Localization Packet Scheduling for Underwater Acoustic Sensor Networks

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***Abstract*—Medium access control (MAC) determines how sensor nodes share the channel for packet exchanging. To obtain the maximum network efficiency for accomplishing a specific task, the network has to adapt its parameters accordingly. In other words, different MAC protocols are required for different tasks. Localization is a crucial task of an underwater acoustic sensor network (UASN) which requires multiple packet exchanges. This article concerns the problem of designing a MAC protocol for a UASN which efficiently schedules the localization packets of the anchors. Knowing the relative positions of the anchors and their maximum transmission range, the scheduling protocol takes advantage of the long propagation delay of underwater communications to minimize the duration of the localization task. First, we formulate the concept of collision-free packet transmission for localization, and we show how the optimum solution can be obtained. Furthermore, we model the problem as a mixed integer linear program both in single-channel and multi-channel scenarios. Then, we propose two low-complexity algorithms, and through comprehensive simulations we compare their performances with the optimal solution as well as with other existing methods. Numerical results show that the proposed algorithms perform near optimum and better than alternative solutions.**

***Index Terms*—Underwater acoustic sensor network, localization, MAC protocol, single-channel, multi-channel, packet scheduling.**

I. Introduction

Due to the high attenuation of radio frequency signals or magnetic induction [3], [4] over large distances and high operating frequencies, underwater sensor networks usually employ acoustic signals for communications. Despite the fact that the underwater acoustic channel is one of the most challenging wireless propagation media, a large number of applications such as early warning systems (e.g., for tsunamis), ecosystem monitoring, oil drilling, military surveillance and so on, leaves us no choice but utilizing underwater acoustic sensor networks (UASNs). One of the requirements of a UASN is packet exchange among different nodes of the network which is handled by the medium access control (MAC) layer. Although extensive research has been done on the design of MAC protocols for wireless sensor networks (WSNs), the unique characteristics of the underwater acoustic communication environment, e.g., a very low and distance-dependent bandwidth [5], high power consumption in transmit and receive mode [6], and long propagation delay, make the existing WSN algorithms and protocols inefficient for UASNs. To overcome these issues, researchers have suggested several modifications to WSN MAC protocols or proposed different alternatives. For instance, in a time division multiple access (TDMA) system, in order to decrease the collision probability, the slotted floor acquisition multiple access (FAMA) [7] sets the time slot duration equal to the packet length plus the maximum network propagation delay. The distance aware collision avoidance protocol (DACAP) [8] uses request to send (RTS) and clear to send (CTS) handshaking to reserve the channel. To increase the network efficiency in point-to-point communications, DACAP estimates the mutual distance between two nodes and uses this information to minimize the duration of a handshake. With the knowledge of mutual distances among the sensor nodes, further steps have been taken in [9] where a transmitting node adjusts the time guard of its TDMA slot according to its distance to the other nodes. In addition to these modifications, many other works recently tried to improve the UASN performance by introducing new features such as a reservation period [10], back-off [11], parallel reservation strategy [12], scheduling [13], [14], and spatial fairness [15]. However, all of these mentioned protocols are dedicated to source-to-destination packet exchanges. In contrast, some tasks in a network may require packet broadcasting. Underwater localization [16] is an example of such an inevitable task where anchors broadcast their localization packets to other nodes. Generally, localization packets only have a few bits of information, mainly about the anchor's position and the time when the packet is transmitted. As shown in Fig. 1, the localization packet may also include other information such as a preamble, the anchor's ID, the guard time, and channel coding [17].

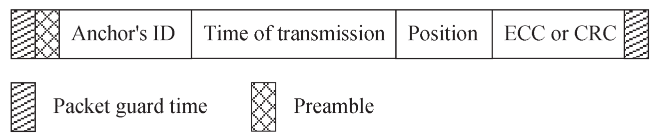

Fig. 1. Structure of a localization packet.

Kim *et al.* [18] evaluate the impact of the MAC on localization in a large-scale UASN. They show that the performance of a simple MAC protocol, namely carrier sense multiple access (CSMA), is better than T-Lohi [10] (a recently designed underwater MAC protocol). Ordered CSMA (OCSMA) [19] is a scheduling protocol which has been introduced for packet

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transmission in a fully connected network. In OCSMA, a coordinator finds the scheduling sequence based on the full knowledge of the relative positions of the anchors, and informs them of the resulting sequence. Then, the anchors start their packet transmission one after another according to the given scheduling sequence. Nevertheless, this kind of broadcasting protocol is not optimum, because it does not support simultaneous transmission for a broadcasting task. To overcome this problem, a single-hop all-to-all broadcasting transmission scheduling (AAB-MAC) is proposed in [20]. Knowing the propagation delay matrix, i.e., the propagation delays between all nodes, the goal of this protocol is to minimize the all-to-all transmission period in a way that no collisions occur. Although AAB-MAC performs better than OCSMA, it cannot be used for the localization task, because first we do not know the positions of all the underwater sensor nodes, and second, using the AAB-MAC only for the anchor nodes causes collisions at the sensor nodes. There are also a few other broadcasting MAC protocols [21], [22] which are not suitable for the localization task, because they do not consider collision-free broadcasting by the localization beacon.

In [23], the problems of position estimation and synchronization are combined with a recently proposed localization packet scheduling [24]. The authors consider the anchors that are within the communication range of each other, and schedule them to transmit their packet in a such a way that none of the sensor nodes experiences a collision. They have also extended their proposed idea for a large scale network in [25]. In contrast to these works, we consider multi-channel and dynamic multi-channel packet scheduling. We also evaluate the collision-free conditions when the anchors are not in the communication range of each other. Furthermore, we show how the optimization problem can be represented as a mixed integer linear program (MILP) problem.

Two efficient tone broadcast MAC protocols (TB-MACs) are proposed in [26] which are an adaptation of slotted-ALOHA and slotted-FAMA [7], but modified to work with broadcast traffic. Before broadcasting, TB-MACs use different handshaking mechanisms (NACK and NCTS instead of ACK and CTS) to handle the "reply storm" problem. Albeit these broadcasting protocols aim to enhance the network efficiency through reducing the handshaking overhead, they still rely on TDMA-like signaling which is not advisable for underwater networks.

Beside the relative position information of the nodes, another factor that increases the system efficiency is the use of several independent channels for packet exchanges [27]. According to [28], multi-channel MAC protocols help to improve the network efficiency. The paper [29] analytically evaluates the idea of multi-channel MAC protocols, and shows that the theoretical analysis closely follows the estimated system performance which is better in comparison with single-channel MAC protocols. The multi-channel packet exchange scheme basically reduces the possibility of collision in the network. However, it is not clear how it behaves in a collision-free packet scheduling which is tackled in this paper.

In contrast to the above works on underwater MAC protocols, in our previous papers, we have focused on designing a scheduling protocol for the specific task of anchor-based partially-connected single channel [1] and multi-channel underwater localization [2]. To do that, we have utilized the information about the relative positions of the anchors and their maximum transmission range to minimize the duration of the localization task. The localization procedure finishes when all the anchors have transmitted their packets. In this work, we combine the problem of localization packet scheduling for single-channel and multi-channel networks, and mention practical issues for this problem. Furthermore, we state that the problem is NP-hard, and we show how the optimal solution can be obtained, and how the problem can be converted to a standard MILP problem. Our contributions are listed below.

- The problem of minimizing the duration of the localization task is formulated in single-channel and multi-channel partially connected networks.
- For the localization task, an anchor is usually not interested in the transmitted packets from other anchors, unless it wants to estimate a physical phenomenon, or other information that is included in the localization packets. If that is the case we talk about the broadcast scenario. We show how the problem can be modified to support broadcast packets.
- The concept of dynamic multi-channel packet scheduling is introduced. In this approach, the system is able to split the existing channel into a few subchannels, and to schedule the localization packets not only in time but also in a specific subchannel.
- Several practical issues such as multi-path, sound speed variations, interference and moving anchors are considered, and it is shown how the formulation can be adapted accordingly.
- It is shown that the optimization problem can be converted to a combinatorial one which is NP-hard. Furthermore, it is shown how the optimum solution can be obtained through exhaustive search among all possible solutions.
- We also model the optimization problem as a MILP problem, and use tools such as CPLEX to solve the problem.

The rest of the paper is organized as follows. In Section II, we explain the network model, define the concept of collision-free anchors, and formulate the problem. Next, in Section III, we show how the optimum solution of the problem can be obtained, and in Section IV, we introduce the MILP model of the problem. Further, in Section V, a number of novel algorithms to tackle the problem are proposed. Section VI evaluates the performance of the proposed algorithms through several simulations, and finally, Section VII concludes the paper and mentions some future works.

II. Network Model

We consider an underwater sensor network with N surface-located anchor nodes (they can be located anywhere if their positions are known) with a maximum communication range of R meters. The following assumptions are made in this work.

- The anchors are equipped with GPS devices, as well as radio (or satellite) and half-duplex acoustic modems. It is further assumed that the anchors are synchronized with each other.

- The information about the positions of the anchors can be collected by a fusion center through their radio modems.
- There is no information about the position of the underwater sensor nodes, and they can be located anywhere in the operating area. In addition, they are not necessarily synchronized with the anchors.
- The sensor nodes are equipped with an inertial navigation system, and freely move in the environment, while the anchor nodes only drift around their nominal positions.

The localization task is required repeatedly in the network, and is carried out when decided by a fusion center, or upon requests from underwater nodes. The fusion center is responsible for scheduling the localization packet transmission of the anchors where each packet has a duration of t_p. Beside the localization data, other information can be encapsulated in the localization packets. Under this condition the packet size of each anchor can be different. Despite the fact that this condition can be included in our problem, we do not consider that in this paper. The underwater sensor nodes receive the transmitted packets, and use them for self-localization. In a 3D environment, each node requires at least 4 (3 if the depth is known [30]) localization packets for self-localization. The localization accuracy and localization coverage depends on the density of the anchors per squared meter. If each sensor node is located under the coverage of four or more anchors, and receives the packets correctly, it can localize itself (full coverage). Still, the localization accuracy depends on the orientation of the anchors, and the position of the sensor node. The goal is to minimize the localization time, and to avoid any possible collision in the packet reception at all underwater sensor nodes. In order to accomplish this task, the fusion center gives each anchor i a waiting time w_i before it starts its packet transmission. In a multi-channel scenario with M subchannels, the fusion center also determines which subchannel $m_i \in 1, 2, \ldots, M$ each anchor i has to transmit in.

So the problem we have to solve is to minimize the maximum waiting time, thereby avoiding any possible packet collision. To solve that problem, we have to analyze how collisions occur in the network. A collision will happen, if two or more transmitted packets overlap with each other at a sensor node. But since the sensor nodes can be located anywhere in the medium, there may be a collision if the transmitted packets from two anchors collide anywhere inside the intersection of the transmission ranges of these two anchors. Hence, as shown in Fig. 2, even if two anchor nodes are not located within their acoustic communication ranges they may cause a collision in the network. Briefly stated, two anchor nodes with a mutual distance smaller than twice the maximum transmission range are *collision-risk neighbors*, and therefore, they may cause collisions. The symbol $\leftrightarrow$ is defined to show that two nodes are collision-risk, i.e., $i \leftrightarrow j$ means that anchors i and j are collision-risk anchors. In addition $\Leftrightarrow$ is used to show that the anchors are within the communication range of each other. If $i \Leftrightarrow j$ they are also collision-risk anchors.

In order to eliminate the collision problem, we introduce the concept of *collision-free anchors*, and we will show how waiting times can be modified to make anchors collision-free in order to eliminate collisions at the sensor nodes.

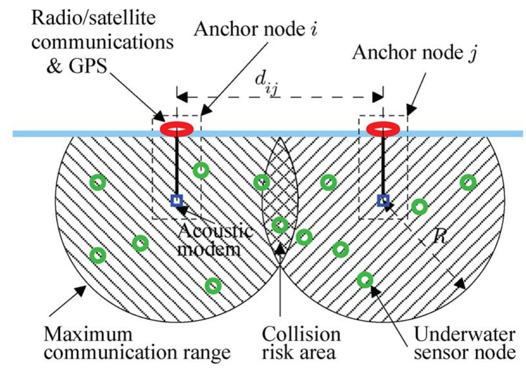

Fig. 2. Example of two collision-risk anchors.

A. Collision-Free Anchors

Imagine that there are two anchors, namely i and j, at distance d_{ij} that are going to transmit their packets in the respective subchannels m_i and m_j and, with respective waiting times w_i and w_j where $w_i > w_j$. We then want to find out whether under these conditions the two anchor nodes are collision-free. Below, we define a few conditions that will help us to analyze this problem.

Condition 1: If anchor i and j transmit their packets at different subchannels, i.e., $m_i \neq m_j$, they are collision-free anchors.

Condition 2: When the mutual distance between the two anchors is larger than $2R$, their transmission packets never collide for any pair of waiting times, because their communication ranges have no intersection. We call such two anchors strictly distance-related collision-free anchors.

Condition 3: Assume that the sound speed in the underwater medium is c. If the difference between the two waiting times is greater than $\frac{R}{c} + t_{\text{p}}$, the transmitted packets of these nodes will never collide with each other for any mutual distance. We call such two anchors strictly time-related collision-free anchors.

Condition 4: If anchors i and j transmit in the same channel, they are collision-free anchors if $w_i - w_j > \frac{2R - d_{ij}}{c} + t_p$ as shown in Fig. 3 for the minimum value of $w_i - w_j$. It can be observed that the crossing area is swept by the first, and the second anchor without any collision. This condition is useful when $d_{ij} > R$, otherwise, the term $\frac{2R - d_{ij}}{c} + t_p$ is greater than $\frac{R}{c} + t_{\text{p}}$, and Condition 3 covers this case. We can deduce that if we have $R < d_{ij} < 2R$, and w_j is already set, then the minimum value for w_i that makes these anchors collision-free can be obtained by

$$w_{i,\min} = w_j + \frac{2R - d_{ij}}{c} + t_p. \tag{1}$$

In general, when w_i is not necessarily greater than w_j, for a collision-free transmission of the localization packets when the waiting time of anchor j is already set, w_i has to meet the following inequality:

$$|w_i - w_j| \geq \frac{2R - d_{ij}}{c} + t_p, \tag{2}$$

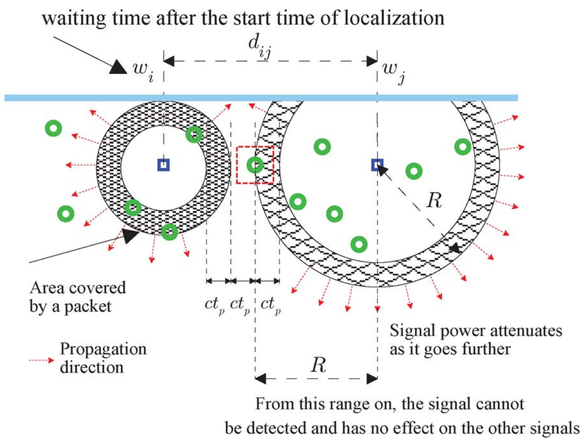

Fig. 3. Snapshot of the packet transmissions of two collision-free anchors at time $t = w_j + \frac{R}{c}$, and at distance d_{ij} where $R < d_{ij} < 2R$. The hatched parts show the area where the localization packets reside. Given w_j, anchor i has transmitted its packet at minimum w_i according to (1). At time $t = w_j + t_p + \frac{R}{c}$, the effect of the packet transmitted from j-th anchor vanishes and the sensor node which is located on the border (inside the red box in the figure) starts receiving the transmitted packet from the i-th anchor.

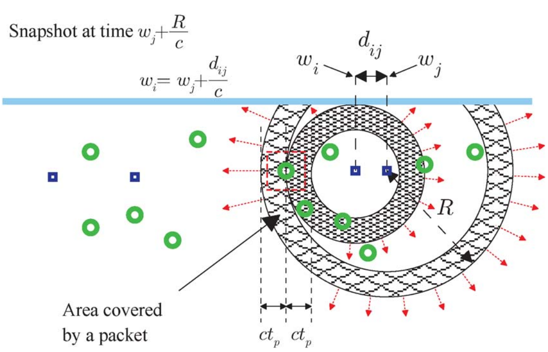

Fig. 4. Snapshot of the packet transmissions of two collision-free anchors located $d_{ij} < R$ meters away from each other at time $t = w_j + \frac{R}{c}$. Given w_j, anchor i transmits at the minimum waiting time according to (3). The transmitted packet from the i-th anchor follows that of the j-th anchor, and does not overlap with that.

Condition 5: If anchors i and j transmit in the same channel, they are collision-free anchors if $w_i - w_j > t_\text{p} + \frac{d_{ij}}{c}$ as shown in Fig. 4 for the minimum value of $w_i - w_j$. This condition is useful if $d_{ij} < R$, otherwise, like Condition 4, it can be represented by Condition 3. In other words, if we have $d_{ij} < R$, and the waiting time of anchor j is already set to w_j, then the minimum value for w_i, that makes these two anchors collision-free can be obtained as

$$w_{i,\min} = w_j + t_p + \frac{d_{ij}}{c}. \tag{3}$$

As before, when w_i is not necessarily greater than w_j, for a collision-free transmission of the localization packets when the waiting time of anchor j is already set, w_i has to be outside the following boundaries:

$$|w_i - w_j| \geq \frac{d_{ij}}{c} + t_p. \tag{4}$$

This condition is similar to what is explained in [23], [24].

B. L-MAC: Localization Packet Scheduling

Now that the concept of collision-free packet transmission has been clarified, we can formulate the optimization problem as

$$\min_{\{w_i\},\{m_i\}} \max\{w_i\} \text{ s.t.}$$
$$w_i \geq 0, \text{ for } i \in \{1, 2, .., N\} \tag{5a}$$
$$|w_i - w_j| > t_\text{p} + \frac{\check{d}_{ij}}{c} \text{ if } m_i = m_j \text{ and } i \leftrightarrow j. \tag{5b}$$

where

$$\check{d}_{ij} = \min(d_{ij}, 2R - d_{ij}), \tag{6}$$

$w_i \geq 0$ states that we cannot have a packet transmission at negative times, and Conditions 1 to 5 are merged into (5b).

From Conditions 4 and 5, it can be observed that in a collision-free packet transmission, setting the waiting time of an anchor imposes limitations on the waiting times of its collision-risk neighbors. These limitations not only relate to the time after the packet transmission of the considered anchor, but also to the time before its packet transmission. This is really important for finding the optimal solution of (5). In the next subsection, we show how the problem of scheduling can be formulated for a broadcast scenario.

C. B-MAC: Broadcasting Packet Scheduling

In a broadcast scenario, the transmitted packet from an anchor has to be received not only by the sensor nodes in its communication range, but also by the anchors which are within the communication range of this anchor. Since, simultaneous reception and transmission is not allowed in half-duplex underwater nodes, to receive the transmitted packet another condition has to be added to (5), namely

$$|w_i - w_j| > t_\text{p} + \frac{d_{ij}}{c} \text{ if } i \Leftrightarrow j, \text{ for any } m_i \text{ and } m_j. \tag{7}$$

In an actual scenario, the packet exchanges between anchors may be used for sound-speed estimation, or to check the functioning of their acoustic modems. If the network supports packet exchanges between neighboring anchors, we refer to the scheduling protocol as B-MAC.

D. Dynamic Multi-Channel Packet Scheduling

In dynamic multi-channel packet scheduling, the fusion center can decide to use the whole operating bandwidth as a single channel for packet transmission, or to divide it into several subchannels. Under this condition, the number of subchannels M would be a variable, and this can be included in (5). Note that since the number of bits in a localization packet is constant, the packet duration varies with the number of subchannels as

$$t_\text{p}^M = \frac{M}{1 - \alpha_M} t_\text{p}^1, \tag{8}$$

where t_p^M is the packet duration if M subchannels are employed, t_p^1 is the packet duration for the single-channel case (whole bandwidth is used), and α_M is the penalty that the system suffers from splitting the channel into M subchannels [2]. In underwater acoustic communication, the signals which are transmitted at higher frequencies are attenuated more. Therefore, if the anchors transmit with the same power in each subchannel, the communication range of each subchannel would be different. However, with a simple power allocation strategy, they can maintain a similar communication range for each subchannel. The localization algorithms are usually based on range estimation which can be obtained via time of flight estimation between the sensor node and an anchor. The variance of error in time of flight (ToF) estimation grows linearly with the inverse of the received signal bandwidth [31] and the time of signal observation. Since the time of signal observation (packet duration) increases as the channel is split (signal bandwidth reduction), the accuracy of the ToF estimation does not change. However, we assume that the system cannot generate more than $M_{\max}$ subchannels. In general, for dynamic multi-channel B-MAC we can formulate the problem as

$$\begin{aligned}
&\min_{M,\{m_i\}\{w_i\}} \max \left\{w_i + t_{\mathrm{p}}^M\right\}, \text{ s.t.} \\
&w_i \geq 0, \text{for } i \in \{1, 2, .., N\}, \\
&M_{\max} \geq M \geq 1, \\
&|w_i - w_j| > t_{\mathrm{p}}^M + \frac{\check{d}_{ij}}{c} \text{ if } i \leftrightarrow j \text{ and } m_i = m_j, \qquad (9a) \\
&|w_i - w_j| > t_{\mathrm{p}}^M + \frac{d_{ij}}{c} \text{ if } i \Leftrightarrow j, \text{for any } m_i \text{ and } m_j. \qquad (9b)
\end{aligned}$$

where $\check{d}_{ij}$ has been defined in (6). Note that for L-MAC condition (9b) is not required.

E. Problem Formulation in a TDMA System

In a TDMA system, if the time duration of each slot is set to $t_{\mathrm{s}} = \frac{R}{c} + t_{\mathrm{p}}$, and we have $\frac{R}{c} \to 0$, then the optimization function in (5) is equivalent to minimizing the number of slots under a collision-free transmission of localization packets. With the above definitions, this problem can be modeled as TDMA broadcast scheduling which is well-studied in [32]. As mentioned in [32], scheduling the packets in the minimum number of slots is an NP-hard problem.

TDMA broadcast scheduling leads to the optimal solution for minimizing the localization task if $\frac{R}{c} \to 0$. For cases where $\frac{R}{c} \neq 0$, this solution is not optimal, but it can still be hired for localization packet scheduling, as we will discuss in Section III-A1. We label optimal and suboptimal algorithms that try to minimize the number of slots for the TDMA broadcast scheduling problem as TDMA-based algorithms. In WSNs, the wave speed is the speed of light and the propagation delay is negligible, so slotted algorithms are quite acceptable. In contrast, the propagation delays in underwater communications are large, and sometimes even greater than the packet length, especially for localization packets. In that case, TDMA-based algorithms are inefficient, and other schemes have to be devised.

F. Practical Issues for the Problem

Albeit this paper tries to take advantage of the long propagation delay of underwater acoustic communications to minimize the time duration of the localization task, there are some other issues that would adversely affect the time duration of the localization task. In this subsection, we list these challenges, and we suggest how they can be considered in our optimization problem.

1) Problem Formulation Considering Full Coverage: To be able to localize its position in a three dimensional (3D) environment, each node requires at least four time of flight (ToF) measurements to the known anchors. If each sensor node is equipped with a pressure sensor, then it can measure its depth, and with this information, it only requires three ToF measurements to find its location. Three-dimensional localization based on the surface-located anchors and the depth information of the sensor nodes has been analyzed in [30] and [33]. Although the more ToFs a node acquires, the better the localization accuracy, one may say that for the localization task, each point in the operational area has to be covered by at least four (without pressure sensor) or three (with pressure sensor) anchors. Hence, it is not needed to include all the anchors in the localization task if this condition is satisfied with a smaller number of anchors. In this situation, before running the MAC protocol, we can eliminate those unnecessary anchors and reduce the time of the localization task. This can also be taken into account in the optimization function (5) if the map of the area is known. However, in practical situations we are interested in utilizing all the available information from the anchors and perform the localization task with minimum error. Furthermore, when unwanted phenomena such as fading exist, the more anchors we employ in the network, the possibility of a full coverage of the operating area increases.

2) Multi-Path: Underwater acoustic communications are subject to severe multipath. Multiple reflections from the surface, seabed, other layers of water or other objects located inside the water cause the transmitted signal to be received from different paths with different delays. If we assume that the maximum channel delay spread is $\tau_{\max}$, then due to the convolutional property, the time duration of the received packet at a sensor node increases by this maximum delay. Hence, only adopting the conditions of Section II-A, the received packets from two subsequent collision-risk anchors might collide in some parts of the operating area. This can simply be avoided by adding a guard time of length $\tau_{\max}$ to the end of the packet. According to experimental data [34], the value of the maximum channel delay spread or consequently the value of the required guard time depends on the system parameters (bandwidth, operating frequency, transmitted power), location of the reflectors (shallow or deep water), depth of the receiving and transmitting nodes, and the distance between the transmitter and the receiver, and it may vary from 10 ms to 150 ms (typically between 10 ms to 25 ms).

3) Sound Speed Variations: The sound speed in an underwater medium is not constant but varies with temperature, pressure, and salinity [35]. This causes a transmitted signal not to travel along a straight line as it propagates. On the other hand, a wave travels along a curved path to the destination, which is longer but also faster. This upsets the assumption of spherical wave propagation in an underwater medium, and it cannot be stated that the maximum propagation range in each direction is R meters. This issue can easily be handled by setting R to the maximum value that a wave can propagate in different directions. The typical range of the underwater sound speed is from 1480 to 1520 m/s. In [36] and [37] it is shown that the influence of the sound speed on signal propagation becomes more severe if the horizontal distance between the transmitter and the receiver increases. Although considering a worst case radius R resolves this issue, the effect of a varying sound speed is negligible for short distances, particularly for just a few kilometers.

4) Interference in Packet Reception: The maximum transmission range of an anchor can be defined as the distance at which the receiver is not able to decode the data anymore, for instance because of the sensitivity level of the receiver, or the low signal strength in comparison with the in-band ambient noise power. However, even if the maximum transmission range is limited due to the low signal to noise ratio, interference from other transmitters may still corrupt the packet reception at a sensor node. Interference occurs if two or more transmitted signals sweep the same point at the same time which may happen even for ranges beyond the maximum transmission range of an anchor. This explanation implies that two anchors with a mutual distance $d_{ij} > 2R$ are not necessarily collision-free, and the probability of a collision due to interference is not zero. In order to include this phenomenon in our formulation, we define a maximum interference range, R_I, which is the distance to an anchor beyond which a sensor node does not experience interference from that anchor. This can be considered in our problem formulation (5) by substituting R with R_I.

5) Moving Anchors: In actual scenarios, the assumption of fixed anchors may not hold. The anchors may drift due to the waves in windy weather, move with water currents, or follow a predetermined trajectory. When the velocity vector of each anchor for each time is known, we can compute the relative distance between the anchors i and j in time as $d_{ij}(t)$, and as a result, the effect of network movement can be included in the optimization function when the future positions of the anchors are known. However, it is hard to take a random movement of the anchors into account, unless we predict them [38] which for a long time duration is not practical. If we assume that the maximum displacement from the anchor's original position during the localization task is d_{drift}, then we can add a guard time at the end of the packet to remove any possible collision. The value of this guard time can be computed as $\frac{2d_{\text{drift}}}{c}$. Note that, under the condition that a guard time, t_{g}, is added to the actual packet, the packet length in scheduling algorithms [see (8)] has to be modified to

$$t_{\text{p}}^{M} = \frac{M}{1-\alpha_M} t_{\text{p}}^{\text{ng}} + t_{\text{g}}, \tag{10}$$

where t_{p}^{ng} is the packet length in single-channel scheduling approaches without considering the guard interval.

6) Quantized Waiting Time: In practice, the fusion center quantizes the waiting-times before transferring this information to the anchors. That would affect the precision of the localization task. In this work, we assume that enough bits are allocated to the waiting-times, and no quantization error exists.

III. Optimal Solution

In this section, we first show how the optimal solution for the single-channel slotted scenario can be obtained, and based on that, we explain how this solution can be extended to the multi-channel problem and to finding the optimal solution of our problem (5).

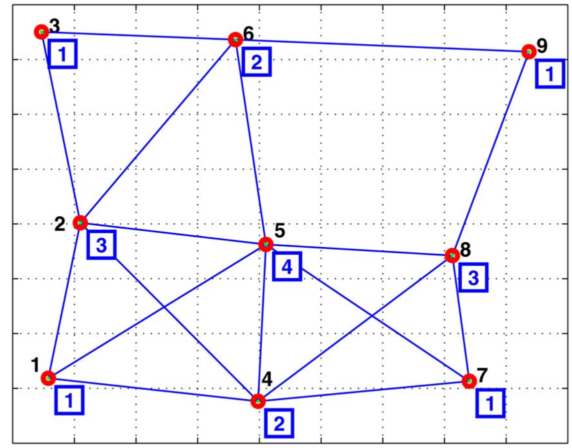

Fig. 5. Network graph for a TDMA-based scheduling problem. Vertices represent the anchors where each anchor is labeled by its index, and an edge connecting two anchors shows there is a collision risk. The boxed numbers represent the time slot that each anchor can use to transmit its localization packet.

anchor index	1	3	7	9	4	6	2	8	5
time slots	1	1	1	1	2	2	3	3	4
waiting time	0.00	0.00	0.00	0.00	1.05	1.05	2.10	2.10	3.15

Fig. 6. Optimum solution when a TDMA-based algorithm is used. Note that the anchors 1, 3, 7, and 9 are allocated the same time slot. Anchor 4 cannot transmit in time slot 1 because it is a neighbor of some previously scheduled anchors, namely 1 and 7.

A. Optimal Solution in Single-Channel Scenario

1) TDMA-Based Scheduling: As stated before, TDMA-based scheduling based on the definition of strictly distance-related collision-free anchors, and strictly time-related collision-free anchors is an NP-hard problem. The TDMA-based approach can be employed in UASNs where no information about the anchors' relative positions is available.

The optimal solution (which may not be unique) belongs to a set of $N!$ possible candidate anchor sequences, and can be obtained by an exhaustive search. Based on a given anchor sequence, we start with the first anchor, and allocate it to the first time slot. Then, we move to the next anchor, and allocate it to the earliest possible time slot that causes no collision with considering the previously scheduled anchors. The same procedure continues until the last anchor gets scheduled. At the end, we count the number of used slots, and among all possible $N!$ anchor sequences we choose the sequence with the lowest number of slots. An example of a possible solution for the network in Fig. 5 is shown in Fig. 6. The vertices in this graph represent the anchors, and each edge connecting two vertices indicates that there is a collision risk.

2) Distance-Aware Scheduling: To find the optimal solution in a distance-aware network, we follow the same procedure as for TDMA-based scheduling. Here, we again start from the fact that the optimal solution (which is not unique) belongs to at most $N!$ sequences of anchor indices. For each anchor sequence,

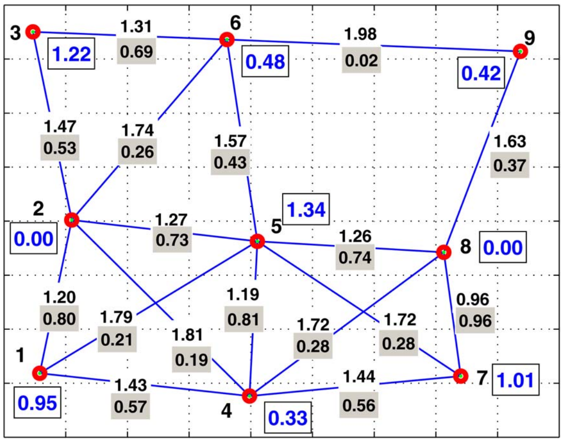

Fig. 7. Network graph for the distance-aware scheduling problem. The edge weights with white background color represent the normalized distances between collision-risk anchors, and the edge weights with gray background color show the normalized modified distances, $\min\{d_{ij}, 2R - d_{ij}\}$, between collision-risk anchors. The boxed numbers display the waiting times of the anchors.

anchor index	2	8	4	9	6	1	7	3	5
waiting time	0.00	0.00	0.33	0.42	0.48	0.95	1.01	1.22	1.34

Fig. 8. Optimum solution when the optimal distance-aware scheduling algorithm is used.

the anchor that appears earlier has to transmit its packet sooner than the ones which appear later. Conditioned on a given anchor sequence, the minimum duration of the task, $w_{\max}$, can simply be computed based on Conditions 2, 4, and 5 of Section II-A. In this procedure, the first anchor is assigned to transmit its packet first. Then, the limitations on the transmission time of the other anchors are computed, and the second anchor computes the earliest available time (which is greater than or equal to the transmission time of the previously scheduled anchors) it can transmit without causing collisions. Finally, by comparing the maximum waiting times ($w_{\max}$) of all $N!$ anchor sequences, we choose the sequence of anchor indices which has the minimum $w_{\max}$.

For instance, consider the network graph depicted in Fig. 7, where the maximum transmission range, R, is equal to c meters (normalized to one only in the figure), and the packet length is 0.05 s. In this graph, each edge weight with white background color shows the normalized distance between the two collision-risk anchors. The optimal anchor sequence and the related waiting times have been computed by the explained procedure, and the result is shown in Fig. 8.

B. Optimal Solution in a Multi-Channel Scenario

The optimal solution of a TDMA-based system in a multi-channel scenario can be obtained similarly by examining all possible ways that the time slots can be allocated to the nodes. It can be shown that when $M < N$, the number of possible solutions is smaller than $\frac{(MN)!}{(MN-N)!}$,[1] and greater than $N!$, which makes finding the optimal solution a combinatorial problem. This is also true for the distance-aware algorithms. Given the order of packet transmission and the subchannels that they are going to use, we can find the minimum waiting-times of all nodes as explained in the single-channel case. After comparing the results of all possible solutions, we select the one which leads to the lowest number of time slots, or the lowest maximum waiting-time.

[1]This is equivalent to the selection of N candidates from MN items where ordering is important. This amount can hugely be reduced via heuristic approaches.

IV. Mixed-Integer Linear Programming

In this section we show how the optimization problem of (5) [and similarly (9)] can be modeled as a standard mixed-integer linear programing (MILP) problem. The basic form of a MILP problem is given by

$$\begin{aligned} &\min \mathbf{d}^T\mathbf{x}, \text{ s.t.} \\ &\quad \mathbf{x}_L \le \mathbf{x} \le \mathbf{x}_U \\ &\quad \mathbf{b}_L \le \mathbf{A}\mathbf{x} \le \mathbf{b}_U \\ &\quad x_i \text{ integer for } i \in I \end{aligned} \tag{11}$$

where $\mathbf{d} \in \mathbb{R}^{P\times 1}$ collects the linear objective cost function coefficients, P is the number of variables in the design parameter $\mathbf{x}, \mathbf{x}_L, \mathbf{x}_U \in \mathbb{R}^{P\times 1}$ are respectively the lower and upper bound on the design parameter, $\mathbf{A} \in \mathbb{R}^{M\times P}$ is a linear constraint matrix stacking the linear constraints, $\mathbf{b}_L, \mathbf{b}_U \in \mathbb{R}^{M\times 1}$ are respectively the lower and upper bound on the constraints, and I is a subset of $\{1, 2, \ldots, M\}$, which contains the indices of integer variables.

It is well-known that the min max problem can be transformed into a linear one by introducing N additional constraints as

$$\min z, \;\; \text{s.t. } w_i \le z \text{ for } i \in \{1, 2, \ldots, N\}. \tag{12}$$

In addition, by defining of a new Boolean variable, δ_{ij}, (5b) in a single-channel scenario can be modeled by 2 linear inequalities as

$$-w_i + w_j - Q_1\delta_{ij} \le -t_{\mathrm{p}} - \frac{\check{d}_{ij}}{c} \tag{13a}$$

$$+w_i - w_j + Q_1\delta_{ij} \le -t_{\mathrm{p}} - \frac{\check{d}_{ij}}{c} + Q_1, \tag{13b}$$

where Q_1 is a constant which has to be greater than $\max\left(|w_i - w_j| + \frac{\check{d}_{ij}}{c} + t_{\mathrm{p}}\right)$, for $i, j \in \{1, 2, \ldots, N\}$ (or in the worst case $Q_1 > N\left(\frac{D}{c} + t_{\mathrm{p}}\right)$). This means that if $\delta_{ij} = 0$, then (13a) has to be satisfied and (13b) is always true, and vise versa. Under this condition the MILP problem has $N+1$ continuous variables (z and $w_i, i \in \{1, 2, \ldots, N\}$), N_c Boolean variables (δ_{ij}), and $2N_c + N$ inequality constraints [see (12) and (13)], where N_c is the number of collision-risk connections.

In the multi-channel L-MAC scenario, (9a) can be modeled as

$$|w_i - w_j| + Q_2|m_i - m_j| > t_{\mathrm{p}}^M + \frac{\check{d}_{ij}}{c}, \tag{14}$$

where $Q_2 > \max\left(\frac{\check{d}_{ij}}{c} + t_{\mathrm{p}}^M\right)$ for $i, j \in \{1, 2, \ldots, N\}$ is a constant, and can be considered as $Q_2 > \frac{D}{c} + t_{\mathrm{p}}^M$. This means that if $m_i \neq m_j$ then (14) is always true and w_i is independent of w_j. The non-linear inequality of (14) can be expanded into four non-linear inequalities as

$$-w_i + w_j - Q_2(+m_i - m_j) - Q_3(0 + \delta_{ij} + \gamma_{ij}) \leq -\Delta_{ij},$$
$$-w_i + w_j - Q_2(-m_i + m_j) - Q_3(1 - \delta_{ij} + \gamma_{ij}) \leq -\Delta_{ij},$$
$$+w_i - w_j - Q_2(+m_i - m_j) - Q_3(1 + \delta_{ij} - \gamma_{ij}) \leq -\Delta_{ij},$$
$$+w_i - w_j - Q_2(-m_i + m_j) - Q_3(2 - \delta_{ij} - \gamma_{ij}) \leq -\Delta_{ij},$$

where $\Delta_{ij} = t_{\mathrm{p}}^{M} + \frac{\check{d}_{ij}}{c}$, $\gamma_{ij}, \delta_{ij} \in \{0, 1\}$, $m_i \in \{1, 2, \ldots, M\}$ for $i \in \{1, 2, \ldots, N\}$, and

$$Q_3 > \max\left(|w_i - w_j| + Q_2|m_i - m_j| + \Delta_{ij}\right),$$

for $i, j \in \{1, 2, \ldots, N\}$ is a constant, and can be considered as $Q_3 > N\left(\frac{D}{c} + t_{\mathrm{p}}\right) + (M-1)Q_2$.

The multi-channel B-MAC optimization problem can similarly be modeled as a MILP problem. There, for each pair of anchors i and j, if $i \leftrightarrow j$ we have 4 inequalities like what extracted for (14), and if $i \nLeftrightarrow j$ we have two inequalities like (13). Note that the constraints we have in a single-channel L-MAC include the ones defined for the single-channel B-MAC, and therefore there is no difference between them in a single-channel scenario.

V. Proposed Algorithms

The complexity of the optimal solution (without any heuristic approach) is equal to or greater than $N!$, which makes it impossible to be used when the number of anchors or subchannels are large. In this section, we propose two heuristic algorithms with a smaller complexity (of order N and N^2) that can be adopted for practical applications. In the networking concept, the heuristic algorithms are similar to the standard greedy nearest neighbor with slight modifications. In the numerical section, we show that these suboptimal algorithms can perform near optimal.

The first suboptimal algorithm is based on a greedy approach, and its steps are shown in Algorithm 1. In the initial phase, the waiting times of the transmitting nodes are set to zero, and a buffer of size $N \times M$ is defined to store the limitations on the waiting time of the nodes in all subchannels. The algorithm starts with scheduling a pre-set arbitrary anchor (for instance the I-th anchor in which case we refer to the algorithm as the I-th starter or IS) or a random anchor (RS), and assign the first subchannel to this node. Therefore, the waiting time of this anchor is fixed to zero, and it will transmit in the first subchannel. When the waiting time of an anchor gets fixed, it will be removed from the scheduling task. Based on this fixed waiting time, the collision-risk neighbors of the selected anchor are detected, and their corresponding waiting times are modified in such a way that no collisions will occur in the network (collision-free anchors based on Conditions 1 to 5). Then, from the unscheduled anchors, the one which has the lowest waiting time in all possible subchannels will be selected, and the above steps will be repeated until the waiting times of all anchors get fixed. It may happen that there are two or more anchors with the same minimal waiting time. In this case, we select the one which has the lowest index as well.

Algorithm 1 IS: Start from the I-th anchor

Input: distances between collision-risk nodes, d_{ij}, maximum transmission range, R, Number of subchannels, M, Packet duration, t_{p},
Output: waiting times before packet transmission, w_k for $k = 1, 2, \ldots, K$, channel in which each node has to transmit its packet, m_k, Task duration, $T_{\mathrm{broadcast}}$.
Set all the waiting times to zero: $w_k = 0$, for $k = 1, 2, \ldots, K$,
Set all entries of $\mathbf{W}_{K\times M}$ to zero.
Set $m = 1$.
Set $\Omega = \{1, 2, \ldots, K\}$.
Start with the pre-defined anchor index I, $j = I$,
for $k = 2$ to $K - 1$ **do**
  Remove j-th anchor from the network: $\Omega = \Omega - \{j\}$
  Find the collision-risk neighbors of the j-th anchor, and modify their waiting time to eliminate possible collisions:
  for $i \in \Omega$ **do**
    if $d_{ij} \leq 2D$ **then**
      if L-MAC **then**
        if TDMA-based **then**
          $[\mathbf{W}]_{i,m} = \max([\mathbf{W}]_{j,m} + t_{\mathrm{p}} + \frac{D}{c}, [\mathbf{W}]_{i,m})$
        else
          $[\mathbf{W}]_{i,m} = \max([\mathbf{W}]_{j,m} + t_{\mathrm{p}} + \frac{\check{d}_{ij}}{c}, [\mathbf{W}]_{i,m})$
        end if
      else if B-MAC **then**
        if $d_{ij} \leq D$ and $\frac{d_{ij}}{c} - |[\mathbf{W}]_{j,m} - [\mathbf{W}]_{i,m}| < t_{\mathrm{p}}$ **then**
          for $p = 1$ to M **do**
            $[\mathbf{W}]_{i,p} = \max([\mathbf{W}]_{j,p} + t_{\mathrm{p}} + \frac{\check{d}_{ij}}{c}, [\mathbf{W}]_{i,p})$
          end for
        else
          $[\mathbf{W}]_{i,m} = \max([\mathbf{W}]_{j,m} + t_{\mathrm{p}} + \frac{\check{d}_{ij}}{c}, [\mathbf{W}]_{i,m})$
        end if
      end if
    end if
  end for
  Select the anchor with the minimum waiting time: $[j, m] = \arg \min_{i\in\Omega, m\in\{1 \text{ to } M\}} [\mathbf{W}]_{i,m}$
end for
Compute the waiting times of each anchor and its channel
for $k = 1$ to K **do**
  $w_k = \min_{m=1 \text{ to } M} [\mathbf{W}]_{k,m}$,
  $m_k = \arg \min_{m=1 \text{ to } M} [\mathbf{W}]_{k,m}$.
end for
Compute the broadcasting task duration: $T_{\mathrm{broadcast}} = \max_{i=1 \text{ to } N} w_i + t_{\mathrm{p}}$

As can be seen from Algorithm 1, Condition 3 is not included. Condition 3 states that if $|w_i - w_j|$ is greater than $\frac{R}{c} + t_p$, the two anchors are collision-free. Since in each step of the algorithm we choose the anchor with the minimal waiting time, it never happens that $w_i < w_j$, and we only have to check the condition $w_i - w_j > \frac{R}{c} + t_p$. If it is met, then the two anchors are collision-free and no modification on w_i is required. This condition is hidden behind the max operation of the algorithm.

If this condition holds, the algorithm does not modify w_i which means that the algorithm excludes the corresponding anchor from a possible waiting time modification.

The best starter algorithm (BS) is an extension of IS. In BS, we run IS for all the anchors ($I = 1$ to N), and select the one (the best starter) which results in the minimal total scheduling time.

For the dynamic multi-channel (DMC) packet scheduling, we run the algorithm for different number of channels $M \in \{1, \ldots, M_{\max}\}$, and select the M which results in the lowest scheduling time. Note that for DMC, for each value of M, the packet duration, t_p, has to be modified according to (8) or (10). The DMC can be used for both RS (IS) and BS.

VI. Numerical Results

In this section, we evaluate the performance of the proposed low-complexity algorithms and compare them with MILP and optimal solutions. In order to find the solution of the MILP problem we have used the TOMLAB/CPLEX [39] and MATLAB MILP solver with their default setting. Moreover, we also compare their performance with the traditional TDMA-based ones.

Unless otherwise stated, the simulation set up is as follows. For the computation of each point in the following figures, we average the solution over 10^3 (10^2 for MILP) independent Monte Carlo runs. The localization packet length is $t_p =$ 150 ms (150 bits for an acoustic modem with a data rate of 1 kbps), which is long enough to convey the information about the anchor's ID, position and time of transmission. The maximum transmission range of each anchor is assumed to be $2c$ m (3 km). The positions of the anchors are assumed to be uniformly distributed at random over a squared area with dimensions $d_x = d_y = 5c$ m (7.5 km). The system can split the existing channel to at most $M_{\max} = 3$ subchannels, and the penalty in channel splitting is formulated as $\alpha_M = 0.1(M - 1)$.

In our first simulation, we consider a single-channel (SC) network in which each pair of anchors are within the communication range of each other (fully connected network). The maximum transmission range of the anchors for this simulation is set to $5c\sqrt{2}$ m. We compare the performance of different position-aware algorithms (L-MAC-SC-RS, L-MAC-SC-BS, L-MAC-SC-MILP, and L-MAC-SC-Optimal)[2] with an algorithm where no position information is assumed (position-unaware). In the position-unaware algorithm the first anchor transmits its packet, and after the complete reception of the packet, the second anchor starts its transmission. This continues until the last packet is transmitted from the N-th anchor. Here, the order of transmission is fixed, and no position information or a fusion center is required. Fig. 9 shows the performance of each algorithm for different numbers of anchors (in the x-axis). The y-axis shows the average time of the localization task, as defined by $t_{\text{avg}} = \mathbb{E}[w_{\max} + t_{\text{p}}]$. As Fig. 9 demonstrates, the increase in the number of anchors makes the duration of the localization task more lengthy. That is because a network with more anchors requires more packet transmissions. Another fact resulting from the figure is the performance superiority

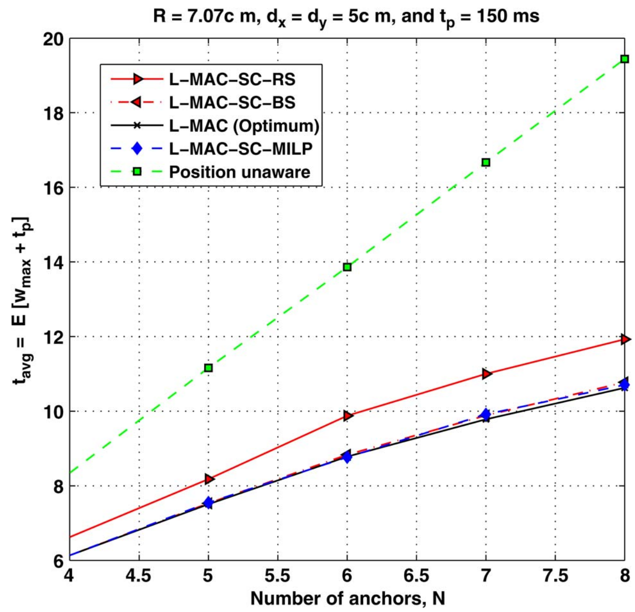

Fig. 9. Average packet transmission time versus number of anchors.

of position-aware algorithms in comparison with the position-unaware one. Not only do they perform much better than their opponents, their performances are also very close to each other and to the optimal solution. Therefore, when complexity is an issue in practical situations, L-MAC-RS can be adopted as the appropriate scheduling protocol for the localization task.

For the rest of the simulation results, the performance of the optimal solution is not computed because it takes a huge amount of time. Furthermore, the complexity of the TOMLAB/CPLEX increases greatly with the number of integer variables. It has been observed that the TOMLAB/CPLEX solution is very close to the BS algorithms. Therefore, to reduce the simulation time, we have not included the results of the MILP problem when the network size is large.

The effect of the maximum transmission range on t_{avg}, where the dimension of the area is fixed, is depicted in Fig. 10. In this scenario, with an increase in R, the number of strictly distance-related collision-free anchors gets lower (see upper part of the figure), and as a result, the possibility of simultaneous packet transmission in the network decreases, and t_{avg} increases. This growth in t_{avg} for the distance-aware algorithms stops when the network is fully connected and $\min\{d_{ij}, 2R - d_{ij}\} = d_{ij}$. At this point, the performance of OCSMA is the same as that of L-MAC-SC, because in a fully connected network the L-MAC-SC does not support simultaneous transmissions (see Condition 5), and therefor anchors transmit one after each other (no simultaneous transmissions) similar to OCSMA. In the TDMA-based algorithms, the average localization time increases because the time-slot length is proportional to $\frac{R}{c}$. The performances of the DMC algorithms are included in this graph as well. It can be observed that they work better than their single-channel counterparts. Furthermore, the performance of L-MAC-DMC is better than B-MAC-DMC, because in L-MAC the anchors are not interested in the packet reception from other anchors, and they experience less strict limitations on their waiting times. Under the condition that a guard time has been added to the packet,

[2]Note that, SC means *single channel*, RS means *random starter*, BS means *best starter*, and DMC means *dynamic multi-channel*.

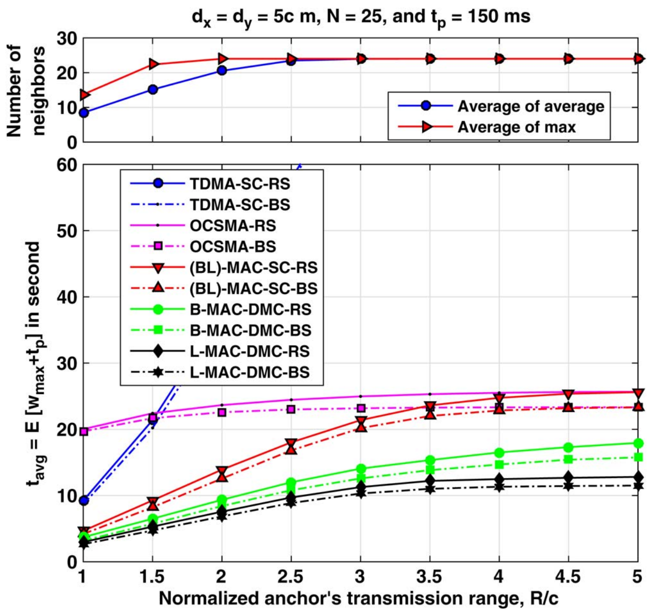

Fig. 10. Average packet transmission time versus anchors' maximum transmission range.

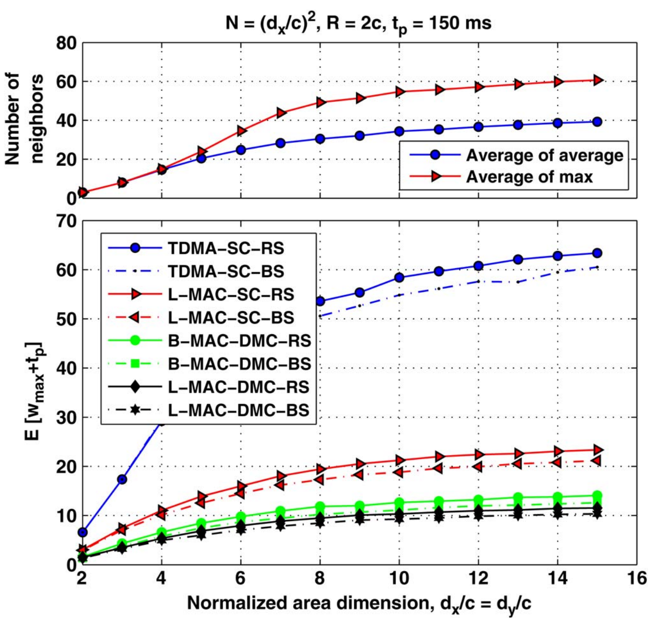

Fig. 11. Performance of the algorithms versus network scalability.

the packet length can be obtained by (10), and the performance of the multi-channel schemes would be better than the ones depicted in Fig. 10 in comparison to the single-channel schemes.

In Fig. 11, the performance of the proposed algorithms versus network scalability is evaluated. For this simulation, as the dimension of the operating area increases, the number of anchor nodes increases too such that the average number of anchors per square meter is constant. Again, as the network gets larger, the probability that more nodes are strictly distance-related collision-free decreases (see upper part of the figure) and the nodes experience a larger waiting time. However, at a specific network size, the average number of collision-risk neighbors converges to a fixed value as depicted in the upper part of the figure, and as a result, the performance of both the

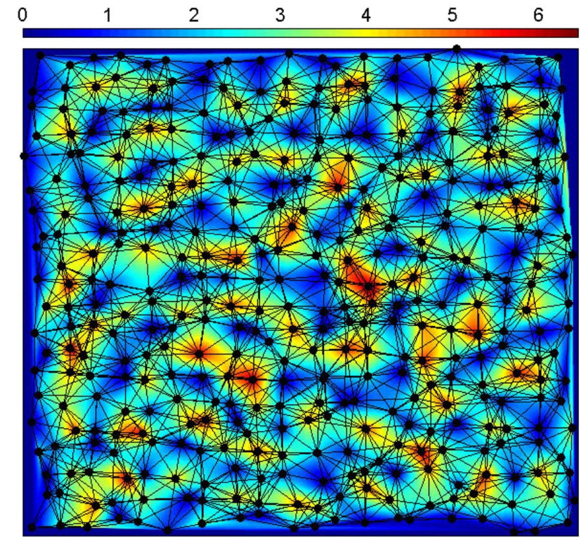

Fig. 12. Waiting time map for a specific network of $N = 400$ anchors nodes, $R = 1.1c$ m, and $d_x = d_y = 20c$ m. The vertices show the anchors' locations and the edges show which anchors have a collision risk. The waiting times are computed based on the L-MAC-BS algorithm.

TDMA-Based and the proposed algorithms saturates. Still we can see that the proposed algorithms perform better than the TDMA-based one, and the ones which use DMC greatly reduce the average time that is required for localization.

A map of the waiting times for a specific single-channel network with a large number of anchors ($N = 400$) is shown in Fig. 12. The colormap shows the range of waiting time values, the color behind each anchor node represents its waiting time, and the colors in between convey no particular meaning. It can be noticed that different disjoint clusters of the network transmit their localization packets simultaneously. This is the reason why the network scalability does not influence the performance of the proposed algorithms. On the other side, the performance of the algorithms is directly related to the average number of collision-risk neighbors around an anchor, and their average modified distances, $\min\{d_{ij}, 2R - d_{ij}\}$, (see Fig. 7).

In Fig. 13, as the dimension of the area increases, we increase the maximum transmission range of the anchors, but keep the number of anchors constant. It can be observed that, when d_x/R is constant, for large values of $\frac{R}{c}$, t_{avg} is linearly related to R for all algorithms. On the contrary, when the value of $\frac{R}{c}$ is small relative to the packet length, the performance of the algorithms tends to be constant as a function of $\frac{R}{c}$. As also anticipated from the formulation of the objective function, as the ratio $\frac{R}{c}$ becomes smaller and smaller, the performance of TDMA-based algorithms approaches the performance of distance-aware algorithms or equivalently the optimal solution. A similar analysis can be carried out when the packet size increases and other parameters are fixed. As the packet size gets larger, the required guard time, $\frac{R}{c}$, with respect to the slot duration, becomes negligible for TDMA-based algorithms and again both single-channel distance-aware and TDMA-based ones perform similar. This concept is illustrated in Fig. 14. In the reverse direction, when the ratio of the packet length and $\frac{R}{c}$ approach zero, its value is not dominant anymore in the performance of the algorithms.

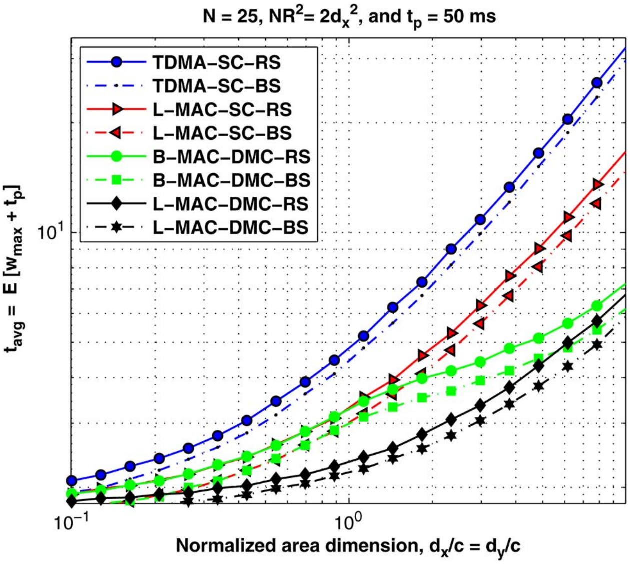

Fig. 13. Average packet transmission time versus anchors density.

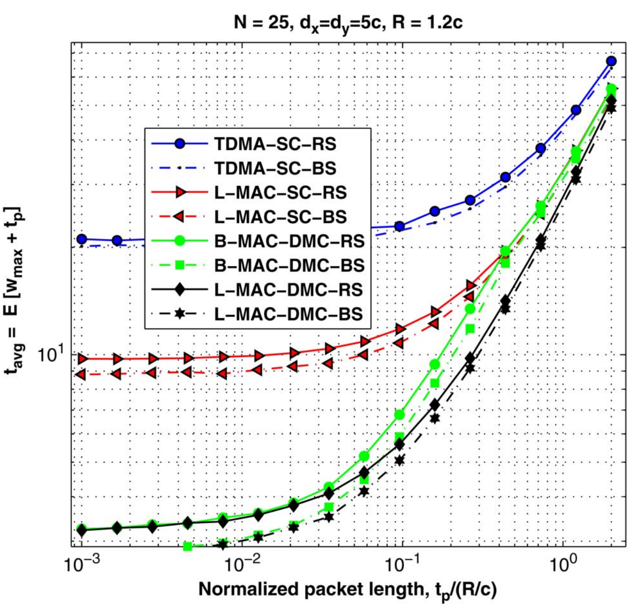

Fig. 14. Average packet transmission time versus packet length.

From Fig. 13 and Fig. 14, it can be seen that L-MAC-DMC always requires less localization time in comparison with its single-channel counterparts. As the number of subchannels increases the number of collision-risk anchors at the same subchannel decreases and the limitations on the waiting time of the anchors become less. In contrast, as the ratio of $\frac{t_{\mathrm{p}}^{1}c}{R}$ gets larger in B-MAC-DMC, the inequality (9b) becomes dominant, and because of the penalty we have in channel splitting in order to reduce the localization time the system will work with less subchannels. As the ratio of $\frac{t_{\mathrm{p}}^{1}c}{R}$ gets very large, the B-MAC-DMC performs the same as B-MAC-SC.

In order to compare the performance of the algorithms with the one of MILP, we have considered a small network of 6 anchors depicted in Fig. 15 with different transmission ranges. The MATLAB MILP solver is used to find the solution. The localization time for each scheme is show in Table I.

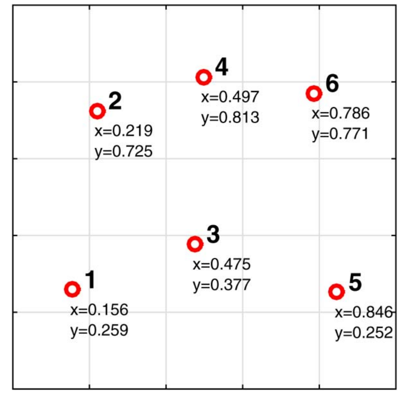

Fig. 15. Anchors positions normalized to $5c$.

TABLE I
LOCALIZATION TIME VS. DIFFERENT TRANSMISSION RANGE AND DIFFERENT ALGORITHMS. THE $^{(M)}$ SHOWS THE NUMBER OF USED SUBCHANNELS IN DMC

Algorithm	$R = 2c$	$R = 3c$	$R = 4c$
TDMA-SC-RS	8.7500s	15.9000s	20.9000s
TDMA-SC-BS	8.7500s	15.9000s	20.9000s
L-MAC-SC-RS	5.5239s	9.5535s	10.0881s
L-MAC-SC-BS	5.0113s	9.4192s	9.8322s
L-MAC-DMC-RS	2.5831s$^{(2)}$	3.0818s$^{(3)}$	4.6049s$^{(3)}$
L-MAC-DMC-BS	2.3717s$^{(2)}$	3.0818s$^{(3)}$	3.7337s$^{(3)}$
L-MAC-SC-MILP	5.0113s	9.4192s	9.8322s
L-MAC-DMC-MILP	2.3717s$^{(2)}$	3.0818s$^{(3)}$	3.4779s$^{(3)}$

VII. CONCLUSION

We have formulated the problem of scheduling the localization packets of the anchors in single-channel and multi-channel partially-connected underwater sensor networks. We have introduced the concept of dynamic multi-channel packet scheduling. In this approach the network splits the existing channel into several subchannels adaptively in order to reduce the scheduling time. Furthermore, we have proposed two low-complexity algorithms in order to minimize the duration of the localization task. We have shown that the proposed algorithms perform near optimal, and much better than other alternative solutions such as TDMA-based or position-unaware approaches. Furthermore, through comprehensive simulations, it has been revealed that the mean of the localization task duration depends on the number of subchannels, localization packet length, the anchors' maximum transmission range, the number of collision-risk neighbors and their modified average distances. We have found that, multi-channel scheduling approaches perform better than their single-channel ones especially when the ratio of the packet length to the average pair-wise distance is low. Moreover, we observed that a system that adjusts the number of subchannels dynamically has the highest performance among other position-aware algorithms. The proposed scheduling algorithms cannot directly be used for cooperative localization, unless a localized sensor node participates in the localization process as an anchor before scheduling. In the future, we want to address the problem of localization when most of the underwater nodes are not under the coverage of the anchors. The optimal scheduling protocol for such networks can be considered as an extension of the work carried out in this paper.

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