Joint Time and Spatial Reuse Handshake Protocol for Underwater Acoustic Communication Networks

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***Abstract*—In most existing handshake-based collision avoidance protocols, nodes in the proximity of the transmitter or receiver are kept silent during an ongoing communication session. In this paper, we utilize the long propagation delay in the underwater acoustic channel and the (possible) sparsity of the network topology to increase network throughput. We formalize conditions for which a node can transmit even when it is located one-hop away from a node participating in another communication session. We consider these conditions as problem constraints and form a distributed collision-avoidance handshake-based protocol, which jointly applies spatial and time reuse techniques. Our simulation results show that at a price of complexity, our protocol outperforms a recently proposed handshake protocol in terms of throughput and transmission delay.**

***Index Terms*—underwater acoustic communication (UWAC), handshake protocol, spatial reuse, time reuse, collision avoidance.**

I. Introduction

Underwater acoustic communication (UWAC) is required for applications such as oceanography data collection, ocean exploration, undersea navigation and control over autonomous underwater vehicles (AUV), to name just a few [1]. UWAC is challenging due to the characteristics of the underwater acoustic channel, which are high channel attenuation as well as relatively small bandwidth due to absorption loss (which increases with frequency) and noise level (which decreases with frequency) [2]. Moreover, the long propagation delay in the channel, caused by the low sound speed in water (approximately 1500 m/sec) and half-duplex communication, greatly reduces the efficiency of collision avoidance (CA) scheduling protocols designed for UWAC networks [3].

Most UWAC network CA scheduling protocols rely on the handshake-based protocol standardized in IEEE 802.11 [1], in which a communication session (CS) is established by exchanging request-to-send (RTS), clear-to-send (CTS) and notification (NT) control packets. Designing CA handshake-based scheduling for UWAC networks is challenging since, due to the long propagation delay in the channel, reception of control packets is delayed, increasing packet collision rate. Considering this problem [4] suggested a slotted handshake protocol in which globally established time slots, the size of which is comparable to the propagation delay, are used, and transmissions are restricted to the beginning of these time slots.

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In [5], throughput was improved by allowing the receiver to warn the transmitter of expected interferences.

Handshake-based scheduling protocols require nodes in the proximity of a CS to remain silent, which limits channel utilization. In fact, the number of silenced nodes grows quadratically with the transmission range, which decreases the efficiency of these protocols [6]. This effect is even more noticeable in UWAC networks, where longer silence periods are imposed by the long propagation delay [4]. One way to increase channel utilization is to use timing-advance techniques, often called *time reuse* [7], such that more nodes can transmit. Time reuse is related to the utilization of the long propagation delay in the underwater acoustic channel. Utilizing time reuse, [8] suggested a distance-aware protocol where channel utilization is improved by allowing both nodes involved in a handshake CS to transmit simultaneously. Similarly, [7] suggested exploiting the long propagation delay in the channel to allow simultaneous transmissions in exposed terminal links. However, channel utilization can be further increased by scheduling transmissions such that links are simultaneously used even in a fully connected network, utilizing the long propagation delay in the underwater acoustic channel.

Since nodes located at different areas of the network experience different transmission limitations, applying spatial reuse on top of time reuse can further improve channel utilization [9]. Spatial reuse refers to simultaneous CSs in different parts of the network, and it is specifically applicable to UWAC networks since low-power half-duplex transceivers, range and frequency dependent absorption loss [2], and acoustic non-line-of-sight scenarios [10] lead to sparse topologies.

In this paper, we consider the case of UWAC networks which support peer-to-peer communication of long messages between any pair of neighboring nodes. The main contribution of this paper is a distributed CA handshake-based scheduling protocol that makes use of joint time and spatial reuse and will be referred to as the joint time and spatial reuse handshake (TSR) protocol. The remainder of this paper is organized as follows. System model and assumptions are introduced in Section II. In Section III we formalize the problem of maximizing channel utilization in CA handshake scheduling. Next, in Section IV we suggest a distributed sub-optimal solution for this problem and describe the details of our TSR protocol. Simulation results are presented in Section V, and conclusions are offered in Section VI.

II. System Model and Objectives

Let $\mathcal{N}$ denote the set of nodes in the network and $\mathcal{K}_j$ the set of one-hop neighbor nodes of node $j \in \mathcal{N}$. Furthermore, let $T^{\rm pd}_{j,j'}$ denote the propagation delay for a message from node j to node j' [1]. We consider a UWAC network in which each node $j \in \mathcal{N}$ has a fixed-size message of duration $T^{\rm msg}$ second, to transmit to its one-hop neighbor node $j' \in \mathcal{K}_j$, and j' always responds with its own message to j, where we assume $T^{\rm msg}$ to be much greater than the propagation delay in the channel, $T^{\rm pd}_{j,j'}$. We consider packets sent from different nodes and arriving simultaneously at the same receiving node to be lost and refer to this scenario as *primary conflict*. Furthermore, we consider applications where nodes are static, e.g., submerged buoys, underwater structures, etc., such that propagation delay information up to two-hops away is known or can be estimated by each node with a certain accuracy.

Given this setup, we are interested in a CA handshake-based resource allocation protocol that achieves both high medium access control (MAC) throughput and low scheduling delay. We formalize these objectives in the following subsections.

A. MAC Throughput

Let the network be described by the undirected graph $G(\mathcal{N},\mathcal{E})$ with the set $\mathcal{E}$ of edges, representing communication links, and the set of $\mathcal{N}$ vertices, representing nodes. Denote $M^{\rm opt}_{j,j'}(W)$ the number of (original and relayed) unicast messages the user of node $j \in \mathcal{N}$ wishes to transmit to node $j' \in \mathcal{K}_j$ during the time interval of W seconds. Since messages are assumed equal size, for $M^{\rm succ}_{j,j'}(W)$ of the $M^{\rm opt}_{j,j'}(W)$ messages successfully received at node j', the per-link MAC throughput is defined as

$$\rho_{\rm through,link}(j,j') = \frac{M^{\rm succ}_{j,j'}(W)}{M^{\rm opt}_{j,j'}(W)},\ (j,j') \in \mathcal{E}\ . \qquad (1)$$

Consequently, the average per-link MAC throughput is defined as

$$\rho_{\rm through} = \frac{1}{|\mathcal{E}|} \sum_{(j,j')\in\mathcal{E}} \rho_{\rm through,link}(j,j')\ , \qquad (2)$$

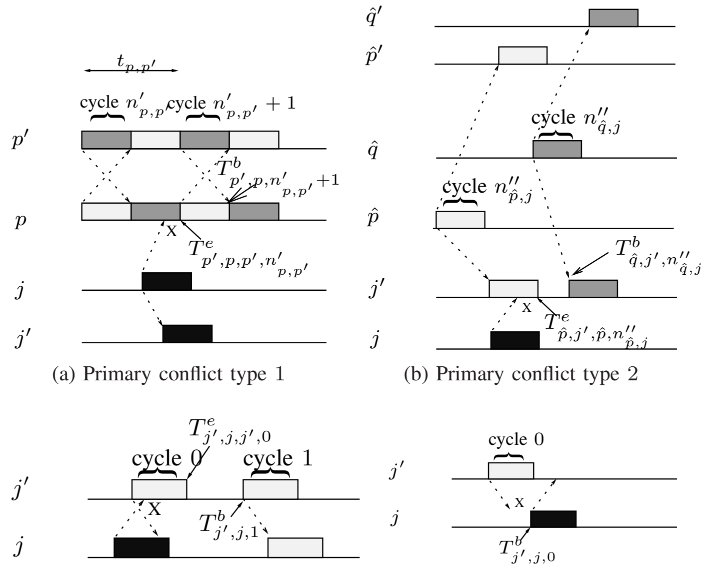
where $|\mathcal{E}|$ is the cardinality of set $\mathcal{E}$.

B. Scheduling Delay

We only consider the portions of link delay that are affected by the scheduling protocol, which we denote as *scheduling delay*. The scheduling protocol affects link delay by allowing nodes to transmit (original or relayed packets) at specific times. Denote $s^{\rm init}_{j,j',i}$ the time node $j \in \mathcal{N}$ tries to reserve the channel to transmit message i to node $j' \in \mathcal{K}_j$, and $s^{\rm finish}_{j,j',i}$ the time node j' successfully received message i from node j. Then, scheduling delay is defined as

$$\rho_{\rm delay} = \frac{1}{|\mathcal{E}|} \sum_{(j,j')\in\mathcal{E}} \frac{1}{M^{\rm succ}_{j,j'}(W)} \sum_{i=1}^{M^{\rm succ}_{j,j'}(W)} s^{\rm finish}_{j,j',i} - s^{\rm init}_{j,j',i} - T^{\rm msg}\ . \qquad (3)$$

[1]We indicate the destination node for the message of node x as x'.



(a) Primary conflict type 1 (b) Primary conflict type 2

(c) Primary conflict type $3a$ (d) Primary conflict type $3b$

Fig. 1: Illustration of different types of primary conflicts.

For clarity, in the following we neglect the message subindex and refer to the scheduling and transmission of one single message.

III. Maximizing Channel Utilization in Handshake Protocols

In this section, we make use of time and spatial reuse and formalize constraints enabling several simultaneous *neighbor CSs*, which are CSs whose nodes can construct a connected sub-graph. Following [8], we divide each message into a series of packets and improve channel utilization by allowing both nodes in the CS to transmit.

The CS $C_{j,j'}$, $(j,j') \in \mathcal{E}$, is defined by three characteristic parameters referred to as the *CS parameters*: 1) $s_{j,j'}$, 2) $d_{j,j'}$ and 3) $t_{j,j'}$, where $s_{j,j'}$ is the time node j transmitted its first data packet to node j', $d_{j,j'}$ is the duration of a single packet transmitted from j to j', and $t_{j,j'}$ is the time difference between the starting transmission times of consecutive packets, referred to as the *cycle time* of the message. Consequently,

$$s^{\rm finish}_{j,j'} = s_{j,j'} + (N^{\rm cycle}_{j,j'} - 1)t_{j,j'} + d_{j,j'},\ (j,j') \in \mathcal{E}\ . \qquad (4)$$

where $N^{\rm cycle}_{j,j'} = \dfrac{T^{\rm msg}}{d_{j,j'}}$ is the number of cycles in the CS $C_{j,j'}$.

We next formalize specific constraints to avoid three different types of primary conflicts and merge them into a single optimization problem.

A. Different Types of Primary Conflicts

Consider nodes p, q and j with destination nodes p', q' and j', respectively, and let $n_{p,p'} = \{0, \ldots, N^{\rm cycle}_{p,p'} - 1\}$ be the index of a single cycle in the CS $C_{p,p'}$. In the following we use functions $T^{\rm b}_{p,q,n_{p,p'}}$ and $T^{\rm e}_{p,q,j,n_{p,p'}}$ being the time the $n_{p,p'}$th packet arrives at node q and the time it arrives at node q plus the duration of a packet from node j to node j', respectively, such that for $(p,p') \in \mathcal{E}, (p,q) \in \mathcal{E}$ and $j \in \mathcal{N}$

$$\begin{aligned} T^{\mathrm{b}}_{p,q,n_{p,p'}} &= s_{p,p'} + T^{\mathrm{pd}}_{p,q} + n_{p,p'} t_{p,p'} \\ T^{\mathrm{e}}_{p,q,j,n_{p,p'}} &= T^{\mathrm{b}}_{p,q,n_{p,p'}} + d_{j,j'} \ . \end{aligned} \quad (5)$$

In order to ensure interference-free packet transmission, our scheduling protocol avoids primary conflicts. In the following we consider three types of primary conflicts: 1) when scheduling of a newly established CS interferes active CSs, 2) when transmissions from active CSs interfere a new CS and 3) when transmission and reception occur simultaneously.

1) Conflict type 1: Interference to neighbor CS: Consider the CS $C_{p,p'}$ and a node $j \in \mathcal{N}$, where $(p,j) \in \mathcal{E}$. In conflict type 1, packets from node j arrive at node p while it is receiving packets from node p'. This scenario is illustrated in Figure 1a. To avoid conflict type 1, we require the packets of node j to arrive at node p before or after packets transmitted from node p' would arrive at p. Denote $n'_{p,j}$ as the index of the first packet transmitted from p' which possibly experiences interference from the transmissions of j. Since j is ready to transmit at time $s_{j,j'}$, for $T^{\mathrm{ref}}_{j,p} = s_{j,j'} + d_{j,j'} + T^{\mathrm{pd}}_{j,p}$ and $x_{n_{p,p'},p,j} = T^{\mathrm{b}}_{p',p,n_{p,p'}+1} - T^{\mathrm{ref}}_{j,p}$,

$$\begin{aligned} n'_{p,j} &= \arg\min_{n_{p,p'}} (x_{n_{p,p'},p,j}) \ , \\ \text{s.t.} \quad & x_{n_{p,p'},p,j} \geq 0 \ . \end{aligned} \quad (6)$$

Obtaining $n'_{p,j}$ $\forall p \in \mathcal{N} \cap \mathcal{K}_j, p \neq j'$ from (6), constraint 1 is formalized as

$$s_{j,j'} + T^{\mathrm{pd}}_{j,p} \geq T^{\mathrm{e}}_{p',p,p',n'_{p,j}}, \quad (7a)$$

$$s_{j,j'} + d_{j,j'} + T^{\mathrm{pd}}_{j,p} \leq T^{\mathrm{b}}_{p',p,n'_{p,j}+1} \ . \quad (7b)$$

2) Conflict type 2: Interference from neighbor CS: Conflict type 2 involves transmission from node $j \in \mathcal{N}$ arriving at node $j' \in \mathcal{K}_j$ while j' is experiencing interferences from several neighbor CSs, as illustrated in Figure 1b. To formalize constraint 2, we find nodes $\hat{p} \in \mathcal{N}$ and $\hat{q} \in \mathcal{N}$ and corresponding packet indexes $n''_{\hat{p},j}$ and $n''_{\hat{q},j}$, whose transmissions are the first to possibly interfere the packets of node j, such that

$$\left(\hat{p}, \hat{q}, n''_{\hat{p},j}, n''_{\hat{q},j}\right) = \underset{\left(p,q,n_{p,p'},n_{p,q'}\right)}{\arg\min} \ T^{\mathrm{b}}_{q,j',n_{q,q'}} - T^{\mathrm{e}}_{p,j',p,n_{p,p'}} \ , \quad (8a)$$

$$\text{s.t.} \ : T^{\mathrm{e}}_{p,j',p,n_{p,p'}} \leq s_{j,j'} + T^{\mathrm{pd}}_{j,j'} \leq T^{\mathrm{b}}_{q,j',n_{q,q'}} \ , \quad (8b)$$

$$T^{\mathrm{e}}_{p,j',p,n_{p,p'}+1} > s_{j,j'} + T^{\mathrm{pd}}_{j,j'} \ , \quad (8c)$$

$$T^{\mathrm{b}}_{q,j',n_{q,q'}-1} < s^{\mathrm{init}}_{j,j'} + T^{\mathrm{pd}}_{j,j'} \ , \quad (8d)$$

$$p, q \in \ \mathcal{N} \cap \mathcal{K}_{j'} \ . \quad (8e)$$

Solving (8), we set the following constraints

$$s_{j,j'} + T^{\mathrm{pd}}_{j,j'} \geq T^{\mathrm{e}}_{\hat{p},j',\hat{p},n''_{\hat{p},j}}, \quad (9a)$$

$$s_{j,j'} + d_{j,j'} + T^{\mathrm{pd}}_{j,j'} \leq T^{\mathrm{b}}_{\hat{q},j',n''_{\hat{q},j}} \ . \quad (9b)$$

3) Conflict type 3: Transmitting while receiving: In this type of conflict, a packet from node $j \in \mathcal{N}$ arrives to node j' while the latter is transmitting to j. Due to the half-duplex property of the acoustic transducers [11], j' would not be able to detect the packet from node j. This is illustrated in Figure 1c. Assuming nodes j and j' start transmitting in the same CS cycle with the same desired starting transmission time and that $T^{\mathrm{pd}}_{j,j'} = T^{\mathrm{pd}}_{j',j}$, we set the following condition

$$s_{j,j'} + T^{\mathrm{pd}}_{j,j'} \geq T^{\mathrm{e}}_{j',j,j',0} - T^{\mathrm{pd}}_{j,j'}, \quad (10a)$$

$$s_{j,j'} + d_{j,j'} + T^{\mathrm{pd}}_{j,j'} \leq T^{\mathrm{b}}_{j',j,1} - T^{\mathrm{pd}}_{j,j'} \ . \quad (10b)$$

Similarly, node j should consider arrival times of packets from node j' while scheduling its own transmissions as illustrated in Figure 1d. Here, we ensure that node j will start transmitting before receiving the first packet of node j' by setting

$$s_{j,j'} + d_{j,j'} \leq T^{\mathrm{b}}_{j',j,0} \ . \quad (11)$$

We observe that the four conditions in (7), (9), (10), (11) can be merged into two constraints. In order to avoid conflict of type 1 we should consider all neighbor CSs. To formalize this, referring to condition (7) we construct upper bound vector $\boldsymbol{u}_1$ and lower bound vector $\boldsymbol{l}_1$ with elements $l_1 = T^{\mathrm{e}}_{p',p,p',n'_{p,j}} - T^{\mathrm{pd}}_{j,p}$ and $u_1 = T^{\mathrm{b}}_{p',p,n'_{p,j}+1} - T^{\mathrm{pd}}_{j,p}$, respectively, $\forall p \in \mathcal{N} \cap \mathcal{K}_j, p \neq j'$. Considering the other two conflict types and referring to (9), (10) and (11) we set the lower bounds

$$\begin{aligned} l_2 &= T^{\mathrm{e}}_{\hat{p},j',\hat{p},n''_{\hat{p},j}} - T^{\mathrm{pd}}_{j,j'} \\ l_3 &= T^{\mathrm{e}}_{j',j,j',0} - 2T^{\mathrm{pd}}_{j,j'} \ , \end{aligned} \quad (12)$$

and the upper bounds

$$\begin{aligned} u_2 &= T^{\mathrm{b}}_{\hat{q},j',n''_{\hat{q},j}} - T^{\mathrm{pd}}_{j,j'} \\ u_3 &= T^{\mathrm{b}}_{j',j,1} - 2T^{\mathrm{pd}}_{j,j'} \\ u_4 &= T^{\mathrm{b}}_{j',j,0} \ . \end{aligned} \quad (13)$$

Then, the four constraints introduced above can be merged into

$$s_{j,j'} \geq \max\left(\boldsymbol{l}_1, l_2, l_3\right) \quad (14a)$$

$$s_{j,j'} + d_{j,j'} \leq \min\left(\boldsymbol{u}_1, u_2, u_3, u_4\right) \ . \quad (14b)$$

B. Synchronizing Constraints

We note that transmissions of neighbor CSs need to be synchronized, otherwise primary conflicts avoided in certain CS cycles might still exist in later cycles, resulting in packet collisions. Synchronization of two neighbor CSs is achieved if the cycle time of one is an integer multiple of the other. In addition, since communications are half-duplex, $t_{j,j'}$ should be greater than $T^{\mathrm{pd}}_{j,j'}$. Let us denote the cycle time vector $\mathbf{t}_j = [\mathrm{t}_{p_1,p'_1}, \ldots, \mathrm{t}_{p_I,p'_I}]$ with rational elements t_{p_i,p'_i} such that $p_i \in \mathcal{N} \cap (\mathcal{K}_j \cup \mathcal{K}_{j'})$, where I is the number of such elements (note that $\boldsymbol{t}_j = \boldsymbol{t}_{j'}$). Avoiding primary conflicts of type 1 and 2, the cycle time $t_{j,j'}$ should be a common multiple of all the elements of $\boldsymbol{t}_j$. Moreover, avoiding primary conflicts of type

3, $t_{j,j'}$ should be greater than $d_{j,j'} + T^{\text{pd}}_{j,j'}$. Incorporating both constraints, let $L(\boldsymbol{t}_j)$ be the least common multiple (LCM) of all the elements of $\boldsymbol{t}_j$, and let

$$n_{\max} = \frac{L(\left[\boldsymbol{t}_j, Q(d_{j,j'} + T^{\text{pd}}_{j,j'})\right])}{L(\boldsymbol{t}_j)} \tag{15}$$

represent an integer multiple of $L(\boldsymbol{t}_j)$ for which $t_{j,j'} = n_{\max} \cdot L(\boldsymbol{t}_j)$ satisfies both constraints, where $Q(x)$ is the nearest rational number of x such that $Q(x) \geq x$. Then, we set $t_{j,j'} = \hat{n} \cdot L(\boldsymbol{t}_j)$, and find $\hat{n}$ by solving

$$\hat{n} = \min(n) \tag{16a}$$

$$\text{s.t. } : (s_{j,j'} + n \cdot L(\boldsymbol{t}_j)) - \left(s_{j,j'} + d_{j,j'} + T^{\text{pd}}_{j,j'}\right) \geq 0 \tag{16b}$$

$$n \in \{1, \ldots, n_{\max}\} \,. \tag{16c}$$

Then, we obtain the following constraint

$$t_{j,j'} - t^{\text{tol}} = \begin{cases} L(\boldsymbol{t}_j) & \text{if } L(\boldsymbol{t}_j) \geq d_{j,j'} + T^{\text{pd}}_{j,j'} \\ \hat{n} \cdot L(\boldsymbol{t}_j) & \text{otherwise} \end{cases}, \tag{17}$$

where t^{tol} is used to increase the CS cycle time, accounting for propagation delay estimation errors.

Finally, in order for two nodes $j \in \mathcal{N}$ and $j' \in \mathcal{K}_j$ to simultaneously transmit in a CS, the duration of their packets should be smaller than $T^{\text{pd}}_{j,j'}$. Thus, we set an additional constraint over the packet duration

$$d_{j,j'} \leq T^{\text{pd}}_{j,j'} \,. \tag{18}$$

C. Channel Utilization Maximization Problem

Regarding the scheduling constraints introduced in the previous sections, in this section we formalize the channel utilization maximization problem (CUMP). Let $\mathcal{R}$ be a set of node-pairs whose CSs need to be scheduled. We are interested in maximizing channel utilization by maximizing packet duration and minimizing transmission cycles for each CS $C_{j,j'}$, $(j, j') \in \mathcal{R}$ while avoiding scheduling conflicts. Considering constraints (17), (18) and (14), for a concave utility function $f(t_{j,j'}, d_{j,j'})$ the CUMP is formalized as

$$\text{minimize} \sum_{(j,j') \in \mathcal{R}} f(t_{j,j'}, d_{j,j'}) \tag{19a}$$

$$\text{s.t. } : s_{j,j'} \geq \max(\boldsymbol{l}_1, l_2, l_3) \tag{19b}$$

$$s_{j,j'} + d_{j,j'} + t^{\text{tol}} \leq \min(\boldsymbol{u}_1, u_2, u_3, u_4) \tag{19c}$$

$$s_{j,j'} \leq s^{\text{init}}_{j,j'} + T_{\text{offset}} \tag{19d}$$

$$d_{j,j'} + t^{\text{tol}} \leq T^{\text{pd}}_{j,j'} \tag{19e}$$

$$t_{j,j'} - t^{\text{tol}} = \begin{cases} L(\boldsymbol{t}_j) & L(\boldsymbol{t}_j) \geq d_{j,j'} + T^{\text{pd}}_{j,j'} \\ \hat{n} \cdot L(\boldsymbol{t}_j) & \text{otherwise} \end{cases}, \tag{19f}$$

where T_{offset} is a fixed offset time interval used to bound $s_{j,j'}$, and as in (17) we decrease the packet duration by t^{tol} accounting for propagation delay uncertainties.

We observe that the elements in the righthand side of (19b), (19c) and (19f) are functions of the problem variables, $s_{j,j'}, d_{j,j'}, t_{j,j'}$. Unfortunately, these cannot be separated due to the arg-min operations in (6) and (8) and the non-linear operation in (17). Thus, the CUMP in (19) is not a convex problem and may be difficult to solve even for small networks. More importantly, such optimization requires a centralized approach which significantly increases the communications overhead. Therefore, next we describe a sub-optimal distributed solution for the CUMP (19).

IV. The TSR Protocol - A Sub-Optimal Approach

Let $\mathcal{R}_j$ be the set of nodes participating in neighbor CSs to $C_{j,j'}$ at time $s^{\text{init}}_{j,j'}$. Assuming nodes j and j' can measure the CS parameters of their active neighbor CSs, we are interested to schedule transmissions in CS $C_{j,j'}$ in a distributed fashion, while avoiding interference to and from all nodes in $\mathcal{R}_j$. In the following we describe the process used by nodes to reserve the channel and to schedule their transmissions.

We relax (19) by considering symmetric communication in each CS such that $s_{j,j'} = s_{j',j}, d_{j,j'} = d_{j',j}$ and $t_{j,j'} = t_{j',j}$. As a result, conflict type 3 need not be considered. Moreover, we consider only nodes in set $\mathcal{R}_j$ for the purpose of avoiding conflicts type 1 and 2 to form modified constraints $\tilde{\boldsymbol{u}}_1, \tilde{u}_2, \tilde{\boldsymbol{l}}_1, \tilde{l}_2$ and $\tilde{\boldsymbol{t}}_j$ using (12), (13) and (17), respectively. We then form the modified bounds

$$\begin{aligned} \tilde{u} &= \min(\tilde{\boldsymbol{u}}_1, \tilde{u}_2) \\ \tilde{l} &= \max\left(\tilde{\boldsymbol{l}}_1, \tilde{l}_2\right) \,, \end{aligned} \tag{20}$$

and introduce the relaxed CUMP

$$\underset{s_{j,j'}, d_{j,j'}, t_{j,j'}}{\text{minimize}} \; f(t_{j,j'}, d_{j,j'}) \tag{21a}$$

$$\text{s.t. } : s_{j,j'} \geq \tilde{l} \tag{21b}$$

$$s_{j,j'} + d_{j,j'} + t^{\text{tol}} \leq \tilde{u} \tag{21c}$$

$$s_{j,j'} \leq s^{\text{init}}_{j,j'} + T_{\text{offset}} \tag{21d}$$

$$d_{j,j'} + t^{\text{tol}} \leq T^{\text{pd}}_{j,j'} \tag{21e}$$

$$t_{j,j'} - t^{\text{tol}} = \begin{cases} L(\tilde{\boldsymbol{t}}_j) & \text{if } L(\tilde{\boldsymbol{t}}_j) \geq d_{j,j'} + T^{\text{pd}}_{j,j'} \\ \hat{n} \cdot L(\boldsymbol{t}_j) & \text{otherwise} \end{cases}, \tag{21f}$$

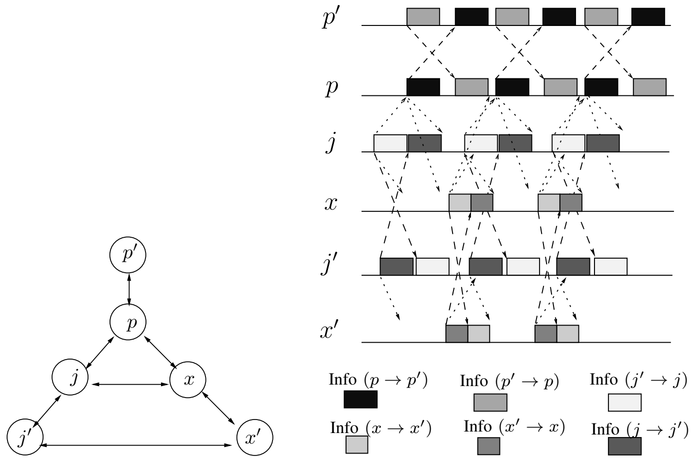
Since in (21a) $t_{j,j'}$ is minimized and $d_{j,j'}$ is maximized, regardless of the utility function, if $\tilde{l} \leq s^{\text{init}}_{j,j'} + T_{\text{offset}}$ the solution for (21) is found by

$$s_{j,j'} = \tilde{l} \tag{22a}$$

$$d_{j,j'} + t^{\text{tol}} = \tilde{u} - \tilde{l} \tag{22b}$$

$$t_{j,j'} - t^{\text{tol}} = \begin{cases} L(\tilde{\boldsymbol{t}}_j) & \text{if } L(\tilde{\boldsymbol{t}}_j) \geq d_{j,j'} + T^{\text{pd}}_{j,j'} \\ \hat{n} \cdot L(\boldsymbol{t}_j) & \text{otherwise} \end{cases}. \tag{22c}$$

By exchanging information with node j', parameters $s_{p,p'}, t_{p,p'}$ and $d_{p,p'}$ $\forall p \in \mathcal{R}_j \cap (\mathcal{K}_j \cup \mathcal{K}_{j'})$ are known to j at time $s^{\text{init}}_{j,j'}$. In addition, $[\tilde{\boldsymbol{u}}_1, \tilde{u}_2]$ and $\left[\tilde{\boldsymbol{l}}_1, \tilde{l}_2\right]$ can be calculated by both j and j' to form $\tilde{u}$ and $\tilde{l}$ as well as $L\left(\tilde{\boldsymbol{t}}_j\right)$ using (20) and (17), respectively. Hence, both j and j' can solve (22) and obtain $s_{j,j'}, d_{j,j'}$ and $t_{j,j'}$.



(a) (b)

Fig. 2: Illustration of packet exchange mechanism.

Consider, the network topology in Figure 2a for the purpose of illustration of our protocol. The propagation delay in all links is assumed to be equal to $T^{\rm pd}$. We start with node p transmitting $N_{\rm cycle}$ packets each of duration $T^{\rm pd}$ to node p'. In this case, for a time window of $T = N_{\rm cycle}T^{\rm pd}$, MAC throughput is simply 1. Next, we allow p' to transmit to p. This is possible if packet transmissions are spaced by at least $T^{\rm pd}$ seconds, as suggested in [8] and illustrated in Figure 2b. Since both nodes can transmit $N_{\rm cycle}/2$ packets during the time window T, neglecting channel reservation time, MAC throughput remains the same. We now consider the case where node j tries to establish CS $C_{j,j'}$. By implementing our protocol we allow j and j' to transmit together with p and p'. Since transmissions in the CS $C_{j,j'}$ are only limited by the CS $C_{p,p'}$ as illustrated in Figure 2b, MAC throughput for the time window of $T = N_{\rm cycle}T^{\rm pd}$ is expected to increase to 2. Finally, we consider the case of CS $C_{x,x'}$ joining CSs $C_{p,p'}$ and $C_{j,j'}$. Avoiding interference, nodes x and x' schedule their transmissions according to (22) such that their transmissions do not interfere $C_{p,p'}$ and $C_{j,j'}$. This process is illustrated in Figure 2b, where $d_{x,x'}$ and $s_{x,x'}$ are set such that packets from x arrive at p and j while they are transmitting and at x' while it is not experiencing interference from j', and such that packets from x' arrive at j' while it is transmitting and at x while it is not experiencing interference from j and p. Numerical results (see Section V below) showed that for the latter case MAC throughput for a time window of $T = N_{\rm cycle}T^{\rm pd}$ increases to 2.5.

V. Results

In this section we present simulation results comparing performance of the TSR protocol with those of the BiC-MAC protocol [8] in terms of throughput and scheduling delay. For Monte-Carlo simulations, a set of $1,000$ connected symmetric random graphs with 6 nodes and edge probability of $\frac{1}{2}$ for all vertices was generated. In each simulation, the locations of the 6 nodes were randomly chosen with uniform distribution

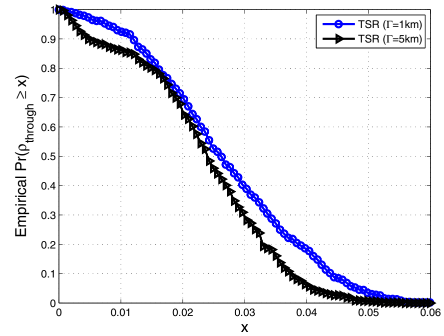


Fig. 3: Empirical C-CDF of $\rho_{\rm through}$ in (2) for the TSR and BiC-MAC protocols.

in a square area of $\Gamma \times \Gamma$ km^2, and values $\Gamma = 1$ km and $\Gamma = 5$ km were tested. We measured the network performance for a fixed time interval of $W = 500$ seconds in which nodes were assigned with unicast data messages of length 10 kbit to transmit to their one-hop neighbors, where the arrival time of each message was a Poisson distribution random process with variance 0.01 sec^2. For RTS, CTS and NT control packets of duration 100 bit, and a bit rate of 10 kbps, the duration of the data messages was $T^{\rm msg} = 10$ seconds and the duration of the control packets was 10 msec.

In each link, the propagation delay was calculated considering a propagation speed of 1500 m/sec. We assumed a perfect propagation delay estimation (i.e., $t^{\rm tol} = 0$) and that packets are lost in the channel only due to mutual access interference (MAI). In addition, packets are dropped even if MAI affects only a fraction of the packet (i.e., no error correction mechanism is included), and we considered a data message transmission as successful only if all its packets were successfully received by the destination node.

Figure 3 shows the empirical complementary cumulative density function (C-CDF) for $\rho_{\rm through}$ from (2). We observe that the TSR protocol consistently outperforms the BiC-MAC protocol. This is due to the spatial reuse in the TSR protocol that allows simultaneous transmission of multiple packets. Thus, although the time it takes to transmit a message in the TSR protocol once the channel is reserved has increased, compared to BiC-MAC, $\rho_{\rm through}$ still increases. We observe that throughput of the TSR protocol with maximum transmission range of $\Gamma = 1$ km is higher than that for $\Gamma = 5$ km. That is, throughput of the TSR protocol decreases when the network nodes are more widespread. This is due to the need to synchronize neighbor CSs in (17), where such spread would cause larger variation in $\boldsymbol{t}_j$, thus increasing the CS cycle. As a result, fewer CSs would occur simultaneously, affecting throughput. This effect is also observed for the BiC-MAC protocol due to the communications overhead of the channel reservation process, which increases with Γ.

Finally, in Figure 4 we show the empirical cumulative density function (CDF) of $\rho_{\rm delay}$ in (3) for the considered protocols. We note that the x-axis is divided by $T^{\rm msg}$. We

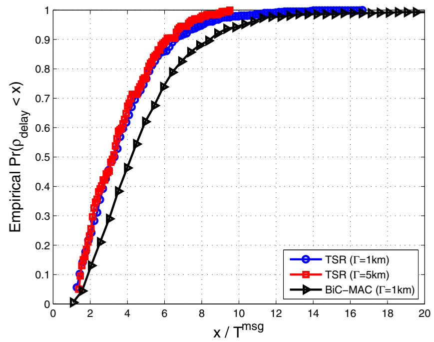


Fig. 4: Empirical CDF of ρ_{delay} in (3) for the TSR and BiC-MAC protocols.

observe that the scheduling delay of the TSR protocol is considerably lower than that of the BiC-MAC protocol. This is due to the time reuse in the TSR protocol that renders fewer messages to be delayed by the MAC layer due to channel interference sensing. We note that the delay performance of the TSR protocol is only slightly affected by Γ. That is, scheduling delay of the TSR protocol is not affected by the location of the network nodes. This can be explained by the fact that nodes which are mostly affected by this spread rarely reserve the channel (as reflected by the throughput performance), while the definition of scheduling delay takes into account only succesful transmissions.

We note that the improvement in MAC throughput and scheduling delay of the TSR protocol is achieved at only a small cost of communications overhead and complexity, as only the CS parameters are exchanged between the transmitting nodes. In addition, the protocol is fully distributed.

VI. Conclusions

In this paper we considered the problem of handshake-based scheduling for UWAC networks supporting CA unicast communications. We formalized the problem of resource assignments to nodes to maximize the per-link channel utilization while avoiding mutual access interference as a non-convex optimization problem, and suggested a sub-optimal distributed protocol to solve it. Our protocol combines spatial reuse and timing advance techniques to utilize the long propagation delay in the channel and the expected sparsity of the network graph. By means of simulation results, we demonstrated that at the cost of a slight increase of communication overhead and complexity, our protocol outperforms a recently proposed handshake protocol in terms of per-node throughput and scheduling delay. For further work, we plan to test our protocol in a real sea environment to validate our assumptions and results.

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