NLOS Identification Using a Hybrid ToA-Signal Strength Algorithm for Underwater Acoustic Localization

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Abstract—The existence of obstacles in harbors or near shore environments leads to Non-Line-Of-Sight (NLOS) links between two underwater acoustic communication (UWAC) nodes. That is, only echoes of the transmitted signal arrive at the receiving node. Mistaking the first (strong) echo as a Line-Of-sight (LOS) measurement and using it for ranging causes significant degradation of the accuracy level of UWAC-based localization. In this paper, we propose a solution for the NLOS identification problem in underwater acoustic localization. Results from both extensive simulations and sea trial experiments confirm our approach and demonstrate a high detection rate of NLOS measurements.

I. INTRODUCTION

Underwater acoustic communication (UWAC) networks are envisaged to fulfill the needs of a multitude of applications such as navigation aids, early warning systems for natural disasters, ecosystem monitoring and military surveillance. The data derived from UWAC networks is typically interpreted with reference to a node’s location, e.g., reporting an event occurrence, tracking a moving object or monitoring a region’s physical conditions. However, location discovery for underwater nodes is non-trivial in the oceanic medium as its efficacy is impacted by propagation delays, motion-induced Doppler shift, phase and amplitude fluctuations, multipath interference etc. [1].

In particular, since GPS signals do not propagate through water, each ordinary underwater node needs to exchange messages with anchor nodes (with known positions) to estimate its distance from them (ranging), from which its position is then computed. Ranging is typically based on the Time-of-Arrival (ToA), Time-Difference-of-Arrival (TDoA) or Received-Signal-Strength (RSS) of the messages. Most existing underwater acoustic localization schemes, e.g., [2]–[4], implicitly assume that these messages are received based on Line-Of-Sight (LOS) acoustic links, from which distances are estimated, and positions are calculated using multilateration.

However, the underwater acoustic channel is a frequency selective channel with a relatively long delay spread [5], and multipath models [6] have shown that the energy of the direct path of the channel’s impulse response is not always the strongest, and therefore Non-Line-Of-Sight (NLOS) reflected signals may be mistakenly treated as the LOS signal (multipath NLOS).

In addition, the existence of obstacles such as rocks, ship hulls, in harbors or near shore environments may also result in NLOS scenarios in which two underwater nodes do not share a direct link, but only echoes of the transmitted signal arrive at the receiver. We refer to this scenario as obstacle NLOS.

An example of a matched filter output for a chirp signal transmitted in a sea trial described in this paper (whose setup is described in Section V-B) is shown in Figure 1. Large errors may result from mistakenly using NLOS signals in ranging [7], which in turn leads to inaccurate UWAC-based localization.

To illustrate the effects of obstacle NLOS measurements on localization accuracy, consider the scenario shown in Figure 2 where signals from three anchor nodes, \(a_1, a_2, a_3\), are received by node \(n\), and are used for its localization. Assume that reference nodes \(a_2\) and \(a_3\) are connected to \(n\) via LOS links. However, node \(n\) is “blocked” from node \(a_3\), e.g., due to the presence of a physical obstacle between them such that it only receives the reflected signal from \(a_3\). Consequently, the propagation delay corresponds to \(d_{31} + d_{32}\), where \(d_{31}\) and \(d_{32}\) are...
is the path length of the signal from \( a_3 \) to the reflecting surface and from the reflecting surface to \( n \) respectively, whereas the actual distance between \( a_3 \) and \( n \) is \( d \).

![Diagram](image)

**Fig. 2.** Illustration of deployment scenario with NLOS signals.

If the difference between \( d_{31} + d_{32} \) and \( d \) is large enough, the localization accuracy will be significantly affected. Hence, obstacle NLOS measurements need to be identified and discarded prior to performing multilateration.

In this paper, we propose a solution for the identification of obstacle NLOS links in UWAC-based localization, which is a problem that has not been treated in previous literature. The novelty of our approach lies in combining both time based ranging techniques (ToA or TDoA) and signal strength based ranging techniques (RSS) using an attenuation model. By comparing these distance estimates, we classify received signals as stemming from NLOS or LOS links. Considering the difficulty in acquiring an accurate attenuation model, we require only a simplified model with lower bounds. Results from both extensive simulations and sea trial experiments demonstrate the validity of our approach through achieving a high detection rate for obstacle NLOS measurements.

The remainder of this paper is organized as follows. In Section II, we describe the state of the art in dealing with the NLOS problem in localization. System model and assumptions are described in Section III. In Section IV, we describe our hybrid ToA-signal-strength algorithm and show the performance of the algorithm obtained for synthetic UWAC environments and in a sea trial in Section V. Finally, conclusions are offered in Section VI.

II. NLOS Problem in Localization

In a multipath environment such as the underwater acoustic channel, NLOS measurements affect the accuracy of ranging considerably. These errors are usually regarded as part of the measurement noise [8]. In [2], these noises were modeled as the Ultra Wideband Saleh-Valenzuela (UWB-SV) underwater acoustic fading channel model [9], while a method for developing a lower bound for multipath noise mitigation for a given multipath model was introduced in [10]. To limit measurement noise, the authors in [8] suggested using direct sequence spread spectrum signals (DSSS) which have narrow auto-correlation. Following this approach, curve fitting of ToA measurements based on DSSS was suggested in [11]. Incoherent integration of ToA measurements from different signals is suggested in [12] where results show considerable reduction in measurement errors, and a Kalman filter for the evaluation of both range and its rate of change was suggested in [13].

In [14], measurements which increase the global variance are rejected, assuming that NLOS measurements have larger variance than LOS measurements. In [15], it was shown that the best performance is achieved by selecting ToA measurements based on minimal statistical mode (i.e., minimal variance and mean). Alternatively, the authors in [16] suggested a method of reducing the effect of NLOS measurements by assigning each measurement with a weight inversely proportional to the difference between the measured and expected distances from previous localization. In [17], NLOS measurements are not rejected but rather, they are utilized by estimating the NLOS factor (i.e., the difference \( d_{31} + d_{32} - d \) in Figure 2) using a maximum likelihood estimator based on an attenuation model and incorporating those measurements after a factor correction.

Due to NLOS links and measurement errors, location ambiguities such as flips and rotations might exist. This problem was considered in [18] where additional anchor nodes are used to resolve such ambiguities. In [19], a three phase protocol is suggested for this problem. First, an ambiguous-free sub-tree of nodes is determined; then, localization based on triangulation is performed where the node is first assumed to be located in the center of a rectangular area; and finally, a refinement phase is performed using a Kalman filter to mitigate noise arising from ranging. A robust protocol for mitigating localization ambiguities is suggested in [20] by rejecting measurements leading to ambiguities, e.g., when there are insufficient anchor nodes or when the location of anchor nodes is almost collinear. However, these protocols are only applicable when a large number of anchor nodes are available.

While the above protocols offer NLOS error mitigation, only a few considered the case where all measurements are NLOS, i.e., no direct path exists. This issue is regarded in [21] where the relationship between base station distances and NLOS factor is considered and the problem of evaluating the NLOS factors is formalized as an optimization problem. However, to the best of our knowledge, no prior work considered NLOS error mitigation for the special characteristics of the underwater acoustic channel.

III. System Model and Assumptions

Our system comprises one ordinary node (to be localized) and \( L \) anchor nodes (with known locations). We denote the ordinary node as \( n \), the reference nodes as \( a_i \), \( 1 \leq i \leq L \) and the link between node \( n \) and \( a_i \) as \( (n,a_i) \).

In our algorithm, we identify obstacle NLOS links based on a comparison between ranging based on signal strength, \( d_{SS,i} \), and time of arrival, \( d_{time,i} \), for the link \( (n,a_i) \).

Considering the difficulty in acquiring an reliable attenuation model for the underwater acoustic channel, we do not directly estimate \( d_{SS,i} \) but rather, we estimate the lower bound of \( d_{SS,i} \), \( d_{SS,min,i} \). We rely on the following widely used simplified attenuation model [22] for underwater acoustic
communications to estimate $d_{SS,i}$:

$$TL_{\text{LOS}}(d_i) = PL_{\text{LOS}}(d_i) + AL(d_i),$$

(1)

where $d_i$ is the transmission distance, $PL_{\text{LOS}}(d_i) = \gamma \log(d_i)$ is the propagation loss, $AL(d_i) = \alpha d_i^{1000}$ is the absorption loss and $\gamma, \alpha$ are the propagation and absorption coefficients, respectively. Using (1), we estimate $d_{SS,\text{min},i}$ by setting $\gamma$ and $\alpha$ according to the environment in which the system is expected to operate. We assume that node $n$ knows the transmitted power, such that it can estimate $TL_{\text{LOS}}(d_i)$ by measuring the power of the received signals.

We assume that $d_{\text{time},i}$ can be directly estimated via either ToA (e.g., [23]) or TDoA (e.g., [2]) techniques. However, for link classification purpose we do not require accurate evaluation of $d_{\text{time},i}$ and measurement errors of the order of the channel’s delay spread is acceptable.

We further assume that the power loss of the reflected signal in the channel for an obstacle NLOS link is [5]

$$TL_{\text{NLOS}}(d_{i1}, d_{i2}) = PL_{\text{LOS}}(d_{i1} + d_{i2}) + AL(d_{i1} + d_{i2}) + TS + SL,$$

(2)

where $d_{i1}, d_{i2}$ are the distance from node $a_i$ to the reflecting surface and from the reflecting surface to node $n$, respectively, as illustrated in Figure 2, and SL and TS are the reflecting surface spreading loss and target strength (i.e., power absorbed by the surface), respectively. These parameters depend on the surface material and structure and the carrier frequency of the transmitted signals and are assumed to be large such that

$$TL_{\text{NLOS}}(d_{i1}, d_{i2}) \gg TL_{\text{LOS}}(d_{i1} + d_{i2}).$$

(3)

IV. HYBRID ALGORITHM FOR NLOS IDENTIFICATION

Referring to Figure 2, our proposed hybrid algorithm to identify whether a link $(a_i, n)$ is LOS or NLOS comprises three basic steps, described in the following.

- **Estimation of $d_{\text{time},i}$**

  By applying TDoA or ToA techniques, we estimate the propagation delay, $T_{pd,i}$, of signal transmission from node $a_i$ to node $n$ at node $n$. Then, utilizing several measurements of $T_{pd,i}$, we estimate $d_{\text{time},i}$ for a given sound speed in water.

- **Estimation of $d_{SS,\text{min},i}$**

  By measuring the power of the received signals at node $n$ and using a-priori knowledge of the transmission power at node $a_i$, we estimate the transmission loss of arriving signals at node $n$. Next, applying the attenuation model in (1), we estimate $d_{SS,\text{min},i}$ using lower bound of $\gamma$ and $\alpha$ reflecting the accuracy of our model.

- **Thresholding**

  Finally, we compare $d_{\text{time},i}$ with $d_{SS,\text{min},i}$: if $d_{SS,\text{min},i} \leq d_{\text{time},i}$, then link $(n,a_i)$ is classified as an LOS link; otherwise, it is determined as an NLOS link.

We note that the classification in the last step of our algorithm is based on the assumption in (3) such that a noticeable difference between $d_{SS,i}$ and $d_{\text{time},i}$ is expected when the link is NLOS. Hence, the efficacy of our NLOS identification algorithm relies on the validity of the assumption that the difference between $TL_{\text{NLOS}}$ and $TL_{\text{LOS}}$ is much larger than the effects of measurement noise or attenuation model inaccuracies. We validate this assumption in a sea trial described in a later section.

A. Performance analysis

In this section, we analyze the expected performance of our hybrid NLOS identification algorithm, assuming that estimation noise is Gaussian distributed with zero mean and variance of $\sigma^2$. We consider both false detection probability, $P_{\text{false}}$, in which LOS links are falsely identified as NLOS, and detection probability, $P_{\text{detect}}$, in which NLOS links are correctly classified.

For the case where the link is an LOS link, assuming the bounds of our attenuation model are accurate, $d_{SS,\text{min},i} \leq d_{\text{LOS},i}$, where $d_{\text{LOS},i}$ is the true transmission distance in the LOS link $(n,a_i)$. Therefore, the probability of false detection is given by

$$P_{\text{false}} = 1 - Q\left(\frac{d_{SS,\text{min},i} - d_{\text{LOS},i}}{\sigma}\right),$$

(4)

where $Q(x)$ is the Gaussian Q-function, and $d_{SS,\text{min},i}$ is evaluated numerically according to (1). Numerical values of $P_{\text{false}}$ as a function of $d_{\text{LOS},i}$ and $\gamma$ for $\gamma_{\text{min}} = 15, \sigma = 100$ are presented in Figure 3. Results show that $P_{\text{false}}$ is still low even for high ToA measurement noise. We also observe that $P_{\text{false}}$ decreases with the transmission distance but increases with $\gamma$ such that if $\gamma_{\text{min}} < \gamma$ LOS identification fails.

![Fig. 3. Probability of false LOS link identification as a function of $d_{\text{LOS},i}$ and $\gamma$.](image-url)

When the link is an NLOS, $d_{SS,\text{min},i}$ is expected to be larger than the estimated $d_{\text{time},i}$ since the measured transmission loss is affected by both SL and TS as in (2). Denoting the true transmission distance in the obstacle NLOS link as $d_{\text{NLOS},i} = d_{i1} + d_{i2}$, the detection probability is

$$P_{\text{detect}} = 1 - Q\left(\frac{d_{SS,\text{min},i} - d_{\text{NLOS},i}}{\sigma}\right).$$

(5)

Numerical results of $P_{\text{detect}}$ are presented in Figure 4 as a function of $d_{\text{NLOS},i}$ and $\gamma$ for $\gamma_{\text{min}} = 15, \sigma = 100, TS +
\( SL = 10 \). Results show that \( P_{\text{detect}} \) is high when \( \gamma \geq \gamma_{\text{min}} \) even when the ToA measurement noise is high. When \( \gamma < \gamma_{\text{min}} \), \( P_{\text{detect}} \) is not monotonous with \( d_{\text{NLOS},i} \).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{Probability of correct NLOS link identification as a function of \( d_{\text{LOS},i} \) and \( \gamma \).}
\end{figure}

When the carrier frequency is low or when the transmission distance is small, the absorption loss in (1) can be neglected [5]. Here, when the link is an obstacle NLOS, we have

\[
d_{\text{SS,\text{min},i}} = (d_{\text{NLOS},i})^{\gamma_{\text{min}}} \cdot e^{\frac{\text{SL}+\text{TS}}{\gamma_{\text{min}}}},
\]

where \( \gamma \) is the true propagation parameter in the channel and \( \gamma_{\text{min}} \) is the lower bound of the attenuation model. While it is clear that \( P_{\text{detect}} \) increases with \( \text{SL} \) and \( \text{TS} \), from (6) we observe that \( d_{\text{SS,\text{min},i}} \) also increases with \( \gamma \). Thus, a worst case scenario is when \( \gamma = \gamma_{\text{min}} \). Here we get

\[
P_{\text{detect}} = 1 - Q\left(\frac{d_{\text{NLOS},i}}{\alpha} \frac{\text{SL}+\text{TS}}{\gamma_{\text{min}}} - 1\right).
\]

\( \text{V. RESULTS} \)

In this section, we evaluate the performance of the hybrid NLOS identification algorithm both by simulations and sea trial results. We start with a simulation in which the simplified attenuation model in (1) is used, and then validate our assumptions of the boundaries of this model in the sea trial.

A. Numerical Results

To obtain a better insight of the analysis made in Section IV-A, we conducted extensive simulations in which we placed 3 anchor nodes and one ordinary node randomly in a square area of size 1 km \( \times \) 1 km. Four horizontal obstacles and one vertical obstacle were placed at random positions (but not on a node) and with lengths that are uniformly distributed in [100, 200] m. A link between the ordinary node and an anchor node is an LOS link if there is no obstacle obstructing the line-of-sight between them; otherwise, the link is an NLOS link where signals are reflected from the edges of the square area. In the example simulation scenario depicted in Figure 5, \( (n,a_3) \) is an LOS link while \( (n,a_2) \) is an NLOS link due to obstruction by the vertical obstacle.

For each link, we calculated the attenuation of the signals in the channel according to the model in (1), where \( \gamma \) was a simulation parameter and \( \alpha \) was fixed at 2 dB/km to correspond to a carrier frequency of the order of 20 kHz according to Thorp’s formula [5]. If a certain link was determined to be an obstacle NLOS link, the attenuation of signals in the link was calculated according to the model in (2) for various values of \( \text{TS} \) and \( \text{SL} \). For each link, the transmission distance was set according to the Euclidean distance for LOS links and the sum of Euclidean distances to and from the reflecting surface for obstacle NLOS links, as illustrated in Figure 2. The value of the ToA in the link was set by the transmission distance divided by a sound speed in water of 1500 m/sec and a zero-mean Gaussian distributed measurement noise with variance 0.01 (corresponding to an error in the distance estimation of 15 m) was added to it. The value of \( d_{\text{time},i} \) was set according to the mean value of all ToA samples.

For each topology, we classified the communication links using the hybrid NLOS identification algorithm and compared the results with the true nature of the link. Average results for \( P_{\text{false}} \) of LOS links and for \( P_{\text{detect}} \) of obstacle NLOS links are presented in Figure 6 and Figure 7, respectively, as a function of \( \gamma \) and \( \text{SL}+\text{TS} \). Figure 6 shows that \( P_{\text{false}} \) increases with \( \gamma \). This result was expected since \( d_{\text{SS,\text{min},i}} \) increases with \( \gamma \). Figure 7 shows that, as expected, \( P_{\text{detect}} \) increases with \( \text{SL}+\text{TS} \). We also observe that \( P_{\text{detect}} \) increases with \( \gamma \). This result is obtained since the larger the difference between \( d_{\text{SS,\text{min},i}} \) (which increases with \( \gamma \)) and \( d_{\text{time},i} \), the better obstacle NLOS identification is.

Although the results show relatively low \( P_{\text{false}} \) and high \( P_{\text{detect}} \) for expected values of attenuation in the underwater acoustic channel, we note that the accuracy of the attenuation model determines the performance of the algorithm. Since we relied on the boundaries of a rather simplified attenuation

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{An example of a simulation scenario.}
\end{figure}
The four nodes were time synchronized using GPS and transmitted with equal transmission power. Each reference node sent frequent broadcast messages which were detected by the ordinary node. The transmission time of each packet was globally known using a spatial reuse time division multiple access (STDMA) medium access control (MAC) protocol [24]. For each link, \((2,j), j \in \{1,3,4\}\), we evaluated (i) \(d_{\text{time},i}\) using ToA measurements and (ii) the transmission loss according to the value of the first peak of the matched filter output for the received signals. Since we locked on a single path for the transmission delay evaluation, we considered free space propagation loss such that \(\gamma = 20\) and set \(\alpha = 1.5\) according to Thorp’s equation for a carrier frequency of \(12\ kHz\) [5]. To determine \(d_{SS,\text{min},i}\), we considered inaccuracies in our attenuation model by setting \(\gamma_{\text{min}} = 15\), expecting less than \(15\ dB\) difference between the actual attenuation in the channel and TL-LOS\(_{\text{min}}(d)\) for all transmission distances tested in the sea trial.

Throughout the trial, 9 different communication links were classified, and the evaluated values of \(d_{SS,\text{min},i}\), \(d_{SS,\text{max},i}\), \(d_{\text{time},i}\) in meters from the sea trial for both NLOS and LOS links are presented in Table I. Using our proposed hybrid algorithm, all 4 obstacle NLOS links were correctly classified and there were no false classification of the LOS links.

<table>
<thead>
<tr>
<th>LOS links</th>
<th>(d_{SS,\text{min,i}})</th>
<th>(d_{\text{ToA}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>((2A,3B))</td>
<td>579</td>
<td>780</td>
</tr>
<tr>
<td>((2A,4A))</td>
<td>179</td>
<td>242</td>
</tr>
<tr>
<td>((2A,4B))</td>
<td>343</td>
<td>415</td>
</tr>
<tr>
<td>((2A,1A))</td>
<td>428</td>
<td>610</td>
</tr>
<tr>
<td>((2A,3A))</td>
<td>647</td>
<td>817</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NLOS links</th>
<th>(d_{SS,\text{min,i}})</th>
<th>(d_{\text{ToA}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>((2A,1B))</td>
<td>1957</td>
<td>1105</td>
</tr>
<tr>
<td>((2A,3C))</td>
<td>1639</td>
<td>740</td>
</tr>
<tr>
<td>((2A,1D))</td>
<td>1549</td>
<td>1254</td>
</tr>
<tr>
<td>((2A,1C))</td>
<td>1816</td>
<td>950</td>
</tr>
</tbody>
</table>

| Table I | SEA TRIAL RESULTS FOR NLOS AND LOS CLASSIFICATION. |

Referring to Table I, we observe that all the estimated \(d_{\text{time},i}\) were much lower than \(d_{SS,\text{min},i}\) for all obstacle NLOS to validate the boundaries of the simplified attenuation model used in our simulations links, which implies that the spreading loss and target strength of the reflecting surfaces (which could have been the harbor dock, ship hulls, etc.) are relatively high. In addition, comparing the values of \(d_{SS,\text{min},i}\), we observe that although the propagation distance of a link \(i\) was longer than that of link \(j\), e.g., link \((2A,1D)\) compared with link \((2A,1C)\) and link \((2A,1B)\), it was not always that \(d_{SS,\text{min},i} > d_{SS,\text{min},j}\). This is due to the highly complex environment in the harbor where reflections do not necessarily hold the same values of SL and TS.

VI. CONCLUSIONS

In this paper, we suggested a novel algorithm for the identification of NLOS links in the underwater acoustic channel.

Fig. 6. Simulation results of \(P_{\text{false}}\) for LOS links.

Fig. 7. Simulation results of \(P_{\text{false}}\) for NLOS links.

model in this paper, the results need to be validated in a real sea environment, which we show next.

B. Sea Trial Results

In this section, we show results of the NLOS identification algorithm in a sea trial conducted at the Haifa harbor, Israel, in May 2009. The trial included four vessels, each of which represented an individual node in the network. In each vessel, a transceiver was deployed at a fixed depth of 3 m. The four vessels were placed in various locations inside the harbor where the maximum distance in the harbor was 1500 m.

Throughout the trial, both obstacle NLOS and LOS scenarios occurred. The ordinary node, node 2, was placed at a fixed location 2A, while the reference nodes 1,3 and 4 moved between various locations, as presented in Figure 8. For example, node 1 moved between locations 1A, 1B, 1C and 1D. The obstacle NLOS links are \((2A,1D)\), \((2A,3C)\), \((2A,1C)\), \((2A,1B)\), where the last link was determined as an obstacle NLOS since a ship hull blocked the LOS link between location 1B and 2A.
We argued that such an identification is crucial for underwater acoustic localization in which NLOS links can be mistaken for LOS links, leading to considerable localization errors. Based on a comparison between time of arrival based range estimations and signal strength based range estimations, we presented a simple thresholding condition for determining if a certain communication link is NLOS or LOS. Accounting for possible inaccuracies in the attenuation model for signal strength based range estimations used, we only assumed loose lower bounds of the model and considered a simplified attenuation model for the underwater acoustic channel in both extensive simulations and a sea trial. The results show that our algorithm can achieve a low probability of mistakenly identifying LOS links as NLOS links while maintaining high detection probability of actual NLOS links. In future work, we intend to design an algorithm to identify ToA measurements distorted by NLOS signals due to multipath where the LOS signal exists.

REFERENCES


