L-MAC: Localization packet scheduling for an underwater acoustic sensor network

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Abstract—**This article concerns the problem of scheduling the localization packets of the anchors in an underwater acoustic sensor network (UASN). Knowing the relative positions of the anchors and their maximum transmission range, we take advantage of the long propagation delay of underwater communication 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 propose two low-complexity algorithms, and through comprehensive simulations we compare their performances with the optimal solution as well as other existing methods. Numerical results show that the proposed algorithms perform near optimum and better than alternative solutions.**

I. Introduction

In order to accomplish specific underwater applications, an underwater acoustic sensor network (UASN) is responsible to measure parameters like, water temperature, density of chemical materials, seabed shape and so on. Sensed data are usually meaningless if they are not tagged with time and location of each measurement, and thus localization is a crucial task for UASNs. This triggered a lot of research on underwater localization (see e.g. [1] and [2] and references therein). However, in spite of these recently published articles on UASN localization, little work has been done on medium access control (MAC) protocol design for localization. Although, we can employ existing wireless sensor network (WSN) MAC protocols and algorithms for the localization task, the unique properties of UASNs, such as long propagation delay, low data rate, and high transmission loss [3], make them inefficient for UASNs

Kim et all [4], evaluate the impact of 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 [5] (a recently designed underwater MAC protocol). The paper [6] uses a previously proposed scheduling protocol, ordered CSMA (OCSMA) [7], for broadcasting massages from the anchors. In OCSMA, a coordinator finds the transmission 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 sequence. Nevertheless, this protocol is not optimum for the localization task, because it does not support simultaneous transmission in the network. To overcome this problem, a single-hop all-to-all broadcasting transmission scheduling (AAB-MAC) is proposed in [8]. Knowing the propagation delay matrix, i.e., the propagation delays among all nodes, the goal of this protocol is to minimize the all-to-all transmission period in a way that no collisions occur. In spite of the fact that 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. Two efficient broadcasting MAC protocols (TB-MACs) are proposed in [9], which are an adaptation of slotted-ALOHA and slotted-FAMA [10], but modified to work with broadcast traffic. Before broadcasting, these TB-MACs use different handshaking mechanisms (NACK and NCTS instead of ACK and CTS) to handle the 'reply storm' problem. There are also other existing MAC protocols for underwater networks based on scheduling, such as [11], [12]. But again, they are not suitable for the localization task, because they are designed for unicast packet exchanges, and do not consider collision-free broadcasting by the localization beacon.

In this paper, we utilize the information about the position of the anchors and their maximum transmission range to minimize the duration of the localization task. The localization procedure finishes when all the anchors transmit their packets. Each packet of an anchor includes information about the anchor ID, the anchor position, and the packet transmission time. Here, we formulate the problem of minimizing the duration of the localization task, and we show how the optimum solution can be obtained. Then, we propose two scheduling-based low-complexity algorithms (L-MACs) for this problem, and through several simulations we show that they perform near optimum, and superb in comparison with other existing solutions.

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 we propose two low-complexity algorithms in Section IV. Section V evaluates the performance of the proposed algorithms through several simulations, and finally, Section VI concludes the paper and mentions some future work.

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II. NETWORK MODEL

We consider an underwater sensor network with N surface-located anchor nodes (can be located anywhere if their positions are known) with a maximum communication range of R meters, and M underwater sensor nodes under the coverage of the anchors.[1] It is assumed that the surface anchors are equipped with GPS devices, as well as radio (or satellite) and acoustic modems. In addition, the information about the positions of the anchors can be collected by a fusion center through their radio modems. On the other hand, there is no prior information about the position of the underwater sensor nodes, and they can be located anywhere in the operating area. The fusion center is responsible to schedule the localization packet transmission of the anchors where each packet has a duration t_p. The goal is to minimize the localization time, and to avoid any possible collision in the packet reception of 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.

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 the anchors collide anywhere inside the intersection of the transmission ranges of the two anchors. Hence, as shown in Fig. 1, even if two anchor nodes are not located within their acoustic communication ranges they may cause a collision in the network. In order to eliminate the collision problem, we introduce the concept of *collision-free anchors*. 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. In the next section we will show how waiting times can be modified to make the anchors collision-free in order to eliminate collisions at the sensor nodes.

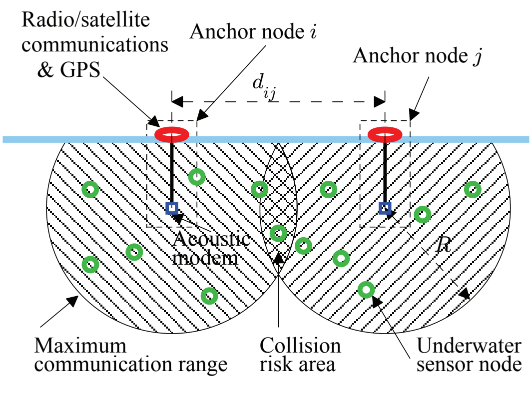

Fig. 1. Example of two collision-risk anchors.

[1]Three-dimensional localization based on the surface-located anchors and the depth information of the sensor nodes has been analyzed in [13].

A. Collision-free anchors

Imagine that there are two anchors, namely i and j, at distance d_{ij}, with waiting time w_i and w_j where $w_i > w_j$, respectively. 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: 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 2: Assume that the sound speed in the underwater medium is c. If the difference between the two waiting times is greater than $\frac{R}{c} + t_\mathrm{p}$, 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 3: Anchors i and j are collision-free anchors if $w_i - w_j > \frac{2R-d_{ij}}{c} + t_p$ as shown in Fig. 2 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 $\frac{R}{c} + t_\mathrm{p}$, and Condition 2 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

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

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 be outside the following boundaries:

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

$$w_i \leq w_j - \frac{2R - d_{ij}}{c} - t_p. \tag{2b}$$

Condition 4: Anchors i and j are collision-free anchors if $w_i - w_j > t_\mathrm{p} + \frac{d_{ij}}{c}$ as shown in Fig. 3 for the minimum value of $w_i - w_j$. This condition is useful if $d_{ij} < R$, otherwise, like Condition 3, it can be represented by Condition 2. In other

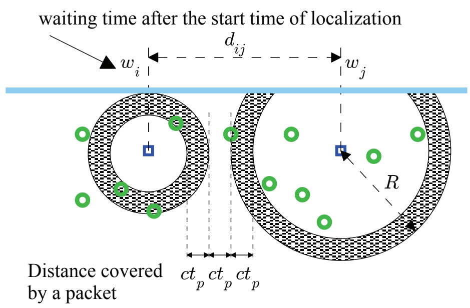

Fig. 2. collision-free anchors when $R < d_{ij} < 2R$.

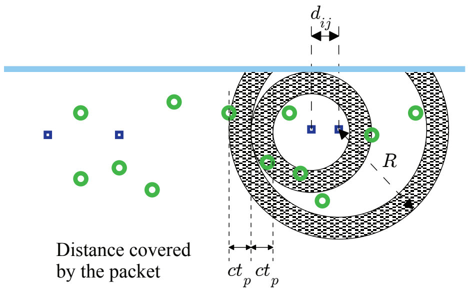

Fig. 3. collision-free anchors when $d_{ij} < R$

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

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

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:

$$w_i \geq w_j + \frac{d_{ij}}{c} + t_p, \tag{4a}$$

$$w_i \leq w_j - \frac{d_{ij}}{c} - t_p. \tag{4b}$$

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

$$\min \max_{i\in\{1,\dots,N\}} w_i, \tag{5}$$

s.t.

$$\textbf{I}\ .\ w_i \geq 0,\ \text{for } i = 1,2,\dots,N$$

$$\textbf{II}\ .\ |w_i - w_j| > \min\left(t_\text{p} + \frac{R}{c}, t_\text{p} + \frac{d_{ij}}{c}\right),\ \text{or}$$

$$d_{ij} > \min\left(2R, 2R - |w_i - w_j|c + t_\text{p}c\right),$$

where **I** states that we cannot have a packet transmission at negative times, and Conditions 1 to 4 are merged into **II**.

From Conditions 3 and 4, it can be observed that in a collision-free packet transmission, setting the waiting time of an anchor imposes limitations on the waiting time 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 in (5) can be formulated in a time division multiple access (TDMA) system.

B. Problem formulation in a TDMA system

In a TDMA system, if the time duration of each slot is set to $t_\text{s} = \frac{R}{c} + t_\text{p}$, 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 [14]. As mentioned in [14], scheduling the packets in the minimum number of slots is an NP-hard problem. However, the solution of the broadcast scheduling is optimum for minimizing the localization task if $\frac{R}{c} \to 0$. For cases where $\frac{R}{c} \neq 0$, this solution is not optimum, but it can still be hired for the localization packet scheduling. We label optimal and suboptimal algorithms that try to minimize the number of slots in the broadcast scheduling problem as slotted or 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. On the other hand, the propagation delays in underwater communications are really large, and sometimes even greater than the packet length, especially for localization packets. In that case, slotted algorithms are inefficient, and other schemes can be devised.

III. Optimal solution

In this section, we first show how the optimal solution for the slotted method can be obtained, and based on that, we explain how this solution can be extended for finding the optimal solution of our problem.

As stated before, time slot scheduling based on the definition of strictly distance-related collision-free anchors, and strictly time-related collision-free anchors is an NP-hard problem, and it can be formulated as a mixed integer linear program (MILP). Due to the limited available space, we only briefly explain how it works.

The optimal solution (which may not be unique) belongs to $N!$ possible solutions, and can be obtained by an exhaustive search. Given a sequence of anchors, we show how one can allocate them to minimum number of time-slots in such a way that no collision occurs. Based on the given sequence, we start with the first anchor, and allocate it to the first time slot. Next, we move to the second anchor, and allocate it to the earliest possible time slot that causes no collision with considering the previously scheduled anchors. Then, the same procedure continues until the last anchor gets scheduled. At the end, we count the number of used slots, and among all possible $N!$ sequences we choose the sequence with the lowest number of slots.

To find the optimal solution for our problem, we follow the same procedure. However, this time we determine the time duration that an anchor cannot transmit a packet (due to a possible collision considering the previously scheduled anchors). When, based on a given ordering sequence, an anchor wants to transmit a packet, it computes the earliest available time duration that it can transmit without causing collisions knowing the waiting time of the previously scheduled anchors (see Conditions 1, 3, and 4). We again execute this procedure until the last anchor gets scheduled. Finally, by a comparison of the maximum waiting time (w_max) of all anchor sequences ($N!$ possible sequences), we choose the optimum order which has the minimum w_max. We label any algorithm that can solve the optimization function in (5) as L-MAC.

IV. PROPOSED ALGORITHMS

The complexity of the optimal solution (without any heuristic approach) is on the order of $N!$, which makes it impossible to be used when the number of anchors is 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 numerical section, we show that these algorithms can perform near optimum.

A. L-MAC-IS

The steps of L-MAC-IS algorithm are shown in Algorithm 1. In this algorithm, all the waiting times are set to zero in the initial stage. The algorithm starts with scheduling a pre-set arbitrary anchor (for instance the I-th anchor). Therefore, the waiting time of this anchor is fixed to zero. 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 previously selected anchor are detected, and their waiting times are modified in such a way that no collisions will occur in the network (collision-free anchors based on Conditions 1 to 4). Then, from the unscheduled anchors, the one which has the lowest waiting time 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 who has the lowest index as well.

Algorithm 1 L-MAC-IS : Start from the I-th anchor

```
Set all the waiting times to zero: w_i = 0, for i = 1, 2, ..., N,
Set Ω = {1, 2, ..., N},
Start with the pre-defined anchor index I, j = I,
for k = 2 to N do
    Remove j-th anchor from the network:   Ω = Ω − {j}
    Find the collision-risk neighbors of the j-th anchor, and modify their
    waiting time in a way to eliminate possible collisions:
    for i ∈ Ω do
        if d_ij ≤ R then
            w_i = max(w_j + t_p + d_ij/c, w_i)
        else if d_ij ≤ 2R then
            w_i = max(w_j + t_p + (2R − d_ij)/c, w_i)
        end if
    end for
    Select the anchor with the minimum waiting time:  j = arg min_{i∈Ω} w_i
end for
Compute the maximum waiting time:  w_max = max_{i∈{1,..,N}} w_i.
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As can be seen from Algorithm 1, Condition 2 is not included. Condition 2 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.

B. Best select starter

The best starter algorithm (L-MAC-BS) is an extension of L-MAC-IS. In L-MAC-BS, we run the L-MAC-IS for all the anchors ($I = 1$ to N), and select the one (best starter) which results in the minimal total scheduling time. The steps of this algorithm are shown in Algorithm 2.

Algorithm 2 L-MAC-BS :Start from the best anchor

```
Set c = [c_1, c_2, ..., c_N] = [0, 0, ..., 0]
for I = 1 to N do
    Run Algorithm 1, and store the maximum waiting time in vector c:
        c_I = w_max.
end for
Find the index of the minimum element of c:   I_min = arg min_{i∈{1,...,N}} c_i
Select I_min as the best starter of the localization task
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V. NUMERICAL RESULTS

In this section, we evaluate the performance of the proposed algorithms and compare them with the optimum solution. In order to show the superiority of the proposed algorithms, we also compare their performance with appropriate existing underwater MAC protocols such as OCSMA, and traditional slotted methods (Slotted). In OCSMA, no simultaneous packet transmission is allowed, and each anchor can transmit after the complete reception of the previous anchor. It can be deduced that optimum OCSMA is the optimal solution of the localization time minimization if each anchor is in the acoustic communication range of all the other anchors. Finding the optimum solution of OCSMA is NP-hard [7]. Hence, we again use the concept of the first and best starter for this algorithm, and we compare its performance to ours. For the computation of each point in the following figures, we average the solution over 10^3 independent Monte Carlo runs. Furthermore, the localization packet length is 50 ms, (50 bits for an acoustic modem with a data rate of 1kbps), which is long enough to convey the information about the anchor's ID, position and time of transmission.

In Fig. 4, a squared area of dimension $d_x = d_y = 5c$ is considered, and the anchors are assumed to be uniformly distributed over this area. The maximum transmission range of the anchors is assumed to be $2c$. Here, we increase the number of anchors and compute the average time of the localization task, as defined by $t_{\text{avg}} = \mathbb{E}[w_{\max} + t_{\text{p}}]$. As Fig. 4 demonstrates, the performances of the L-MAC-BS, the L-MAC-1S (the anchor with index 1 is scheduled first) and the optimum solution are very close to each other, and L-MAC-1S can be adopted for practical situations where complexity is an issue. For the rest of the simulation results, the performance of the optimum solution is not computed because it takes a huge amount of time.

The effect of the maximum transmission range on t_{avg}, where the dimension of the area is fixed, is depicted in Fig. 5. It is shown that, with an increase in R, the number of strictly distance-related collision-free anchors gets lower, and as a result, the possibility of a simultaneous packet transmission decreases, and t_{avg} increases. This growth in t_{avg} stops when

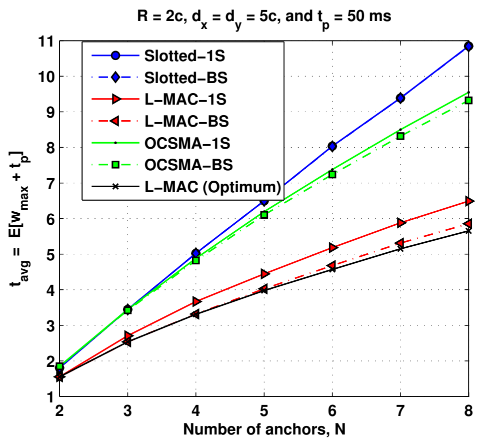

Fig. 4. Average packet transmission time versus number of anchors.

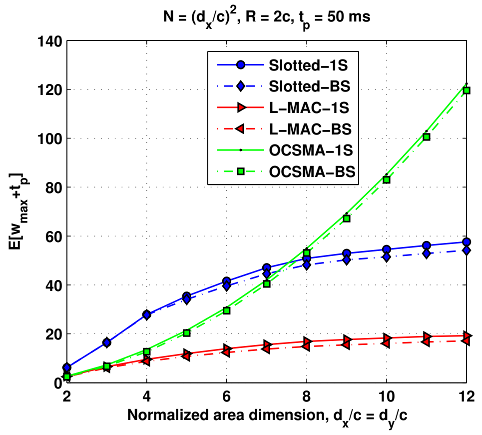

Fig. 6. Performance of the algorithms versus network scalability.

the network is fully connected, and as predicted before, it can be seen that in this case OCSMA performs similarly as the proposed algorithms. In Fig. 6, the performance of the 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 squared meter is constant. Again, as the network gets larger, the probability that more nodes are strictly distance-related collision-free decreases and the nodes experience a larger waiting time. However, as the network gets larger and larger, the average number of collision-risk neighbors converges to a fixed value, and as a result, the performance of both the slotted and the proposed algorithms saturate. In contrast, the performance of OCSMA gets worse, because the number of anchors increases, and as a result the total time of localization increases too.

VI. Conclusion

We have formulated the problem of scheduling the localization packets of the anchors in an underwater sensor network. 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 optimum, and much better than other alternative solutions such as TDMA-based approaches and OCSMA. 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 MAC protocol for such networks can be considered as an extension of the work carried out in this paper.

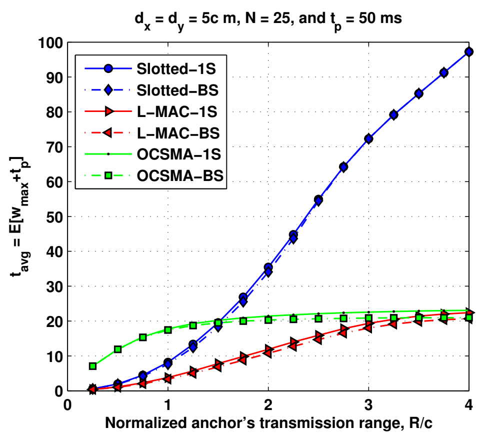

Fig. 5. Average packet transmission time versus anchors' maximum transmission range.

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