A TDMA-based MAC Protocol Exploiting the Near-Far Effect in Underwater Acoustic Networks

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***Abstract*—One prime source of collisions in underwater acoustic communication networks (UWANs) is the so called near-far effect, where a node located farther from the receiver is jammed by a closer node. While common practice considers such situation as a challenge, in this paper we consider it as a resource, and use it to increase network throughput of spatial reuse time-division multiple access. We propose a transmission allocation algorithm that opportunistically utilizes information of near-far scenarios in UWANs to maximize channel utilization. Numerical results show that, at a slight cost in terms of fairness, our scheduling solutions achieve higher throughput and lower transmission delay than benchmark spatial-reuse scheduling protocols. To allow the reproducibility of our results, we publish the implementation of our proposed algorithm.**

***Index Terms*—Underwater acoustic networks, near-far effect, spatial-reuse scheduling, time-division-multiple-access (TDMA), long propagation delay, optimization**

I. Introduction

The design of medium access control (MAC) protocols for underwater acoustic networks (UWANs) faces several challenges, usually summarized into the concept of space-time uncertainty. The significant delays induced by the low propagation speed of underwater acoustic signals imply that channel access decisions are not optimal when informed only by instantaneous channel sensing. Rather, a considerable amount of wait time would be required to safely gain channel access and ensure collision avoidance [1]. Otherwise, packet collisions are possible, where a collision is defined as the superposition of one or more packets at the receiver, possibly leading to the incapability to receive correctly some or all of them.

One type of collision is the *primary conflict*, which occurs when the receiver cannot resolve packets arriving at the same time. In UWANs, where power attenuation in the channel is large, colliding packets are often characterized by conspicuous differences among their received power levels. As a result, the packets of a closer node may be received while jamming those of a farther node. In the current state-of-the-art, this so called near-far problem is eliminated by avoiding simultaneous transmissions of near-far node pairs (NFNPs) [2], [3]. However, we argue that, by means of careful scheduling, the simultaneous transmissions of NFNPs can actually increase the network performance. Allowing transmissions of near-far node pairs (NFNPs) to different destination nodes in an STDMA fashion opens the possibility to overcome one of the most limiting assumptions in scheduling UWANs, namely, that the network can support the transmission of only a single packet type.

In this paper, we describe a scheduling MAC algorithm for both contention-free and contention-based transmissions. Our algorithm, referred to as the *near-far spatial reuse TDMA* (NF-STDMA), maximizes the network throughput and minimizes the delivery delay by allowing multiple nodes to transmit in the same time slot. To that end, given information on the network topology and the NFNPs (e.g., using a topology-discovery initial phase), we formulate an optimization problem that yields collision-free scheduling for a target minimum packet transmission rate. Our results show that our NF-STDMA achieves much better throughput and delivery delay. This comes at a slight cost in terms of fairness in the transmission of contention-based packets.

The remainder of this paper is organized as follows. In Section II we survey relevant related work in the area. Section III introduces the system model. Section IV proposes our NF-TDMA protocol. Section V shows numerical results. Finally, we offer some concluding remarks in Section VI.

II. State-of-the-Art

To compensate for the low channel utilization of TDMA, UWAN-MAC [4] proposes to schedule sleep/transmit/receive epochs among the nodes via a network discovery mechanism, and to adaptively shift these epochs over time in case joining nodes cause receive-receive collisions. Similarly, I-TDMA [5] proposes to postpone colliding transmission schedules by assuming that the propagation delay is known (something which was not strictly needed in UWAN-MAC). However, these solutions are prone to uncontrolled drifts in the sleeping schedules of the nodes [6].

Exploiting the propagation delay to avoid receiver-side collisions has been shown to be a promising approach in [7]. The STUMP protocol [8] extends this approach by scheduling transmissions in a multihop network so that all types of primary conflicts can be avoided. The design assumes that the nodes are aware of propagation delays and transmission requirements in their 2-hop neighborhood. STUMP-WR [9] adds routing to the picture, which operates on links instead of rings and therefore requires only the solution of a simpler link scheduling problem.

The work in [10] takes a fundamental approach by showing that optimal schedules in any network with a single broadcast domain are periodic, and that the maximum achievable throughput is $N/2$, where N is the number of nodes. The authors provide a computationally efficient algorithm to compute good schedules. The same result has been shown to extend to complex topologies in [11]. Based on the above work, [12] adds realistic modem constraints and shows that an implementation of the scheme proposed in [10] actually works in practice in simple topologies. The approach in [3] further observes that any scheduling approach which relies on topology and propagation delay information may incur excessive overhead or even fail when such information is subject to change due to even limited mobility or channel variability. For this reason, a topology-transparent schedule is taken as the basis to create a topology-based schedule which is also robust to topological changes. The results are successfully tested both in simulations and in a field experiment.

Unlike all previous approaches, in this paper we argue that not all collisions are harmful, and that near-far communication scenarios can be in fact exploited to decouple interfering transmission. With the above in mind, we propose a scheduling algorithm that is specifically designed to exploit near-far transmission opportunities. We introduce our scheduling design by starting from some preliminary definitions in the next section.

III. Preliminaries

Our system includes a group of nodes (e.g., divers or submerged devices) represented by a set $\mathcal{N} = \{i_1, \ldots, i_{N-1}\}$ of nodes. Each of the nodes is directly connected to a single node, i_0, referred to as the *cluster head*, or sink. However, a node $i_n \in \mathcal{N}$ may or may not be connected to a node $i_m \in \mathcal{N}$, $m \neq n$. Each node in $\mathcal{N}$ is assumed to always have a health packet to transmit to node i_0. Health packets convey the status of the node (location, energy level, air supply, mission progress, etc.) and are to be transmitted in a contention-free manner. In addition, health packets are transmitted periodically and should be received by the cluster head at least once every T_L seconds.

With respect to the cluster head, i_0, the information about the *receiver-side topology* is given in the form of an $N \times N$ matrix $\mathbf{M}$. Specifically, the diagonal elements of $\mathbf{M}$ represents the direct link between node i_0 and its neighbor nodes, while the rest of the matrix entries indicates the possibility of multiple packet reception (MPR). More specifically, the (x, y)th entry, $M_{x,y}$, equals 1 if node i_0 can successfully receive a packet from node i_x even while node i_y is transmitting, and 0 otherwise. In case $M_{x,y} = 1$ and $M_{y,x} = 1$, nodes i_x and i_y can be scheduled for simultaneous transmissions, as neither would impede the reception of the other. However, in case $M_{x,y} = 1$ but $M_{y,x} = 0$, if transmitting together, node i_x will overshadow (or jam) the transmissions of node i_y. That is, the near-far effect occurs.

To form $\mathbf{M}$, we require an MPR probability matrix $\mathbf{P}$ whose entry $P_{x,y}$ represents the probability of successful reception of packets from node x while node y is transmitting. Then, $M_{x,y} = 1$ if $P_{x,y} \geq \theta$, where θ is a target packet reception probability. Both matrices $\mathbf{M}$ and $\mathbf{P}$ are inputs to our algorithm, and can be measured during an initial phase for topology discovery.[1] An example of a topology exhibiting a near-far scenario is illustrated in Fig. 1. In this example, node i_1 is much closer to node i_0 than node i_2 and jams the transmissions of the latter.

IV. The Near-Far Scheduling Solution

A. Key Idea

We are interested in a collision-free transmission schedule of each node $i_n \in \mathcal{N}$ with respect to the cluster head. This schedule is set by the cluster head node, i_0, which in turn broadcasts the solution to its one-hop neighbors, i.e., to the nodes in $\mathcal{N}$. While this is a centralized solution, the special position of node i_0 ensures fast and reliable sharing of the scheduling solution with all nodes. In addition, the communication overhead is especially low, as i_0 obtains $\mathbf{M}$ by its own means, and nodes only share their neighbor list.

Our solution is based on the observation that in a near-far situation, only one collision occurs and the jammer can still transmit. Then, in case the receiver holds MPR capabilities, it can directly decode the packet from the jammer while applying interference cancellation techniques to decode the jammed packet. Since MPR is not always guaranteed, we also allocate transmission epochs where each node is allowed to transmit exclusively. In these transmission epochs, we allow the jammer to transmit only if it employs power control to ensure the reception of the transmission from the jammed node. Moreover, even without MPR capabilities, spatial reuse is still available by utilizing information about NFNPs and guiding the jammer and jammed nodes to transmit packets to different destinations.

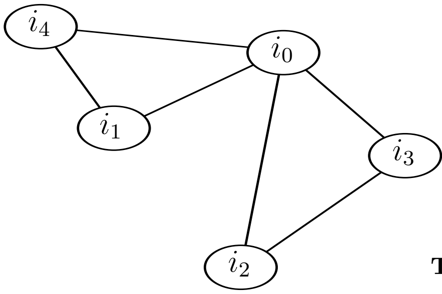
B. The NF-STDMA

The output of the NF-STDMA scheduling algorithm is an $N \times L$ matrix $\mathbf{S}$ for allocating the transmissions of N nodes over L time slots. Given $\mathbf{S}$, a node i_n is allowed to transmit in time slot ℓ with probability $S_{n,\ell}$. Then, the case of $\sum_{n=0}^{N-1} S_{n,\ell} > 1$ for some ℓ (i.e., more than one nodes are allowed to transmit together in one or more slots) is typically referred to as STDMA, and the case where $\exists\, i_{m,\ell} \mid S_{n,\ell} > 0,\ S_{m,\ell} > 0,\ M_{m,n} \neq M_{n,m}$ characterizes NF-STDMA.

The steps of the NF-STDMA algorithm are demonstrated in Fig. 1. To readily obtain solution $\mathbf{S}$, the topology information in matrix $\mathbf{M}$ is rearranged. First, we form a list of all node pairs involved in a near-far situation. This list is found by inspecting non-symmetric entries in matrix $\mathbf{M}$. We then identify the MPR probability [2] ,$p_{n,m}$, to properly decode a packet from i_n while simultaneously receiving a packet from node i_m. Clearly, without MPR capabilities we have $p_{n,k} = 0$.

[1] Topology information can be obtained by measuring the rate of successful packets [13], [14] or by estimating the SINR through measuring the distances among the nodes and applying an attenuation model [2]. This process is beyond the scope of this paper.

[2] The MPR probability can be found by calculating the expected signal-to-interference-pulse-noise ratio (SINR) for each of the received symbols and setting a threshold for the target symbol error rate probability (e.g., [15])



$$\mathbf{M}(i_0) = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \longrightarrow \tilde{\mathbf{M}}(i_0) = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & p_{1,2} \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} \longleftarrow \mathbf{R} = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & p_{2,1} \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

$$\mathbf{S} = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & p_{1,2} & p_{1,2} & p_{1,2} & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \qquad \mathbf{S}_{\text{ref}} = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & p_{1,2} & p_{1,2} & p_{1,2} & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix}$$

Fig. 1. Example for the illustration of the NF-TDMA algorithm.

Next, we form a symmetric version of $\mathbf{M}$, namely $\tilde{\mathbf{M}}$, and find its list of all K independent sets. This will yield all the possible collision-free transmission scheduling combinations. Let the vector $\mathbf{w}^{(k)},\ n = 1, \ldots, N-1$ be the kth independent set. The following three options apply:

1) $w_n^{(k)} = 0$: node i_n does not transmit;
2) $w_n^{(k)} = 1$: if node n transmits, its packet will be received with probability 1;
3) $w_n^{(k)} = p_{n,k}$: if node n transmits, its packet will be received with probability $0 < p_{n,k} < 1$.

The third case applies when

$$\exists\, i_m \ \mid\ (i_n, i_m) \in \mathcal{R},\ \wedge\ w_m^{(k)} > 0\ ,$$

i.e., when there is a node m that is in a near-far pair with n, and they both transmit in combination k. In this case, we set $p_{n,k} = p_{n,m}$. As a first-order approximation, near-far scenarios with more than one node are considered by setting $p_{n,k}$ as a multiplication of all the relevant near-far probabilities. For example, if node i_n is the "far" node with respect to both nodes i_m and i_q, and $w_m^{(k)} > 0$, $w_q^{(k)} > 0$, $w_n^{(k)} > 0$, we set $p_{n,k} = 1-(1-p_{n,m})(1-p_{n,q})$. The K different vectors $\mathbf{w}$ are arranged in columns to form an $N \times K$ *reception* matrix $\mathbf{R}$, whose entry $R_{n,k}$ is the probability of the cluster head node i_0 to receive a packet from node i_n for the kth transmission set. Matrix $\mathbf{R}$ for our example is presented in Fig. 1.

Second, we form an $N \times K$ *transmission* matrix $\mathbf{T}$, whose entry $T_{n,k}$ represents the probability that node i_n transmits in the kth possible transmission combination. For a node i_n for which $w_n^{(k)} = 1$, we set $T_{n,k} = 1$. However, for a near-far node pair (i_n, i_m) and time slot k for which $w_n^{(k)} > 0$ and $w_m^{(k)} > 0$, we prefer to allow the jammer node i_m to always transmit. In this case, the probability of the jammed node i_n to transmit depends on the ability of i_0 to receive the jammer (rather than the jammed node). That is, we set $T_{m,k} = 1$ and $T_{n,k} = p_{m,n}$.

To obtain the scheduling matrix $\mathbf{S}$, we wish to allocating the maximum possible number of transmission time slots while ensuring that packets arrive without collisions. To that end, we denote a $K \times 1$ vector $\mathbf{a}$, whose entries a_j represent the number of times that column j from $\mathbf{T}$ is chosen in the scheduling solution. In matrix form, we obtain the *reception vector*

$$\mathbf{r}(\mathbf{R}, \mathbf{a}) = \mathbf{R}\mathbf{a}\ , \tag{1}$$

such that for row n in matrix $\mathbf{R}$, $r_n(\mathbf{R}, \mathbf{a})$ packets are sent by node i_n and successfully received at node i_0.

To allow a minimum number of transmissions (including at least one health packet) by each node i, we fix the number of time slots in one time frame to be

$$L = \frac{T_L \cdot \max_i c_i}{T_s}\ , \tag{2}$$

where T_s is the duration of the time slot. Then, considering the scheduling constraints in (**??**) and (**??**), the scheduling problem can be written as

$$\hat{\mathbf{a}} = \underset{\mathbf{a}}{\operatorname{argmax}} \sum_{n=1}^{N-1} r_n(\mathbf{R}, \mathbf{a}) \tag{3a}$$

$$\text{s.t.} \quad \sum_n a_n = L\ , \tag{3b}$$

$$r_n \geq c_n,\ \forall n \in \mathcal{N}\ . \tag{3c}$$

Problem (3) is an NP-hard integer linear problem, whose worst-case complexity grows exponentially with the size of $\mathbf{a}$. However, it can be solved in polynomial time (on average) via the branch-and-bound algorithm [16]. The solution of (3) is readily transformed into the scheduling matrix $\mathbf{S}$, whose columns are replicas of the columns of the transmission matrix

$\mathbf{T}$. That is, the scheduling solution matrix $\mathbf{S}$ contains $\hat{a}_k$ replicas of the kth column of $\mathbf{T}$.

V. Numerical Results

A. Simulation Setup

In this section, we discuss the performance of our NF-TDMA algorithm. We show results for three configurations of the NF-TDMA protocol: 1) (*Ideal NF-TDMA*) where the MPR probability is ideal and both the jammer and the jammed nodes of each NFNP are assumed to be decoded with probability 1; 2) (*Realistic NF-TDMA*) where the MPR probability is set according to the evaluated SINR; and 3) (*Limited NF-TDMA*) where nodes do not have MPR capabilities. For clarity, for all three schemes we do not apply the power control mechanism in Section **??**. Our implementation of the algorithm is published for reproducibility.[3]

We measure performance in terms of throughput, scheduling delay and fairness. Assuming each node always has a health packet to transmit, we define throughput as

$$\rho_{\text{through}} = \frac{1}{T} \sum_{n=1}^{N-1} x_n N_{\text{bit}} \ , \tag{4}$$

where N_{bit} is the number of information bearing bits in each packet, and x_n is number of successfully received health packets sent by node i_n to node i_0 over a given time interval of duration T seconds. Scheduling delay captures both the end-to-end transmission and the queuing delay. Let $x_{n,m}$ be the number of packets generated by node i_n and successfully received by node i_m. Also let $t_{n,m,j}$ be the delay from the time a packet j is transferred to the MAC layer of source i_n till it is successfully delivered to its destination i_m. Then, the average per-node scheduling delay is

$$\rho_{\text{delay}} = \frac{1}{N} \sum_{n=0}^{N-1} \sum_{\substack{m=0 \\ m \neq n}}^{N-1} \frac{1}{x^{\text{c}}_{n,m}} \sum_{j=1}^{x_{n,m}} t_{n,m,j} \ . \tag{5}$$

Last, we measure fairness by comparing the differences in the per-node throughput. By applying Jain's fairness index [17], we define the throughput fairness to be

$$\rho_{\text{fair}} = \frac{\left(\sum_{n=0}^{N-1} \sum_{\substack{m=0 \\ m \neq n}} x_{n,m} \right)^2}{N \sum_{n=0}^{N-1} \left(\sum_{\substack{m=0 \\ m \neq n}} x_{n,m} \right)^2} \ . \tag{6}$$

We compare results with the simple TDMA protocol (*TDMA*) where in each time slot only one node can transmit. Since we consider a star topology where all nodes are directly connected to the cluster head node i_0, all other available spatial-reuse protocols would converge to the simple TDMA protocol. For a fair comparison with the NF-STDMA algorithm, we duplicate the frame of the simple TDMA schedule to match that of the NF-TDMA schemes (i.e., $L = T_L/T_s$).

[3] http://www.dei.unipd.it/~diamant/documents/NearFarPublishCode.zip

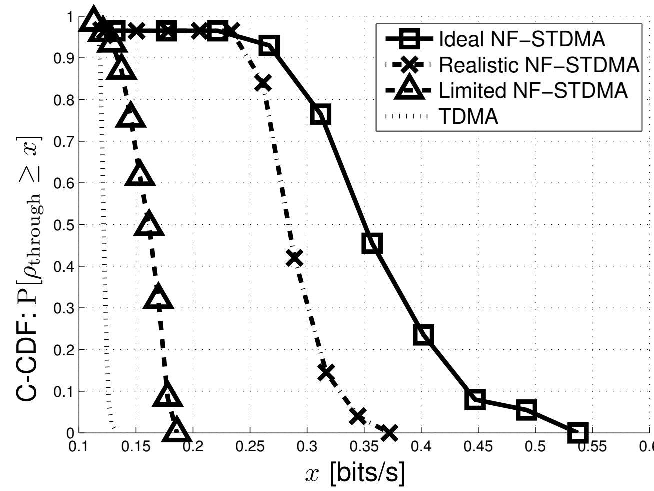


Fig. 2. Empirical C-CDF of per-node throughput from (4).

Our simulation setup includes a Monte-Carlo set of 200 topologies. In each simulation run, $N = 8$ nodes are placed uniformly at random in a volume of $5{\times}5$ km^2 with water depth of 100 m. For each node pair in line-of-sight, we perform a Bellhop run [18, Ch. 3], and set a communication link between a line-of-sight node pair if the bit error rate is below 10^{-3}. We consider a target transmission rate of one packet every $T_L = 100$ s (see (**??**)), and the time slot to be $T_s = 5$ s.

B. Simulation Results

In Fig. 2, we show the empirical complementary cumulative density function (C-CDF) of the per-node throughput. Clearly, since TDMA does not depend on network topology and since health packets are always available, the throughput of TDMA changes negligibly across different topologies. Compared to the performance of TDMA, we observe a significant improvement using our schemes, where even without MPR capability (i.e., for Limited NF-TDMA) the throughput increases by 40%, whereas with perfect MPR the improvement can be as large as a factor of 4. Since no health packets collide at the cluster head when using Ideal NF-TDMA, the results are expectedly better than those of Realistic NF-TDMA. However, even for the latter, the throughput improves by a factor of 3 compared to TDMA.

The empirical CDF results of the scheduling delay are shown in Fig. 3. Here we observe that, on average, the scheduling delay is roughly 16.5 s for TDMA. We observe that MPR capabilities improve the delay performance of Realistic NF-TDMA and Ideal NF-TDMA by respectively 1.5 and 1.8 times, compared to TDMA. Still, even without MPR capabilities we see that in most cases Limited NF-TDMA outperforms TDMA.

To compare fairness performance of the different metrics, in Fig. 4 we show C-CDF results of ρ_{fair} from (6). Since TDMA evenly allocates packet transmissions, its fairness is better than that of the NF-TDMA schemes. While the difference between

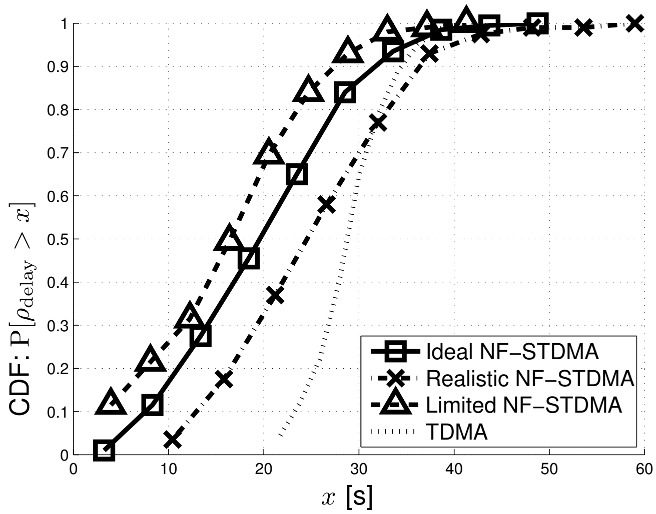


Fig. 3. Empirical CDF of scheduling delay from (5).

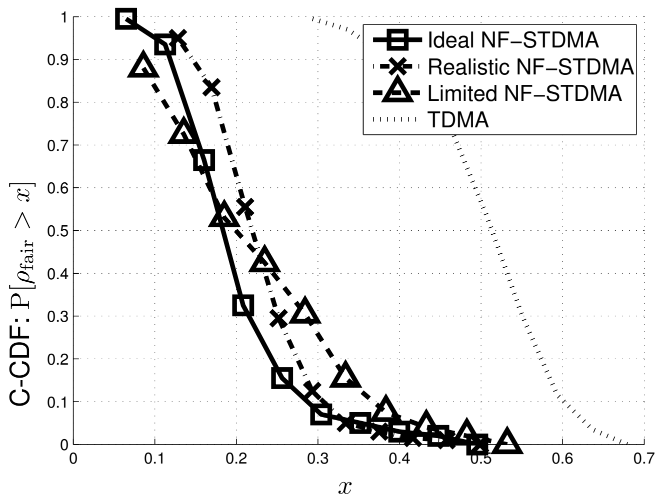


Fig. 4. Empirical CDF of ρ_{fair} from (6).

the three NF-TDMA schemes is not significant, we observe that Realistic NF-TDMA consistently outperforms Ideal NF-TDMA. This is because the latter correctly allocates more packet transmission opportunities to nodes located close to the cluster head. We also observe that the fairness of Limited NF-TDMA varies compared to that of Realistic NF-TDMA and Ideal NF-TDMA. This is because, in terms of fairness, the performance of Limited NF-TDMA strongly depends on the topology. That is, for a certain NFNP with respect to the cluster head, spatial reuse in Limited NF-TDMA is determined by the ability of the far node to find a destination which is not connected to the near node. In some topologies, such destination nodes are found for only one or a few nodes, which adversely impacts fairness; conversely, in other topologies several far nodes can find proper destination nodes, and fairness improves as a consequence.

VI. Conclusions

In this paper, we focused on the problem of transmission assignment, which is the bottleneck of UWANs. We considered a time slot-based scheduling and a common network topology where all nodes are directly connected to the sink and primary conflicts are not allowed. Utilizing the near-far effect, we proposed a scheduling solution that offers spatial reuse and allows concurrent transmissions even in these conditions and even when MPR is not available. Our numerical results show that in terms of all three objectives our schedule significantly outperforms the TDMA protocol, to which all current spatial-reuse scheduling protocols converge under the considered network topology.

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