Interference-aware Spatio-Temporal Link Scheduling for Long Delay Underwater Sensor Networks

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***Abstract*—In underwater sensor networks (UWSNs), acoustic communication is commonly used unlike that in terrestrial wireless networks. The long propagation delay of acoustic signals causes spatio-temporal uncertainty, which makes the link scheduling in UWSNs a challenging problem. To describe the propagation delays of the transmission links and deal with the spatio-temporal uncertainty, we construct a so called slotted spatio-temporal conflict graph. We propose efficient scheduling algorithms with constant approximation ratios to the optimum solutions. We consider both unified and weighted traffic load scenarios when designing the scheduling algorithms. In the weighted traffic load scenario, we consider the scheduling with and without the consecutive constraint. Simulations validate our theoretical results, and show the efficiency of our proposed algorithms.**

I. Introduction

Underwater sensor networks (UWSNs) consist of a variable number of sensors deployed in an oceanic environment that organize themselves into multi-hop networks, and have received a lot of interest in both academia and industry [1], [2].

UWSNs are significantly different from terrestrial sensor networks in the aspects of low propagation speed, long transmission range, and limited bandwidth due to the underwater acoustic communication channel. Firstly, the propagation speed of acoustic signals is approximately 1500 m/s, which is several orders of magnitude slower than the 3×10^8 m/s wireless propagation. Secondly, the transmission range of acoustic signals (2-4 *km*) is much larger than that of wireless signals (150*m*), thus, the propagation delay can be quite long. Thirdly, since the frequency band of acoustic channels is narrow, the data rate of underwater sensors is much smaller than that of terrestrial sensors, and thus the link transmission delay of underwater sensors is much longer. Moreover, UWSNs are usually with the feature of three-dimensional topology.

Due to the long propagation delay of acoustic signals, current terrestrial MAC approaches are not suitable for UWSNs. In traditional MACs, the arrival of a packet is generally uncertain, and this uncertainty only considers the transmission time uncertainty. As the propagation delay is neglected, the reception time of a packet is assumed to be the same as the transmission time, i.e., the reception time uncertainty is removed. In UWSNs, however, the reception time uncertainty depends on both the transmission time and relative propagation

This work is supported in part by grants PolyU 5236/06E, PolyU 5243/08E and 1-ZV5N.

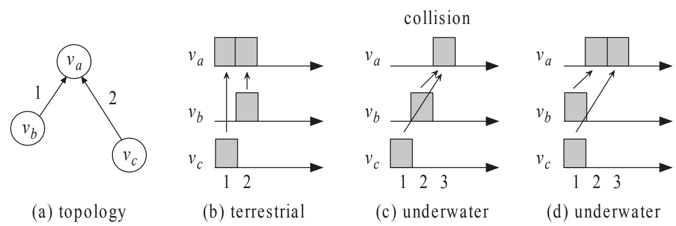


Fig. 1. Propagation delay in UWSNs.

delay to the receiver. This phenomenon is called "spatio-temporal uncertainty" in [3]. Fig. 1 illustrates the effect of the propagation delay on the time slot assignment in UWSNs. Fig. 1(a) shows the network topology. In the underwater scenario, the propagation delays from nodes v_b and v_c to node v_a are 1 and 2 time units respectively. In the terrestrial scenario, the collision can be avoided when nodes v_b and v_c transmit at time 2 and 1 respectively as shown in Fig. 1(b). But the same assignment for the topology in the underwater scenario results in a collision as shown in Fig. 1(c). If nodes v_b and v_c transmit at the same time as shown in Fig. 1(d), the collision is eliminated, which is significantly different from the terrestrial scenario.

In this paper, we adopt the time division multiple access (TDMA) MAC procols which eliminate collisions and guarantee fairness in UWSNs. We assume that time is slotted and synchronized, and previous work [4], [5] has provided some time synchronization mechanisms for UWSNs. A link scheduling is to assign each transmission link a set of time slots. A link scheduling is said to be interference-aware if a scheduled transmission will not result in a collision at both sender and receiver. The objective of the link scheduling is to maximize the network throughput, and previous work [6], [7] shows that it is NP-hard in general. Recently, a number of constant approximation algorithms [8], [9] have been proposed for terrestrial wireless networks.

In this paper, we focus on dealing with the problem of spatio-temporal uncertainty, and investigate the interference-aware link scheduling in UWSNs. Our contributions are summarized as follows: (1) We identify the spatio-temporal link scheduling problem in UWSNs, which is significantly different from terrestrial wireless networks and also NP-hard. (2) We propose a new conflict graph called slotted spatio-temporal conflict graph, which is constructed based on the network topology, conflict relationship, propagation delay and link transmission delay. (3) We present efficient scheduling algorithms that have theoretical performance bounds for both unified and weighted traffic load scenarios. In the weighted traffic load scenario, we consider the scheduling with and without the consecutive constraint. (4) We develop simulations to show the efficiency of the algorithms.

II. Related Work

In this section, we survey the MAC protocols in UWSNs. According to the underlying mechanism for collision avoidance, MAC protocols can be classified into two categories: contention-based protocols and contention-free protocols.

Traditional contention-based protocols in terrestrial wireless networks perform poorly in underwater networks due to the long propagation delay. Several researchers have attempted to modify them to be suitable for UWSNs. In [10], Chirdchoo et al. investigate the Aloha protocol for UWSNs, and propose two enhanced schemes. In the schemes, each sender needs to transmit a notification packet first and then wait a lag period for receiving replies from its neighbors before transmitting. However, such a scheme suffers from large energy waste from packet collisions and the low achievable throughput. In [11], Syed et al. propose a tone-based MAC mechanism that exploits the spatio-temporal uncertainty and high latency to detect collisions. The mechanism requires each sensor to equip with two interfaces: the low power tone receiver and the data receiver. In [12], Zhou et al. propose a new MAC protocol called CUMAC for long delay multi-channel UWSNs, which utilizes the cooperation of neighboring nodes for collision detection, and a simple tone device for distributed collision notification. In [13], Noh et al. propose the delay-aware opportunistic transmission scheduling (DOTS) algorithm to increase the opportunity of concurrent transmissions while reducing collisions. In the algorithm, each node has the propagation delay information and expected transmission schedules of its neighbors, and is scheduled to transmit its upcoming packages (RTS/CTS/DATA/ACK) which do not collide with current transmissions.

To obtain the optimal energy-efficient MAC in UWSNs, TDMA approaches have attracted much attention. In [14], Kredo and Mohapatra propose a hybrid architecture which combines TDMA with a contention-based approach. In [15], Park and Rodoplu propose a TDMA-based MAC protocol that assigns randomly selected time slots to each node, but its performance suffers from the long propagation delay. In [16], Huang et al. consider the problem of link scheduling in a single broadcast domain UWSN, and focus on low-complexity distributed, randomized and topology-independent (DRT) schemes, and find the optimal DRT scheduler by using nonlinear programming. In [17], Hsu et al. construct the spatial temporal conflict graph to describe the conflict delays among transmission links, model the link scheduling problem as a vertex coloring problem of the spatial-temporal conflict graph, and propose a new link scheduling called ST-MAC to overcome the spatio-temporal uncertainty. However, the link transmission delay is not considered in this conflict graph, which underestimates the effect of interferences and may lead to collisions in UWSNs. In [18], Kredo et al. propose a scheduled, interference-free TDMA-based MAC protocol called STUMP that increases channel utilization by leveraging node position diversity and the low propagation speed of the underwater channel. In STUMP, it segments the area around a node into concentric rings and then the uncertainty of node location would lead to the overestimation of the effect of interferences. However, to the best of our knowledge, our proposed schemes are the first ones with constant approximation ratios to the optimum solutions in UWSNs. Moreover, the slotted spatio-temporal conflict graph most accurately models the spatio-temporal uncertainty problem in UWSNs.

III. System Model and Problem Formulation

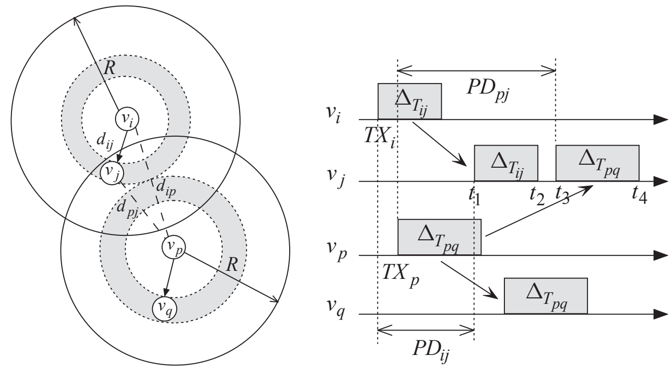
In this section, we present the system model consisting of a network model and an interference model, then we formulate the spatio-temporal link scheduling problem for UWSNs.

A. System Model

We assume that an UWSN has n static sensor nodes, which are all equipped with single half-duplex antennas. The network can be represented as a communication graph $G = (V, E)$, where $V = \{v_1, v_2, \cdots, v_n\}$ denotes the set of nodes, and E denotes the set of directed edges referring to all the communication links. If $\{v_i, v_j\} \subseteq V$, the edge $l_{ij} = (v_i, v_j) \in E$ when v_j is located within the transmission range of v_i. For link l_{ij}, node v_i is the transmitter and v_j is the receiver. The traffic load of link l_{ij} is tl_{ij}, the data rate of underwater sensors is B, and then the transmission delay of link l_{ij} is $\Delta_{T_{ij}} = \frac{tl_{ij}}{B}$. The propagation speed of acoustic signals in underwater environments is c.

In acoustic networks, the packets transmitted by a node can be received by multiple nodes within its transmission range. Interferences may occur when two transmissions collide. Similar to those in wireless networks, there are two types of interferences in acoustic networks: primary interference and secondary interference [19]. The primary interference occurs when a node has more than one communication task in a single time slot. Typical examples are RX-RX interference (receiving from two different transmitters simultaneously), TX-TX interference (transmitting to two different receivers simultaneously), and RX-TX interference (receiving and transmitting simultaneously). The secondary interference occurs when a node tuned to a particular transmitter is also within the transmission range of another transmission intended for other nodes. Both primary interference and secondary interference are considered in this paper.

The interference between two links in the network depends on the interference model, and we use the protocol model [20]. In the protocol model, each node v_i has a transmission range r and an interference range R, where $R > r$. We denote the ratio between the interference range and the transmission range as $\gamma = \frac{R}{r}$. The transmission time of node v_i is denoted by TX_i and the propagation delay between node v_i and v_j is denoted by PD_{ij}.



(a) Link transmission in UWSNs (b) Time diagram

Fig. 2. Interference analysis in UWSNs.

Lemma 1. *In UWSNs, a transmission from v_i to v_j fails due to the secondary interference if the transmission time TX_p of node v_p which is located within a distance R from v_j meets the following formula:*

$$TX_i+PD_{ij}-PD_{pj}-\Delta_{T_{pq}} \leq TX_p \leq TX_i+PD_{ij}-PD_{pj}+\Delta_{T_{ij}}, \quad (1)$$

where $\Delta_{T_{ij}}$ and $\Delta_{T_{pq}}$ are the link transmission delays of link l_{ij} and link l_{pq}.

Proof: As shown in Fig. 2, node v_j starts to receive the data from node v_i at time $t_1 = TX_i + PD_{ij}$ due to the propagation delay. Node v_j can finish the reception at time $t_2 = TX_i + PD_{ij} + \Delta_{T_{ij}}$ considering the link transmission delay. Another transmitter v_p is located with in a distance R from v_j, and thus, v_p starts to interfere the data reception of v_j at time $t_3 = TX_p + PD_{pj}$ and ends the interference at time $t_4 = TX_p + PD_{pj} + \Delta_{T_{pq}}$.

If the transmission of link l_{pq} interferes the reception of link l_{ij}, intervals $[t_1, t_2]$ and $[t_3, t_4]$ must have an overlap. We can see that these two intervals $[t_1, t_2]$ and $[t_3, t_4]$ are overlapped if and only if $t_3 \leq t_2$ and $t_1 \leq t_4$. If $t_3 \leq t_2$, i.e., $TX_p + PD_{pj} \leq TX_i + PD_{ij} + \Delta_{T_{ij}}$, we can get $TX_p \leq TX_i + PD_{ij} - PD_{pj} + \Delta_{T_{ij}}$. If $t_1 \leq t_4$, i.e., $TX_i + PD_{ij} \leq TX_p + PD_{pj} + \Delta_{T_{pq}}$, we can get $TX_P \geq TX_i + PD_{ij} - PD_{pj} - \Delta_{T_{pq}}$. ■

Note that the primary interference can be treated as a special case of the secondary interference, we can extend Lemma 1 to the primary interference where two links share some common node.

Lemma 2. *In UWSNs, a transmission from v_i to v_j fails due to the primary interference if the transmission time of another link meets the following formulas:*

(1) *For the RX-RX interference that two links l_{ij} and l_{pj} have the same receiver v_j, $TX_i + PD_{ij} - PD_{pj} - \Delta_{T_{pj}} \leq TX_p \leq TX_i + PD_{ij} - PD_{pj} + \Delta_{T_{ij}}$.*
(2) *For the TX-TX interference that two links l_{ij} and l_{iq} have the same transmitter v_i, $TX_i - \Delta_{T_{iq}} \leq TX_i' \leq TX_i + \Delta_{T_{ij}}$, where TX_i' is the transmission time from v_i to v_q.*
(3) *For the RX-TX interference that the receiver v_j in link l_{ij} is also the transmitter in link l_{jq}, $TX_i + PD_{ij} - \Delta_{T_{jq}} \leq TX_j \leq TX_i + PD_{ij} + \Delta_{T_{ij}}$.*

Proof: For the RX-RX interference, link l_{pj} plays the role of link l_{pq} in Lemma 1, then we can replace the subscript q with j in Eq. (1), and get $TX_i + PD_{ij} - PD_{pj} - \Delta_{T_{pj}} \leq TX_p \leq TX_i + PD_{ij} - PD_{pj} + \Delta_{T_{ij}}$.

For the TX-TX interference, link l_{iq} plays the role of the link l_{pq} in Lemma 1, then we can replace the subscript p with i in Eq. (1), and get $TX_i + PD_{ij} - PD_{ij} - \Delta_{T_{iq}} \leq TX_i' \leq TX_i + PD_{ij} - PD_{ij} + \Delta_{T_{ij}}$, i.e., $TX_i - \Delta_{T_{iq}} \leq TX_i' \leq TX_i + \Delta_{T_{ij}}$.

For the RX-TX interference, link l_{jq} plays the role of the link l_{pq} in Lemma 1, then we can replace the subscript p with j in Eq. (1), and get $TX_i + PD_{ij} - PD_{jj} - \Delta_{T_{jq}} \leq TX_j \leq TX_i + PD_{ij} - PD_{jj} + \Delta_{T_{ij}}$, i.e., $TX_i + PD_{ij} - \Delta_{T_{jq}} \leq TX_j \leq TX_i + PD_{ij} + \Delta_{T_{ij}}$. ■

B. Problem Formulation

Given an interference model, the interference of the links in the communication graph $G = (V, E)$ can be represented as a *conflict graph* [21]. To deal with the propagation delay in UWSNs, Hsu et al. [17] proposed the spatial-temporal conflict (STC) graph $G'(V', E')$, where $V' = E$ and E' is the set of conflict relationships between transmission links. There is a conflict relationship $Conflict(u \rightarrow v)$ $(u, v \in V')$, if the transmission of link l_{pq} (denoted by u) interferes the reception of link l_{ij} (denoted by v). The conflict delay $c_{u,v}$ is used to describe the spatio-temporal uncertainty for each edge $e(u, v) \in E'$. Link u would conflict with link v if the transmission time TX_p of u is just $c_{u,v}$ time units after the transmission time TX_i of v, i.e., $TX_p = TX_i + c_{u,v}$. If two links u and v have the same destination, we can easily get $c_{u,v} = -c_{v,u}$.

Fig. 3 shows a sample UWSN and its corresponding conflict graphs. Fig. 3(a) shows the communication graph, where the dashed line denotes that node v_2 is in the interference range of node v_5 and the numbers on each edge denote the propagation delays of data transmissions. Fig. 3(b) shows the corresponding STC graph. For example, links b and d (i.e., vertices b and d in Fig. 3(b)) interfere with each other, so both $Conflict(b \rightarrow d)$ and $Conflict(d \rightarrow b)$ exist, and the conflict delays are $c_{b,d} = 1.1$ and $c_{d,b} = -0.8$. For links b and c that have the same destination node v_2, $Conflict(b \rightarrow c)$ and $Conflict(c \rightarrow b)$ both exist, and $c_{b,c} = -0.2$ and $c_{c,b} = 0.2$. Due to the symmetrical conflict relationships between links b and c, their conflict relationship is represented in only one direction in the STC graph.

In the STC graph, since the link transmission delay is not considered, the conflict delay is only a time value. Thus, it underestimates the effect of interferences in UWSNs. Suppose that link u interferes the reception of link v. When link u is transmitting a data packet, the transmission process needs a time duration to complete. Thus, the time slots that link v cannot be assigned form an interval. Therefore, the conflict delay $c_{u,v}$ is not a time value, but a time interval. As $c_{u,v} = TX_p - TX_i$, according to Lemma 1, $c_{u,v}$ should be an interval $[PD_{ij} - PD_{pj} - \Delta_{T_{pq}}, PD_{ij} - PD_{pj} + \Delta_{T_{ij}}]$ for the secondary interference. According to Lemma 2, for the RX-RX, TX-TX and RX-TX interferences in the primary interference, $c_{u,v}$

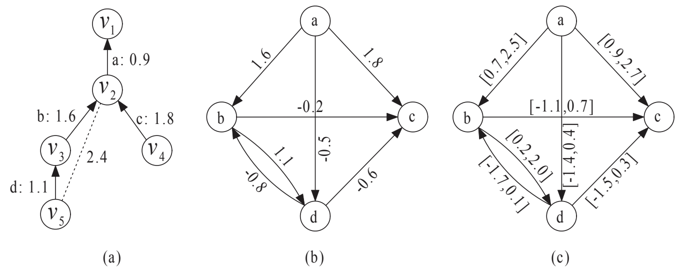


Fig. 3. Communication graph and corresponding conflict graphs: (a) Communication graph, (b) Spatial-temporal conflict graph, (c) Improved spatial-temporal conflict graph considering the link transmission delay. The dashed line represents the interference relationship, and the link transmission delay is assumed to be 0.9 time unit.

should be intervals $[PD_{ij} - PD_{pj} - \Delta_{T_{pj}}, PD_{ij} - PD_{pj} + \Delta_{T_{ij}}]$, $[-\Delta_{T_{iq}}, \Delta_{T_{ij}}]$ and $[PD_{ij} - \Delta_{T_{jq}}, PD_{ij} + \Delta_{T_{ij}}]$ respectively.

To further consider the link transmission delay, we revise the STC graph to be a new graph, as shown in Fig. 3(c). In the given sample network, assume the link transmission delay for a packet is $\Delta_T = 0.9$ time unit, where one time unit is equal to the length of one time slot. The conflict delay for each link is an interval with $2 \times \Delta_T = 1.8$ time units. For example, the conflict delay between link a and link b belongs to $[1.6 - 0.9, 1.6 + 0.9] = [0.7, 2.5]$. This means that link a would interfere with link b's reception if link a transmits a packet $[0.7, 2.5]$ time units after link b. For example, if link b is assigned at time slot 2, then link a cannot transmit during the time interval $[2.7, 4.5]$. As each link starts to transmit its package from the beginning of the assigned time slot, link a cannot be assigned the time slots which begin during the interval, i.e., time slots 3 and 4. Interestingly, although the time interval occupies part of time slot 2 (i.e., from 2.7 to 3.0), link a can transmit at time slot 2, for links a and b can transmit simultaneously.

To eliminate the conflict delay in the conflict graph, we add a time dimension in the conflict graph, and transform the STC graph to a novel three dimensional conflict graph called *slotted spatio-temporal conflict graph* (S-STC graph). In the S-STC graph $G_{sstc} = (V_{sstc}, E_{sstc})$, $V_{sstc} = \{(u, t_i) | u \in E, t_i \in T\}$, $E_{sstc} = \{e((u, t_i), (v, t_j)) | u, v \in E, t_j \in T\}$, where $e((u, t_i), (v, t_j))$ denotes the transmission of link u at time t_i conflicts the transmission of link v at time t_j. Fig. 4 shows the S-STC graph corresponding to the communication graph in Fig. 3(a). For example, $(b, 0)$, $(a, 1)$, $(a, 2)$ denote link b at time slot 0, link a at time slot 1 and link a at time slot 2, respectively. From the STC graph, link a cannot transmit 1 or 2 time units later than link b. Therefore, there is an edge between $(b, 0)$ and $(a, 1)$ as well as an edge between $(b, 0)$ and $(a, 2)$ in the S-STC graph. Obviously, we can see that the S-STC graph is a periodical graph.

Link scheduling is to assign each link u a list of time slots at which it could send packets without interferences. Let $X_{u,t} \in \{0, 1\}$ be an indicator variable, $X_{u,t} = 1$ if link u transmits at time t and $X_{u,t} = 0$ if link u does not transmit at time t. In TDMA, we assume that time is divided into slots with slot size t_s and a scheduling period T is composed of $|T|$ consecutive time slots. We assume that the scheduling is periodical, that is, $X_{u,t} = X_{u,t} + i \cdot T$ for any integer i. For a link u, let $I(u, t)$ denote the set of links v that interfere with u if v transmits at time t', where $t' = t + c_{u,v}$. A scheduling is interference-aware if $X_{u,t} + X_{v,t'} \leq 1$ for any $v \in I(u, t)$.

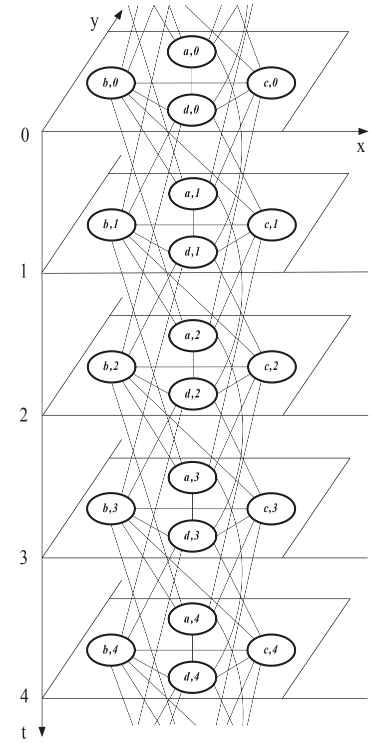


Fig. 4. Slotted spatio-temporal conflict graph.

In the unified traffic load scenario, as the traffic load of each link l_{ij} is unified to be tl, the link transmission delay of each link is $\Delta_T = \frac{tl}{B}$. We assume that all links can transmit their packets using one time slot, i.e., $\Delta_T \leq t_s$. In the weighted traffic load scenario, we assume that each link l_{ij} has a weight $w_{ij} = \lceil \frac{tl_{ij}}{B \cdot t_s} \rceil$, which is the number of time slots it requires to complete the transmission. The objective of link scheduling is to find a scheduling with the smallest period, i.e., the number of time slots assigned is smallest. As the throughput of the network is inverse proportional to T, the network throughput can be maximized by obtaining the smallest period. In [16], it is proven that the link scheduling in a single broadcast domain UWSN is NP-hard. As the single broadcast domain UWSN is a special topology of UWSNs, the interference-aware spatio-temporal link scheduling problem is also NP-hard. Therefore, it is necessary to design efficient heuristic algorithms with performance guarantee.

IV. Interference-aware Spatio-Temporal Link Scheduling with Unified Traffic Load

In this section, we investigate the link scheduling with unified traffic load in UWSNs. To solve this link scheduling problem, we propose an approximation algorithm called *Interference-aware Spatio-Temporal Link Scheduling with*

Unified traffic load (ISTLS-U), which is shown in Algorithm 1.

Algorithm 1 Interference-aware Spatio-Temporal Link Scheduling with Unified Traffic Load (ISTLS-U)

Input: A graph $G = (V, E)$.
Output: A valid ISTLS-U scheduling.
1: Construct the S-STC graph G_{sstc} based on G, and let graph $G^* = G_{sstc}$. Initialize stack $S = \varnothing$.
2: **while** $G^* \neq \varnothing$ **do**
3: Select a link $u \in E$ with the smallest degree in G^* and remove all the vertices (u, t_i) from G^* and all their incident edges. Push u into stack S.
4: **while** $S \neq \varnothing$ **do**
5: Pop link u from S. Assign u with the smallest available time slot t_u. For any neighbor (v, t_v) of (u, t_u) in G_{sstc}, time slot t_v turns unavailable for link v.

We first describe how to utilize the S-STC graph in the link scheduling. Different from the traditional vertex coloring, the S-STC graph is three-dimensional. In the S-STC graph, we need to select one and only one vertex (u, t_u) in all (u, t_i) where $i = 0, 1, 2, ...$ as it indicates that link u transmits at time slot t_u. After (u, t_u) is assigned, the vertices adjacent to (u, t_u) cannot be selected. This procedure continues until every vertex is selected, that is, each link is assigned its own transmission time. Take Fig. 4 as an example, we can select vertices $(a, 0)$, $(b, 0)$, $(c, 2)$ and $(d, 3)$, that is, links a, b, c and d transmit at time slots 0, 0, 2 and 3 respectively. As there exists the propagation delay in UWSNs, the transmission and reception of a link are not at the same time, and they should be scheduled separately. In the assignment, the selected time slot represents the transmission time, and the reception time can be calculated by adding the propagation delay of the link to the transmission time. The scheduling period is $T = \max_{u \in E}\{t_u + \Delta_T + PD_u\}$, where PD_u is the propagation delay of link u. The objective of the link scheduling is to minimize the scheduling period T. As Δ_T and PD_u are determined by the network environment, we can try to minimize $\max_{u \in E}\{t_u\}$.

To solve the link scheduling problem in the S-STC graph, we use the smallest-degree-last ordering method [22]. The basic idea is to firstly sort the links using the smallest-degree-last ordering which is shown as follows: Every time we select a link with the smallest degree from the remaining graph, and then remove the link from the graph. Repeat this until the remaining graph becomes empty. We reverse the order of the selected links, and assign time slots to these links in sequence using the first-fit heuristic, that is, the smallest available time slots that are not used by the interfering links will be assigned. Take the sample network in Fig. 3(a) as an example, the ISTLS-U algorithm first constructs the S-STC graph as shown in Fig. 4, and then finds a scheduling order using the smallest-degree-last method as b, d, c and a. Then each link is assigned the smallest time slot without interferences one by one. After the assignment, links a, b, c and d are assigned time slots 3, 0, 3 and 1, respectively.

In the S-STC graph, the degree $deg(u_i)$ of a vertex (u, t_i) is the number of vertices adjacent to it assuming time is infinite. Then $deg(u_1), deg(u_2), deg(u_3), \cdots$ are all equal to a value $deg(u)$, which is called the degree of link u in the S-STC graph. For example, $deg(b) = 7$ in Fig. 4. The number of vertices adjacent to a link u in the STC graph is denoted as $deg'(u)$. For example, in Fig. 3(b), $deg'(b) = 3$. It is easy to see that $deg'(u)$ is different from $deg(u)$.

Lemma 3. *For any link u, the degree of u in the S-STC graph is at most four times the degree of u in the STC graph.*

Proof: Suppose that link v is adjacent to link u in the STC graph. In the worst case, link u may interfere the reception of link v with conflict delay $c_{u,v}$, and link v may interfere the reception of link u with conflict delay $c_{v,u}$. Then, the vertices adjacent to a vertex (u, t_i) in the S-STC graph are (v, t) and (v, t'), where $t = t_i - c_{u,v}$ and $t' = t_i + c_{v,u}$. As both $c_{u,v}$ and $c_{v,u}$ are time intervals of $2\Delta_T$, both t and t' are also time intervals of $2\Delta_T$. If $\Delta_T \in [0, 0.5ts)$, the number of vertices in all (v, t_j) adjacent (u, t_i) is not larger than 2. If $\Delta_T \in [0.5ts, ts)$, the number of vertices in all (v, t_j) adjacent to (u, t_i) is not larger than 4. Hence, we can get that for each vertex adjacent to link u in the STC graph, there are at most four vertices adjacent to (u, t_i) in the S-STC graph. Therefore, $deg(u) \leq 4deg'(u)$. ■

We denote the minimum degree of all vertices by $\delta(G)$ in $G = (V, E)$, and the inductivity of G by $\delta^*(G) = max_{U \subseteq V}\delta(G[U])$, where $G[U]$ is the subgraph of G induced by $U \subseteq V$. A vertex coloring of G is an assignment of colors to nodes in V such that adjacent vertices are assigned different colors. It is well known that we can produce a proper vertex coloring in G using at most $1 + \delta^*(G)$ colors by applying a smallest-degree-last ordering of vertices [22]. Although the scheduling in the S-STC is different from the vertex coloring problem, the number of transmitting time slots used by the ISTLS-U algorithm is at most $\delta^*(G_{sstc}) + 1$.

Theorem 1. *The upper bound of the number of transmitting time slots used by the ISTLS-U algorithm is* $\delta^*(G_{sstc}) + 1$.

Proof: In the ISTLS-U algorithm, we suppose the scheduling order is $u_1, u_2, \cdots, u_n$. Let G_i be the S-STC graph induced by links u_1, u_2, $\cdots$, and u_i, and $deg_i(u)$ be the degree of u in G_i. Thus, $deg_n(u)$ is the degree of u in G_{sstc}.

Suppose k_i is the number of transmitting time slots used after links u_1, u_2, $\cdots$, and u_i are scheduled by the scheduling algorithm. When considering link u_{i+1}, if a used time slot can also be assigned to u_{i+1}, we have $k_{i+1} = k_i$; otherwise, a new time slot has to be assigned to it, then we have $k_{i+1} = k_i + 1$ and $deg_{i+1}(u_{i+1}) \geq k_i$. By mathematical induction on i, we deduce $k_i \leq 1 + max\{deg_i(u_i)|i = 1, 2, \cdots, n\}$. Since $deg_i(u_i)$ is clearly bounded by both $deg_n(u_i)$ and $i - 1$ (the number of other vertices in G_i), $k_n \leq 1 + max\{\min_{1 \leqslant i \leqslant n}\{deg_n(u_i), i - 1\}\}$.

Notice that, we use the smallest-degree-last ordering method, then we have $deg_i(u_i) = min\{deg_i(u_j)|u_j \in G_i\}$. According to the definition, we have $k_n \leq \delta^*(G_{sstc}) + 1$, that is, the number of transmitting time slots used by the ISTLS-U algorithm is at most $\delta^*(G_{sstc}) + 1$. ■

Lemma 4. *The distance between two nodes simultaneously transmitting without interferences should be at least $c\Delta_T$.*

Proof: Suppose receiver v_j in link l_{ij} is in the interference range of another transmitter v_p in link l_{pq}, as shown in Fig. 2(a). We use d_{xy} to denote the distance between nodes x and y. Due to the propagation delay, we have $d_{ij} = c \cdot PD_{ij}$ and $d_{pj} = c \cdot PD_{pj}$. From Lemma 1, we get $|TX_p + PD_{pj} - TX_i - PD_{ij}| > \Delta_T$ for l_{pq} does not interfere with l_{ij}. As nodes v_p and v_i transmit simultaneously, $TX_p = TX_i$, then $|PD_{pj} - PD_{ij}| > \Delta_T$. Thus, the distance betwee v_i and v_p is $d_{ip} \geq |d_{pj} - d_{ij}| = c|PD_{pj} - PD_{ij}| > c\Delta_T$. ■

Theorem 2. *The lower bound of the number of transmitting time slots used by the ISTLS-U algorithm is $\frac{\delta^*(G_{sstc})}{4C}$ in two-dimensional networks, where $C = \frac{1}{2}(2L + \frac{4L}{\gamma} + 1)^2 + \frac{4}{\pi}(L + \frac{2L}{\gamma} + \frac{1}{2}) - 1$, $L = \frac{R}{c\Delta_T}$ and $\gamma = \frac{R}{r}$.*

Proof: Let G^* be a subgraph of G_{sstc} such that every vertex in G^* has a degree of at least $\delta^*(G_{sstc})$. Let $v_j \in G^*$ be the bottom-most node in this subgraph and v_i is the transmitter of the link l_{ij}. In G^*, the transmitters of the links that interfere with the link l_{ij} lie in a semi-disk with radius $R + 2r$, as shown in Fig. 5. There are two cases:

Case1: A link incident to v_j interferes the reception of the link with transmitter v_p. For example, l_{ij} interferes the reception of link l_{pq} as shown in Fig. 5. As v_p can communicate with v_q, $d_{pq} \leq r$. As l_{ij} interferes with l_{pq}, $d_{qi} \leq R$. As v_i can communicate with v_j, $d_{ij} \leq r$. Hence, $d_{pj} \leq d_{pq} + d_{qi} + d_{ij} + \leq R + 2r$.

Case 2: A link with transmitter v_p interferes the reception of v_j, and $d_{pj} \leq R$.

From Lemma 4, the distance between two nodes simultaneously transmitting without interferences should be at least $c\Delta_T$. That is, for a disk with diameter $c\Delta_T$, there is at most one transmitter simultaneously transmitting with v_i. Therefore, the number of non-overlapped disks, excluding the disk centered at v_i, is upper bounded by

$$C = \frac{\frac{1}{2}\pi(R + 2r + \frac{c\Delta_T}{2})^2 + 2(R + 2r + \frac{c\Delta_T}{2})(\frac{c\Delta_T}{2})}{\pi(\frac{c\Delta_T}{2})^2} - 1$$
$$= \frac{1}{2}(2L + \frac{4L}{\gamma} + 1)^2 + \frac{4}{\pi}(L + \frac{2L}{\gamma} + \frac{1}{2}) - 1.$$

From Lemma 3, the number of links that can interfere with the link incident to v_j is at least $\frac{\delta^*(G_{sstc})}{4}$. So the number of transmitting time slots used is at least $\frac{\delta^*(G_{sstc})}{4C}$. ■

We are now ready to obtain the approximation ratio of the ISTLS-U algorithm in two-dimensional networks.

Theorem 3. *The number of transmitting time slots used by the ISTLS-U algorithm is at most a constant factor of the optimum in two-dimensional networks, and the approximation ratio is $4C$.*

Proof: According to Theorems 1 and 2, the approximation ratio of the ISTLS-U algorithm is $\frac{\delta^*(G_{sstc})+1}{\frac{\delta^*(G_{sstc})}{4C}} \simeq 4C$, so the number of transmitting time slots used is at most a constant factor of the optimum. ■

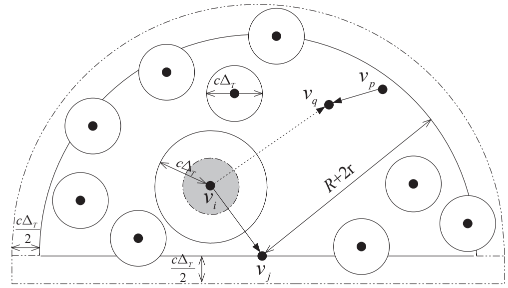


Fig. 5. Bounding minimum degree in the ISTLS-U algorithm.

The approximation ratio in three-dimensional networks is determined similar to that in two-dimensional networks. The transmitters of the links that interfere with the reception of a receiver v_j lie in a semi-sphere with radius $R + 2r$ and center v_j. Then we can get the number of non-intersecting spheres with diameter $c\Delta_T$ is upper bounded by:

$$C_1 = \frac{\frac{1}{2} \cdot \frac{4}{3}\pi(R + 2r + \frac{c\Delta_T}{2})^3 + \pi(R + 2r + \frac{c\Delta_T}{2})^2 \cdot \frac{c\Delta_T}{2}}{\frac{4}{3}\pi(\frac{c\Delta_T}{2})^3} - 1$$
$$= \frac{1}{2}(2L + \frac{4L}{\gamma} + 1)^3 + 3(L + \frac{2L}{\gamma} + \frac{1}{2})^2 - 1.$$

Corollary 1. *The number of transmitting time slots used by the ISTLS-U algorithm is at most a constant factor of the optimum in the three-dimensional networks, and the approximation ratio is $4C_1$, where $C_1 = \frac{1}{2}(2L + \frac{4L}{\gamma} + 1)^3 + 3(L + \frac{2L}{\gamma} + \frac{1}{2})^2 - 1$.*

V. Interference-aware Spatio-Temporal Link Scheduling with Weighted Traffic Load

In this section, we investigate the link scheduling with weighted traffic load in UWSNs. In general, the traffic load in each link is different. For the link scheduling with weighted traffic load, we assume that link u has weight $w_u = \lceil \frac{tl_u}{B \cdot t_s} \rceil$ upon the load requirement, and the traffic load tl_u is determined by a certain routing. Then in the link scheduling, link u is assigned w_u time slots.

We consider the interference-aware spatio-temporal link scheduling with weighted traffic load in two scenarios: One scenario is that each link does not have the consecutive constraint, that is, each link can transmit its packets in multiple time slots arbitrarily in each scheduling period such as [9]. The other one is that each link has the consecutive constraint, that is, each link must use consecutive time slots to transmit its packets and can only transmit once in each scheduling period such as [23], [24].

A. Interference-aware Spatio-Temporal Link Scheduling with Weighted Traffic Load

The *Interference-aware Spatio-Temporal Link Scheduling with Weighted traffic load* (ISTLS-W) algorithm is shown in Algorithm 2, which does not consider the consecutive constraint. The basic idea is to create a clique with size w_u for each vertex (u, t_i) in the S-STC graph, and then there is a set of virtual links u_1, u_2, $\cdots$, u_{w_u} for each link u, and all these virtual links are assigned time slots using the ISTLS-U algorithm. Finally, link u is assigned the w_u time slots which are assigned to its virtual links. In the scheduling, the w_u time slots assigned to link u may be not consecutive.

Algorithm 2 Interference-aware Spatio-Temporal Link Scheduling with Weighted Traffic Load (ISTLS-W)

Input: A graph $G = (V, E)$ with weights on each link.
Output: A valid ISTLS-W scheduling.

1: Construct the S-STC graph G_{sstc}, and assign a weight w_u to each vertex (u, t_i).
2: Construct a new S-STC graph G'_{sstc} as follows: For each vertex (u, t_i) with weight w_u, we create w_u virtual vertices, $(u_1, t_i), (u_2, t_i), \cdots, (u_{w_u}, t_i)$, and add them to G'_{sstc}. Add to graph G'_{sstc} the edges connecting (u_j, t_i) and (u_k, t_i) for all $1 \leq j < k \leq w_u$. Add to graph G'_{sstc} an edge between (u_j, t_i) and (v_k, t_l) if and only if there is an edge between (u, t_i) and (v, t_l) in G_{sstc}.
3: Run the ISTLS-U algorithm on G'_{sstc}.
4: Assign link u all the time slots which are assigned to u_j for $1 \leq j \leq w_u$ in G'_{sstc}.

Theorem 4. *The number of transmitting time slots used by the ISTLS-W algorithm is at most a constant factor of the optimum in two-dimensional networks, and the approximation ratio is* $4C$.

Proof: The minimum number of transmitting time slots used by the ISTLS-U algorithm in G'_{sstc} and the minimum number of transmitting time slots used by the ISTLS-W algorithm in G_{sstc} are denoted by $\chi(G'_{sstc})$ and $\chi(G_{sstc})$ respectively. Notice that for any valid ISTLS-W scheduling for G_{sstc}, link u is assigned at least w_u time slots. By assigning each virtual link u_j in G'_{sstc} a distinct time slot from the w_u time slots which are assigned to link u, we obtain a valid ISTLS-U scheduling for G'_{sstc}. Thus, $\chi(G'_{sstc}) \leq \chi(G_{sstc})$. Since the ISTLS-U algorithm will return a scheduling with at most $4C \cdot \chi(G'_{sstc})$ transmitting time slots, the ISTLS-W algorithm produces a scheduling with at most $4C \cdot \chi(G'_{sstc}) \leq 4C \cdot \chi(G_{sstc})$ transmitting time slots. ■

Corollary 2. *The number of transmitting time slots used by the ISTLS-W algorithm is at most a constant factor of the optimum in three-dimensional networks, and the approximation ratio is* $4C_1$.

B. Interference-aware Spatio-Temporal Link Scheduling with Weighted Traffic Load under the Consecutive Constraint

The *Interference-aware Spatio-Temporal Link Scheduling with Weighted traffic load under the Consecutive constraint* (ISTLS-WC) algorithm is shown in Algorithm 3. The basic idea is that a link with a heavier traffic load will be scheduled earlier. Different from the ISTLS-W algorithm, gaps exist in the time slot assignment, because each link u has to be assigned w_u consecutive time slots. For example, suppose the weights of links a, b, c and d in Fig. 4 are 3, 4, 5, 6 respectively. Based on the ISTLS-WC algorithm, the scheduling order is d, c, b and a. After the scheduling, we can easily get that link d is assigned time slots from 0 to 5, link c is assigned time slots from 7 to 11, and link b is assigned time slots from 12 to 15. Then link a cannot be assigned time slots from 0 to 5, from 8 to 13 and from 13 to 17 due to the interferences with links d, c and b respectively. Because of the consecutive constraint, time slots 6 and 7 cannot be assigned, and these time slots are referred to as gaps in the scheduling. By using the first-fit heuristic, link a is assigned time slots from 18 to 20.

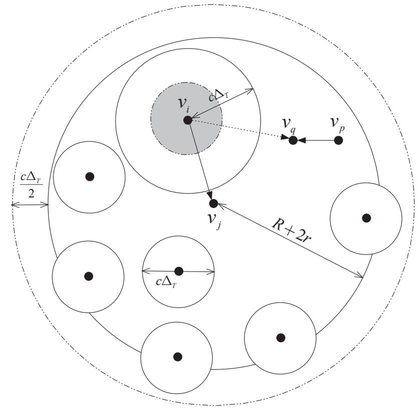


Fig. 6. Bounding minimum degree in the ISTLS-WC algorithm.

Algorithm 3 Interference-aware Spatio-Temporal Link Scheduling with Weighted Traffic Load under the Consecutive Constraint (ISTLS-WC)

Input: A graph $G = (V, E)$ with weights on each link.
Output: A valid ISTLS-WC scheduling.

1: Construct the S-STC graph G_{sstc}, and assign a weight w_u to each vertex (u, t_i).
2: Sort the vertices according to the weight information.
3: Schedule the link with higher weight earlier, and assign each link u the smallest w_u available consecutive time slots.

When the ISTLS-WC algorithm is used, the scheduling order based on the weight information is not the same as the smallest-degree-last order used in the ISTLS-U algorithm. Therefore, the approximation ratio of $4C$ derived from Theorem 3 does not hold any more. However, we can use a method similar to that used in Theorem 2 to derive a new approximation ratio. We first proof that using the ISTLS-WC algorithm can derive an approximation ratio in the unified traffic load scenario, and then derive the approximation ratio in the weighted traffic load scenario.

Lemma 5. *In the unified traffic load scenario, the number of transmitting time slots used by the ISTLS-WC algorithm is at most a constant factor of the optimum in two-dimensional networks, and the approximation ratio is* $4C'$, *where* $C' = (2L + \frac{4L}{\gamma} + 1)^2 - 1$, $L = \frac{R}{c\Delta_T}$ *and* $\gamma = \frac{R}{r}$.

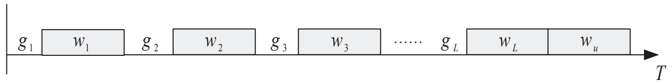


Fig. 7. The time slots that cannot be assigned to link u in G_{sstc} when u is scheduled.

Proof: In the unified traffic load scenario, as all links have equal weights, the scheduling order is just a random order. As shown in Fig. 6, if link l_{pq} interferes with link l_{ij}, similar to Theorem 3, we can get that the distance between receiver v_j and transmitter v_p is at most $R+2r$. From Lemma 4, the distance between two nodes simultaneously transmitting without interference should be at least $c\Delta_T$. That is, for a disk with diameter $c\Delta_T$, there is at most one transmitter simultaneously transmitting with transmitter v_i. Therefore, the number of non-overlapped disks, excluding the disk centered at v_i, is upper bounded by

$$C' = \frac{\pi(R + 2r + \frac{c\Delta_T}{2})^2}{\pi(\frac{c\Delta_T}{2})^2} - 1 = (2L + \frac{4L}{\gamma} + 1)^2 - 1.$$

The maximum degree of a vertex in the slotted spatio-temporal conflict graph is denoted as $\Delta(G_{sstc})$. From Lemma 3, the number of links that can interfere with the link incident to v_j is at least $\frac{\Delta(G_{sstc})}{4}$. So the lower bound of the number of transmitting time slots used by the ISTLS-WC algorithm is $\frac{\Delta(G_{sstc})}{4C'}$. As the first-fit heuristic is used in the algorithm, the upper bound of the number of transmitting time slots used is $\Delta(G_{sstc})+1$. Hence, the approximation ratio is $\frac{\Delta(G_{sstc})+1}{\frac{\Delta(G_{sstc})}{4C'}} = 4C'$. ■

Theorem 5. *The number of transmitting time slots used by the ISTLS-WC algorithm is at most a constant factor of the optimum in two-dimensional networks, and the approximation ratio is* $8C'$.

Proof: Suppose that all the links have been already scheduled using the ISTLS-WC algorithm, and link u is assigned the last w_i time slots, as shown in Fig. 7. In the figure, w_i ($1 \leqslant i \leqslant L$) is the number of consecutive time slots occupied by the links that interfere with link u in the S-STC graph G_{sstc}, and $g_1, g_2, \cdots, g_L$ represent the gaps which are not large enough for scheduling link u. Note that the links scheduled before link u may reuse some time slots. Since the links are scheduled in the non-increasing order of weights, w_i ($1 \leqslant i \leqslant L$) is not smaller than w_u. Since link u is assigned the smallest w_u consecutive time slots using the first-fit heuristic, g_i ($1 \leqslant i \leqslant L$) is smaller than w_u. The upper bound of the number of transmitting time slots used by the ISTLS-WC algorithm is

$$\sum_{i=1}^{L} g_i + \sum_{i=1}^{L} w_i + w_u < L \cdot w_u + \sum_{i=1}^{L} w_i + w_u < 2(\sum_{i=1}^{L} w_i + w_u).$$

From Lemma 5, the lower bound of the number of transmitting time slots used by the ISTLS-WC algorithm is $\frac{\sum_{i=1}^{L} w_i + w_u}{4C'}$. Therefore, we get the approximation ratio is $\frac{2(\sum_{i=1}^{L} w_i + w_u)}{\frac{\sum_{i=1}^{L} w_i + w_u}{4C'}} = 8C'$. ■

The approximation ratio in three-dimensional networks is determined similar to that in two-dimensional networks. The transmitters of the links that interfere with the reception of a receiver v_j lie in a sphere with radius $R + 2r$ and center v_j. Then we can get the number of non-intersecting spheres with diameter $c\Delta_T$ is upper bounded by:

$$C_2 = \frac{\frac{4}{3}\pi(R + 2r + \frac{c\Delta_T}{2})^3}{\frac{4}{3}\pi(\frac{c\Delta_T}{2})^3} - 1 = (2L + \frac{4L}{\gamma} + 1)^3 - 1.$$

Corollary 3. *The number of transmitting time slots used by the ISTLS-WC algorithm is at most a constant factor of the optimum in the three-dimensional networks, and the approximation ratio is* $8C_2$, *where* $C_2 = (2L + \frac{4L}{\gamma} + 1)^3 - 1$.

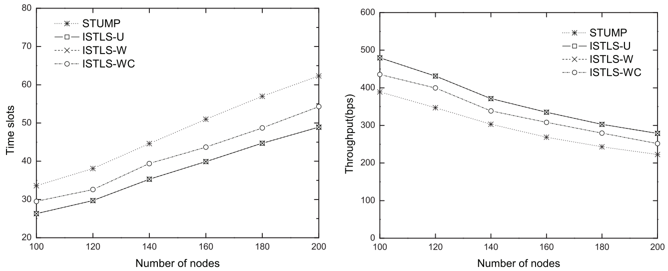
VI. Simulation Results

In this section, we study the performance of the interference-aware spatio-temporal link scheduling in UWSNs, and we also compare our approaches with the STUMP algorithm [18]. The performance metrics used in the simulation are the number of transmitting time slots used and throughput. The throughput is defined as the average rate of the amount of information delivered to the sink .

We adopt the following simulation parameters: the propagation speed of the acoustic signal is $1.5km/s$, the data packet length is 300 bytes, the radio bandwidth is 15 kbps, and the link transmission delay of one data packet is $0.16s$. The length of the time slot (i.e., one time unit) is set to be $0.2s$. In the deployment, nodes with a transmission range of $1.5km$ and an interference range of $3km$ are deployed in a three dimensional area of $10km \times 10km \times 1km$. We test the networks when the network size varies from 100 nodes to 200 nodes in steps of 20 nodes. For each case, 50 network topologies are randomly generated, and the average performances over all these networks are reported. We assume there is a sink in the center of the water surface, and all traffics are towards it. We construct a shortest path tree routed at the sink node as the topology of the network, and this topology determines the routing of each source to the sink.

In the simulations, we test the link scheduling algorithms in both unified and weighted traffic load scenarios. In the unified traffic load scenario, we assume that nodes have the ability of data aggregation and can use one time slot to transmit all data in one link, then each link is assigned one time slot to transmit its package. In the weighted traffic load scenario, the traffic load of each link is calculated by the total amounts of traffics that need to transmit, and then each link u has its weight information w_u.

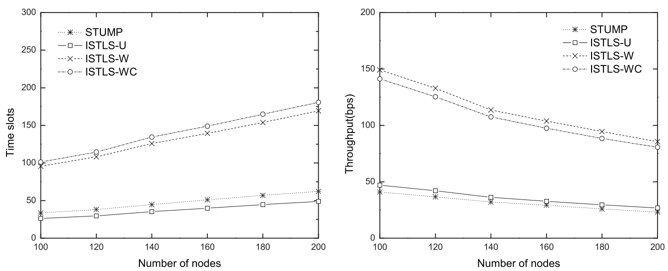
We first evaluate the impact of network size on the performance of our algorithms in the unified traffic load scenario. The ISTLS-U algorithm is actually same as the ISTLS-W algorithm in this scenario. Fig. 8 shows the number of transmitting time slots used and throughput in average. As the number of nodes increases, the average numbers of transmitting time slots used in the all the four algorithms increase, as shown in Fig. 8(a). But the average throughput decreases as the



(a) Average number of transmitting time slots used

(b) Average throughput

Fig. 8. Scheduling with unified traffic load.



(a) Average number of transmitting time slots used

(b) Average throughput

Fig. 9. Scheduling with weighted traffic load.

number of nodes increases, as shown in Fig. 8(b). The STUMP algorithm performs worse than the ISTLS-U algorithm as it overestimates the effect of interferences. The ISTLS-WC algorithm performs worse than the ISTLS-U algorithm because the scheduling order in the ISTLS-WC algorithm is random in the unified traffic load scenario.

We then test the impact of network size in the weighted traffic load scenario. Fig. 9(a) shows that the average number of transmitting time slots used by the ISTLS-U algorithm is fewer than those of the ISTLS-W and ISTLS-WC algorithms. But the average throughputs of the ISTLS-W and ISTLS-WC algorithms are much better than that of the ISTLS-U algorithm as shown in Fig. 9(b), as the traffic load information is used and links with heavier traffic loads are scheduled earlier. We can also see that the ISTLS-W algorithm has better performance than the ISTLS-WC algorithm due to the consecutive constraint.

VII. Conclusion

In this paper, we investigate the interference-aware spatio-temporal link scheduling in UWSNs. To solve the spatio-temporal uncertainty, we propose a novel slotted spatio-temporal conflict graph which considers both the packet propagation delay and link transmission delay. We present efficient scheduling algorithms that have theoretical performance bounds for both unified and weighted traffic loads. Finally, we evaluate the proposed algorithms via simulations, which show the efficiency of the algorithms in terms of the number of transmitting time slots used and throughput. In our future work, we will extend our approaches to heterogeneous networks, where nodes have different transmission and interference ranges. Moreover, we will design efficient distributed algorithms for the spatio-temporal link scheduling in UWSNs.

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