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Experimental evaluation of Net-LBL: an acoustic network-based navigation system

Jan Śliwka[1], Roberto Petroccia[1], Andrea Munafò[2] and Vladimir Djapic[3]

***Abstract*— This paper describes the use and in-field evaluation of a Networked-Long Base Line system (Net-LBL) where a network of underwater nodes cooperate to support the localisation and navigation of mobile vehicles. To avoid the use of dedicated transponders, as for traditional long baseline systems, each node of the network makes use of its underwater acoustic modem to transmit both data and positioning information. The use of the proposed Net-LBL systems has been validated and evaluated during two at-sea campaigns. More specifically, this paper investigates how the use of different communication schemes to reserve the shared underwater channel (*i.e.* Time Division Multiple Access (TDMA) and Carrier Sensing Multiple Access (CSMA)) impact on the acquisition of range measurements and on the localisation results. The collected results show that CSMA, being more flexible and responsive, can obtain a reduction of the impact on the localisation error by 30% on average and up to 90% with respect to TDMA.**

I. INTRODUCTION

Navigation is essential to accomplish most unmanned robotic missions. On the surface, the problem of navigation is solved using GPS, a globally available positioning system. However, the rapid attenuation of radio-frequency signals makes underwater mobile robots unable to rely on GPS to localise and navigate during underwater missions. There are two commonly used approaches to solve this problem. One approach makes use of dedicated acoustic messages to provide global position to underwater nodes. For this purpose, various strategies are used such as Long Base Line (LBL), Short Base Line (SBL) or Ultra Short Baseline (USBL) [1]. Traditional LBL systems [2] require the deployment of dedicated transponders to obtain positioning, thus incurring additional costs, deployment steps, calibration and mounting efforts. Furthermore, since the transponders have to be deployed in fixed positions, moored or mounted on the sea-floor, the area of operation cannot be extended without adding more transponders. SBL and USBL systems do not require a priori the presence of an infrastructure but due to their shorter base line, they tend to be less accurate with respect to the LBL.

The second approach for typical Autonomous Underwater Vehicle (AUV) missions is to use dead-reckoning in support to navigation. Dead reckoning is usually achieved using a proprioceptive sensor suite consisting of a Doppler Velocity Log (DVL), when the vehicle is close to the bottom, and an Inertial Navigation System (INS). However, regardless of the quality of the sensors used, the error in the position estimate based on dead-reckoning grows without bound and it requires periodic surfacing to get GPS fixes.

This can be an unacceptable constraint in scenarios where stealth or continuous sensing are required. Additionally, the time to do the required task is reduced relatively to the total mission time. This leads to having less results or a longer mission causing higher energy consumption and delayed results.

In many operational scenarios, however, AUVs are part of a larger system, namely a network of sensing nodes, and hence they have the possibility to cooperate to enhance their localisation and navigation capabilities. This networked system can be used to support the operations of cheaper vehicles that cannot rely on expensive navigation systems. Also, it can be used in case of more capable vehicles, extending their operational usage to scenarios where traditional LBL and dead-reckoning systems cannot properly work (*e.g.* when the DVL bottom tracking is not possible). In this paper we describe the use and in-field evaluation of a Networked-LBL system (Net-LBL) where all the nodes of the underwater network cooperate to support the localisation and navigation of mobile vehicles [3]. Instead of deploying dedicated transponders, as for traditional LBL systems, each node of the network can serve as an acoustic beacon for the others, making use of its underwater acoustic modem to transmit both data (*e.g.* sensor measurements, node status report, mission tasks, commands) and positioning information. While the use of a cooperative approach to provide range measurements to the mobile robot(s) is not novel in itself, and it has been considered for instance in [4]–[10], this work studies the impact that different Medium Access Control (MAC) protocols have on the quality of the ranging data and on the underwater node localisation. To the best of our knowledge no previous work has given any attention to the impact that different communication strategies (resulting in different communication delays) have on the quality of the measurements used to support vehicle positioning and navigation.

To be more specific, in this work, we investigate the use of two different MAC solutions in combination with the proposed Net-LBL system: a Time Division Multiple Access (TDMA) solution and a Carrier Sensing Multiple Access (CSMA) protocol. Experimental data collected during two

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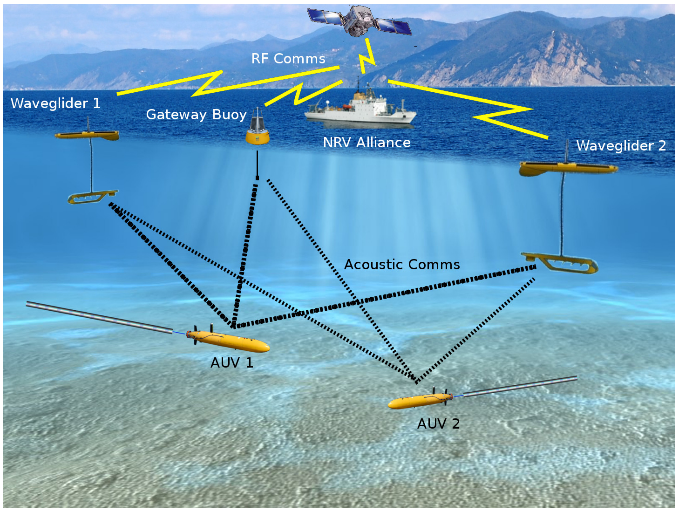

Fig. 1: Heterogeneous underwater acoustic network.

at-sea trials (COLLAB-NGAS14 and REP16-Atlantic) have been considered to evaluate and compare the performance of the proposed Net-LBL system when these different MAC solutions are used.

The rest of the paper is organised as follows. The proposed Net-LBL system is summarised in Section II. Section III presents the equations describing the problem of localisation and introduces the localisation algorithm which uses those equations to compute the desired location. The considered MAC protocols and the corresponding use of the range acquisition scheme is presented in Section IV. Section V illustrates experimental results. Finally, Section VII concludes the paper.

II. NET-LBL SYSTEM

The Net-LBL system is designed to make use of a network of cooperative heterogeneous nodes, such as AUVs, Autonomous Surface Vessels (ASV), surface buoys and ships, to support the localisation and navigation of underwater mobile assets (see Figure 1).

The objective is to provide positioning services without the need to deploy dedicated transponders and acoustic systems, but making use of the same underwater acoustic modems adopted for data transmissions in the network[1]. Additionally, the information in support to vehicle navigation needs to be provided while the network is performing the specific assigned mission, without disrupting the network operation. Different kinds of missions can be performed by such a network, including environmental monitoring, surveillance and detection, search and rescue [11]–[13]. In all these missions knowing the positions of the various assets and having georeferenced measurements is of paramount importance. In the proposed Net-LBL system, each node can transmit (periodically or on request) its position and additional data used to compute the distance at the receiving node. This information can be transmitted using either short control messages or in piggyback to regular data packets, thus reducing the overhead, delays and energy consumption introduced in the network by the localisation. The possibility to compose different types of messages in support to vehicle navigation and to send updated node positions over time enables the use of mobile anchor points using ASVs or ships, thus extending the operational area of the network [14].

A. Net-LBL system architecture

This section presents the generic system architecture of a Net-LBL underwater acoustic network node. Figure 2 shows the different modules needed for a node to operate within the underwater network and to perform positioning and navigation in the case of mobile nodes.

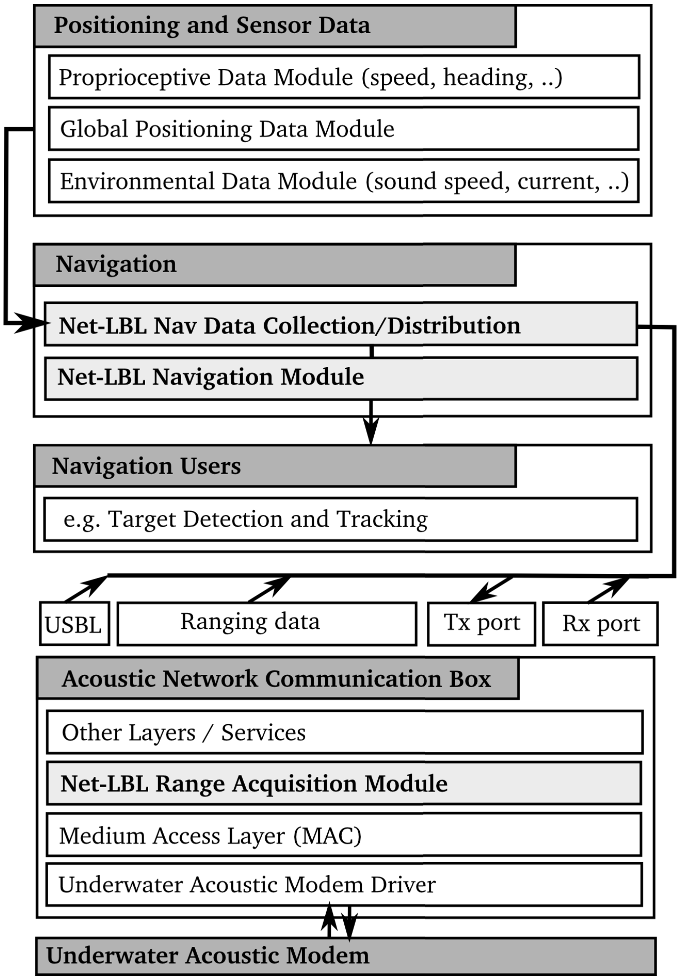

Fig. 2: Software architecture of the Net-LBL system running on each node of the underwater acoustic network nodes.

The Net-LBL system is composed of three modules. The *Navigation Module*, the *Data Collection/Distribution Module* and the *Range Acquisition Module*.

The *Net-LBL Navigation Module* is responsible for computing the position of underwater vehicles within the network, based on the collected information. The position is

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[1] For the Net-LBL system we assume that the deployed nodes are equipped with compatible underwater acoustic modems.

finally passed to other system modules on board of the node which need it to operate.

The *Data Collection/Distribution Module* is responsible for collecting the information needed by the local *Navigation Module* while sharing acoustically the information that is needed for navigation by the other nodes. For example, a baseline node needs to share its global position with the underwater nodes.

The full list of data used by the *Data Collection/Distribution Module* is the following:

- Data computed locally on the node:
  - *Ranging information (range, acoustic message timestamps, acquisition delays);*
  - *Proprioceptive information (Euler angles, velocity, inertial information);*
  - *Global position (usually when on surface);*
  - *Environmental data (sound speed, sea current);*
  - *Possibly other data useful for improving navigation,* e.g. *USBL angles if the AUV has a USBL capable modem, range and bearing from alternative devices.*
- Data collected from remote nodes via acoustic communication:
  - *Acoustic message timestamps;*
  - *Remote nodes global positions (usually when on surface);*
  - *Possibly other data useful for improving navigation,* e.g. *remote nodes proprioceptive information.*

The *Data Collection/Distribution Module* relies on the use of an *Acoustic Network Communication box* which is responsible to deliver the intended information to remote nodes of the network and to provide the local data used by the Net-LBL system. Various networking communication architectures have been proposed in the recent past [15]–[18] and the Net-LBL modules can be used with any of them. Some of these solutions have already modules devoted to collect ranging and timing information that can be used by the Net-LBL system [5], [7]–[10]. When this is not the case, an additional module, named *Net-LBL Range Acquisition Module* in Figure 2 and described in Section II-B, has to be added to the communication stack.

B. Net-LBL Range Acquisition Module

The Net-LBL Range Acquisition Module has the following main tasks:

- Collecting the timestamps at which messages are transmitted and received;
- Using the collected timestamps to calculate the distance between the interrogator and replying node;
- Sharing this information with the rest of the Net-LBL localisation and navigation modules.

In general, measuring the distance between two nodes breaks down to measuring the sound velocity and the time-of-flight (TOF) of the acoustic messages. The sound velocity is usually measured using a Conductivity Temperature Depth (CTD) sensor. The measurements can be performed directly on the nodes or from a ship and communicated to the nodes.

The TOF between two nodes, i and j, is instead computed exchanging messages that include enough information, namely reception and transmission times, to make it possible to calculate the message round trip time. Figure 3 shows a two-way message exchange between node i and node j, with the relevant information that needs to be transmitted. The absolute times of emission and reception of the messages are denoted $t_1, .., t_4$.

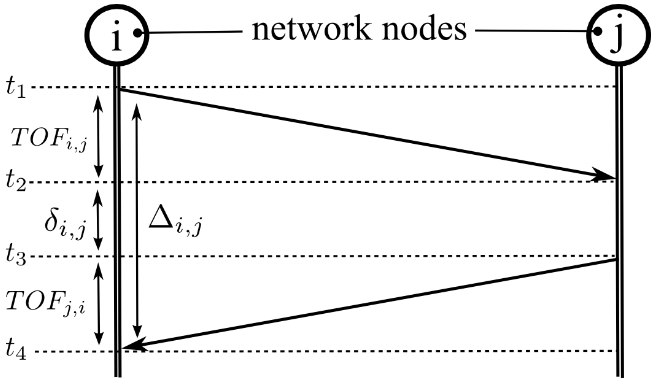

Fig. 3: Measuring the time-of-flight (TOF) and the two-way TOF between nodes i and j

Note that, when accurate clock synchronisation is ensured in the network [19], the time of emission of the message t_1 can be either known a priori to the receiver or it can be transmitted acoustically. When j receives the message at t_2, the TOF can then be calculated as $t_2 - t_1$. Accurate clock synchronisation however requires additional measures such as the use of an atomic clock [20], thus increasing the complexity, cost and energy consumption of the node.

When the network nodes are not synchronised, the TOF can be computed using two-way transmissions and obtaining the round-trip-delay. The interrogation cycle is started by node i at time t_1. Node j receives the request at time t_2 and replies at t_3. Finally, the message reply is received by node i at t_4. In the case where all the nodes are not synchronised, in order for i to compute the round-trip-delay and the TOF, node j has to include in its response either the timings t_2, t_3 or their relative difference $\delta_{i,j} = t_3 - t_2$. Node i can then compute the TOF as $(t_4 - t_1 - \delta_{i,j})/2$. Usually, absolute times are sent when time-synchronisation algorithms are used [21], whereas relative measurements are sufficient to calculate the range, allowing to reduce the amount of transmitted information. For this reason, in the rest of the paper we assume that only relative time differences are acoustically sent through the network.

Note that since both nodes i and j can be moving and the acoustic messages require some time to travel over long distances, the TOF computed when the message is received (at t_2 or t_4) may not correspond exactly to the actual TOF at the time of the computation, but it has to be projected back in time. We project the TOF measurement to t_r which is the mid-time between the request of the range and the acquisition of the range.

For the case of one way TOF we use:

$$\begin{array}{rcl} r_{i,j}(t_r) & = & c_s \frac{(t_2 - t_1)}{2} \\ t_r & = & (t_2 + t_1)/2 \end{array} \tag{1}$$

While for the case of computing the TOF using two-way transmission we assume:

$$\begin{array}{rcl} r_{i,j}(t_r) & = & c_s \frac{(t_4 - t_1 - \delta_{i,j})}{2} \\ t_r & = & (t_4 + t_1)/2 \end{array} \tag{2}$$

It is noted however that equation 2 is accurate only when the motion of the nodes is linear and constant otherwise there is a residual error due to the second order motion of the nodes. This error increases with the range acquisition delay and this is of particular interest in our analysis, as highlighted in the experimental section (Section V).

III. ACOUSTIC LOCALISATION

The problem of localisation of the node i can be expressed as finding $\mathbf{x}_i(t)$, the position of the node i at any time t using previously acquired range measurements[2]. Let $r_{i,j}(t_r)$ be one range measurement between node i and j at time t_r obtained using the range acquisition protocol described in II-B. Given the position $\mathbf{x}_j(t)$ of node j, the range $r_{i,j}(t_r)$ constrains the position of node i through the following equation:

$$\|\mathbf{x}_i(t_r) - \mathbf{x}_j(t_r)\| = r_{i,j}(t_r). \tag{3}$$

Due to the acquisition delay, this measurement is actually obtained only at time $t_p > t_r + \frac{\Delta_{i,j}}{2}$.

The evolution function of the vehicle is then used to compensate for it:

$$\mathbf{x}_i(t_b) = \mathbf{f}_{i,t_a,t_b}(\mathbf{x}_i(t_a), \mathbf{v}_i) = \mathbf{x}_i(t_a) + \int_{t_a}^{t_b} \mathbf{v}_i(t)dt. \tag{4}$$

where $\mathbf{f}_{i,t_a,t_b}$ is the evolution function of the node i between times t_a and t_b. Function $\mathbf{f}_{i,t_a,t_b}$ is based on the kinematic model of the moving vehicle. $\mathbf{v}_i$ is the velocity of the node i in the global frame of reference.

It is worth pointing out, that depending on the available sensors on the vehicle, the velocity might be measured with a substantial error $\mathbf{w}_i$ (*e.g.* DVL without bottom lock):

$$\tilde{\mathbf{v}_i} = \mathbf{v}_i + \mathbf{w}_i. \tag{5}$$

Finally, the positions of node j together with their timestamps are periodically updated on node i using acoustic communication. Node i then estimates the position of the node j at all time, and specifically at time t_r using interpolation or extrapolation on the received position points.

The final equation with the unknown $\mathbf{x}_i(t_p)$ is then:

$$\left\| f^{-1}_{i,t_r,t_p}(\mathbf{x}_i(t_p), \mathbf{v}_i) - \mathbf{x}_j(t_r) \right\| = r_{i,j}(t_r). \tag{6}$$

One can note that because of the uncertainty in the evolution function, the bigger the range acquisition delay, the more uncertain this equation becomes and the less useful it becomes for the localisation. This fact is of interest of our analysis and it is brought up in the experimental section (Section V).

A. *Interval Methods*

There are many ways to solve the localisation problem. Usual approaches range from probabilistic methods such as Extended Kalman Filters (EKF) and Particle Filters (PF) [22] to deterministic techniques such as interval programming [23]. This work follows this latter approach and provides localisation results based on interval analysis. Without entering into too much detail, interval methods represent the uncertainty of the variables (*e.g.* measurements) using intervals of values (*e.g.* $x \in [x^-, x^+]$). When a measurement falls outside the specified interval it is simply considered an outlier. Intervals are then combined together using an interval solver, and more exactly a continuous constraints satisfaction problem (CSP) solver, to provide the optimal solution set.

The input of the interval solver is a set of equations or constraints which bind the unknown variables, which in the case of vehicle localisation is the vehicle position, and the known variables, namely the range measurements and the environmental variables (*i.e.* the sound speed).

The solver returns a set of all possible positions of the localised node which satisfy the equations which stems from the correct measurements (as some of them might be outliers). The interval methods are global methods and work from the first range measurements. In fact, in the absence of outliers, the first solution is a ring with the diameter equal to the range measurement and the thickness equal to the range measurement uncertainty. After receiving few more measurements from diverse nodes, the solution quickly converges to a smaller set. When there are no range updates, the solution set size grows with time as the movement of the localised node is uncertain.

More details on interval analysis, including examples of in-the-field operations can be found, for instance, in [24] for underwater SLAM, in [25] for underwater shape detection and in [26] for underwater robot localisation.

IV. MAC PROTOCOLS

The MAC functionality is responsible for proper sharing of the acoustic channel between the different nodes. Although the Net-LBL navigation system principle of operation is MAC independent, the choice and configuration of the MAC influences the quality of the measured ranges. In our analysis two different designs for the MAC protocol have been considered:

- **TDMA**. Time Division Multiple Access (TDMA) is a well-know protocol largely adopted for terrestrial networks [27], satellite systems [28], and underwater networks [29], [30]. When using a TDMA approach, each node of the network has an assigned time slot and it is allowed to perform a transmission only in its own

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[2] Other measurements (*e.g.* bearing) can be used, if available, to improve the accuracy of the computed position.

time slot, while being idle in the other slots. The sum of different time slots plus the guard times composes the TDMA frame. Guard times between slots are needed to avoid overlapping of transmissions and receptions given the long propagation delays. In order to work, TDMA assumes that the all network nodes are clock synchronised.

- **CSMA**. Carrier Sensing Multiple Access [31] is another well-known protocol for channel access. Since it does not need to use specialised control messages to reserve the channel and to avoid collisions, CSMA has the advantage of having a low overhead. Moreover, it does not require time synchronisation. When a node has a data packet to transmit, it first checks whether the channel is idle or busy. In the first case, it starts the packet transmission. If the channel is busy, the node delays the transmission according to the CSMA exponential back off mechanism.

The use of a TDMA approach avoids possible transmission/reception and reception/reception collisions at the price of reducing the channel utilisation due to the need of guard times. TDMA solutions can obtain good performance in small networks, deployed over a limited area, because in these scenarios, the impact of guard times is limited [32]. However, when the size of the deployment area or the number of the nodes increases, the overhead introduced by the guard times increases as well, reducing the actual use of the acoustic channel and potentially introducing long delays for a node that has to wait for its slot to transmit. Note how this behaviour might become critical when the data to be transmitted has a high priority and should be transmitted immediately. Additionally, when multi-hop networks are considered, or when transmissions are not meant to be received by all the other nodes in the network, it might be possible to have nodes transmitting/receiving at the same time without interfering with each other or without actually affecting the delivery of the messages to the intended nodes. In all these cases traditional TDMA protocols may result in poor network performance.

On the contrary, the CSMA protocol does not impose any fixed structure in the packet transmission hence increasing the network responsiveness. However, it is prone to collisions, thus possibly resulting in a larger number of retransmissions, increasing the overhead and the delays introduced in the network.

A. Net-LBL Range acquisition scheme for the considered MAC protocols

In this section we describe how the Net-LBL range acquisition procedure works according to the considered MAC solutions. For both CSMA and TDMA we assume the use of a two-way transmission scheme. Although TDMA requires node synchronisation, a lower accuracy in the synchronisation can be sufficient to compute the time of each slot for short deployments. Nodes equipped with less accurate clocks (*e.g.* the clock installed on the computational board of the underwater nodes) can be synchronised before the deployment. Their drifting can be then compensated increasing the guard time between slots to avoid transmission/reception and reception/reception collisions. The increment in the guard timing depends on the duration of the mission and it can be a viable solution for short deployments. This approach makes possible to avoid paying the costs associated with the use of atomic clocks, but it imposes the use of a two-way transmission scheme to compute the range measurements.

The range acquisition solution is added to the protocol stack between the MAC and the upper layers, as displayed in Figure 2. Messages created by the upper layers for transmission or received by the lower layers, if addressed to the node, pass through the ranging protocol that adds and removes its own necessary information. Ranging requests and responses can be transmitted as dedicated control messages or in piggybacking to data messages from the upper layers. In our implementation, one extra byte is required for a request, two extra bytes for a response. We assume that the exact timings for a packet transmission/reception (as provided by the acoustic modem [33]) are made available to the ranging protocol. Similarly the modem is informed about the time at which a transmission has to be performed, if any. Additionally, when a packet reaches the acoustic modem for transmission, all the protocol layers are asked to encode their information to create the actual stream of bits to be transmitted. At that time the ranging protocol is able to define the time at which requesting the modem to perform the transmission and it can compute the δ value to be encoded in the ranging responses[3].

Figure 4 shows an example of range acquisition when a TDMA approach is considered. In this case the transmission of the ranging requests and responses follows the TDMA slot structure. Multiple ranging responses, related to different requests received in the previous slots, can be transmitted by a node in its own time slot. Due to the fixed scheme imposed by the TDMA protocol, each node has to wait for all the transmissions occurring in the other slots in order to collect the various ranging estimations, regardless if the requesting node is actually in the communication range to the other nodes.

When a CSMA protocol is used instead, a more flexible design can be considered, as displayed in Figure 5. When a vehicle needs to collect ranging measurements, a broadcast request is passed to the CSMA protocol. When a ranging request is received, a short random delay is introduced before passing the response to the CSMA protocol. This delay is introduced to avoid that the various responses collide at the requesting node. The ranging protocol computes this random delay according to the duration of the packet and to the expected average number of neighbour nodes for the requester. Since few bytes are required for each response

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[3] In case the considered protocol stack does not support for a just-in-time encoding capability, the δ value has to be computed when the ranging protocol processes the outgoing message. In this case longer $delta$ values have to be considered to cope with the possible delays added by the lower layers, thus impacting the network performance.

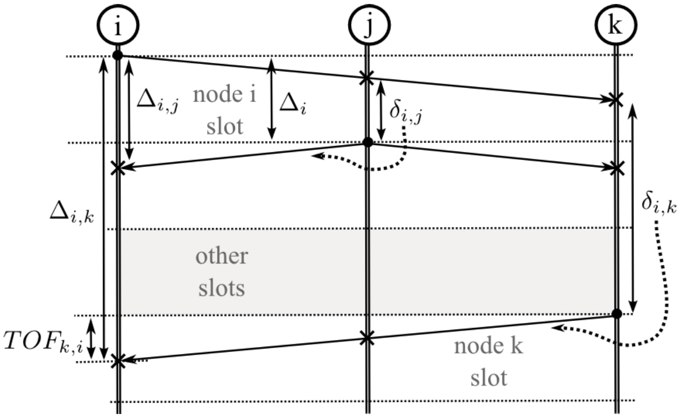

Fig. 4: Example of range acquisition in a TDMA MAC scheme

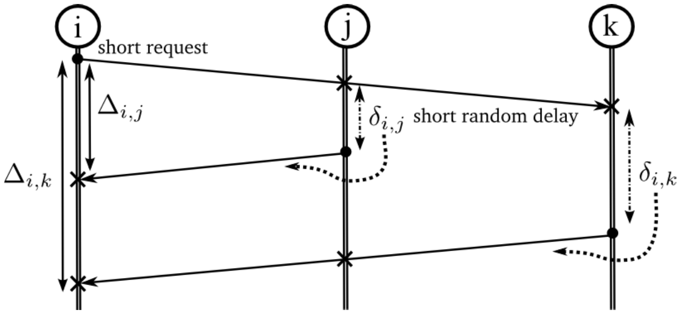

Fig. 5: Example of range acquisition in an CSMA MAC scheme

and acoustic networks are usually sparse, the introduced delay can be limited. Additionally, only the nodes that are actually in the communication range of the requester will send their responses, thus avoiding to wait for the transmissions of unreachable nodes. One can see that the worst case acquisition time is the longest randomly generated delay for the CSMA.

V. EXPERIMENTAL RESULTS

In this section we characterise the performance of the Net-LBL system using the data collected during two at-sea campaigns: COLLAB-NGAS14 and REP16-Atlantic. Each of these experiments involved a similar set-up with an underwater acoustic network composed by six to eight heterogeneous nodes (Ships, moored buoys, ASVs and AUVs). Each of the nodes was equipped with an Evologics modem [33] capable of synchronous transmission. Experiments making use of TDMA and CSMA were considered. In this section we analyse the impact that the MAC layer has on the quality of range measurements and consequently on the performance of the localisation algorithm.

A. Impact of the MAC on range measurements

The MAC impacts the way underwater nodes access the shared medium and particularly the delays in range measurement acquisition. In order to quantify that impact we define the following metrics:

- **Acquisition delay**: This metric is defined as the delay between the transmission of a ranging request and the collection of a ranging reply. This metric is computed for each pair of nodes as the acquisition delay mean value may differ from one pair of nodes to another.
- **N-diversity acquisition delay**: This metric is defined as the time it takes to acquire n ranges from n different sources. This metric is useful to characterise the quality of the range measurement for navigation purposes. A particular case is the 1-diversity which is the rate at which the node acquires a range measurement. This might be useful if the AUV can measure the direction to the baseline node (*e.g.* using USBL). Another particular case is the 2-diversity which is of interest to range-only navigation as the latter requires the node to have at least ranges to two different baseline nodes to work in a nominal way.

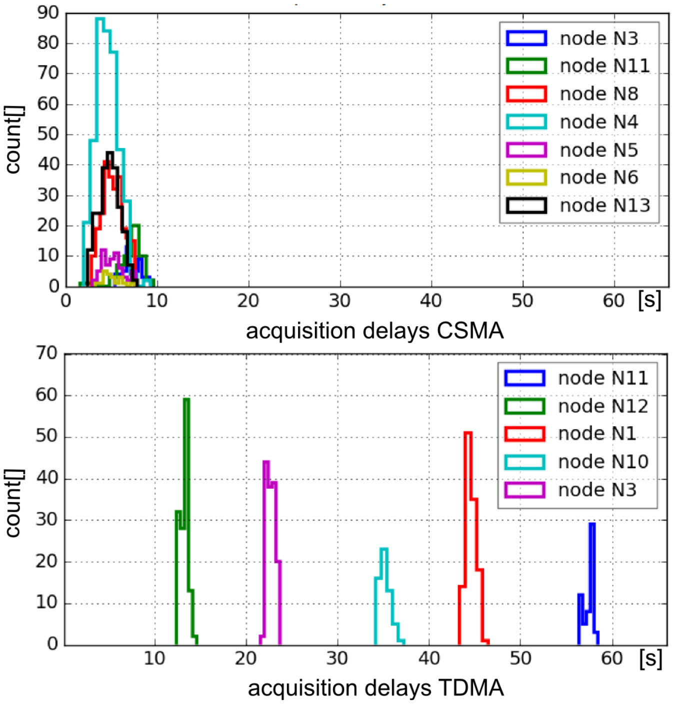

Fig. 6: Histogram for range acquisition delay samples for a node of the network. The CSMA case is represented on the top figure. The TDMA case is represented on the bottom figure.

1) Acquisition delay: Figure 6 shows two sets of plots characterising the range acquisition delay for the two MAC solutions. The main observation here is that for the CSMA case the acquisition delay is practically independent of the pair of nodes considered for range computation while the TDMA acquisition delay is pair dependant. This is due to the constraints imposed by the TDMA slotted structure.

2) N-diversity: Figure 7 shows the N-diversity performance for the two MAC protocols within one range acquisition cycle[4]. For every value of N the N-diversity delay is considerably lower for the CSMA case with respect to the TDMA one. Additionally, when increasing N, the N-diversity acquisition delay increases for TDMA due to the slotted structure of the transmissions, while similar delays occur for the CSMA case.

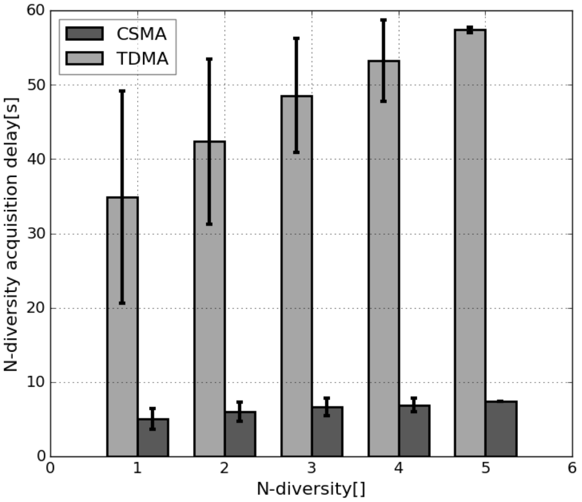

Fig. 7: Comparison between N-diverse acquisition delays in an CSMA-based network and in a TDMA-based network.

The N-diversity can also be computed for several consecutive range acquisition cycles. In fact, there are several cases where the underwater communication is very poor and only a few messages are received. It is then likely to receive N-diverse range updates across several range acquisition cycles. Figure 8 shows two plots of the 2-diversity for the two MAC solutions considering several consecutive range cycles. Since one of the advantages of the CSMA over the TDMA is that, considering a network with the same amount of nodes, it takes less time to acquire all of the ranges, this improves the overall N-diversity performance in the CSMA case. Consequently, this improves the quality of the navigation.

B. Impact of node motion on ranging

In section II-B, the formula used to compute the range is exact only when the motion of the nodes is linear and constant. In the presence of second order motion, there is a residual error between the measured range and the ground truth which increases with the range acquisition delay. In this section we analyse the impact of the range acquisition delay on this residual error. This analysis makes possible to infer the impact of the MAC solution on the ranging performance.

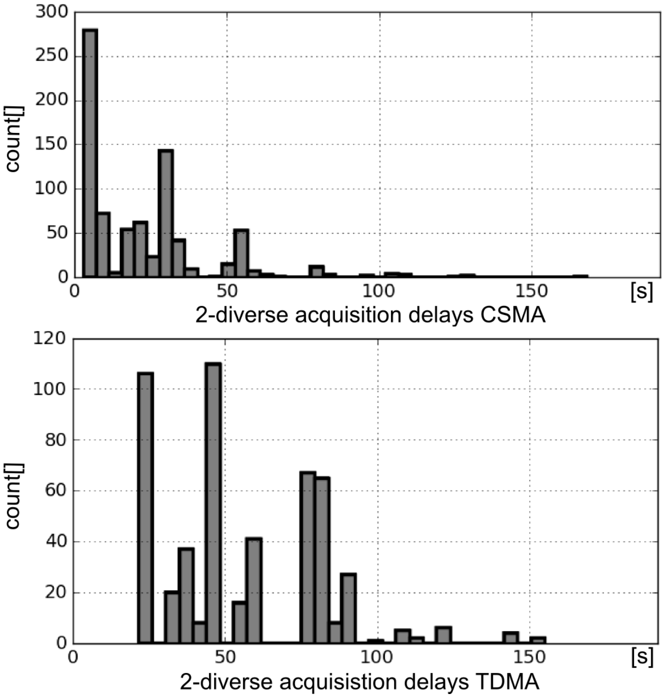

Fig. 8: Histogram for the 2-diversity for a node of the network. The CSMA case is represented on the top figure. The TDMA case is represented on the bottom figure.

Figure 9 shows a plot representing statistics on the ranging error due to the curvature of the trajectory for different values of the range acquisition delay. The analysis is performed from the perspective of one of the AUVs of the COLLAB-NGAS14 dataset. The curve is obtained by comparing the computed range values using equation 2 with respect to the ground truth range for all points of the AUV trajectory and with respect to all of the baseline nodes when considering different acquisition delays. This allows to account for all of the different manoeuvres of the nodes.

As expected, the error increases with the acquisition delay. As a matter of fact, the analysis of the datasets showed that using the CSMA-based approach it is possible to acquire most of the ranges within 10 seconds. This causes an error with a standard deviation of about 1 meter most of the time. On the other hand, the TDMA-based approach have range acquisition delays ranging from 10 to 60 seconds. The standard deviation of the error is in this case several times higher than in the case of the CSMA.

VI. IMPACT OF THE MAC LAYER ON LOCALISATION

In this section we analyse the impact of the range acquisition delay on the quality of localisation. As shown in Section III the acquisition delay introduces an uncertainty in the range equation. This uncertainty depends on how good the evolution function is, *i.e.* how accurate is the measurement of the velocity of the AUV. A cheap AUV with no DVL can easily reach very high drift values (as high as 60m per minute [34]). For the results presented in this section we consider the COLLAB-NGAS14 dataset. This dataset contains all the data needed for validating a navigation solution such as: range measurements with the corresponding timestamps and acquisition delays, positions

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[4] The range acquisition cycle for a node is defined as the time between the transmission of two consecutive range requests.

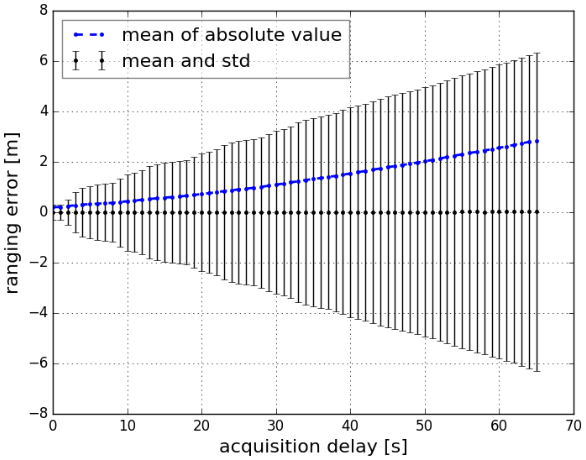

Fig. 9: Ranging error due to the curvature of the trajectory for different values of the acquisition delay from the perspective of an AUV from the COLLAB-NGAS14 network.

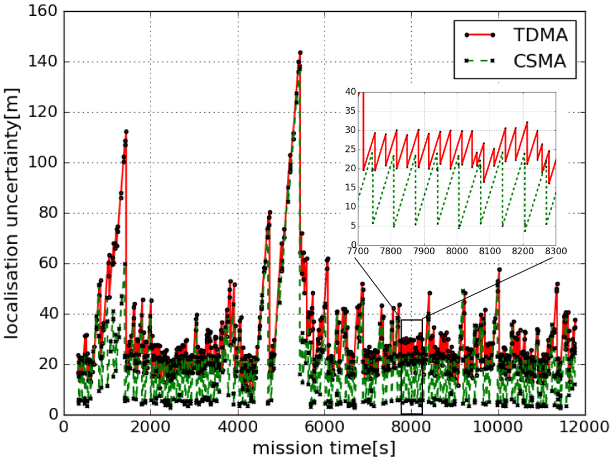

Fig. 10: The effect of the range acquisition delays due to the MAC on the performance of localisation.

of the baseline nodes, proprioceptive measurements of the localised node and its ground truth positions. In order to compare the TDMA and CSMA results using the same exact network conditions, we have considered an experiment where the TDMA protocol was used. For the CSMA protocol we have considered the same network configurations (*i.e.* same node positions, trajectories, environmental effects, errors on the underwater acoustic channel), but we have applied a range acquisition delay reflecting the statistical analysis presented above.

We need to consider that during the in-field experiments the collected ranging and the localisation data are affected by several sources of error. Possible errors can be in fact introduced by inaccurate measurements of the sound speed or misplacement of the baseline node modem with respect to the actual node position (this could be the case for surface station where the modem is cabled to the floating part - hosting the GPS sensor - but it is subject to movements due to currents and waves). In order to put in evidence the impact of only the acquisition delay on the localisation, the measured ranges are replaced with the ground truth values of the range. Similarly, to obtain a uniform drift of the position estimate in the absence of range updates, the evolution function, which is based on proprioceptive sensors, is replaced with the ground truth evolution function with a constant uncertainty.

Figure 10 shows the localisation uncertainty obtained for the TDMA and CSMA protocols. Most of the time, the localised node obtained at least 2-diverse range measurements. There were, however, some time intervals where only one baseline node was reachable, due to errors on the acoustic channel. This is evident in time interval $[4000, 6000]$ seconds where a larger error in the localisation accuracy is obtained. One can see how the time distribution and quality of ranges affect the localisation uncertainty. In fact, as already shown in Figure 6, the TDMA-based ranging scheme provides regularly distributed range updates which can result in higher acquisition delays while the CSMA-based scheme provides grouped ranges with lower acquisition delay. This results in a sawtooth like uncertainty for the CSMA case with a considerably lower minimum than in the TDMA case. By comparing the uncertainty for all times one can note a reduction on localisation uncertainty of 30% on average. However, when considering the times when the uncertainty is at its minimum in the case of the CSMA-based scheme, the improvement can be even up to 90%.

VII. CONCLUSION

In this paper we presented a Networked-LBL system which makes use of the recent advances in acoustic communication modem technology to perform concurrent communication and ranging. The use of a cooperative underwater network composed by heterogeneous nodes has been presented in support to mobile vehicle positioning and navigation. The data collected during two different at-sea trials has been used to validate the proposed system and to evaluate the impact on the localisation error when different communication strategies are used to reserve the shared underwater acoustic channel. Two MAC protocols have been considered: Time Division Multiple Access (TDMA) and Carrier Sensing Multiple Access (CSMA). The conducted analysis shows the impact that the selected MAC protocol has on the ranging acquisition strategy and on the accuracy of the collected measurements. This results in different errors when performing localisation. The collected results show that CSMA-based solutions, being more flexible and responsive with respect to rigid slotted schemes, can achieve better performance leading to a reduction of the impact on localisation error by 30% on average and up to 90% with respect to TDMA-based solutions.

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Title

Experimental evaluation of Net-LBL: An acoustic network-based navigation system

Abstract

This paper describes the use and in-field evaluation of a Networked-Long Base Line system (Net-LBL) where a network of underwater nodes cooperate to support the localisation and navigation of mobile vehicles. To avoid the use of dedicated transponders, as for traditional long baseline systems, each node of the network makes use of its underwater acoustic modem to transmit both data and positioning information. The use of the proposed Net-LBL systems has been validated and evaluated during two at-sea campaigns. More specifically, this paper investigates how the use of different communication schemes to reserve the shared underwater channel (i.e. Time Division Multiple Access (TDMA) and Carrier Sensing Multiple Access (CSMA)) impact on the acquisition of range measurements and on the localisation results. The collected results show that CSMA, being more flexible and responsive, can obtain a reduction of the impact on the localisation error by 30% on average and up to 90% with respect to TDMA.

Keywords

Navigation, acoustic measurements, robot sensing systems, underwater acoustics, transponders, mobile communication

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