SAUCeR: A QoS-aware Slotted-Aloha based
UWB MAC with Cooperative Retransmissions

Summary

The inherent temporal connectivity and existence of impairments in wireless channels pose challenges to network performance. Cooperative communication has been proposed as an effective technique to mitigate the imperfections of the wireless medium by exploiting channel diversity and availability of neighboring nodes that can act as relays. Although numerous cooperative communication techniques have been proposed in the literature, most of them do not consider Quality of Service (QoS) issues in a wireless sensor network.

In this work, we study how cooperative communication can be applied to achieve differentiated QoS in a sensor network that uses Ultra-Wideband (UWB) as its underlying PHY layer technology. SAUCeR is a Slotted-Aloha based Ultra-wideband medium access control protocol with Cooperative Retransmissions that provides differentiated QoS in networks with varying traffic classes. Despite the high transmission rates provided by UWB, its impulse-based nature renders many conventional carrier sensing MAC protocols incompatible. Consequently, SAUCeR utilizes Slotted-Aloha to reduce packet collisions without the need for carrier sensing. Differentiated QoS is provided by allocating different resources (time slots) to varying traffic classes to segregate the contention between them. A QoS-aware cooperative retransmission technique and two distributed relay selection schemes are also introduced to improve overall traffic throughput and reduce end-to-end delay, while preventing the starvation of any traffic class.

KEY WORDS: cooperative communication; quality of service; medium access control; ultra-wideband

1. Introduction

The inherent temporal connectivity and existence of impairments in wireless channels have long posed challenges to the performance of wireless networks. Cooperative communication [1][2][3][4][5][6] has been proposed as an effective technique to mitigate the imperfections of the wireless medium by exploiting channel diversity and availability of neighboring nodes that can act as relays of the transmitter. Effectively, instead of the source node retransmitting over the same intermittent link after a failed transmission, an intermediate relay can be used to cooperatively retransmit the overheard packet to the intended destination. Such a communication paradigm has several notable advantages, including high spatial diversity, robustness to channel variations, increased reliability and improved overall network performance.

Following the release of First Report and Order [7] by the Federal Communications Commission (FCC) in 2002, which legalized the commercial use of unlicensed Ultra-Wideband (UWB) [8], there has been mounting interest in the adoption of cooperative networking techniques in UWB-based networks. Using very narrow duration pulses for the transmission of bits, UWB is able to achieve extremely large bandwidths and data rates [9]. This makes it a viable physical (PHY) layer technology for use in wireless sensor networks, which can be deployed.
for a multitude of applications such as healthcare monitoring and tactical surveillance.

Cooperative communication techniques have been applied to UWB-based networks at various layers of the networking protocol stack. At the PHY layer, the receiver can combine and decode signals from multiple simultaneous retransmissions using either Amplify and Forward (AF) or Decode and Forward (DF) [10]. In medium access control (MAC) layer cooperative solutions such as UCORS [11], the receiver can decode only one signal at a time and multiple simultaneous collisions result in packet collisions. Network layer cooperative communication has also been proposed [12][13], whereby the next-hop of a routing path is dynamically selected depending on prevailing link conditions. A joint cooperative MAC and routing (JCMR) protocol is presented in [14] to reduce the number of attempts required for successful packet transmissions. However, these existing protocols for UWB-based networks typically do not consider Quality of Service (QoS) issues in their designs.

QoS is of particular importance in UWB-based networks [15] as the high bit rates supported by UWB allows data of varying information quality and bandwidth or delay requirements to be collected from the nodes. One such application scenario is a continuous health monitoring system [16], whereby sensors of varying modalities may be deployed for data acquisition. Multimedia data, such as video and voice that are captured by cameras and acoustic arrays, can typically provide richer information content about the environment. Consequently, data traffic that is generated from these sources should be provisioned with better QoS than text-based data containing pressure or temperature information. On the other hand, it is also crucial not to starve low priority data as these may provide valuable information diversity. Although QoS schemes have been proposed in the literature [17], most of them are designed for generic wireless systems and do not exploit the unique characteristics of impulse-based UWB, such as availability of precise location information at low cost and multipath resolution.

In this paper, we study how cooperative communication can be used to provide differentiated QoS in a network that uses UWB as its underlying PHY layer technology. SAUCeR is a Slotted-Aloha based Utra-wideband medium access control protocol with Cooperative Retransmissions that provides differentiated QoS in a network with varying traffic classes. Despite the high transmission rates provided by UWB, its impulse-based nature renders many conventional carrier sensing MAC protocols incompatible. Consequently, SAUCeR utilizes Slotted-Aloha to reduce packet collisions without the need for carrier sensing. Differentiated QoS is provisioned by allocating different resources (time slots) to varying traffic classes to segregate the contention between them. A QoS-aware cooperative retransmission technique and two distributed relay selection schemes, viz. Strongest Overall Signal Strength (SOSS) and Random Relay (RR), are proposed to improve overall traffic throughput and reduce end-to-end delay, while preventing the starvation of any traffic class. SOSS exploits localization information that is cheaply available using the UWB PHY to select the best relay. In contrast, RR does not have pre-determined relays; instead, potential relays are assigned relaying probabilities using little overheads such that packet collisions and duplicates are minimized. The efficacy of SAUCeR is demonstrated through both theoretical analysis and simulations.

The rest of the paper is organized as follows. Section 2 discusses background and related work. Protocol details of SAUCeR and its analytical framework are presented in Section 3. In Section 4, we evaluate and discuss the performance of SAUCeR using extensive simulations. We conclude this work in Section 5.

2. Background and Related Work

2.1. Medium Access Control in UWB Networks

The MAC layer is responsible for the arbitration of resources to the nodes in the network. Existing MAC protocols for wireless networks typically utilize carrier sensing for Clear Channel Assessment (CCA) and to avoid collisions between concurrent transmissions that are within interference ranges. However, the impulse-based nature and low transmission power of UWB makes it difficult for the efficient detection of UWB signals. Consequently, conventional carrier sensing based MAC protocols are incompatible with a UWB PHY [18][19] and special considerations must be given to the design of the UWB MAC protocol [20] to exploit the unique characteristics of UWB [21].

Aloha is considered the most feasible MAC in impulse-based Time-Hopping (TH) UWB networks [21], due to its direct applicability without the need for excessive signaling or control overheads, low duty-cycles which significantly reduces packet collision probability, and in-built medium access mechanism...
based on TH codes. As such, a number of Aloha-based MAC protocols for UWB networks have been proposed in the literature [19][22][23][24][25][26].

The IEEE 802.15.4a standard for LR-WPANs (Low-Rate Wireless Personal Area Networks) [23] which includes UWB as an alternative PHY uses slotted-Aloha for medium access. It adopts a superframe structure (Figure 1) similar to IEEE 802.15.3 [27] to allow for interoperability between existing narrowband WPANs and UWB-based WPANs. Each superframe comprises of a beacon, an active period and an inactive period. The time slots within the active period can be further divided into contention access period (CAP) and contention free period (CFP).

U.C.A.N. [24] adapts the IEEE 802.15.3 MAC standard with the inclusion of additional ranging and relaying features, and uses slotted-Aloha instead of CSMA/CA for random access during the CAP of the superframe. (UWB)$^2$ [25] is a multi-channel MAC protocol that adopts a pure Aloha approach and uses a common TH code as the control channel. Dedicated data channels are provided via transmitter-oriented TH codes that are distributed using a code assignment algorithm. In [26], the authors show that the performance of (UWB)$^2$ improves when slotted-Aloha is used instead of pure Aloha in high traffic loads, due to lower probability of packet collisions. Tan et al [19] evaluates the performance of slotted-Aloha over TH-UWB in a single-hop sensor network.

SASW-CR [22], which is a QoS MAC protocol for UWB networks, utilizes slotted-Aloha for medium access in each MAC frame.

A UWB-based joint PHY/MAC protocol based on Dynamic Channel Coding (DCC) has also been proposed in [28]. Instead of enforcing mutual exclusion, DCC-MAC adapts channel codes and uses incremental redundancy to mitigate interference. Contention among sources with the same intended destination is then resolved using a private MAC that is achieved via a combination of receiver-based and invitation-based selection of TH sequences.

Despite the widespread adoption of Aloha to avoid carrier sensing in impulse-based UWB networks, it should be noted that there exists alternative mechanisms for CCA in these networks. August et al [29] proposes the use of a pulse sense mechanism which enables the detection of a busy medium by examining the spectral power components of the received signal. It thus provides a service that is synonymous to carrier sensing in the narrowband domain, at the cost of additional circuit complexity.

2.2. MAC Layer Cooperative Communication

Cooperative communication is an effective technique to leverage the advantages of spatial diversity without the need for complex signal processing and presence of multiple antennas on a tiny sensor node. By overhearing and buffering packets that are transmitted by the neighbors, a node can potentially help to retransmit a failed direct transmission to the destination and thus improve transmission quality.

Existing work on MAC layer cooperative communication includes [4][11][30][31][32] and involves two main issues: (i) selection of neighbors to help in the relaying process; and (ii) assignment of relaying probability of each selected neighbor. The selection of neighbors as relays may be based on the shortest distance to the destination, best link quality, lowest traffic load and/or highest remaining energy. In situations where multiple relays are selected to help in the cooperative retransmission process, different relaying probabilities (or backoff delays) are usually assigned to potential relays to minimize packet collisions and duplicates. However, these schemes do not consider QoS issues in the network. Although SASW-CR [22] studies cooperative communication with resource allocation based on QoS, it uses a deterministic relay selection mechanism that is not robust in the face of temporal link connectivity.

2.3. QoS MAC Protocols in UWB Networks

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

The standard protocol which provides QoS support for WLANs (Wireless Local Area Networks) is IEEE 802.11e [33]. The Distributed Coordination Function (DCF) in IEEE 802.11e uses CSMA/CA and a backoff mechanism for contention resolution within a contention window. In order to provide QoS support, Enhanced Distributed Channel Access (EDCA) is used to assign different traffic priority classes to varying types of traffic. The different priority classes in each node utilize non-overlapping contention windows of varying sizes. The contention window for high priority traffic precedes that for low priority traffic (see Figure 2); this is achieved by using shorter backoff periods for high priority traffic. Consequently, the high priority traffic from a particular node can achieve higher average throughput and less average delay than the low priority traffic that is generated from the same node.

However, contention between high and low priority traffic from different nodes can still happen as contention windows belonging to a particular class of traffic at one node may overlap with another traffic class at another node. Low priority traffic may be delayed infinitely by high priority traffic, and vice versa. Starvation of one traffic class may also occur when traffic is dominated by the other traffic class. In addition, IEEE 802.11e is not suitable for UWB WSN as it requires carrier sensing.

A centralized MAC for QoS support has been proposed in the context of UWB-based sensor networks [34][35]. A joint scheduling and resource control algorithm is used to assign each transmission session to a time slot, as well as to dynamically assign transmission rates and powers to nodes. The algorithm is based on a superframe structure and can differentiate between QoS and best effort traffic types; however, it does not prevent starvation of best effort traffic. [36] presents a distributed MAC that uses separate data and control channels based on different TH sequences. The adaptive resource allocation algorithm assigns power and bit rates according to prevailing traffic conditions; however, each node has to keep track of the current condition of the entire network.

Our proposed MAC protocol for UWB sensor networks combines the frame structure of IEEE 802.15.3 with differentiated contention windows in the EDCA component of IEEE 802.11e to provide differentiated QoS. In addition, it utilizes a QoS-aware cooperative retransmission technique and two distributed relay selection schemes that exploit the unique characteristics of UWB to improve overall throughput and reduce packet delays.

3. SAUCeR: Protocol Description

In this section, we describe the protocol details of SAUCeR - a Slotted-Aloha based UWB medium access control protocol with Cooperative Retransmissions that provides differentiated QoS in networks with varying traffic classes. We first present the network and traffic models, followed by the three main mechanisms of SAUCeR: (i) resource allocation; (ii) cooperative retransmission; and (iii) relay selection.

3.1. Network Model

SAUCeR is a distributed MAC protocol that can be applied in generic sensor networks. For ease of illustration, we consider a subset of the network comprising of N sensor nodes connected to a destination node via a single hop link. The underlying PHY layer used by SAUCeR is TH-UWB, whereby each signal is transmitted over several symbols, and each of these symbols comprises of a burst of extremely short pulses. The transmitted signal undergoes large scale fading, which can be characterized by [37]:

\[
PL(d) = PL_0 + 10n\log_{10}\frac{d}{d_0} + S, \tag{1}
\]

where \(d\) is the distance between the transmitter and the receiver; \(d_0\) is the reference distance of 1 meter; \(PL_0\) is the pathloss at the reference distance; \(n\) is the pathloss exponent; and \(S\) is a Gaussian-distributed random variable with zero mean and standard deviation \(\sigma_S\).

Due to the impulse nature of TH-UWB, carrier sensing is not feasible. Although Slotted-Aloha requires time synchronization and incurs more control overheads than pure Aloha, it has been shown to provide better throughput performance than the latter [26], and is directly inter-operable with the IEEE 802.15.4a standard [23], which also uses

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**Figure 2.** Contention window (CW) of IEEE 802.11e.
Slotted-Aloha. Furthermore, time synchronization can be provided with high accuracies at low cost in impulse-based TH-UWB networks [38]. Consequently, SAUCeR makes use of Slotted-Aloha as the MAC protocol with TH-UWB incorporated into the frame structure [19].

In the simplified frame structure as shown in Figure 3, a beacon slot $B$ of length $T_{\text{beacon}}$ precedes each MAC frame and is used for various purposes such as synchronization, signaling and other network status updates. To minimize collisions in dense and/or multihop networks, each node transmits beacons only when updates are necessary. The beacon frequency is dependent on various factors such as node mobility and link transitivity, and has to be selected such that SAUCeR adapts its resource allocation quickly enough without excessive overheads.

A frame also comprises of $m$ time slots, each of length $T_{\text{slot}}$. A node selects only one out of the $m$ possible time slots within each $T_{\text{frame}}$ to transmit its data. Each data packet (and its corresponding ACK) is assumed to be transmitted within $T_{\text{slot}}$. A packet collision (and subsequently packet loss) arises whenever one or more packets are transmitted in the neighborhood using the same time slot. Packet losses may also arise due to radio propagation impairments.

### 3.2. Traffic Model and QoS Provisioning

We assume that all the $N$ neighboring nodes of the destination in the network can be classified as high priority or low priority nodes, depending on the traffic class (or modality) of the data they generate. Figure 4 shows a network topology whereby the different nodes in the network generate data of different priorities to be transmitted to a particular destination.

SAUCeR provides differentiated QoS support in the following ways:

- Maximize the total traffic throughput;
- Prevent starvation in all traffic classes by allocating as least $R$ proportion of the resources (time slots) to each traffic class; and
- Improve transmission quality and QoS of high priority traffic whenever possible through exploitation of cooperative retransmissions by low priority nodes.

### 3.3. Resource Allocation

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

Recall that $m$ is the total number of time slots within each MAC frame. We further denote the number of time slots within $H_{\text{cwin}}$ and $L_{\text{cwin}}$ as $|H_{\text{cwin}}|$ and $|L_{\text{cwin}}|$ respectively, where $|H_{\text{cwin}}| + |L_{\text{cwin}}| = m$. Let the number of active nodes (as seen by the destination) within the previous time epoch be $N_a \leq N$; 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 corresponding values of $|H_{\text{cwin}}|$ and $|L_{\text{cwin}}|$ are adaptively adjusted based on $N_H$ and $N_L$ using Algorithm 1, and broadcasted by the destination to its neighboring nodes during the beacon duration $T_{\text{beacon}}$ after each update.

The following describes the resource allocation component of SAUCeR as illustrated in Algorithm 1. If the proportion of active high priority nodes in the last time epoch is less than or equal to $R$ (i.e. $N_H \leq R \cdot N_a$), where $0 < R \leq 0.5$ is a predetermined threshold, SAUCeR prevents starvation of high priority traffic by allocating $R \cdot m$ slots to
Algorithm 1 Resource Allocation in SAUCeR

Require: $N_H$ - number of active high priority nodes
$N_L$ - number of active low priority nodes
$N_a$ - total number of active nodes
$m$ - total number of time slots in each $T_{frame}$
$R$ - minimum proportion of resources to be allocated to each traffic class

Ensure: $|H_{cwin}| \geq R \cdot m$ and $|L_{cwin}| \geq R \cdot m$
if $N_H \leq R \cdot N_a$ then
$|H_{cwin}| = R \cdot m$
$|L_{cwin}| = m - |H_{cwin}|$
else
$|L_{cwin}| = R \cdot m$
$|H_{cwin}| = m - |L_{cwin}|$
end if
return

$H_{cwin}$. The remaining $(1 - R) \cdot m$ slots are allocated to low priority nodes, which can use them for direct transmission of low priority traffic or cooperative retransmission of high priority traffic. Otherwise, if the proportion of active low priority nodes in the last time epoch is less than or equal to $R$ (i.e. $N_H \geq R \cdot N_a$), SAUCeR allocates $R \cdot m$ slots to $L_{cwin}$ to prevent starvation of low priority traffic. The remaining slots are allocated to $H_{cwin}$ to improve the QoS of high priority traffic.

By ensuring that the minimum proportion of resources allocated to each class at any time is at least $R$, SAUCeR can effectively minimize starvation of either traffic class. In addition, through the use of differentiated contention windows such that $H_{cwin}$ precedes $L_{cwin}$ within each MAC frame, SAUCeR can achieve differentiated QoS between high and low priority traffic.

3.4. Cooperative Retransmission

SAUCeR utilizes cooperative retransmissions to improve overall transmission quality and QoS of the higher priority traffic class. It exploits the broadcast nature and channel diversity of wireless communications by overhearing neighboring packet transmissions and opportunistically relaying packets that are lost during the initial direct transmission between the source node and the intended destination.

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 that are successfully overheard by $i$. It should be noted that only the originally transmitted data packet will be buffered by neighboring nodes; a cooperatively retransmitted packet that is overheard will not be buffered by any node. This eliminates the ping-pong effect of having multiple relays that cooperatively retransmit the same data packet in subsequent MAC frames. During each MAC frame, node $i$ may transmit a data packet from either its data queue or overhearing buffer, depending on its current mode:

**Selfish Mode** Node $i$ always transmits its own packet from the data queue if the queue is not empty. If the data queue of node $i$ is empty, it selects a packet from its overhearing buffer to transmit.

**Selfless Mode** Node $i$ always selects a packet from the overhearing buffer to relay (if the overhearing buffer is not empty), instead of transmitting from its own data queue. If the overhearing buffer is empty, node $i$ transmits its own 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. A low priority node $i$ is in selfless mode only when the following two conditions are satisfied:

1. the packet delivery ratio of data packets generated by $i$ is at least $R$; and
2. the proportion of low priority nodes is at least $R$, i.e. $N_L \geq R \cdot N_a$.

Otherwise, node $i$ will be in selfish mode to prevent starvation of low priority data.

It is assumed that the ACK corresponding to each data packet can be received correctly by all the one-hop neighbors of the destination node within the same
Fig. 6. Overhearing behavior with cooperative retransmission.

Fig. 7. Cooperative retransmission with multiple relays.

retransmission by LP, the delay of $D_1$ is reduced by at least $t_3 - t_2$.

3.5. Relay Selection

In a realistic network, the direct transmission of a data packet $D$ may be overheard by more than one neighboring nodes. Figure 7 illustrates a network whereby the transmission of $D$ 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 destination. If $D$ does not reach the destination successfully, $LP_1$, $LP_2$ and $LP_3$ become the potential relays to cooperatively retransmit the overheard packet to the destination. 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. It is therefore important to select an appropriate number of suitable relays to participate in each cooperative retransmission process.

It has been shown in existing literature that the optimal number of relays that should help to cooperatively retransmit a packet is one, when the link quality of the cooperative transmission is relatively good [11]. Instead of using an election algorithm to select the optimal relay(s), which is expensive as it requires inter-nodal communications, SAUCeR makes use of simple and distributed schemes to select the best relay(s) in a network. In the following, we describe our generic relay selection framework and two specific schemes that can be incorporated into SAUCeR, viz. Strongest Overall Signal Strength (SOSS) and Random Relay (RR). Table I summarizes the symbols and notations used in the description and analysis of our proposed relay selection schemes.

The one-hop neighborhood of a source node $s$ is denoted as $N_s$. When the direct transmission of a data packet $D$ from the source node $s$ to the destination node $d$ fails, each node $i \in N_s$ independently and distributively determines if it should be a relay for
Table I. Summary of symbols and notations used

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$L$</td>
<td>normalized traffic load ($0 \leq L \leq 1$)</td>
</tr>
<tr>
<td>$m$</td>
<td>number of time slots per MAC frame</td>
</tr>
<tr>
<td>$N_s$</td>
<td>one-hop neighborhood of source node $s$</td>
</tr>
<tr>
<td>$N^{HL}$</td>
<td>set of high priority nodes, equivalent to set of potential relays of a high priority source node</td>
</tr>
<tr>
<td>$N^{LL}$</td>
<td>set of low priority nodes, equivalent to set of potential relays of a low priority source node</td>
</tr>
<tr>
<td>$P_{re}^d$</td>
<td>link error probability of direct transmission link</td>
</tr>
<tr>
<td>$P_{re}^c$</td>
<td>link error probability of cooperative retransmission link</td>
</tr>
<tr>
<td>$p_r^i$</td>
<td>relaying probability of a potential relay $i$</td>
</tr>
<tr>
<td>$p_r^c$</td>
<td>(common) relaying probability such that $p_r^c = p_r^k, i \neq k$</td>
</tr>
<tr>
<td>$</td>
<td>H_{cwin}</td>
</tr>
<tr>
<td>$</td>
<td>L_{cwin}</td>
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</table>

$D$: the probability that $i$ is willing to cooperatively retransmit $D$ to $d$ under such circumstances is denoted as $p_r^i$. Note that here, a potential relay helps to cooperatively retransmit only packets generated by nodes from the other traffic class, i.e. traffic originating from high priority nodes will only be relayed by low priority nodes, and vice versa. This is due to the structure of the MAC frame, whereby the high priority contention windows $H_{cwin}$ and low priority windows $L_{cwin}$ alternate; hence, selecting a relay from the same priority class may not yield significant delay savings. In addition, a high priority node that helps to relay packets for a low priority node will not cause detrimental effects to the performance of high priority traffic, since a high priority node is always selfish mode and will help to relay packets only when it does not have any data to send.

With the use of cooperative retransmissions, a packet $D$ may still fail to reach the destination under any of the below situations:

- The direct transmission from $s$ to $d$ fails, and $s$ does not have any potential relays to help retransmit $D$.
- The direct transmission from $s$ to $d$ fails, and none of the potential relays in $N_s$ successfully retransmit $D$.

Denoting the link error probability of a cooperative retransmission as $P_{re}^c$, the probability $P_{re}^u$ that an arbitrary relay $i \in N_s$ does not successfully retransmit packet $D$ is the probability that: (i) $i$ does not overhear $D$ successfully; (ii) $i$ overhears $D$ successfully, but does not help to cooperatively retransmit $D$; or (iii) $i$ overhears $D$ successfully, cooperatively retransmits $D$, but the retransmitted packet does not reach the destination successfully. Hence, $P_{re}^u$ is given by:

$$P_{re}^u = P_{re}^c + (1 - P_{re}^c) \cdot (1 - p_r^i) + (1 - P_{re}^c) \cdot p_r^i \cdot P_{re}^c.$$  

(2)

In the following derivations, it is assumed that the probability of packet collisions is negligible (as cooperative relays are typically used only when the traffic load is low) and $s$ does not retransmit at all if its direct transmission to the destination fails. Denoting the link error probability of a direct transmission as $P_{re}^d$, the probability $P_f$ that packet $D$ fails to reach the destination is then given by:

$$P_f = P_{re}^d \prod_{i \in N_s} P_{re}^i.$$  

(3)

The (expected) **improvement** on high priority traffic throughput per MAC frame $I_H$ is achieved when at least one potential relay successfully retransmits high priority packets whose direct transmissions to the destination have failed, and is given by:

$$I_H = \min(|H_{cwin}|, L_{cwin} \prod_{i \in N_L} P_{re}^i).$$  

(4)

where $0 \leq L \leq 1$ is the normalized traffic load; and $N_L$ is the set of low priority nodes (taken to be equivalent to set of potential relays of a high priority source node $s$).

As low priority traffic may also be relayed by high priority nodes when high priority nodes do not have packets to transmit, the (expected) improvement of
low priority traffic per MAC frame $I_L$ is:
\[ I_L = \min(|L_{cwin}|L^2P_c^d(1 - L)(1 - \prod_{i \in N^H} P_u^d), \]
\[ |L_{cwin}|), \]

where $N^H$ is the set of high priority nodes (taken to be equivalent to set of potential relays of a low priority source node $s$).

The corresponding loss on low priority traffic throughout $L_L$ is due to low priority nodes relaying high priority traffic at the expense of low priority traffic. The loss happens when there is at least one low priority node that overhears the packet successfully and is willing to relay it; this includes relayed packets that are not successfully transmitted to the destination, and is approximately:
\[ L_L = \min(|H_{cwin}|L^2P_c^d(1 - \prod_{i \in N^L} (1 - P_e^d)p_i^d), \]
\[ |L_{cwin}|). \]

Finally, the overall improvement achieved per MAC frame $I_{total}$ is:
\[ I_{total} = I_H + I_L - L_L \]

In our analysis above, it is assumed that the link error probability of each ACK is zero. This assumption is common in many network models due to the small size of ACKs, which reduces its packet error probability. Although the occasional loss in ACK may cause unnecessary cooperative retransmissions to be triggered by potential relays, resulting in the reception of duplicate packets, these occurrences are very infrequent and will not cause originally successful packet transmissions to be lost.

### 3.5.1. Strongest Overall Signal Strength (SOSS)

We first note that the successful reception of any packet between two arbitrary nodes $i$ and $j$ in a wireless channel is inherently dependent on the signal strength $P_{ij}$ of the packet at the receiver node $j$. This signal strength $P_{ij}$ can be derived from the large-scale fading model in Equation 1, which is in turn dependent on the distance between $i$ and $j$. Typically, a higher signal strength denotes a higher probability of successful packet reception.

Due to the wide bandwidth provided by UWB and its high resolution capability in the time domain [39], it can achieve extremely precise ranging results using Angle-of-Arrival (AoA), Time-of-Arrival (ToA) and Time-Difference-of-Arrival (TDoA) techniques. Most of these localization schemes can be implemented with low complexity [40] and low cost [41][42]. Consequently, each source node $s$ is assumed to have complete location information of the set of potential relays $N_s$ in its one-hop neighborhood, which can be readily provided by the underlying UWB PHY. Note that for each potential relay $i \in N_s$, the destination node $d$ is assumed to be within the transmission range of $i$. Any other neighboring node of $s$ that does not have the destination $d$ in its neighborhood will not be able to serve as a potential relay between $i$ and $d$.

Using known location information of its potential relays $N_s$ and the destination $d$, $s$ can compute the estimated signal strength $P_{si}$ and $P_{id}$ $\forall i \in N_s$ before transmitting each data packet $D$ to $d$. The node $j \in N_s$ with the largest value of $P_{sj} + P_{jd}$ will have its node identifier $j$ included in the packet header. All other nodes which overhear $D$ will discard it; only $j$ will store $D$ in its overhearing buffer and retransmit it later if necessary. However, if the selected relay $j$ fails to overhear $D$ during the initial direct transmission from $s$ to $d$, then cooperative retransmission will not take place. Essentially, the SOSS scheme is a specific case of relay selection whereby $p_i^d = 1$ and $p_{id}^c = 0 \forall i \in N_s \setminus j$.

Figure 8 illustrates how the overall throughput improvement $I_{total}$ varies with different traffic loads $L$, when $P_c^d = 0.5$, $m = 8$ and $R = 0.5$ such that $N_H = N_L$ and $|H_{cwin}| = |L_{cwin}| = \frac{m}{2}$. The optimum throughput improvement of SOSS is dependent on $P_c^d$ and generally achieved when the traffic load $L < 0.5$. For high traffic loads ($L > 0.6$), the throughput improvement can be negative as
the throughput loss of low priority traffic exceeds the total throughput improvement of high and low priority traffic, i.e. $\text{Loss}_L > (I_H + I_L)$. When link error probability of cooperative retransmissions is less than that for direct transmissions, i.e. $P_e^c < P_e^d = 0.5$, cooperative retransmissions is generally not used as it cannot improve transmission quality. As nodes which are nearer to the source typically experience lower link error rates, these nodes should be used as relays in preference to nodes that are located further away.

The pre-selection of a relay $j$ using SOSS before direct transmission of packet $D$ from source $s$ to destination $d$ ensures that only one node will cooperatively retransmit each packet, thus reducing packet collisions and overheads, eliminating packet duplicates, as well as maximizing the gain of cooperative retransmissions.

However, as SOSS is mainly designed for relatively static networks where nodes have little or no mobility and links have little variation, the pre-selection of a particular relay may not fully exploit the gains of cooperative retransmissions all the time. In particular, when nodes are mobile or when there are frequent link variations in the cooperative channel, the pre-selected relay may not be able to retransmit the packet to the destination successfully. Under such circumstances, time synchronization as well as localization and network status updates must then be performed more frequently to ensure that the best relay is selected whenever possible. In Section 3.5.2, we describe the Random Relay (RR) selection scheme, which is more robust in varying network conditions.

3.5.2. Random Relay

In the random relay selection scheme, we let each node $i \in N_s$ have equal probability to be a relay for $s$ such that $p_i^s = p_i^c \forall i, k \in N_s, i \neq k$. The common relaying probability $p_r = p_i^c \forall i \in N_s$ is then chosen such that:

$$P_f < T, \quad (8)$$

where $0 < T < 1$ is a threshold that determines the probability that packet losses are acceptable in SAUCeR. A smaller value of $T$ reduces the packet loss ratio but increases the relaying probability $p_r$ of each node, which can lead to increased cooperative retransmission attempts. However, as copies of each successfully delivered packet are flushed from the data queue and overhearing buffers of the source and its potential relays upon reception of an ACK, the likelihood of packet duplicates and collisions remains small. Figure 9 illustrates how the relaying probability $p_r$ varies as the number of potential relays $|N_s|$ increases. It can be seen that as $|N_s|$ increases, $p_r$ decreases to minimize the number of cooperative retransmission attempts among the potential relays.

Figure 10 shows the total throughput improvement $I_{total}^{RR}$ as traffic load $L$ increases, when $P_e^d = 0.5$, $m = 8$ and $R = 0.5$ such that $N_H = N_L$ and $|L_{cwin}| = \frac{m}{T}$. The number of potential relays for each traffic class is taken to be $|N_s^H| = |N_s^L| = 4$ and the corresponding values of $p_r$ for each value of $P_e^c$ are chosen to satisfy $T = 0.01$. As like the SOSS scheme, there exists an optimal traffic load whereby the throughput improvement of the relay selection scheme is at its peak; however, it can also be observed that the RR scheme generally achieves higher throughput improvements than SOSS for varying traffic loads.
In our study, each node uniform-randomly selects one slot for data transmission, from the $H_{\text{cwin}}$ and $L_{\text{cwin}}$ contention windows within the $m$ slots that are available in a MAC frame. When the number of potential relays $|N_r|$ is much larger than $m$, excessive collisions can occur when multiple potential relays attempt to select the same transmission slot to cooperatively retransmit the same packet. However, the optimal throughput gain is achieved when only one relay successfully retransmits the same packet. Hence, an alternative method to the uniform-random selection of slots, is to adopt a truncated geometric distribution as like the one used in the Sift MAC protocol [43], which can help to reduce the number of potential relays that cooperatively retransmit a packet.

In the next section, we evaluate the performance of SAUCeR using simulations and considering more complex scenarios whereby: (i) packet collisions can occur; (ii) the proportion of high priority and low priority nodes may not be equal; (iii) the source node is allowed to retransmit once when the direct transmission fails; and (iv) the relay can be from the same traffic class.

4. Performance Evaluation

We evaluate the performance of SAUCeR in Qualnet 4.0 [44] and compare it with EDCA, which is used by IEEE 802.11e for QoS support, using the same underlying UWB physical channel and Slotted-Aloha MAC frame structure. We adapt EDCA to work with TH-UWB and Slotted-Aloha in the following way: Within each MAC frame, $1 - R$ of the first $m$ time slots are allocated to high priority nodes and the remaining $R$ proportion of the time slots are allocated to low priority nodes. Upon a successful data transmission, a node re-initializes its MAC frame at the next time slot; therefore, the MAC frames of different nodes may not be synchronized (i.e. may not start at the same time) in EDCA. In the event of packet loss, each source node in EDCA and SAUCeR is allowed to have another retransmission attempt.

The network size is fixed at $N = 32$ sensor nodes (sources) and 1 destination. The destination node is within the transmission ranges of all the 32 sensor nodes; hence, each of them is a potential relay for all the other nodes (of a different traffic class) in the network. Two classes of traffic, viz. high priority and low priority, are generated at the sensor nodes. The number of nodes that generate low priority data $N_L$ is increased from 2 to 30; the corresponding number of nodes that generate high priority data $N_H = N - N_L$ is decreased from 30 to 2. The traffic load $L$ used in all our simulations is 20%.

The number of time slots $m$ is fixed at 8 per MAC frame. The time epoch has a duration of $200 \times T_{\text{frame}}$, where $T_{\text{frame}} = 4\text{ms}$; hence, the destination updates its resource allocation and broadcasts the new allocation periodically after every 0.8 seconds. The link error probability of direct transmission $P_e^d$ is fixed at 0.5, while the link error probability of cooperative transmission $P_e^c$ is varied between 0.1 to 0.5 under different scenarios. The link error probabilities of packet transmissions between different node pairs are assumed to be independent and random. The value of the threshold $T$ used in Equation 8 is set to 0.01. The various parameters used in our simulations are summarized in Table II.

### Table II. Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Power</td>
<td>-14.32 dBm</td>
</tr>
<tr>
<td>Channel Frequency</td>
<td>4 GHz</td>
</tr>
<tr>
<td>Center Frequency</td>
<td>4492.8 MHz</td>
</tr>
<tr>
<td>Channel Bandwidth</td>
<td>499.2 MHz</td>
</tr>
<tr>
<td>Network Size $N$</td>
<td>32</td>
</tr>
<tr>
<td>Time Slot Length $T_{\text{slot}}$</td>
<td>0.5 ms</td>
</tr>
<tr>
<td>No. of Time Slots $m$</td>
<td>8</td>
</tr>
<tr>
<td>Frame Length $T_{\text{frame}}$</td>
<td>$8 \times T_{\text{slot}} = 0.5 \text{ ms}$</td>
</tr>
<tr>
<td>Time Epoch (s)</td>
<td>$200 \times T_{\text{frame}} = 0.8 \text{ s}$</td>
</tr>
<tr>
<td>Packet Size (Bytes)</td>
<td>46</td>
</tr>
<tr>
<td>Traffic Load $L$</td>
<td>20%</td>
</tr>
<tr>
<td>$P_e^d$</td>
<td>0.5</td>
</tr>
<tr>
<td>$P_e^c$</td>
<td>${0.1, 0.2, 0.3, 0.4, 0.5}$</td>
</tr>
<tr>
<td>$R$</td>
<td>${0.1, 0.2, 0.3, 0.4, 0.5}$</td>
</tr>
<tr>
<td>Threshold $T$</td>
<td>0.01</td>
</tr>
</tbody>
</table>

4.1. Varying numbers of HP and LP nodes

Figures 11 - 13 illustrate the performance of EDCA and SAUCeR in a network with varying number of LP nodes $N_L$. The relay selection mechanism used in SAUCeR is Strongest Overall Signal Strength (SOSS), whereby a fixed relay is used for each data packet. The value of $R$ is set to 0.3; hence, the minimum proportion of resources (time slots) that are allocated
to each class of traffic is 0.3. The link error probability of cooperative retransmissions $P_e^c$ is fixed at 0.1.

As $N_L$ increases, the generated number of LP data packets increases while the generated number of HP data packets decreases correspondingly. This results in decreasing HP throughput for both EDCA and SAUCeR as shown in Figure 11(a), and increasing LP throughput as shown in Figure 11(b). Figure 11(c) shows that the normalized total throughput achieved by SAUCeR is approximately 15% to 45% higher than that achieved by EDCA for varying values of $N_L$. The throughput improvement is brought about by the joint use of disjoint contention windows and cooperative retransmissions, which efficiently increases the effective utilization of the shared communication channel and reduces the number of packet collisions between the two traffic classes.

Figure 12 shows that the performance improvement in packet delivery ratio (PDR) for HP and LP traffic using SAUCeR is approximately 10% and 30% respectively. As $N_L$ increases, HP PDR generally increases as there is less collisions among the HP traffic and LP PDR decreases due to increased collisions among the LP traffic. Note that the slight drop in HP PDR in Figure 12(a) and corresponding increment in LP PDR in Figure 12(b) when $N_L \approx$
4.2. Varying values of $R$

We study the effect of varying $R$ from 0.1 to 0.5, on the performances of EDCA and SAUCeR in Figure 14. The value of $P_c$ is fixed at 0.1 and the proportions of HP and LP nodes in the network are equal, i.e. $N_H = N_L = 16$. The neighboring node with SOSS is selected as the relay in the event of failed direct transmissions.

Figure 14(a) shows that the HP PDR achieved by EDCA remains relatively constant as $R$ increases from 0.1 to 0.5. Due to the overlapping contention windows between HP and LP traffic from different nodes, the increased proportion of time slots that is allocated to LP traffic (with increasing $R$) does not significantly affect the performance of HP PDR in EDCA. In contrast, the HP PDR achieved by SAUCeR dips slightly when $R \geq 0.4$ as the increased proportion of time slots that is allocated to LP traffic (with increasing $R$) causes the number of collisions among HP traffic to increase. Despite this, the HP PDR achieved by SAUCeR is 20% to 30% higher than that achieved by EDCA due to the cooperative retransmission used in SAUCeR, which improves transmission quality.
The LP PDR shown in Figure 14(b) generally increases with increasing $R$ for both EDCA and SAUCeR. As $R$ increases, more time slots are allocated to LP traffic, which decreases LP packet collisions and improves LP throughput. From Figure 14(c), it can be seen that the normalized total throughput of SAUCeR is about 25% more than that obtained by EDCA for various values of $R$.

We note from Figure 15 that the delays incurred by EDCA for HP and LP traffic generally remains constant for varying $R$ as the contention windows $H_{cwin}$ and $L_{cwin}$ used by different nodes overlap; therefore, allocating a greater proportion of time slots to LP traffic does not have significant impact on its delay performance. The HP delay incurred by SAUCeR increases slightly with increasing $R$ as more cooperative retransmissions take place when the proportion of time slots that are allocated to HP traffic decreases. The LP delay of SAUCeR decreases with increasing $R$ due to the reduction in LP packet collisions when more time slots are allocated to LP traffic (with increasing $R$). Overall, SAUCeR incurs much smaller delays than EDCA due to the use of cooperative retransmissions and disjoint contention windows. As like in Section 4.1, the performance improvement of SAUCeR over EDCA decreases with increasing $P_{c}$. This is consistent with our analytical results in Section 3.5.1.

4.3. Varying Link Error Probability

In a wireless network, there may be frequent variations in mean link error probabilities of the physical medium. We study the performance of SAUCeR using the two proposed relay selection schemes - Strongest Overall Signal Strength (SOSS) and Random Relay (RR) - as the mean link error probabilities of cooperative retransmissions $P_{c}$ increases from 0.1 to 0.5. For instance, if the mean value of $P_{c}$ is 0.4, then the probability that a cooperative retransmission fails is 0.4. The link error probability of the direct transmission $P_{d}$ is set to a constant of 0.5 while the value of $R$ is set to 0.3. The proportion of HP and LP nodes is set to 50% each such that $N_{H} = N_{L} = 16$. In the following figures, we do not include the performance of EDCA as both relay selection schemes in SAUCeR perform better than EDCA.

Figure 16 shows the throughput performances of SOSS and RR with varying values of the mean link error probability $P_{c}$. As the mean value of $P_{c}$ increases, the throughputs of both SOSS and RR decrease correspondingly as there are less successful
cooperative retransmissions. When the mean value of $P_e^c$ is low at 0.1, using SOSS to select a fixed relay provides better performance as the throughput gain of cooperative retransmissions is maximized with fewer packet duplicates. However, as the mean value of $P_e^c$ increases, the likelihood that a fixed relay overhears a directly transmitted packet and cooperatively retransmits it successfully, decreases. Therefore, using multiple random relays maximizes the likelihood of successful cooperative retransmissions and improves overall transmission quality.

We also study the throughput performance of SOSS and RR as the mean value of lognormal shadowing in the physical channel increases from 2 dB to 10 dB, in Figure 17. The increase in the shadowing mean also correspond to an increase in the link error probability, as the received signal strength becomes smaller. The throughput performances of both relay selection schemes under varying shadowing mean values are similar to that under varying mean link errors $P_e^c$ (in Figure 16). When the shadowing mean is low ($\leq 4$ dB), SOSS performs better than RR as the average channel quality is better and using a fixed relay reduces packet duplicates while improving the overall transmission quality. As the shadowing mean increases, the channel quality decreases; hence, the use of multiple relays in RR improves the number of successful cooperative retransmissions and overall transmission quality.

4.4. Summary

We have studied the performance of SAUCeR under varying proportions of traffic classes ($N_H$ and $N_L$), varying proportions of minimum time slots that are allocated to each traffic class ($\mathcal{R}$) and varying mean link error probability $P_e^c$. From our simulation results and analysis, it can be seen that SAUCeR provides good performance improvements as compared to existing QoS-aware MAC protocols such as EDCA. This is due to the cooperative retransmission technique used in SAUCeR, as well as its resource allocation mechanism, which allocates disjoint contention windows to different traffic classes in order to segregate the contention between them.

We have investigated two different schemes to select relays in SAUCeR: (i) Strongest Overall Signal Strength (SOSS); and (ii) Random Relay (RR). Using SOSS, a fixed relay based on the strongest signal strength is pre-selected for every transmitted data packet. SOSS performs well when the wireless link quality is relatively good and the selected relay has a high probability of cooperatively retransmitting a packet successfully. However, SOSS performs poorly when the channel quality is low (link error probability is high). To handle this, multiple random relays are used in the RR scheme to cooperatively retransmit packets that have failed the initial direct transmissions. While the number of cooperative retransmission attempts may increase, the number of duplicates is minimized as each potential relay proactively listens for ACKs from the destination and does not retransmit if they overhear the ACKs. Thus, the choice of the relay selection scheme greatly depends on the characteristics of the wireless channel in use.

Although our simulation results only illustrate the performance of SAUCeR in one-hop networks, the proposed schemes can be applied to larger-scale multi-hop networks. In clustered multi-hop networks, SAUCeR can be used for intra-cluster communications. Inter-cluster communication can take place using different frequency bands available in UWB. SAUCeR can also be applied to flat-hierarchical multi-hop networks as long as the network is time-synchronized. This is achievable with low overheads using existing synchronization protocols in the literature [45][46][47].

5. 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 SAUCeR, which provides QoS support without the use of carrier sensing. SAUCeR allocates disjoint resources to the different traffic classes in the network to segregate the contention between them and provide better QoS to traffic with higher priority. It also utilizes a cooperative retransmission technique to improve transmission quality and overall network performance. Two different relay selection strategies that can be incorporated in SAUCeR are also explored and compared.

References


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