# A Network Protocol for Multiple AUV Localization

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***Abstract*— With maturing of AUV technology and underwater acoustic modem technology, networks of AUVs have come into the focus of research on future systems for ocean observation and monitoring. In this paper, we propose a networking algorithm for communication within a group of AUVs deployed on a cooperative mission in an area covering several square kilometers. The algorithm is based on a time-scheduled operation which enables the AUVs to locate each other by measuring the inter-vehicle signal propagation delays and by exchanging localization maps. The vehicles transmit high-rate PSK signals which can directly be used for delay measurements. At the end of every time-slot, assigned for transmission from a single vehicle, each of the receiving vehicles updates its map based on the newly measured delay from the transmitting vehicle, the stored value of own map, and the value of the map as known by the currently transmitting vehicle. The so-built map may be used directly for localization, and also in a routing table for subsequent location-based dynamic routing of data packets. An example system provides a delay resolution on the order of tenth of a millisecond, and a map updating interval on the order of ten seconds. The basic algorithm operation is demonstrated using a network of several vehicles.**

***Index Terms*— Underwater acoustic communications, autonomous underwater vehicles, multiple vehicle localization, ad hoc communication networks.**

## I. INTRODUCTION

With maturing of the autonomous underwater vehicle (AUV) technology and with the availability of reliable underwater acoustic modems, the idea of deploying multiple AUVs on a coordinated mission becomes a realistic goal. Multiple AUVs are increasingly thought of as a useful tool for operations such as area mapping for detection of objects on the ocean bottom, or plume tracking for pollution monitoring. While some of these tasks can be accomplished by a single vehicle, benefits of multiple vehicle operation include increased system reliability, greater speed and higher quality of measurements.

The number of vehicles in the system depends on the application. Undersea search and survey missions, for example, involve simultaneous operation of various types of underwater vehicles, at operating distances ranging from very long (100 km) to short (100 m). While systems consisting of a small number of vehicles are likely to be demonstrated in the near future, larger fleets of mobile underwater instruments will require a more extensive research phase before they, too, become operational.

Deployment of multiple AUVs on a coordinated mission requires the vehicles to behave in a cooperative manner. An example of a mission that can be better accomplished by multiple AUVs is mapping of an underwater area. Mapping can be performed faster and more accurately if multiple vehicles operate in collaboration. An AUV builds a map by combining the navigation information with the sensor data. When the locally-generated map is simultaneously used for localization, the task is known as concurrent mapping and localization (CML). In a multiple vehicle configuration, CML requires each vehicle to know relative locations of other vehicles in the group in addition to the baseline environment description. This task can be performed by sharing the navigation and the sensor information between the vehicles. In particular, collaborative navigation refers to using the navigation and sensor information from other vehicles to improve one's own position estimate, while collaborative mapping refers to sharing the sensor information between the vehicles to build a larger and more accurate global map. A method for multiple vehicle CML was investigated in [1]. The algorithm for combining the sensor measurements was specified and the improvement in accuracy of feature extraction (map building) obtained by use of multiple vehicles was quantified.

The CML system of [1] is an example of a system that relies on the capability of submerged autonomous instruments to exchange information in a wireless manner. Today, acoustic modems exist which can transmit information at several kilobits per second over distances of several kilometers. Feasibility of integrating acoustic communications and navigation has been demonstrated experimentally using the prototype acoustic modems developed at the Woods Hole Oceanographic Institution [2]. However, to enable information exchange between multiple AUVs equipped with acoustic modems, a communication protocol needs to be developed. Design of a communication protocol to aid concurrent mapping and localization by multiple AUVs is the subject of this paper. More broadly, such protocols are of interest to any application involving multiple

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AUVs accomplishing a collaborative task [3].

The focus of the present project is on a small number of vehicles deployed in an unknown area. The vehicles initially have no knowledge about location of other vehicles in the system. Their goal is to form a communication network and to build a map of relative vehicle locations, e.g. inter-vehicle distances. The two tasks are accomplished simultaneously, thus integrating acoustic communications and navigation. Because the vehicles have no prior knowledge of each other's location, the communication network must be built from scratch. Within the framework of the present project, network connections are to be established between autonomous distributed users without assistance from a common base station. Such networks are often called *ad hoc* wireless networks, and have recently received much attention in the context of radio communications [7].

The communication protocol that we propose provides each node with a matrix of inter-node distances, which can be used for subsequent dynamic routing. Hence, this procedure implicitly sets up a communication network. The protocol is based on a time-scheduled operation, which prevents simultaneous transmissions while the node locations are not known.

While the proposed communication protocol does not depend on the multiple-access capability, direct-sequence spread-spectrum signals, normally used in code-division multiple-access (CDMA) systems, offer advantages to the application of interest. High-resolution pseudo-noise (PN) sequences can be readily employed to measure delay between two communicating nodes. The delay is directly proportional to the distance between the two nodes, which represents the desired entry in the map of relative vehicle locations. In addition, high-rate PSK signals inherently offer a degree of multiple-access interference suppression on frequency-selective underwater acoustic channels [4]. This property is beneficial for the network scenario considered, where unintentional simultaneous transmissions may occur due to imperfect clocking. Should data packets collide at a receiver, the receiver's ability to extract the desired user's signal will prevent loss of information or the need for retransmission.

In Sec.II we give a brief overview of the system considered. The communication protocol is described in Sec.III. Sec.IV addresses the use of localization map in routing of data packets. Finally, Sec.V summarizes the conclusions.

## II. SYSTEM DESCRIPTION

A hypothetical undersea search and survey system of AUVs is considered to consist of a small number of vehicles. The vehicles are dropped initially at distances of several 100 meters to uniformly cover an area to be mapped. The vehicles are capable of moving at varying speeds ranging from zero to approximately 5 knots. These system parameters are used to provide a sense of the system size, rather than to represent a concrete design.

Fig.1 schematically represents five vehicles (users 1-5) located approximately uniformly in shallow water. When a vehicle transmits, it uses certain transmission power, $P_T$, which is sufficient to cover a range $d$. The received power is

$$P_R = P_T / A(d) \tag{1}$$

where $A(d)$ is the attenuation. The attenuation is given by

$$A(d) = d^k a^d \tag{2}$$

where $k$ is the energy spreading factor ($k$=1.5 for "practical" spreading) and $a$ represents the absorption coefficient that depends on the carrier frequency $f_c$. [1]

A connection between the transmitter and a receiver is said to be established when the received power exceeds a pre-specified threshold $P_R$. If a distant vehicle receives signal of power less than $P_R$ it is out of the communication range. (The distant vehicle is either unable to hear the signal, or it decides deliberately that the signal is too weak to be relied upon.) Fig.1 shows a $1 \times 1$ normalized square area with connections indicated for each two vehicles separated by less than $d_{con}$=0.7. To achieve connections within this distance, the transmitter power $P_T = P_R A(d_{\text{con}})$ is needed. By increasing the transmission power to some $P_T = P_R A(d_{max})$, connections can be established between all the vehicles within the design area.

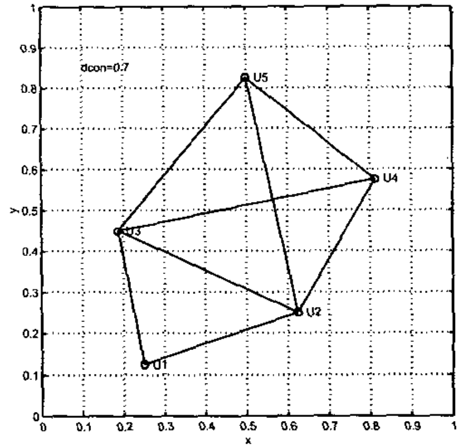

Fig. 1. A placement of vehicles within a square area.

To estimate the distances between them, vehicles transmit an unmodulated PN sequence at rate $R_c$. Current design of WHOI modems supports quadrature transmission in a 5 kHz bandwidth. At the chip rate of $R_c$ = 5 kcps (kilochips per second), delay resolution of $T_c$ = 0.2 ms is achieved. Vehicles are assumed to have a notion of absolute time. Time-keeping capability depends on the type of vehicle, although in general it is possible to outfit any vehicle with a clock that is good enough

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[1] For $f_c$ in kHz, $a$ is given in dB/km as $10 \log a = 0.11 f_c^2/(1 + f_c^2) + 44 f_c^2/(4100 + f_c^2) + 2.75 \cdot 10^{-4} f_c^2 + 0.003$.

to run for about 8 hours and stay within a few milliseconds of a fixed standard.

Inter-vehicle delay estimation is performed by matched-filtering the received probe signal using the known code. Delay estimation in the presence of unknown Doppler shift can be performed by selecting a relatively short sequence period, and transmitting several such periods within a probe signal. Alternatively, a short sequence can be followed by a longer one. For example, a short sequence period of $N_c = 15$ chips can be selected. A cross-correlation between the received signal $v(t)$ and the known sequence $p_0(t)$ is then performed over a single period $T_p$, giving a coarse estimate of the arrival time of the signal:

$$\hat{\tau} = \arg\max_{\tau} \left| \int_0^{T_p} v(t+\tau) p_0^*(t) dt \right| \qquad (3)$$

At a carrier frequency of 50 kHz, and velocity less than 5 knots, the total phase change over the duration of the short sequence will be less than $\pi/2$, which allows coarse timing estimation. Using this initial estimate, it is now possible to align the received signal in time with the entire probe $p(t)$, and perform estimation of the Doppler frequency shift:

$$\hat{f}_d = \arg\max_{f_d} FT\{v(t+\hat{\tau})p^*(t)\} \qquad (4)$$

where $FT(\cdot)$ indicates the Fourier transform taken over the entire probe interval. Finally, delay estimation can be refined, using the Doppler-compensated received signal. Assuming that the frequency offset is caused by a relative vehicle motion at velocity $v$, it follows that $f_d = f_c v/c$, where $c$ is the speed of sound. Thus, the received signal can be corrected in frequency using the estimate $\hat{f}_d$ (or, equivalently, the estimate of velocity) and resampled, i.e. corrected in time, by a factor $1/(1+\hat{f}_d/f_c)$. The so-obtained signal can be used for a second round of delay estimation, which yields a refined delay estimate. However, the initial coarse estimation may be sufficiently accurate.

Most vehicles use a combination of long-baseline acoustic navigation (i.e. ranges to transponders at known locations to determine geographic position), and GPS-aided inertial navigation. Thus, a vehicle knows its position to within a few meters, or at least a few tens of meters, depending upon the quality of the navigation sensors. If a vehicle moves at maximal velocity of 5 knots, it traverses 25 m in 10 seconds. Assuming that moving by 25 m warrants an updated map, we set $T_U$=10 s as the needed updating interval.

Depending on the actual application, the location information and any other information that a vehicle gathers may be appended to the PN probe. This additional information is decoded at the receiver using an adaptation algorithm suited to the type of signals transmitted. High-rate phase-coherent digital signals are well supported by the time-scheduled operation that we describe in the following section. The choice of a signaling method depends on the system requirements. If it is desired to protect the system from unintended listeners, direct-sequence spread-spectrum should be used. A hypothesis-feedback receiver, described in [5] provides a means for detecting spread-spectrum signals in the presence of high Doppler shifts caused by the system mobility. This technique also enables code-division multiple-access. If low-probability-of-intercept (LPI) is not required, the communication technique of [4] offers good performance. This technique uses high-rate, coded PSK signals, and was demonstrated to effectively suppress multiple-access interference coming from a small number of users on a shared multipath channel. As such, it appears suitable for use in a multiple AUV scenario, where a receiver may be exposed to only a few interferers. The only parameter a receiver needs to know in order to tune into the signal of the desired transmitter is that transmitter's training sequence. Finally, array processing, even with a small number of receiving elements (four can currently be mounted on a vehicle equipped with the WHOI prototype modem), provides excellent performance in terms of multiple-access interference suppression [6]. Because the users' signals arrive through different channels, an array processor effectively enables space-division multiple-access.

## III. COMMUNICATION PROTOCOL

The communication protocol is based on scheduled transmissions from vehicles (users, communication nodes) that form the network. Let us assume that there are $N$ users, who need to transmit in a time frame of duration $T_F$. The frame duration must satisfy the desired updating interval,

$$T_F \leq T_U \qquad (5)$$

Within one frame, each vehicle is allocated a time slot of duration $T_F/N$. The structure of the time frame is shown in Fig.2.

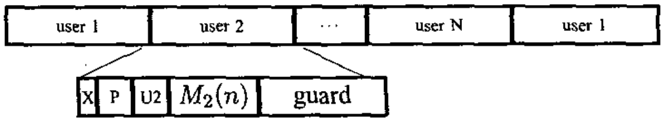

Fig. 2. Time schedule. $N$ slots make one frame. Time slot, shown for user 2, consists of an interval reserved for processing the information received during the previous time slot (X), transmission of probe (P), user's address (U2), and current value of the map. Idle guard interval is chosen long enough to allow all participants to hear user 2 before the next slot (with transmission from user 3) begins.

A slot begins with an interval of time of duration $T_X$ reserved for processing the information received during previous slot and preparing the data to be transmitted in the current slot. Transmission of a data packet then begins. A packet is composed of the probe signal, which we chose the same for all users, the user's number or address, the current value of the localization map and any additional message. The packet duration is denoted by $T_P$. Transmission of a packet is followed by a guard interval whose length is chosen such to allow the packet to reach all the users. If the maximal distance between two nodes is denoted by $d_{max}$, then the guard interval has to satisfy

$$T_G \geq d_{max}/c = T_{Dmax} \tag{6}$$

(If the intended users are only those within some shorter distance of the transmitter, the guard time can be reduced; however, there will exist a possibility of packet collisions, which necessitates receiver processing that is tolerant of multiple-access interference).

Conditions (5) and (6) can be used to determine the number of vehicles that can be supported over a given area. For example, if it is desired to map an $x_{max} \times x_{max}$ square area using a group of vehicles, each of which samples the environment every 10 s, then one can choose $T_F$=10 s, $d_{max} = x_{max}\sqrt{2}$, and the number of vehicles that can be supported is evaluated to be

$$N \leq \frac{T_F}{T_X + T_P + T_{Dmax}} \tag{7}$$

Assuming that processing time $T_X$ is negligible with respect to the propagation delay, and that $T_P$=1s, for a 1km × 1km area, we find approximately that $N = 5$ vehicles can be supported. We now still have to verify that the assumed packet size is sufficient to accommodate the information about relative location of the five vehicles. At 5 kcps, the assumption seems reasonable. In general, the size of the packet will depend on the type of information (map) transmitted. For example, if we assume that the packet must at least contain the amount of information proportional to the number of vehicles, $T_P = NT_1$, then the number of vehicles will be the solution of a quadratic equation,

$$N \leq \frac{T_{Dmax}}{2T_1}(-1 + \sqrt{1 + \frac{4T_1T_F}{T_{Dmax}}}) \tag{8}$$

Again, these numbers are intended only to provide a sense of the system size; actual design would have to be conducted more conservatively.

The basic idea of the communication protocol is that the vehicles maintain a map, or a database of navigation and travel time information available from all the vehicles in the system. At a minimum, the map contains a set of travel time measurements and vehicle locations. Additional information useful for navigation includes the transmitting and receiving platform course made good, speed over ground, and depth. Finally, other data may be included which will allow concurrent mapping and localization algorithm to optimize position estimates. This information is considered to form a map $M(n)$ of relevant localization parameters at time $n$. The map is updated from time measurements directly, and from the information relayed by the transmitting vehicle. The value of the map during the $n$-th time slot is $M(n) = [\mathrm{s}_{i,j}(n)]_{N\times N}$, where $\mathrm{s}_{i,j}(n)$ represents a vector containing the travel time measurement $\tau_{i,j}(n)$ between vehicle $i$ and vehicle $j$, locations and other relevant parameters.

By exercising the communication protocol described below, the vehicles update their maps and position estimates. The protocol is distributed among the nodes, and, hence, each vehicle maintains a copy of the map, denoted by $M_k(n) = [\mathrm{s}^k_{i,j}(n)]$ for vehicle index $k = 1, \ldots N$. During a slot dedicated to a single transmitter, the other vehicles receive new information, which they process to update their maps for the next slot. In general, the updated map at receiver $r$ is a function of the old (stored) version of its own map, the map relayed by the transmitter, and the latest delay calculated by processing the transmitter's probe:

$$M_r(n) = F\{M_r(n-1), M_t(n-1), \tau_{t,r}(n)\}, r = 1, \ldots N \tag{9}$$

Initially, the vehicles have no information about each other, and their corresponding map entries are set to 'empty' $X$. Transmission begins in the first frame by the vehicle whose assigned number is 1. This vehicle transmits the probe signal, followed by its identification code and its current position (address) and the current value of its map. By the end of slot 1, the data packet from vehicle 1 has arrived to all the vehicles within $d_{max}$. The vehicles now process the received information to generate their maps. Let us illustrate the protocol operation using an example of $N$=4 vehicles. For simplicity, we keep track only of inter-vehicle travel times, as indicated by the map superscript $\tau$. The complete map contains more than just the travel time information.

**Slot 1.**

Initial values:

$$M^\tau_k(1) = \begin{bmatrix} 0 & X & X & X \\ X & 0 & X & X \\ X & X & 0 & X \\ X & X & X & 0 \end{bmatrix}, k = 1, 2, 3, 4 \tag{10}$$

Transmission: node # 1 sends $M^\tau_1(1)$ (as part of overall map $M_1(1)$ which in addition contains location of node 1 and other mapping information.)

**Slot 2.**

Processing: for slot # 2, newly measured parameters are $\tau_{1,2}, \tau_{1,3}, \tau_{1,4}$. Nodes 2,3,4 update matrices as follows.

$$M^\tau_1(2) = M^\tau_1(1) \tag{11}$$

$$M^\tau_2(2) = \begin{bmatrix} 0 & \tau^2_{1,2}(2) & X & X \\ X & 0 & X & X \\ X & X & 0 & X \\ X & X & X & 0 \end{bmatrix} \tag{12}$$

$$M^\tau_3(2) = \begin{bmatrix} 0 & X & \tau^3_{1,3}(2) & X \\ X & 0 & X & X \\ X & X & 0 & X \\ X & X & X & 0 \end{bmatrix} \tag{13}$$

$$M^\tau_4(2) = \begin{bmatrix} 0 & X & X & \tau^4_{1,4}(2) \\ X & 0 & X & X \\ X & X & 0 & X \\ X & X & X & 0 \end{bmatrix} \tag{14}$$

Processing for this slot consists only of entering the measured delays. If a vehicle does not hear the signal by the end of allotted time, or decides it is too low, it sets the corresponding

delay to $\infty$, or marks it $X$.
Transmission: node # 2 sends $M_2^\tau(2)$.

**Slot 3.**

Processing: for slot # 3, newly measured parameters are $\tau_{2,1}, \tau_{2,3}, \tau_{2,4}$. Nodes 1,3,4 update matrices as follows.

$$M_1^\tau(3) = \begin{bmatrix} 0 & \tau_{1,2}^2(2) & X & X \\ \tau_{2,1}^1(3) & 0 & X & X \\ X & X & 0 & X \\ X & X & X & 0 \end{bmatrix}$$

$$\rightarrow \begin{bmatrix} X & \tau_{1,2}^1(3) & X & X \\ X & X & X & X \\ X & X & X & X \\ X & X & X & X \end{bmatrix} \tag{15}$$

In the above matrix computed at node 1, the two observations, $\tau_{1,2}^2(2)$, *obtained earlier, and the new observation,* $\tau_{2,1}^1(3)$, are combined to obtain a single value. (Because the system is time-varying and the measurements are noisy, the values obtained in two directions are not the same.)

At node 2,

$$M_2^\tau(3) = M_2^\tau(2) \tag{16}$$

Vehicle #2 is the transmitting vehicle; hence, there is no processing to be performed. The only element of the matrix is kept at the same value: $\tau_{1,2}^2(3) = \tau_{1,2}^2(2)$.

At node 3,

$$M_3^\tau(3) = \begin{bmatrix} 0 & \tau_{1,2}^2(2) & \tau_{1,3}^3(2) & X \\ X & 0 & \tau_{2,3}^3(3) & X \\ X & X & 0 & X \\ X & X & X & 0 \end{bmatrix} =$$

$$= \begin{bmatrix} 0 & \tau_{1,2}^3(3) & \tau_{1,3}^3(3) & X \\ X & 0 & \tau_{2,3}^3(3) & X \\ X & X & 0 & X \\ X & X & X & 0 \end{bmatrix} \tag{17}$$

*In this instance, the matrix is obtained from the stored value* $\tau_{1,3}^3(2)$, the value relayed from the transmitter, $\tau_{1,2}^2(2)$ and the value obtained by measuring the transmitter's probe, $\tau_{2,3}^3(3)$. Through relaying, node 3 learns about the connection between nodes 1 and 2. Finally,

$$M_4^\tau(3) = \begin{bmatrix} 0 & \tau_{1,2}^2(2) & X & \tau_{1,4}^4(2) \\ X & 0 & X & \tau_{2,4}^4(3) \\ X & X & 0 & X \\ X & X & X & 0 \end{bmatrix}$$

$$= \begin{bmatrix} 0 & \tau_{1,2}^4(3) & X & \tau_{1,4}^4(3) \\ X & 0 & X & \tau_{2,4}^4(3) \\ X & X & 0 & X \\ X & X & X & 0 \end{bmatrix} \tag{18}$$

Transmission: node 3 sends $M_3^\tau(3)$.

**Slot 4.**

Processing: for slot # 4, newly measured parameters are $\tau_{3,1}, \tau_{3,2}, \tau_{3,4}$. Nodes 1,2,4 update matrices as follows.

$$M_1^\tau(4) = \begin{bmatrix} 0 & f[\tau_{1,2}^1(3), \tau_{1,2}^3(3)] & \tau_{1,3}^3(3) & X \\ X & 0 & \tau_{2,3}^3(3) & X \\ \tau_{3,1}^1(4) & X & 0 & X \\ X & X & X & 0 \end{bmatrix}$$

$$\rightarrow \begin{bmatrix} 0 & \tau_{1,2}^1(4) & \tau_{1,3}^1(4) & X \\ X & 0 & \tau_{2,3}^1(4) & X \\ X & X & 0 & X \\ X & X & X & 0 \end{bmatrix} \tag{19}$$

In this case, the updated value of $\tau_{1,2}^1(4)$ is obtained by combining the old value $\tau_{1,2}^1(3)$ stored locally, and the value relayed by the transmitter $\tau_{1,2}^3(3)$.

$$M_2^\tau(4) = \begin{bmatrix} 0 & f[\tau_{1,2}^2(3), \tau_{1,2}^3(3)] & \tau_{1,3}^3(3) & X \\ X & 0 & \tau_{2,3}^3(3) & X \\ X & \tau_{3,2}^2(4) & 0 & X \\ X & X & X & 0 \end{bmatrix}$$

$$\rightarrow \begin{bmatrix} 0 & \tau_{1,2}^2(4) & \tau_{1,3}^2(4) & X \\ X & 0 & \tau_{2,3}^2(4) & X \\ X & X & 0 & X \\ X & X & X & 0 \end{bmatrix} \tag{20}$$

$$M_3^\tau(4) = M_3^\tau(3) \tag{21}$$

$$M_4^\tau(4) = \begin{bmatrix} 0 & \tau_{1,2}^3(3) & \tau_{1,3}^3(3) & \tau_{1,4}^4(3) \\ X & 0 & \tau_{2,3}^3(3) & \tau_{2,4}^4(3) \\ X & X & 0 & \tau_{3,4}^4(4) \\ X & X & X & 0 \end{bmatrix} =$$

$$= \begin{bmatrix} 0 & \tau_{1,2}^4(4) & \tau_{1,3}^4(4) & \tau_{1,4}^4(4) \\ X & 0 & \tau_{2,3}^4(4) & \tau_{2,4}^4(4) \\ X & X & 0 & \tau_{3,4}^4(4) \\ X & X & X & 0 \end{bmatrix} = \tag{22}$$

Transmission: node 4 sends $M_4^\tau(4)$. This is the last transmission of frame 1.

**Slot 5.**

Processing: for slot # 5, newly measured delays are $\tau_{4,1}, \tau_{4,2}, \tau_{4,3}$. Nodes 1,2,3 update matrices as follows.

$$M_1^\tau(5) =$$

$$\begin{bmatrix} 0 & f[\tau_{1,2}^1(4), \tau_{1,2}^4(4)] & f[\tau_{1,3}^1(4), \tau_{1,3}^4(4)] & \tau_{1,4}^4(4) \\ X & 0 & f[\tau_{2,3}^1(4), \tau_{2,3}^4(4) & \tau_{2,4}^4(4) \\ X & X & 0 & \tau_{3,4}^4(4) \\ \tau_{4,1}^1(5) & X & X & 0 \end{bmatrix}$$

$$\rightarrow \begin{bmatrix} 0 & \tau_{1,2}^1(5) & \tau_{1,3}^1(5) & \tau_{1,4}^1(5) \\ X & 0 & \tau_{2,3}^1(5) & \tau_{2,4}^1(5) \\ X & X & 0 & \tau_{3,4}^1(5) \\ X & X & X & 0 \end{bmatrix} \tag{23}$$

$$M_2^\tau(5) = \begin{bmatrix} 0 & f[\tau_{1,2}^2(4), \tau_{1,2}^4(4)] & f[\tau_{1,3}^2(4), \tau_{1,3}^4(4)] & \tau_{1,4}^4(4) \\ X & 0 & f[\tau_{2,3}^2(4), \tau_{2,3}^4(4)] & \cdot\tau_{2,4}^4(4) \\ X & X & 0 & \tau_{3,4}^4(4) \\ X & \tau_{4,2}^2(5) & X & 0 \end{bmatrix}$$

$$\rightarrow \begin{bmatrix} 0 & \tau_{1,2}^2(5) & \tau_{1,3}^2(5) & \tau_{1,4}^2(5) \\ X & 0 & \tau_{2,3}^2(5) & \tau_{2,4}^2(5) \\ X & X & 0 & \tau_{3,4}^2(5) \\ X & X & X & 0 \end{bmatrix} \tag{24}$$

$$M_3^\tau(5) = \begin{bmatrix} 0 & f[\tau_{1,2}^3(4), \tau_{1,2}^4(4)] & f[\tau_{1,3}^3(4), \tau_{1,3}^4(4)] & \tau_{1,4}^4(4) \\ X & 0 & f[\tau_{2,3}^3(4), \tau_{2,3}^4(4)] & \tau_{2,4}^4(4) \\ X & X & 0 & \tau_{3,4}^4(4) \\ X & X & \tau_{4,3}^3(5) & 0 \end{bmatrix}$$

$$\rightarrow \begin{bmatrix} 0 & \tau_{1,2}^{4}(5) & \tau_{1,3}^{4}(5) & \tau_{1,4}^{4}(5) \\ X & 0 & \tau_{2,3}^{4}(5) & \tau_{2,4}^{4}(5) \\ X & X & 0 & \tau_{3,4}^{4}(5) \\ X & X & X & 0 \end{bmatrix} \tag{25}$$

$$M_4^{\tau}(5) = M_4^{\tau}(4) \tag{26}$$

Transmission: node 1 sends $M_1^{\tau}(5)$. This is the first transmission of frame 2.

Finally, with the packet of the $N$-th slot processed, all the vehicles have built a full map. During the following slots, the maps will be updated.

If no vehicles are leaving or entering the network, during the $n$-th slot, vehicle number $n(\text{mod})N$ will be transmitting. However, a communication protocol must make provision for vehicles entering/leaving the network. A possible scenario is the following. A new vehicle that comes into the area initially listens to transmissions. In this manner, it learns the number of vehicles currently present in the network, and assigns itself the next higher number. The vehicles that participate in the network occasionally send out an invitation of the form "if there is anyone new, let them speak at the end of this frame" (say every 10 minutes, i.e. 60 frames). A new vehicle is likely to hear at least one of these messages before the end of the frame, and it may then join in. The next frame is devoted to announcing the new node. If two or more vehicles happen to join the network during the same frame (an unlikely event for the supposed small number of vehicles) their transmissions will be detected as different, because of the very nature of the *high-resolution* probe signals. A mechanism can then be set in place to assign the new vehicles different numbers. In the simplest procedure, the vehicles will be left to decide on their own, by randomly choosing whether to transmit or not in the frame following the collision. For this to occur, only a binary feedback (correct/erroneous) is needed from the already established nodes. It has to be mentioned that additional vehicles joining the network will cause the time frame to grow in duration, prolonging the updating interval as well.

If a vehicle leaves the area, its absence will be noticed immediately by the closest neighbors (no data packet) and eventually by nodes that were out of direct reach (no relayed data). To prevent a vehicle that has left from occupying further time-slots, a control message can be sent. However, taking no action will work as well, the only penalty being the waste of time.

## IV. ROUTING

Implicit advantage of localization-driven communication is in the fact that each node generates the map of inter-node distances (delays) which can serve for routing of messages, both those related to localization and other messages. Routing is a network function which determines the best path that a packet generated at a source node should take through the network of nodes to reach the destination node. Finding the shortest path through a network whose properties (path lengths) do not change with time can be accomplished efficiently by the Bellman Ford algorithm. When the network topology changes in time, so do the path lengths, which necessitates use of dynamic routing algorithms.

With the advancement of radio networks, various dynamic routing algorithms, suitable for different environments and network configurations, have been developed [7]; however, it remains for the future to identify their applicability to acoustic underwater networks [3]. Dynamic source routing (DSR) is a method that has been implemented in an experimental wireless radio network, intended for use by a small number of cars operating in a local area [8]. The strong similarity between that scenario and the acoustic network of a small number of AUVs suggests DSR as a candidate for the latter application.

Source routing is a routing technique in which the node that generates the message (source) determines the path through the network that the message will follow. The path, or the route, is represented by a list of nodes. The source then sends the message, along with the route, to the first node on the routing list. The most prominent feature of this routing method is that relaying nodes do not have to perform any routing decisions. Their only task is to forward the message to the next node indicated in the routing header of the packet. The simplicity of this method is obviously conditioned on its use in a small network, where it is easy for a source to determine the entire route to the destination. Below is a simple example of an ongoing communication in which U1 sends a message to U5, U2 sends a message to U5, U3 sends a message to U4, U4 sends a message to U5, and U5 sends message to U2. Messages can be sent concurrently with the localization information, or regardless of it.

Slot 1: P,U1,M1,R135,D15 (Slot 1 contains probe, source address, localization map, route, and data.)
Slot 2: P,U2,M2,R235,D25
Slot 3: P,U3,M3,R135,D15,R235,D25,R324,D34 (U3 forwards packets from U1,U2; adds own packet. By the end of this slot, U5 gets data from U1,U2; U4 gets data from U3.)
Slot 4: P,U4,M4,ACK43,R45,D45 (U4 acknowledges reception to U3; sends data to U5.)
Slot 5: P,U5,M5,ACK53,ACK52,ACK54,R542,D52.

When applied over a broadcast wireless channel, hop-by-hop forwarding provides an additional advantage in the mechanism of passive acknowledgments. Acknowledging a successfully received packet is a function normally performed on the data link layer of a network. This function is necessary for reliable packet delivery: whenever a packet is not acknowledged, its originating node will automatically retransmit it. Automatic repeat request (ARQ) is thus implemented, which guarantees eventual successful delivery. ARQ is especially important on poor quality channels, such as the underwater acoustic channel. Unfortunately, retransmission of an erroneous packet requires other packets to be put on hold, thus decreasing the network efficiency. Long propagation delay and half-duplex operation of acoustic modems greatly contribute to poor link utilization, which aggravates the network utilization as well. However, the broadcast nature of communication ensures that acknowledgments are automatically generated along a route. Consider transmission from U1 to U5. U1 decides that the route will be U1,U3,U5. Accordingly, it sends the packet to U3. U3, upon receiving this packet and checking its header, forwards it to U5. But because the channel is broadcast, U1 overhears the transmission of its packet from U3, which it then takes as an acknowledgment. Thus, every time a packet is forwarded to the next node, the previous node will receive an acknowledgment. Only if the next node is the destination, there will be no such 'passive' acknowledgment. The destination node will thus need to actively acknowledge reception.

If there is a failure on the link between U1 and U3, and U3 does not receive the packet, it will not forward it. U1 will then know that something is wrong with U3. It will make one of two decisions: to try again, or to take an alternate route to U5. If the destination is unreachable, this information will be back-propagated to the source.

The way in which a source determines the "shortest path" to the destination depends on the optimization criterion. Actual path distance (in meters) is an optimal measure only when minimal delay of message delivery is the goal. However, this measure imposes severe requirements on energy consumption. Underwater instruments are battery-powered, and in certain applications care must be taken to conserve their power. To illustrate this effect, let us refer to Fig.1. For distances given in kilometers, the matrix of relative delays is calculated to be

$$M^{\tau}=\begin{bmatrix} 0 & 263 & 221 & 480 & 495 \\ X & 0 & 321 & 250 & 392 \\ X & X & 0 & 425 & 325 \\ X & X & X & 0 & 267 \\ X & X & X & X & 0 \end{bmatrix}\text{ms} \tag{27}$$

Corresponding to each pair of nodes is the transmission power needed to close the link with some required received power $P_R$. Assuming a carrier frequency of 50 kHz to calculate the link attenuations, we find the normalized values of transmission powers:

$$P_T=\begin{bmatrix} 0 & 38 & 22 & 350 & 402 \\ X & 0 & 73 & 32 & 51 \\ X & X & 0 & 208 & 76 \\ X & X & X & 0 & 40 \\ X & X & X & X & 0 \end{bmatrix} P_R \tag{28}$$

From these matrices, one can find minimum delay routes, as well as minimum source level routes for the five-node network. While the minimum delay path is always the direct path, this is not the case with the minimum source level path. For example, going directly from U1 to U5 requires $P(1,5)=402$ (normalized power units), while routing along U1,U3,U5 requires $P(1,3)+P(3,5)=98$, which represents savings of 6dB. The corresponding delays do not differ much: 495 ms for direct path and 546 ms for the two-hop path.

Finally, it is worth noting that building a localization map through measurement of inter-vehicle delays may require transmission at power that is higher than the minimum needed to reach the closest neighbors. Transmission power $P_T$ used for initial map building must be sufficient to provide full connectivity, but it does not have to be as high as required to span the maximal distance $d_{max}$. This power can be determined based on the initial network topology and desired quality of mapping. Obviously, the greater the power, the more nodes will be reached by a transmitted probe, and the more data there will be for mapping. However, the power required to transmit over the maximal distance $d_{max}$ may be too large. For example, connections shown in Fig.1 are achieved whenever the distance between nodes is less than a certain $d_{con}$. If these connections are sufficient to provide good quality of mapping, the parameter $d_{con}$ can be used to determine the transmitter power that will (at least initially) be used by all the nodes. At 50 kHz, this power is 17 dB less than the power required to span $d_{max}$. The fact that this power may not be sufficient to link directly any two nodes does not affect the mapping protocol. The nodes that are as distant as $d_{max}$ will be able to exchange position information through relaying, even though they will not be able to directly measure distances longer than $d_{con}$. Transmission level can also be varied during the mission, starting with fixed allocation at the highest level, then moving on to a reduced level, and eventually allowing sources to adjust their level individually in accordance with the route selection.

## V. SUMMARY AND CONCLUSION

Driven by the needs of concurrent mapping and localization by multiple AUVs, we addressed a communication protocol to aid this application. The protocol is based on a time-scheduled operation, which eliminates the need for simultaneous multiple-user signal detection. The acoustic modems transmit high-rate PSK or QAM signals which can be used to measure inter-vehicle delays. During each time frame, every vehicle in the network transmits within its assigned time slot. The transmitted information contains, at a minimum, a high-resolution channel probe, the vehicle's identification number, its location and the value of localization map currently maintained by that vehicle. Upon reception of a data packet, all the receiving vehicles update their maps using the newly measured delay, the stored value of their own map, and the value of the map relayed by the transmitting vehicle.

Implicit advantage of the localization protocol is formation of a map that can be used for subsequent message routing, if there is such a need in the system. We have proposed a dynamic source routing algorithm that is simple to implement and suitable for a small number of network nodes. Optimal routing was discussed based on minimum source level path selection.

While energy consumption may not be a decisive factor in the design of a network of closely separated AUVs, it is a design aspect that must be addressed for the development of fixed networks of bottom-mounted nodes, and mobile underwater networks with a larger area of coverage. Future work on mobile networks will address both those networks that achieve larger coverage by increasing the distance between highly mobile nodes, and those that populate the area with a greater number of nodes. Time-scheduling on the global scale will no longer be an efficient technique to use in such a situation, and alternative methods of extending the communication range without constraining the network efficiency will have to be sought. Resource allocation, as well as power-efficient routing will become important design issues.

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