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Energy-efficient scheduling and hybrid communication architecture for underwater littoral surveillance

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Abstract

There exists a high demand for reliable, high capacity underwater acoustic networks to allow efficient data gathering and information exchange. This is evidenced by significant research in overcoming the limitations of the shallow water acoustic channel, such as low bandwidth, highly varying multipath effects and large propagation delays. This paper proposes an energy-efficient scheduling mechanism for a scalable network topology with a hybrid RF-acoustic communication architecture, designed for underwater littoral surveillance applications. In combination with a scalable buoy positioning scheme that assures AUV underwater synchronization and position computation, we propose a Time Division Multiple Access scheduling technique for underwater communication that achieves energy-efficient, collision-free data exchange on the low data rate acoustic channel. We measure the performance of the communication architecture by extensive simulations using the Opnet network simulator.

Keywords: Ad hoc wireless networks; Network topology; Energy-efficient scheduling; Communication architecture; Autonomous underwater vehicles; Underwater littoral surveillance

1. Introduction

Recent advances in the shallow-water undersea monitoring, surveillance and exploration demand using the underwater acoustic communication channel as the primary medium for data collection and information exchange. The communication network usually includes autonomous underwater vehicles (AUVs) interconnected by acoustic modems and one or more surface gateways which provides links to a command and control center, which can further be connected to a backbone network, such as the Internet. Surface communication can be done using RF or satellite links. Applications of deploying AUVs in shallow-water includes undersea surveillance in littoral waters, oceanographic data gathering, environmental monitoring, and coastal defense.

One of the major challenges in underwater acoustic networking is the development of networking protocols to overcome harsh communication conditions. Physical layer considerations include limited bandwidth, extreme propagation delays, signal absorption, time-varying multipath with severe intersymbol interference and large Doppler shifts [13]. These physical layer limitations adversely impact throughput, latency, and capacity.

Since the acoustic network components are battery-powered, power efficiency is an important characteristic of the underwater communication protocols. Designing energy-efficient scheduling and communication mechanisms have an important role in prolonging the network operational lifetime.

There exist a large volume of research addressing the difficulties of underwater acoustic networks and proposing solutions at different layers of the network architecture. In [13,15], authors present a comprehensive survey of existing network technology at the physical, data link and network layers and their applicability to underwater acoustic channels.

A cluster-based communication protocol is proposed in [11]. Adjacent underwater vehicles are grouped into clus-

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ters in which in-cluster communication is achieved through TDMA and inter-cluster communication uses CDMA. The focus of this paper is on cluster maintenance, that needs to accommodate a dynamic topology with mobile vehicles.

The Deployable Autonomous Distributed Systems (DADS) [10] are motivated by requirement for wide-area undersea surveillance in littoral waters. The network connects the remote sensor platforms through a gateway (e.g., a sea-surface buoy) to a distant master node across satellite links. Acoustic data is transmitted over multi-hop paths, using half-duplex CDMA links between discrete modem pairs and a three-way handshake protocol for data transfer between each pair of nodes. The paper also describes a series of ocean experiments and measurements.

The work in [18] proposes a networking protocol for underwater acoustic networks of fixed or mobile nodes. The authors propose a centralized topology control scheme by periodic topology discovery probes. The routing protocol proposed is centralized, where the master node determines all routes through the network. CDMA technique is used for multiple access to the communication media.

In this paper, we design a shallow water energy-efficient scheduling mechanism and communication architecture for a littoral surveillance application. Our model includes (1) a number of AUVs deployed for shallow-water undersea surveillance, (2) a number of sea-surface buoys that act as a gateway between the underwater acoustic network (ACnet) and the RF network (RFnet), and (3) a central command and control station on a ship positioned in close proximity to the surveillance area.

The remainder of this paper is structured as follows. Section 2 presents the networking model with parameters considered for ACnet and RFnet. In Section 3, we describe the littoral surveillance scenario and problem definition. Next, we present the network architecture design in Section 4. We continue with our energy-efficient scheduling mechanism. Buoys arrangement mechanism is presented in Section 5, followed by the TDMA slot allocation algorithm in Section 6. Section 7 presents a performance analysis for simulation results and Section 8 concludes our paper.

2. Hybrid networking model

Underwater communication is severely limited by the physical layer characteristics of the communication medium. Usually, acoustic networks in shallow water support a data rate of 100–1000 bps [18], although higher data rates of 16 kbps are reported in [12]. The available bandwidth for an acoustic network is typically around 15 kHz, and it has to be shared among all acoustic nodes. Three major multiple access methods are Time Division Multiple Access (TDMA), Frequency Division Multiple access (FDMA), and Code Division Multiple Access (CDMA) [17]. The work in [13] compares these methods from the point of view of a shallow water acoustic communication network. CDMA and spread-spectrum signaling appear to be a promising multiple access technique.

Another key factor is the acoustic signal propagation speed of approximately 1500 m/s, five orders of magnitude lower than that of a radio channel. The large propagation delays directly affect the achievable throughput. Also, the signal range of an AUV varies from few kilometers up to 90 km [4].

The application we are addressing in this paper is underwater littoral surveillance. The environment we consider is shallow water, with depth less than 50 feet. The hybrid network topology we consider is illustrated in Fig. 1 and its components are described next.

The architecture elements in our model are AUVs, buoys, and a central command and control station, hosted on a ship. Buoys and the central station are considered fixed platforms and the AUVs are mobile sensor platforms. In this paper, we use characteristics of the wireless equipment available at the Florida Atlantic University (FAU), the Department of Ocean Engineering [1].

AUVs and buoys can communicate wireless to synchronize and to share information. Each AUV and buoy is equipped with a FAU Dual Purpose Acoustic Modem (FAU-DPAM) [1,8]. A DPAM has two transceivers:

- the first transceiver has an RF radio with a 2.4 GHz transmitter with omnidirectional antenna for the surface wireless communication, having a 3 km range.

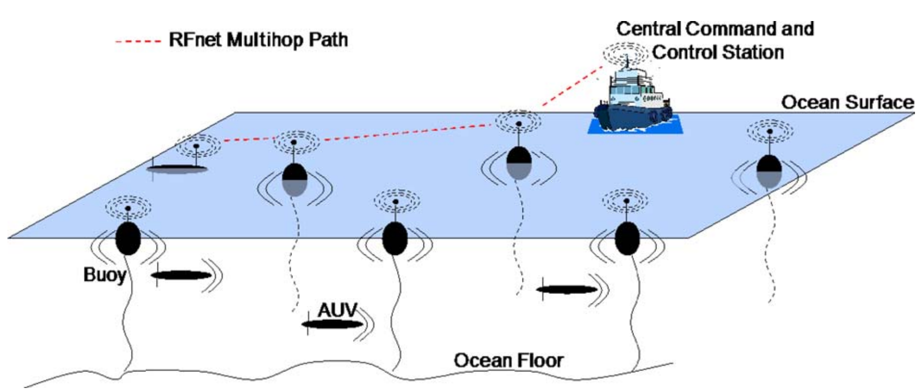

Fig. 1. Hybrid RF-Acoustic Network Components.

We assume a data rate of 1 Mbps. Higher data rate 802.11 COTS products are available [14]. The ship has only RF connectivity.

- the second transceiver is using an acoustic channel in the 15–32 kHz band for underwater acoustic communication; the communication range is about 3 km with a data rate of 300 bps using Direct Sequence Spread Spectrum (DSSS) with Multiple Frequency-Shift Keying (MFSK) or it can be about 500 m with a data rate of 15 kbps by using DSSS with Phase-Shift Keying (PSK) [17]. In this paper, we assume a communication range of 3 km and a data rate of 300 bps.

The AUVs are almost all the time moving with a speed less than 3 m/s. Their main task in this model is to monitor the coastal ocean environment and detect mines and other suspect objects. Each AUV is equipped with a Side Scan Sonar HF Acoustic chirp [2] at 500 kHz, with a sensing range of about 1.5 miles. Every AUV is also equipped with a camera. When a mine or another potentially dangerous object is detected, the AUV takes one or more pictures (of about 25 kbytes each) that need to be sent immediately to the ship. Additionally, an AUV is also equipped with a Global Positioning System (GPS) receiver used for periodic time synchronization and positioning when the AUV surfaces.

Fixed buoys provide communication support for littoral AUV missions. In our model, buoys are deterministically placed at the beginning of the mission by specialized submarines. Buoy deployment positioning is detailed in Section 5. Buoys are equipped with GPS, allowing them to precisely determine time and their location. Buoys periodically broadcast their location on the acoustic network, allowing AUVs within transmission range to triangulate their own location while being submerged.

Both AUVs and buoys are battery-powered, and therefore preserving energy resources by scheduling and efficient communication will increase the network lifetime.

Beside AUVs and buoys, the topology contains a central command and control station on a ship. In our model, we assume the ship is positioned within RF communication range of at least one buoy. Our architecture assumes the ship is moving at low speed, or is stationary.

The hybrid wireless network consists of two ad hoc wireless networks. The RF wireless network (RFnet) runs above the ocean surface, and is formed by buoys, the ship and the AUVs (while at surface). The RFnet has a dynamic topology at the edges, because every AUV joins this network only when it reaches the surface and must communicate at high speed. The RF network has a data rate of 1 Mbps in the 2.4 GHz frequency band. Transceivers for RFnet are available for long range outdoors communication. For example, MikroTik Wireless LAN USB adapter [14] uses 2.4 GHz DSSS radio transmission, for a data rate of 11 Mbps, and has a range of up to 5 km for outside environments. The transmit power is 32 mW.

The second wireless network is the underwater ACoustic network (ACnet). The nodes in the ACnet are buoys and AUVs and they communicate using the acoustic transceiver on the FAU-DPAM modem. As we discussed in the previous paragraphs, the communication in the acoustic network is severely limited by the physical properties of the acoustic channel in shallow water.

The interface between the RFnet and ACnet can be accomplished in two ways. First, buoys are part of both networks, based on their dual modem, therefore they are able to transfer information between the two networks. Second, the AUVs can surface and join the RFnet.

3. Problem definition and surveillance scenario

In this paper, we address the underwater littoral surveillance application. A number of AUVs are deployed and are using their sonar sensing capabilities to detect mines or other related targets. Once a suspicious object is detected, target information needs to be reported immediately to the ship, across the wireless hybrid network.

Our goal in this paper is to design an energy-efficient scheduling mechanism and communication architecture solution for underwater littoral surveillance applications with the following requirements: (1) accommodate the harsh underwater acoustic communication parameters (2) to reliably transmit to the ship, with high priority, messages from AUVs about detected targets (3) to periodically and reliably send updates with AUV status and location (4) to periodically transmit updates to the ship on buoy status, and (5) to reliably transmit commands and/or queries from ship to AUVs or buoys.

With these requirements, we describe a littoral surveillance mission scenario consisting of the following phases:

- *Buoys and AUVs deployment.* This phase occurs at the beginning of the mission. The buoys and AUVs are deployed by a specialized submarine or by a ship. We assume the buoys are deterministically placed, as specified in Section 5. We also assume every AUV and buoy has assigned a unique ID. After deployment, the buoys and AUVs start the network initialization step.
- *Network initialization.* During the initialization phase, buoys and the ship organize into an ad hoc RF wireless network (RFnet) and start the routing protocol initialization. This operation consists in exchanging short control messages and constructing the routing tables, in accordance with the routing protocol employed.
  Once an AUV is deployed, it goes to the surface and sends an initialization message to the ship over the RFnet. This message contains the AUV ID and its current location. Based on this information and using our scheduling algorithms, the ship replies with a message containing coordinates of the surveillance region (where this AUV will perform the sensing task) and a TDMA slot. This TDMA slot will be used by the AUV for communication in the ACnet. Division of

the surveillance area in surveillance regions is described in Section 5. TDMA slot allocation is discussed in Section 6.

- *Idle network operation.* This phase describes the network operation between target detection events. The main task of the RFnet is to maintain the routing information updated, by periodically exchanging control information in accordance with the routing protocol used. Every buoy is responsible for periodically sending status report messages to the ship, containing information about its state (e.g., OK/CriticalCondition) and a list with AUVs in its range. We will refer to this message as the *status-update* message.
  Next, we describe the operations performed in the ACnet. Every AUV and buoy will periodically send a short message with navigation control information. We refer to these messages as buoy beacons and AUV beacons, respectively. A buoy beacon contains the buoy ID, GPS-based location and time information, and other application specific information. For example a buoy beacon may encode a short command sent from the ship to an AUV. An AUV beacon contains the AUV ID, flight time, location, speed, bearing, and one or more fields used for ACK and data exchange.
  Each AUV listens to other buoy beacons and AUV beacons. Based on our design, every AUV moves into a surveillance region with the property any point is within underwater acoustic transmission range of at least three buoys. Using location and time information from at least three buoys, the AUV is able to synchronize its clock and compute its current location through triangulation [5] while submerged. Information from other AUV beacons is used for collision avoidance and other navigation purposes.
  Every time an AUV gets to the surface, it will use its GPS for a precise time and location alignment. The system is also characterized by a *GPS-update-time* attribute. At most every *GPS-update-time*, an AUV surface to get synchronized. Every buoy listens for AUV beacons and updates its AUV database information.
  The main operation performed by AUVs is sensing. Every AUV is equipped with a Side Scan Sonar HF Acoustic chirp. The AUVs navigate and continuously monitor their environment.
- *Target detection.* This phase starts when an AUV detects a mine or a suspicious target. Each AUV is equipped with a digital camera. When a target is detected, the AUV captures one or more photographs that need to be sent with high priority to the ship.
  Because of the limitations in data rate and signal delay in the ACnet, it is not feasible to have AUVs send large data messages (e.g., pictures) over long distances on the underwater network. The solution we adopt is to have an AUV that detects a target go to the surface, join the RFnet and start a message exchange with the ship. In our communication protocol, the AUV sends in the fist message one picture to the ship and then waits for an acknowledgment, a query or a command from the ship. While waiting for the reply, the AUV performs a GPS location and time update. If an acknowledgment is received, the AUV dives and continues the surveillance process. The AUV can also receive a query from the ship, asking for more pictures (already available at the AUV), case in which the AUV starts transmitting the required information and waits for a new ship reply. Besides these two replies, the ship may command the AUV to go to a specific location within its surveillance region and monitor the environment. In this case, the AUV dives, starts the sonar, sets the new waypoint and begins its new task.
- *New sensing task.* The ship can explicitly ask an AUV to navigate at a specific location in its surveillance region and collect data. The message is sent by the ship across the RFnet to the buoys that are within this AUV's communication range. These buoys will then transmit this command on the ACnet, piggybacked in a buoy beacon.
- *Mission termination.* This operation is accomplished by having the ship sending a special *Termination* control packet to every AUV. Upon receiving this message, an AUV performs the termination procedure, navigating toward a specific pick-up location.

4. Hybrid network architecture design

In this section, we describe the networking architecture for the ACnet and RFnet.

In an underwater acoustic environment, the communication mechanism needs to consider poor conditions in terms of latency and data rate. We design the ACnet architecture to include only Physical, Data Link, and Application Layers. Our model does not require a network protocol, because the only communication in ACnet is AUV and buoy beacon broadcast. This is an one-hop information exchange, where nodes do not forward the message they receive. The Physical Layer uses DSSS with MFSK with a data rate of 300 bps and a communication range $R = 3$ km, according with the characteristics of the FAU-DPAM modem, acoustic transceiver (see Section 2). The multiple access scheduling method we adopt for the underwater communication is TDMA. TDMA avoids collisions by allocating a time slot to every AUV and buoy. It is an energy-efficient scheduling mechanism since it avoids additional control messages exchange. For example, a TDMA scheduling mechanism avoids the handshake overhead of wireless MAC protocols such as Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA), and Multiple Access with Collision Avoidance-derived protocols like MACAW (MACA for Wireless) and IEEE 802.11 [16] protocols. Actually, a MAC transmission protocol involving a large number of message exchange is also not feasible because of the long propagation delays in acoustic networks.

Based on the buoy deployment mechanism (see Section 5), five TDMA slots from the TDMA frame will be assigned to the buoys, as represented in Fig. 3 and all other will be assigned to the AUVs. The scheduling using the TDMA slot allocation mechanism is further detailed in Section 6. AUVs and buoys use the TDMA slots for sending short beacons in the ACnet and not for large data transmissions. For example, if we design a beacon with 32 bytes, then we can have a TDMA slot of 3 s. This will suffice for 0.85 s beacon transmission delays and a 2 s propagation delay at 3 km distance.

The RFnet network is used for transmitting long messages between the AUVs and ship, for status-update messages and to issue commands from the ship to the AUVs. A ship command addressed to a submerged AUV will be sent to the buoys in the communication range of that AUV. This is easy to implement, based on information from the status-update messages received by the ship from buoys. The RFnet architecture is typical to an IP ad hoc wireless networks and includes the 802.11 Physical and Data Link layers, and the TCP/IP Network and Transport layers.

At the Physical Layer, we assume the following attributes: radio frequency 2.4 GHz, DSSS signal spreading technique, data rate of 1 Mbps and a communication range of 3 km. The RF communication range should be greater or equal to the acoustic communication range in order to have any AUV at the surface within RF transmission range of at least one buoy. The MAC protocol used in the RFNet is IEEE 802.11 Distributed Coordination Function (DCF). At the Network Layer, we use a reactive routing protocol for ad hoc wireless networks, such as Dynamic Source Routing (DSR) or Ad Hoc On-Demand Distance Vector (AODV). In our simulations we use DSR for its good performances in terms of reliability, routing overhead and path optimality [6,7]. When an AUV joins the RFnet for information exchange it also runs the selected ad hoc routing protocol but is not involved in data forwarding on behalf of other nodes. It is only a leaf in the network topology. At the Transport Layer, we use the TCP protocol [16] for its reliable communication and congestion avoidance mechanism. It is well-known that TCP performs poorly in multihop wireless networks [3], due to its inability to differentiate between retransmissions due to congestion versus packet loss. In our application scenario AUVs find targets infrequently and all high data rate traffic is sent towards the ship node, thus congestion may occur.

5. Buoy positioning

The positioning of the buoys plays an important role in our scheduling mechanism. The factors we considered in designing a mechanism for computing the buoy locations are the following:

- *Mission specifics.* The mission considered in this paper is littoral surveillance, where AUVs are moving along the coastline.
- *AUV location.* AUVs need to be able to triangulate their location based on the GPS information included in the periodic buoy beacons. At any time each AUV should be within transmission range of at least three buoys.
- *Minimized number of buoy slots.* The underwater communication protocol proposed in this paper is TDMA, and, because the frame period is limited (see Section 6), the number of slots allocated to the buoys should be minimized.
- *Maximized surveillance area.* The surveillance area where AUVs navigate should be maximized. Note that any point within the navigation area should be within the communication range of at least three buoys for location identification.

Based on these considerations, we arrange the buoys in two rows along the coastline in order to provide a rectangular surveillance area (see Fig. 2) with the property that any point within this area is within communication range of at least three buoys. Therefore, any AUV navigating within this rectangle receives periodic beacons from at least three buoys, and will be able to periodically update its loca-

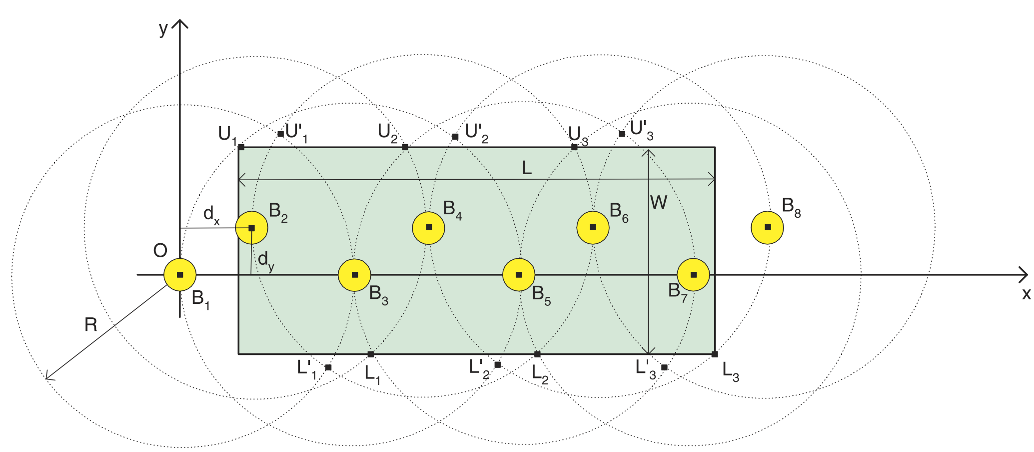

Fig. 2. Buoy positioning for $n = 8$ buoys.

tion through triangulation. The distance between two buoys in the same row is equal to R, where R is the underwater communication range of the buoys and AUVs (e.g., R is set up to 3 km).

Next, we will determine the relative location of the two rows in order to maximize the surveillance area. Let us consider the first row fixed and the Cartesian coordinate system as in Fig. 2. We neglect in this discussion the vertical coordinate, because the mission is performed in shallow water, with depth less than 50 feet, much smaller than the values in the other two horizontal coordinates.

We consider n buoys B_1, B_2, B_3, ..., B_n deployed as in Fig. 2. We organize them in two rows, with B_1, B_3, ... in the first row and B_2, B_4, ... in the second row. Next, we compute the location of the second row (e.g., determine d_x and d_y), in order to maximize the surveillance rectangle area. In the picture, we have represented the two buoy rows and their communication disk, inside a circle with radius R.

In the Fig. 2, we can observe that the points U_1, U'_1, U_2, U'_2, ... and L_1, L'_1, L_2, L'_2, ... establish the upper and lower rectangle edges. The points right above U_1, U'_1, U_2, U'_2, ... or below L_1, L'_1, L_2, L'_2, ... are not within communication range of three buoys. The rectangle width can be expressed as $W = \min\{y_{U_2} - y_{L_2}, y_{U'_2} - y_{L'_2}\}$, where x_A and y_A are the x and y coordinates of the point A.

Considering d_y fixed, basic geometric computation indicates that W is maximized when $d_x = R/2$, case when both U_1, U'_1, U_2, U'_2, ... and L'_1, L_2, L'_2, L_3, ... are collinear.

The left edge of the rectangle is determined by the intersection point (e.g., U_1) of the circle with radius R centered at the third buoy from left (e.g., B_3) with the upper edge, and the right edge of the rectangle is determined by the intersection point (e.g., L_3) of the circle with radius R centered at the third buoy from right (e.g., B_6) with the lower edge.

Note that there will be other points in the rectangle's vicinity that will be covered by at least three buoys, but our goal is to determine a rectangular shape with this property.

Next we want to determine $d_y \in [0, R\sqrt{3}/2]$ such that to maximize the surveillance rectangle area, $Area = W \times L$. $d_y = R\sqrt{3}/2$ corresponds to the case when $B_1B_2 = B_2B_3 = B_1B_3 = R$ and $W = R\sqrt{3}/2$. Cases $d_y > R\sqrt{3}/2$ are not considered, as they produce $W < R\sqrt{3}/2$. Using the geometric computation presented in Appendix A, we obtain that $W(d_y) = \frac{3R}{2} \cdot \sqrt{\frac{7R^2 - 4y_d^2}{9R^2 + 4y_d^2}}$ and $L(n, d_y) = (n-2) \cdot R/2 - d_y\sqrt{\frac{7R^2 - 4d_y^2}{9R^2 + 4d_y^2}}$ for any $n \geqslant 3$. Taking the derivative, we obtain $\frac{d(W(d_y))}{d(d_y)} \leqslant 0$ and $\frac{d(L(n,d_y))}{d(d_y)} < 0$, when $d_y \in [0, R\sqrt{3}/2]$. Therefore, $W(d_y)$ and $L_n(d_y)$ are decreasing functions of d_y, achieving the maximum value when $d_y = 0$.

An important goal of deploying buoys is to broadcast GPS information. In order for the AUVs to perform the triangulation algorithm, the buoys cannot be collinear, therefore d_y needs to be greater than a specific threshold. We assume $d_y = \delta$, where δ is the minimum value required in the triangulation algorithm.

Note that this buoy organization is scalable. Additional buoys can be deployed to increase the surveillance length. Any additional buoy will increase the length with $R/2$. Also, by using this arrangement, only five TDMA slots will suffice for the buoys acoustic communication. TDMA slot allocation is presented in Section 6.

Another observation is that buoys are anchored at the ocean floor, therefore their location on the ocean surface is not fixed, they are continuously moving around the anchor point. Still this distance is very small compared to the distances between buoys and it is therefore neglected in this paper.

6. TDMA slot allocation

In this paper, we propose a TDMA scheduling mechanism both for energy-efficiency considerations, as well as because of the acoustic environment constraints, as discussed previously. TDMA frame period is limited by the frequency with which the AUV and buoys need to send beacons. The beacons are critical for AUV synchronization, positioning, and navigation as well for sending accurate status update information. On the other hand, the TDMA slot size is affected by the low data rate and long propagation delay in the acoustic network. Therefore, the goal of the TDMA slot allocation mechanism is to use a minimum number of TDMA slots in a frame interval.

In our scenario, the first five slots 1–5 are allocated to the buoys. Considering the numbering in Fig. 3, the buoy B_i, $i = 1, 2, \ldots, n$ will be assigned the slot $i \oplus 5 + 1$. In this way, any AUV in the surveillance area will be within communication range of at most one buoy transmitting in the same slot. This is because the communication range of any two buoys assigned to the same slot (e.g., B_1 and B_6) do not intersect.

Let us assume that after allocating the first five slots to the buoys, we are left with s TDMA slots to be allocated to the AUVs. Consider the number of AUVs to be deployed is m and the length of the surveillance rectangle is L.

Next, we present a mechanism for allocating slots to the AUVs, using spatial slot reuse. This mechanism is performed only once, during the initialization phase. The slot allocation algorithm is run by the ship.

The following mechanism can be applied when $L/(r+1) > R$, where r is the number of regions computed by Algorithm 1. If this relation does not hold, then we need to adjust the L, m, and s parameters correspondingly, e.g., either increase L or the number of slots s or decrease m, the number of AUVs.

Next we present two algorithms. Algorithm 1 has as input m, s, L and divides the surveillance rectangle in

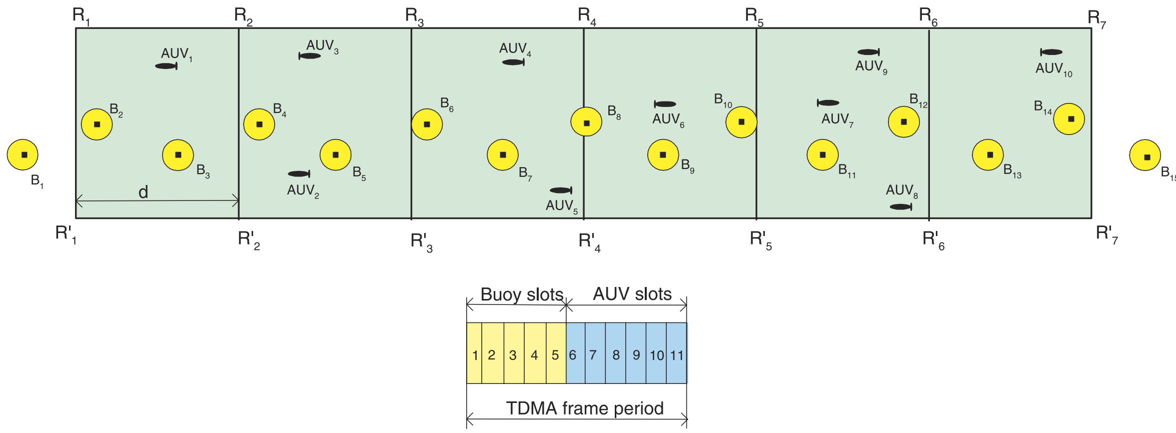

Fig. 3. Surveillance regions for $n = 15$ buoys and time slot allocation when $m = 10$ and $s = 6$.

regions, associates TDMA slots to every region and identifies every buoy to which region it belongs based on its location. Any slot associated to a region is later assigned by the ship to an AUV to use for beacons while performing the surveillance task within that region.

Algorithm 2 assigns a communication slot to an AUV. This algorithm is executed by the ship as result of a request from the AUV sent during the initialization phase, when the AUV is at the ocean surface.

Let us note with S the set of TDMA slots for AUVs, e.g., for example in Fig. 3, $S = \{s_6, s_7, \ldots, s_{11}\}$ and $|S| = s$, where $|S|$ represents the cardinality of the set S.

Algorithm 1 (m, s, L). Input: m, s, L

Output: divide surveillance rectangle in regions, assign TDMA slots to all regions

Step 1. If $m \leqslant s$, then the surveillance rectangle forms one region $\Re_1$. Assign all s slots to $\Re_1$. All buoys will also be part of $\Re_1$. Exit.

Step 2. Compute the number of regions r

First, we divide the slots in S in three sets S_1, S_2, S_3, $|S_1| + |S_2| + |S_3| = s$:

if $(s == 3k)$ where $k \in N$, then $|S_1| = |S_2| = |S_3| = k$

else if $(s == (3k + 1))$ then $|S_1| = k + 1$ and $|S_2| = |S_3| = k$

else if $(s == (3k + 2))$ then $|S_1| = |S_2| = k + 1$ and $|S_3| = k$

Let S_1 contain the first $|S_1|$ slots from S, S_2 the next $|S_2|$ slots, and S_3 the last $|S_3|$ slots. Next, compute the number of regions r as follows:

$r = 3\lfloor m/s \rfloor$

if $((m \oplus s) > (|S_1| + |S_2|))$ then $r = r + 3$

else if $((m \oplus s) > |S_1|)$ then $r = r + 2$

else if $((m \oplus s) > 0)$ then $r = r + 1$

Step 3. Divide the surveillance rectangle into r equal regions

This step divides the surveillance rectangle into $r + 1$ rectangles, with length $d = L/(r + 1)$, as illustrated in Fig. 3. Note that $L/(r + 1) > R$. We define r regions as the following rectangles: $\Re_1 = R_1R_3R'_3R'_1$, $\Re_2 = R_2R_4R'_4R'_2, \ldots, \Re_r = R_rR_{r+2}R'_{r+2}R'_r$.

Step 4. Assign slots to every region $\Re_i$, for $i = 1, \ldots, r$

for $(i = 1, \ldots, r)$ {

if $((i \oplus 3) == 1)$ then assign to $\Re_i$ the slots in the set S_1.

else if $((i \oplus 3) == 2)$, then assign to $\Re_i$ the slots in the set S_2.

else if $((i \oplus 3) == 0)$, then assign to $\Re_i$ the slots in the set S_3.

}

Step 5. Every buoy belongs to one, two or three regions depending on its location.

for $(i = 1, \ldots, n, j = 1, \ldots, r)${

if $(x_{B_i} \in [x_{Rj}, x_{R_{j+2}}])$ then B_i belongs to the region $\Re_j$, where $\Re_j = R_jR_{j+2}R'_{j+2}R'_j$

}

Algorithm 2. Input: AUV_i

Output: Allocate a TDMA slot to AUV_i

Based on the AUV_i location, determine the closest region $\Re_j$ that has a slot u available. If two such regions are available, choose the one with smallest index. Mark the slot u in $\Re_j$ as busy and assign slot u to AUV_i. AUV_i will belong to $\Re_j$, this means that AUV_i will perform the surveillance operation within $\Re_j$ and will transmit its beacon during the slot u in the ACnet.

Theorem 1. *Algorithm 1 provides enough slots to accommodate all m AUVs transmissions. Any buoy and any AUV navigating in a region* $\Re_i$ *will receive collision-free messages from any AUV that has been assigned a slot from* $\Re_i$ *as result of Algorithm 2.*

Proof. First, we prove that the number of slots allocated by the Algorithm 1 in all r regions is greater or equal with m. We distinguish four cases:

1. $(m \oplus s) == 0$. Then there are $r = 3m/s$ regions and number of slots is $(m/s)(|S_1| + |S_2| + |S_3|) = m$.
2. $(m \oplus s) > (|S_1| + |S_2|)$. In this case we have $r = \lfloor m/s \rfloor + 3$ regions and the number of slots allocated to all regions is $(\lfloor m/s \rfloor + 1)(|S_1| + |S_2| + |S_3|) = (\lfloor m/s \rfloor + 1)s > m$.
3. $(|S_1| + |S_2|) \geqslant (m \oplus s) > |S_1|$. In this case we have $r = \lfloor m/s \rfloor + 2$ regions and the number of slots is $(\lfloor m/s \rfloor)(|S_1| + |S_2| + |S_3|) + |S_1| + |S_2| = (\lfloor m/s \rfloor)s + |S_1| + |S_2| > m$.
4. $|S_1| \geqslant (m \oplus s) > 0$. In this case we have $r = \lfloor m/s \rfloor + 1$ regions and the number of slots is $(\lfloor m/s \rfloor)(|S_1| + |S_2| + |S_3|) + |S_1| = (\lfloor m/s \rfloor)s + |S_1| > m$.

If an AUV has been assigned a slot u from region $\Re_i$, then it will navigate and perform surveillance within that region. Based on the way we assign slots to regions (see Algorithm 1, *Step 4*), the closest regions with the same slots are $\Re_i$ and $\Re_{i+3}$, for $i = 1, \ldots, r-3$. The minimum distance between $\Re_i$ and $\Re_{i+3}$ is d and because $d > R$, any node (AUV or buoy) inside $\Re_i$ will not receive any transmission from a node inside $\Re_{i+3}$. □

Let us now show the slot allocation mechanism on the example illustrated in Fig. 3. We know L, $m = 10$, $S = \{6, 7, 8, 9, 10, 11\}$, $s = 6$. Then $S_1 = \{6, 7\}$, $S_2 = \{8, 9\}$ and $S_3 = \{10, 11\}$ and there are five regions: $\Re_1 = R_1R_3R'_3R'_1$, $\Re_2 = R_2R_4R'_4R'_2$, $\Re_3 = R_3R_5R'_5R'_3$, $\Re_4 = R_4R_6R'_6R'_4$, and $\Re_5 = R_5R_7R'_7R'_5$. Time slots in the set S_1 are assigned to $\Re_1$ and $\Re_4$, time slots in S_2 are assigned to $\Re_2$ and $\Re_5$ and time slots in S_3 are assigned to $\Re_3$. Assuming the ten AUVs are deployed uniformly along the rectangle, a possible slot assignment is as follows: $\Re_1$: AUV_1 on slot 6 and AUV_2 on slot 7, $\Re_2$: AUV_3 on slot 8 and AUV_4 on slot 9, $\Re_3$: AUV_5 on slot 10 and AUV_6 on slot 11, $\Re_4$: AUV_7 on slot 6 and AUV_8 on slot 7, $\Re_5$: AUV_9 on slot 8 and AUV_{10} on slot 9.

Advantages of using this slot allocation mechanism include: (1) energy-efficient mechanism with low overhead; (2) it uses a reduced number of time slots s; (3) it proposes a uniform AUV distribution, by organizing the surveillance area in smaller regions; (4) it is scalable. More buoys and AUVs can be deployed following the same pattern, without modifying the existing organization.

7. Simulation results

In this section, we analyze the performance of our protocol through simulations. We implement the communication protocol with the Opnet network simulator [9]. Next, we present the values of the parameters considered in our testing, followed by the performance metrics and simulation results.

For testing, we assume a scenario with n=15 buoys, positioned according to Algorithm 1 (see Fig. 3). This will result in a surveillance area with length $L = 19412$ m for $d_y = 100$ m. The RF communication range is $R = 3$ km and the data rate for the RFnet is 1 Mbps. For the ACnet, we assume an acoustic communication range of 3 km, a data rate of 300 bps using DSSS/MFSK, and a signal propagation speed of 1500 m/s.

For the TDMA slot configuration, we consider that 5 slots are allocated to the buoys and $s = 7$ slots are allocated for AUVs. This result in a TDMA frame period of 12 slots and when the slot time is 3 s, we obtain a TDMA frame of 36 s. The reason for choosing 3 s is as follows. Every AUV and buoy periodically exchange beacons in its allocated slot. We consider beacon size is 32 bytes. An AUV beacon contains the AUV ID, flight time, speed, bearing, location coordinates and one or more fields used for ACK and data exchange. A Buoy beacon contains buoy ID, GPS-based location and time information and one or more fields used for data exchange. We choose the TDMA slot size of 3 s to include the beacon transmission time in the ACnet of 0.85 s and a 3 km propagation time of 2 s.

Note that these attributes are variables in our code and their values can be changed according with the planned scenario.

The scenario considered is presented in Section 3. Once an AUV is deployed, it gets to the surface and sends an initialization message to the ship over the RFnet. The ship responds with a message containing the coordinates of the surveillance region and the TDMA slot allocated to this AUV. The ship does the assignment based on the current AUV location. It will select the closest region that has a TDMA slot available. The AUV then dives and performs the surveillance task. We assume the AUV speed of 3 m/s.

We used the DSR routing protocol [7] for RFnet communication. At the transport layer, we used TCP protocol. We chose TCP protocol because it offers a connection-oriented and reliable communication service. Also, the congestion control mechanism prevents congestion when multiple AUVs transmit long messages (images) to the ship. We used the DSR and TCP protocol models provided by Opnet. The communication in the ACnet uses TDMA, as we described in the previous sections.

The parameters we varied in our simulation are the number of AUVs, the ship location, the target detection interval and the number of image messages sent by an AUV to the ship for every target detected. The performance metrics we measured are the AUV to ship message delay, ship to AUV command delay, status-update message delay (with or without the AUV beacon delay), and aggregate throughput.

In the first set of measurements we vary the number of AUVs deployed, between 1 and 12. We assume the ship is positioned at the center of the surveillance rectangle.

Target detection time is uniformly distributed between 30 min and 1 h and the interval the ship will issue a new command for every AUV is uniformly distributed between 20 and 40 min.

In Fig. 4a, we measure the AUV to ship message delay. This is for the case when an AUV detects a target and gets to the surface to transmit the first image to the ship. This delay is therefore measured over RFnet. The size of an image message is 25 kbytes. Our results indicate an average delay of 1 s and the 95th percentile at 2.5 s. These values are dependent on the number of hops between AUV and

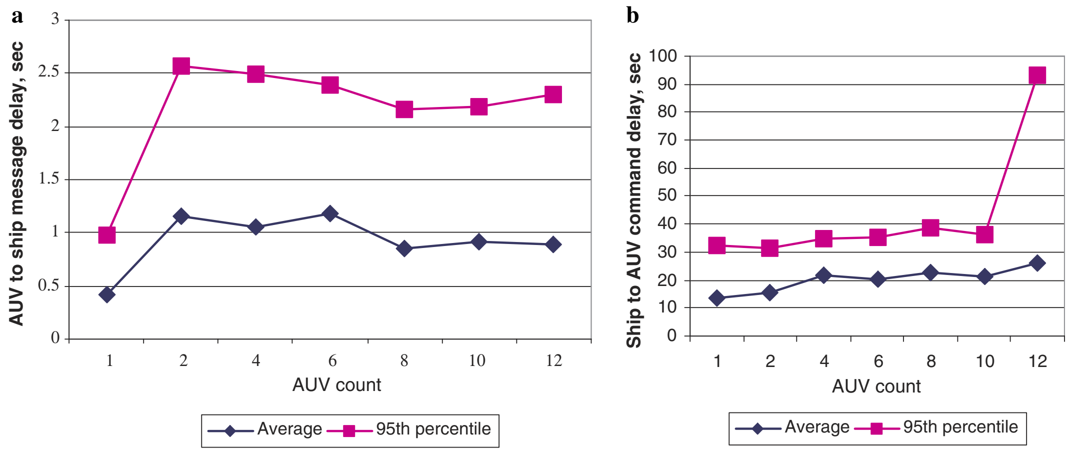

Fig. 4. Message delays in communication between AUV and ship.

ship and are also affected by MAC layer contention, TCP and routing overhead and retransmission delays.

In Fig. 4b, we measure the delay for sending a command from the ship to the AUV. Here the AUV is submerged, so this delay reflects both the RF and acoustic delay. The delay has an average of 20 s, with the 95th percentile at 95 s. The RFnet delay is affected by the factors mentioned before. Regarding the ACnet communication, the command is sent by the buoy during its slot, so the command will be queued at the buoy between 0 and 33 s. As we send only one command per beacon, it may happen that a command is delayed a few TDMA frame periods, especially for cases with more AUVs.

In our model, buoys are responsible for periodically sending status-update messages to the ship with information about AUVs in their range. Buoys collect this information from the AUV beacons received in the ACnet. The frequency of sending information updates by the buoys can be set up to different values. For these simulations we assume status updates are sent every TDMA frame interval, that is, every 36 s. In Fig. 5a, we represent the delay of the status-update messages, whereas in the Fig. 5b, the delay is measured from the moment it was sent by the AUV. This delay includes the time the AUV beacon was sent over the ACnet (3 s), the delay occurred in the buoy (up to 33 s) and the delay over the RFnet.

In Fig. 6, we present the aggregate throughput measured at the ship. As expected, the average value increases with the number of AUVs.

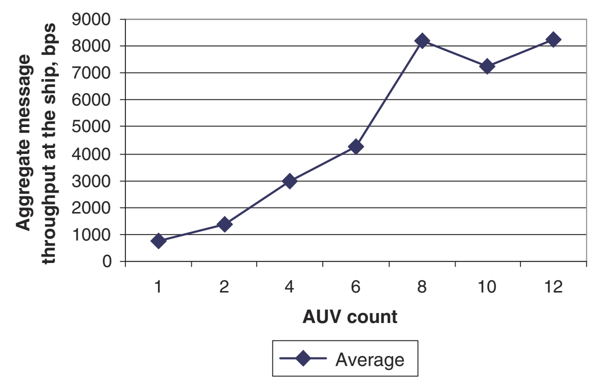

Fig. 6. Aggregate message delay at the ship depending on the number of AUVs.

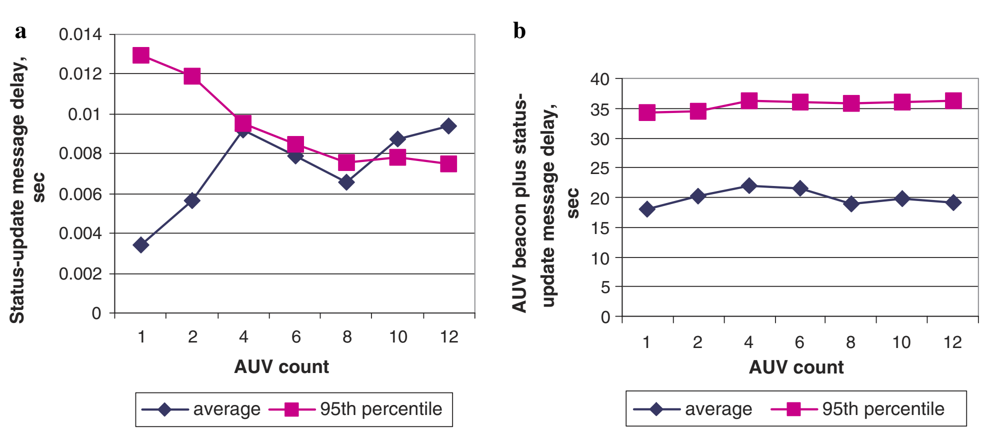

Fig. 5. Status-update message delays.

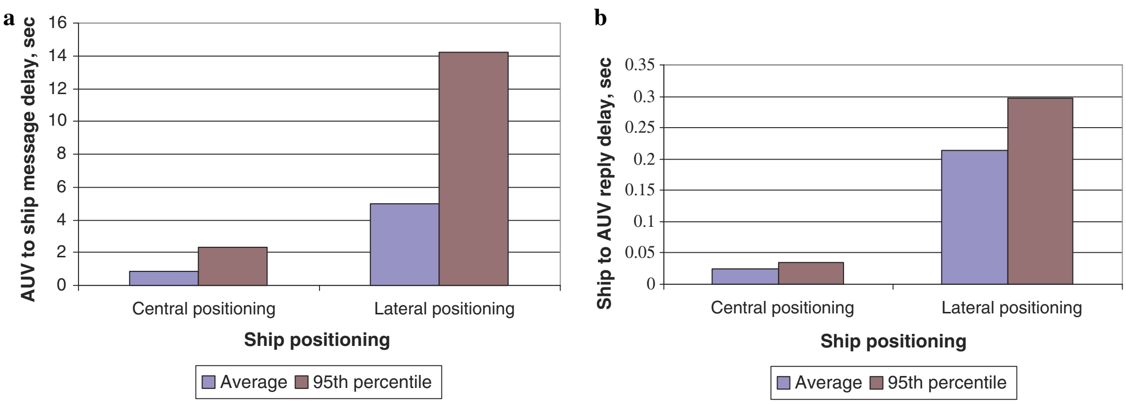

Fig. 7. Message delay depending on the ship positioning.

In the next set of measurements, we study the impact of the ship location on the message delays between the AUV and ship and status-update message delay. We compared the case when the ship is positioned at the middle of the surveillance rectangle (e.g., close to B_6 in Fig. 3), versus the case when it is positioned laterally (e.g., close to B_1 in Fig. 3). A central ship positioning will reduce the average number of hops involved in RFnet communication between ship and buoys or surface AUVs. In Fig. 7a, we measure the delay of the messages with 25 KB images, sent from AUVs to ship. Fig. 7b represents the reply sent from the ship to the surface AUV. This is a 96 bits packet which is used for ACK, or for issuing new commands to the AUV or for requesting for more pictures. Next, Fig. 8 illustrates the variation of the status-update message depending on the ship location.

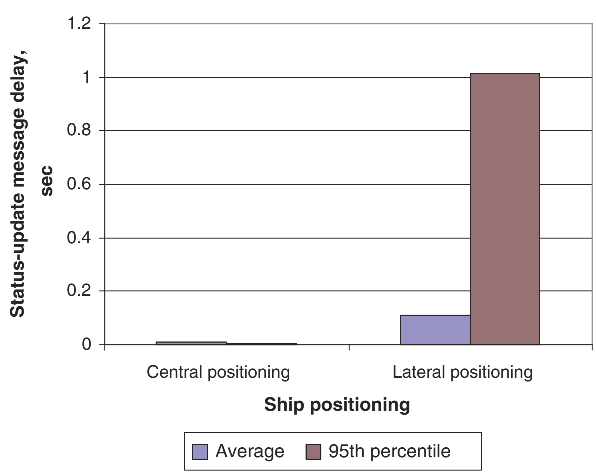

Fig. 8. Beacon delay depending on the ship positioning.

In the next test, we study the impact of varying the rate at which AUVs detect targets: 15, 30, 45, and 60 min. The delay of the messages with pictures sent from AUVs to the ship is represented in Fig. 9a. Also, in Fig. 9b, we represent the aggregate throughput. As more messages are generated with a smaller target detection interval, the aggregate throughput increases correspondingly.

In the last set of experiments, we vary the number of messages sent by AUVs per target detected. We assume that when a target is detected, after the AUV sends the first image message, the ship always asks for all the remaining images. The goal is to test the system comportment when varying the load. In this case we set the target detection interval as being uniformly distributed between 20 and 30 min. We represent in Fig. 10a, the delay of the messages with pictures sent by the AUVs to the ship and in Fig. 10b, the delay of the status-update messages. We observe an

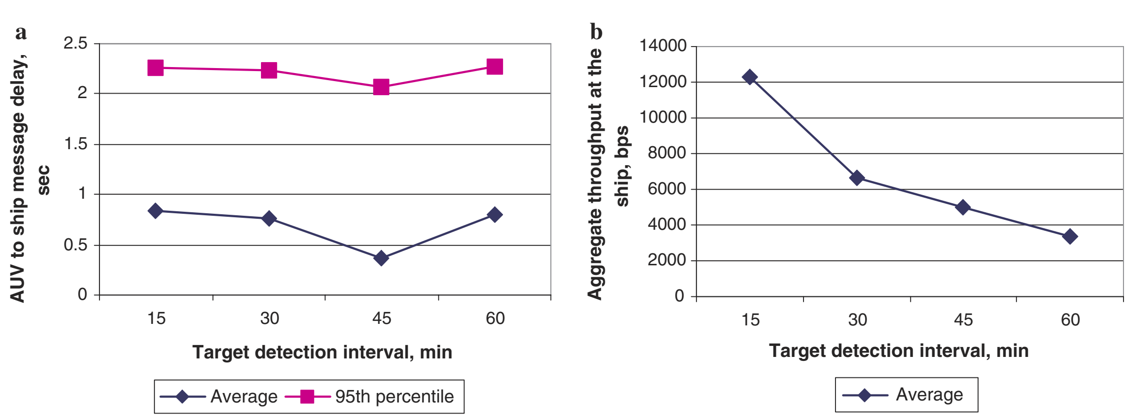

Fig. 9. Message delay and aggregate throughput based on the target detection interval.

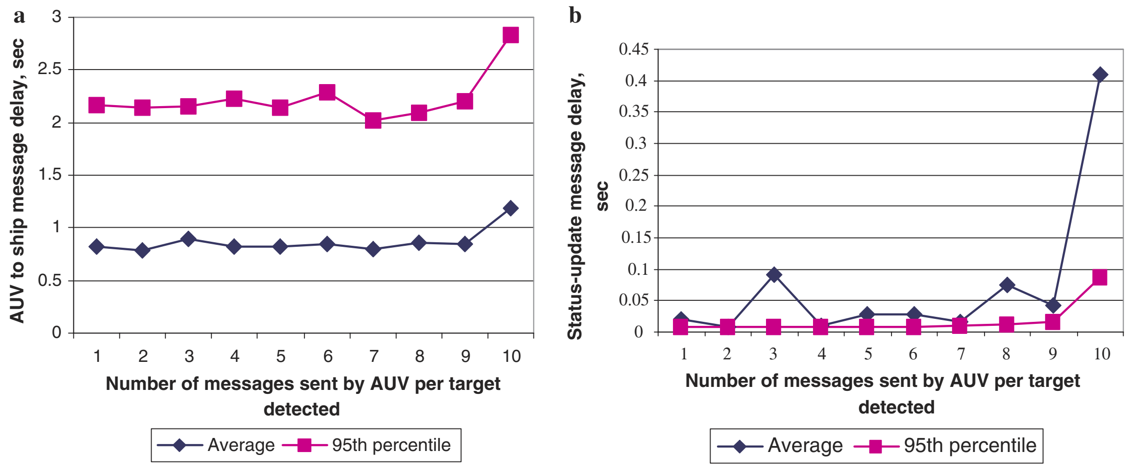

Fig. 10. AUV to ship and status-update message delay depending on the number of messages sent by AUV per target detected.

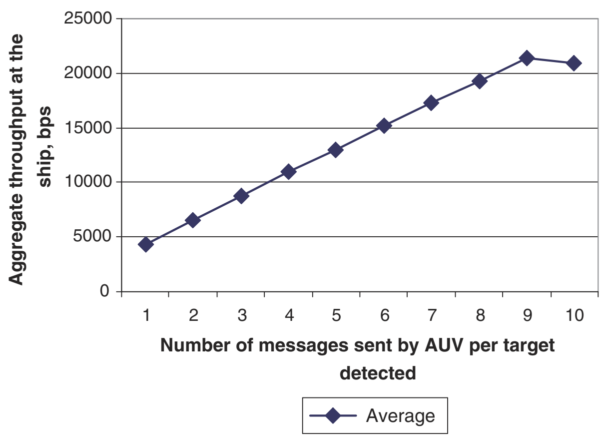

Fig. 11. Aggregate throughput at the ship depending on the number of messages sent by AUV per target detected.

increase in delay when the number of messages sent per target detected is 10. In the last graph, in Fig. 11, we represent the increase in the aggregate throughput with the number of messages sent by AUV per target detected.

8. Conclusions

In this paper, we address the problem of designing an energy-efficient scheduling mechanism and a scalable hybrid RF-acoustic communication architecture, that facilitates transfer of data from AUVs to a central control and command station on a ship. Communicating buoys serve as gateways between the acoustic and RF networks and provide message forwarding across the ad hoc RFnet. Major impediments associated with underwater acoustic networks that were considered are severe bandwidth limitations and long propagation delays.

The Medium Access Control scheduling method adopted is TDMA, providing a collision-free, energy-efficient communication on the low-data rate acoustic channel. We design a scalable TDMA slot allocation mechanism with spatial-reuse characteristics. We also design a scalable buoy positioning mechanism that guarantees every point in the surveillance area is within communication range of at least three buoys for facilitating

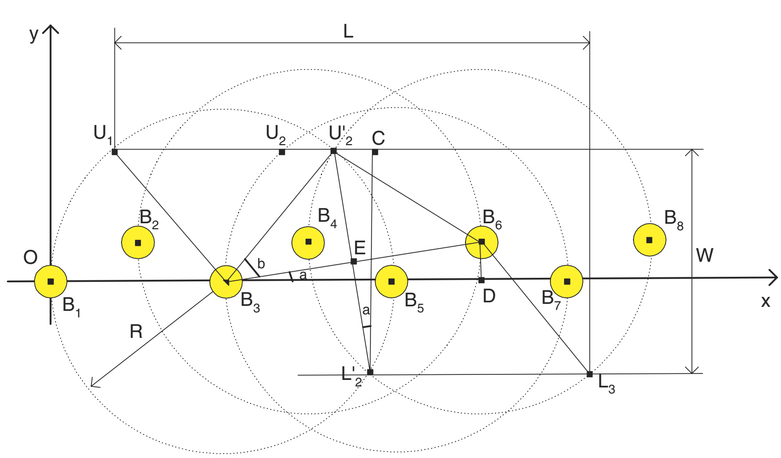

Fig. 12. L and W computation.

AUV underwater triangulation. Performance of our communication system is analyzed with simulations in the Opnet network simulator.

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Appendix A.

In this appendix we compute the length L and width W of the surveillance rectangle, considering n buoys $B_1, B_2, \ldots, B_n$, $n \geqslant 3$, the coordinates of B_2 as being $B_2(R/2, d_y)$, and $d_y \in [0, R\sqrt{3}/2]$. For the notations we refer to Fig. 12 where $n = 8$.

From $\triangle U'_2CL'_2$: $\cos a = \frac{W}{2 \cdot U'_2E}$ and from $\triangle B_3DB_6$: $\cos a = \frac{3R/2}{2 \cdot EB_6}$, therefore $W = \frac{3R}{2} \cdot \frac{U'_2E}{EB_6}$. In $\triangle B_3DB_6$: $EB_6^2 = \frac{1}{4}(d_y^2 + (\frac{3R}{2})^2) = \frac{1}{16}(4d_y^2 + 9R^2)$ and in $\triangle U'_2EB_6$: $U'_2E^2 = \frac{1}{16}(7R^2 - 4d_y^2)$, therefore $W = \frac{3R}{2} \cdot \sqrt{\frac{7R^2 - 4d_y^2}{9R^2 + 4d_y^2}}$.

Let us next compute L. L can be written as $L = 2 \cdot pr(B_3U_1, Ox) + (n-5) * R/2$, where $pr(B_3U_1, Ox)$ is the projection of B_3U_1 on the Ox axis. We have $pr(B_3U_1, Ox) = pr(B_3U'_2, Ox) = R \cdot \cos(a+b)$, and $\cos(a+b) = \cos a \cos b - \sin a \sin b = \frac{3R/2}{2 \cdot EB_6} \cdot \frac{EB_6}{R} - \frac{d_y}{2 \cdot EB_6} \cdot \frac{U'_2E}{R}$ $= \frac{3}{4} - \frac{d_y}{2R} \cdot \sqrt{\frac{7R^2 - 4d_y^2}{9R^2 + 4d_y^2}}$. So we get $L = 3R/2 - d_y\sqrt{\frac{7R^2 - 4d_y^2}{9R^2 + 4d_y^2}}$ $+ (n-5) \cdot R/2 = (n-2) \cdot R/2 - d_y\sqrt{\frac{7R^2 - 4d_y^2}{9R^2 + 4d_y^2}}$, for any $n \geqslant 3$.

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