In both graphs, it can be noted that starvation is less likely to occur in SASW-CR as compared to EDCA, whenever one traffic class is much greater than the other ($N_L \gg N_H$ or $N_L \ll N_H$). This is due to the **Starvation Prevention (SP)** technique being used in SASW-CR, which attempts to allocate resources equally among the two different traffic classes whenever the difference between N_L and N_H is very significant.

An interesting anomaly in Figure 9(b) is that the throughput achieved by the low priority data class drops when $10 < N_L < 20$. Figure 9(c) highlights the reason for this behavior. When the number of high priority nodes N_H is relatively the same as the number of low priority nodes N_L (i.e. $N_H \approx N_L$), SASW-CR enters the **Traffic Prioritization (TP)** state, which then allocates more time slots to the high priority contention window (in order to improve the QoS of high priority data) at the cost of lesser time slots being allocated to the low priority contention window. The value of R determines the ratio of time slots that are being allocated to low priority data whenever SASW-CR is in the TP state. In our simulations, we

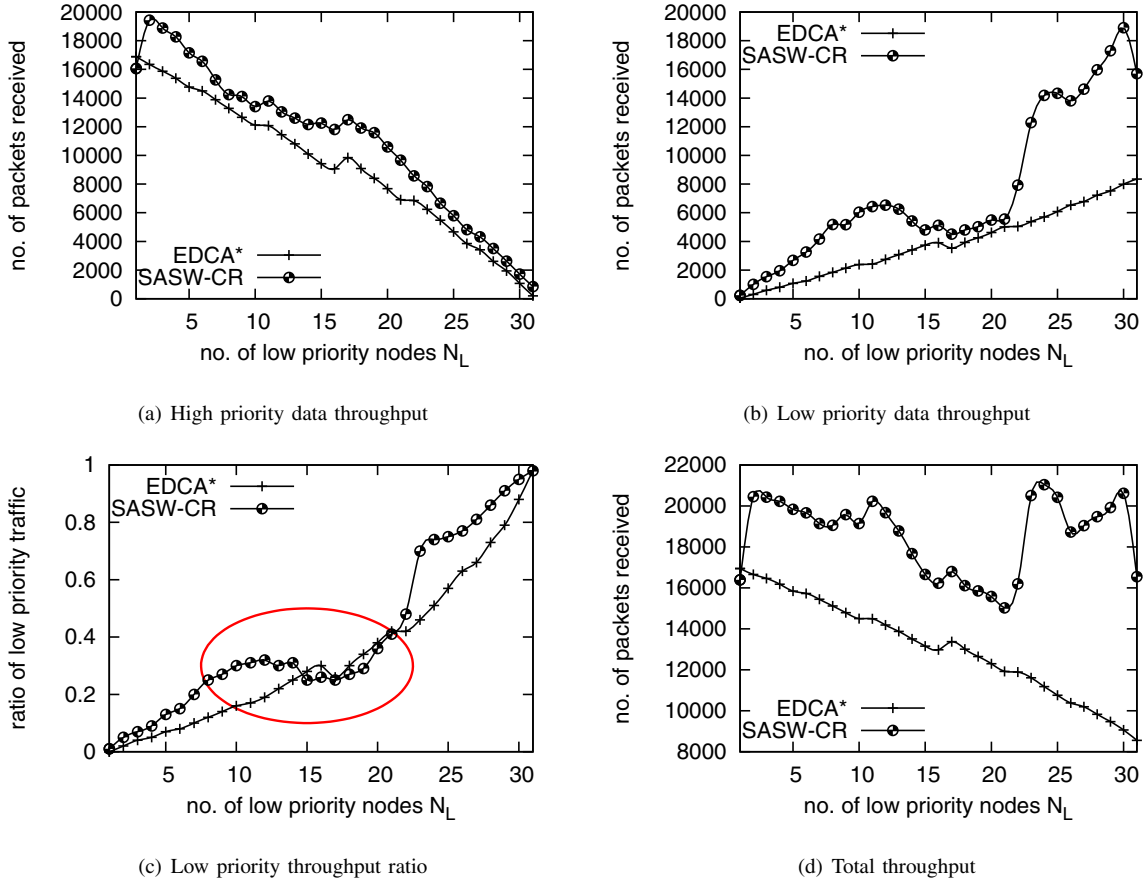


Fig. 9. Throughput Performance of SASW-CR.

have used a constant value of $R = 0.3$; hence, the throughput ratio of the low priority data class remains at approximately 0.3 when the TP state is being triggered at $N_H \approx N_L$.

From Figure 9(d), it can be seen that SASW-CR increases the overall (total) traffic throughput by over 20% as compared to EDCA, for varying values of low priority nodes in the network N_L . The throughput improvement is brought about by the use of the sliding disjoint contention window and cooperative retransmission techniques, which efficiently increases the effective utilization of the shared communication channel and reduces the number of packet collisions between the two different traffic classes.

B. Average Per-Node Throughput Performance

Table II shows the average per-node throughput achieved under the two extreme cases when $N_H \gg N_L$ and $N_L \gg N_H$. T_L^* and T_H^* denote the average per-node throughput of a low priority node and a high priority node, respectively.

In the case of $N_L = 1, N_H = 31$, the per-node throughput of a low priority node achieved by EDCA is significantly less than that achieved by SASW-CR, as the latter prevents starvation of low priority traffic through the use of the control parameter R , which determines the minimum amount of resources that is allocated to each class. We note that T_L^* is approximately 30% of the total throughput achieved by both

TABLE II
AVERAGE PER-NODE THROUGHPUT WHEN $N_H \gg N_L$ AND $N_L \gg N_H$

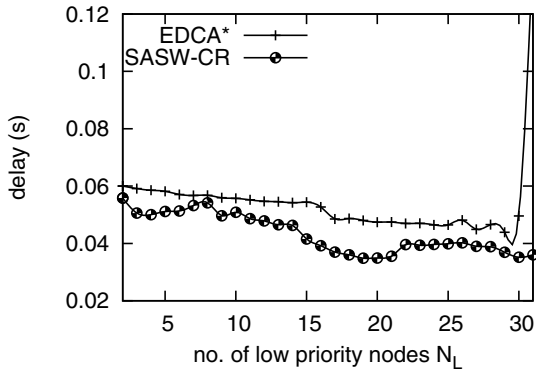
	$N_L = 1, N_H = 31$		$N_L = 31, N_H = 1$	
	T_L^*	T_H^*	T_L^*	T_H^*
EDCA*	59	545	269	206
SASW-CR	236	518	507	843

the high and low priority nodes, which corresponds to the value that we have used in our simulations ($R = 0.3$).

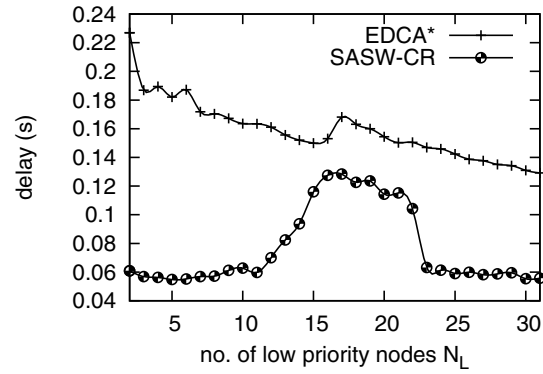
When $N_L = 31, N_H = 1$, the high priority traffic in EDCA suffers severe throughput deterioration as the number of low priority nodes is significantly higher than that of high priority nodes. The cooperative retransmission technique in SASW-CR allows high priority traffic to achieve higher per-node throughput, while maintaining the low priority per-node throughput at about 30%.

C. Delay Performance

The delay performances achieved by EDCA and SASW-CR are illustrated in Figure 10. In Figure 10(a), it can be seen that the delay incurred by the high priority data using SASW-CR is always smaller than that incurred using EDCA, due to sliding contention window and cooperative retransmission techniques



(a) High priority data delay



(b) Low priority data delay

Fig. 10. Delay Performance of SASW-CR.

used by SASW-CR. In addition, as N_L tends towards N , it is more likely for starvation to occur for the high priority data class when EDCA is being used; this results in the extremely long delays being experienced by the small number of high priority data packets that are in the network.

Figure 10(b) illustrates the delay incurred by the low priority data class when N_L increases. When $10 < N_L < 20$, the increase in the delay incurred by low priority nodes using SASW-CR is due to the nodes entering the **TP** state, which allocates more time slots to the high priority contention window. Despite the cooperative retransmission mechanism in SASW-CR, whereby low priority nodes give up their transmission opportunities to retransmit data for high priority nodes, the delay incurred by nodes using SASW-CR is always lower than that using EDCA. This is due to the efficient channel utilization of SASW-CR, which segregates the contention between the high and low priority classes.

VI. CONCLUSION

The impulse based nature of UWB renders many existing MAC protocols unsuitable for use in UWB wireless sensor networks. In this paper, we propose the SASW-CR protocol, which provides QoS support without the use of carrier sensing. SASW-CR utilizes the Sliding Contention Window and Cooperative Retransmission techniques to provide QoS to higher priority traffic. In addition, it is able to improve the overall traffic throughput and delay performance.

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