Underwater Backscatter Localization: Toward a Battery-Free Underwater GPS

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ABSTRACT

Can we build a battery-free underwater GPS? While underwater localization is a long-studied problem, in this paper, we seek to bring it to battery-free underwater networks [13, 20]. These recently-introduced networks communicate by simply backscattering (i.e., reflecting) acoustic signals. While such backscatter-based communication enables them to operate at net-zero power, it also introduces new and unique challenges for underwater localization.

We present the design and demonstration of the first underwater backscatter localization (UBL) system. Our design explores various challenges for bringing localization to underwater backscatter, including extreme multipath, acoustic delay spread, and mobility. We describe how an adaptive and context-aware algorithm may address some of these challenges and adapt to diverse underwater environments (such as deep vs shallow water, and high vs low mobility). We also present a prototype implementation and evaluation of UBL in the Charles River in Boston, and highlight open problems and opportunities for underwater backscatter localization in ocean exploration, marine-life sensing, and robotics.

CCS CONCEPTS

• **Networks → Network architectures**; • **Hardware → Wireless integrated network sensors**; • **Applied computing** → *Environmental sciences.*

KEYWORDS

Subsea IoT, GPS, Localization, Backscatter Communication, Piezoelectricity, Wireless, Energy Harvesting, Battery-free, Acoustics

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1 INTRODUCTION

There is significant interest in low-power and distributed underwater localization systems for environmental, industrial, and defense applications [9, 22, 28, 38]. Climatologists and oceanographers are interested in deploying such systems to obtain location-tagged ocean measurements for constructing subsea heatmaps [28], understanding ocean processes [33], and developing accurate weather and climate prediction models [32]. Marine biologists are interested in such systems for tracking schools of fish and studying their behavior and migration patterns [7, 22]. Accurate and low-power localization is also a key enabler for various underwater robotic tasks including navigation, tagging, and object manipulation [9, 27].

Unfortunately, prior designs for underwater localization remain far from the vision of a low-power, low-cost, and scalable architecture. Since standard GPS signals do not work in water,[1] most existing underwater positioning systems rely on acoustic signals [5, 6, 24]. These systems typically require their nodes to repeatedly transmit acoustic beacons (which are used by a remote receiver for triangulation). Such repetitive transmissions can quickly drain a sensor's battery, thus requiring a frequent and expensive process of battery replacement [10, 11]. To avoid this problem, existing localization systems either heavily duty-cycle their transmissions [12, 42] or tether the localization beacons to a large power source on a ship or submarine [19, 23]. Unfortunately, such workarounds prevent these systems from accurately tracking fast-moving objects (like fish or drones) and/or scaling to large areas of the ocean.

We introduce Underwater Backscatter Localization (UBL), an ultra-low power and scalable system for underwater positioning. UBL builds on our recent work in underwater networking, which has demonstrated the potential to communicate at near-zero power via acoustic backscatter [13, 20]. In contrast to traditional underwater acoustic communication systems, which require each sensor to generate its own signals, backscatter nodes communicate by simply reflecting acoustic signals in the environment. These nodes can also power up by harvesting energy from acoustic signals. Thus, by bringing localization to underwater backscatter, UBL would enable us to build a long-lasting, scalable, battery-free underwater GPS.

Before explaining how UBL works, let us understand why it cannot easily adopt traditional underwater localization techniques. State-of-the-art underwater localization systems rely on computing the time-of-arrival (ToA) between two nodes [4, 43].[2] In these systems, a transceiver sends out an acoustic pulse, and waits for a response from the transponder beacon. The time difference between the initial pulse and the reply is used to determine the separation between the two nodes (by multiplying it with the sound speed in water). Unfortunately, this ToA estimation technique does not work for battery-free nodes. These nodes require an additional wake-up time to harvest energy from acoustic signals before they can start backscattering. This wake-up time cannot be determined a priori

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[1]GPS relies on RF signals which decay exponentially underwater [31, 36].
[2]In contrast, using angle-of-arrival typically requires expensive and bulky antenna arrays and results in poorer accuracy than ToA [16].

and varies with location and environment. As a result, it adds an unknown offset to the time difference between the transmitted and received pulse, preventing us from accurately estimating the ToA and using it for localization.[3]

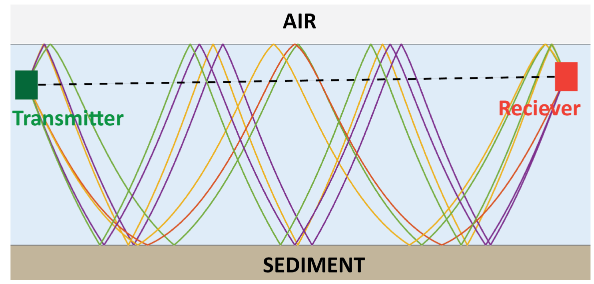
To overcome this challenge, UBL adopts a time-frequency approach to estimate the ToA. Specifically, instead of estimating the ToA entirely in the time domain, it also collects frequency domain features by performing frequency hopping. Since time and frequency are inversely proportional, hopping over a wide bandwidth would enable UBL to estimate the ToA with high-resolution [1, 26, 40]. Transforming this idea into a practical underwater localization system still requires dealing with multiple confounding factors:

- **Multi-path:** When acoustic signals are transmitted underwater, they repeatedly bounce back and forth between the seabed and the water surface before arriving at a receiver. Such dense multipath reflections make it difficult to isolate the direct path to a backscatter node for ToA estimation.
- **Delay Spread:** The slow speed of sound propagation spreads out the above multipath reflections over time, resulting in a large delay spread. This delay spread causes different backscatter bits – *even from the same node* – to interfere with each other. As we show in §2, such *inter-backscatter interference* is unique to acoustic backscatter and exacerbates the ToA estimation problem.[4]
- **Mobility:** Performing accurate localization becomes more challenging for mobile nodes (fish, drones). This is because mobility distorts the estimated frequency features (due to Doppler shift [39]) and because frequency hopping increases the latency of localization, during which a mobile node may have moved to a new location.

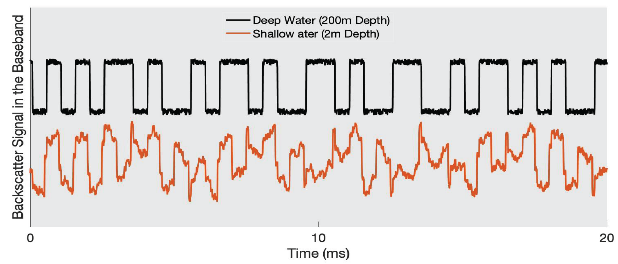
Addressing the above challenges simultaneously requires satisfying competing design requirements. For example, reducing the backscatter bitrate would increase the separation between symbols in a packet (thus mitigating inter-symbol interference), but it also slows down the channel estimation process, making it difficult to localize fast-moving objects. In a similar vein, dealing with multipath and mobility results in conflicting design constraints (for the bitrate and hopping sequence). We argue that designing a robust underwater backscatter localization system requires context-aware algorithms that can adapt their bitrates and hopping sequence to their operating domains. In §3.2, we describe the fundamental constraints arising from these different challenges and how our design of UBL aims to strategically adapt to its surrounding environment.

We implemented a proof-of-concept prototype for UBL and tested in a river. Our prototype consists of a mechanically fabricated backscatter node and a custom-made PCB with a microcontroller and backscatter logic. Our experimental evaluation across three different locations demonstrates the feasibility of achieving centimeter-level accuracy using UBL. Our empirical evaluation is complemented with simulations that demonstrate how the system can adapt to different speeds and multipath environments.

Contributions: This paper presents the first design and demonstration of underwater backscatter localization. Our design can deal with unique challenges that arise from the interaction between underwater multipath and acoustic backscatter, and it can can adapt to various underwater conditions (depth, mobility). The paper also contributes a proof-of-concept implementation and evaluation, and it highlights open problems and future opportunities in underwater backscatter localization.



(a) Multipath in underwater channel



(b) Backscatter signal in deep and shallow water

Figure 1—Multipath and Underwater Backscatter. (a) shows how sound propagates underwater, repeatedly reflecting off the surface and seabed. (b) shows a received backscatter packet in deep (low multipath) and shallow (dense multipath) water.

2 THE (NEW) PROBLEM

Before describing UBL's design, it is helpful to understand why underwater backscatter localization poses new challenges that are different from prior work in RF backscatter localization (e.g., RFID localization [14, 25, 26, 41]). To answer this question, in this section, we provide background on underwater acoustic channels, then explain how these channels pose interesting new challenges for backscatter localization.

Underwater Acoustic Channel. The underwater channel is a confined environment bounded with air on one side and sediment on the other side as shown in Fig. 1(a). When acoustic signals are transmitted underwater, they can travel over very long distances (tens to hundreds of kilometers [34]) due to two factors: (1) the small attenuation of sound in water; and (2) the fact that sound entirely reflects off the air/water and water/sediment boundaries because of the large impedance mismatch between these media. Thus, an acoustic signal travels on various paths from a transmitter to a receiver, most of which involve multiple reflections off the air and water boundaries. As a result, the receiver obtains multiple copies of the signal, which we refer to as underwater multi-path.

Impact of Multipath on Underwater Backscatter. To understand the impact of the underwater channel on acoustic backscatter, we simulated backscatter communication in two different environments corresponding to deep water (depth>200m) and shallow

[3]Note that an approach that introduces pauses between a reader's transmissions is also undesirable since the backscatter node requires continuous signals to stay awake [20].
[4]In contrast, in RF backscatter localization, due to the high propagation speed, all multipath reflections arrive in the same backscatter state [25, 26].

water (depth<10m). In both of these environments, the backscatter node and the receiver are separated by the same distance (4 m).

Fig. 1(b) shows the received backscatter signal in each of these two scenarios. In deep water (black plot of Fig. 1(b)), the received signal shows clear transitions between reflective and non-reflective states. Recall that these states encode bits of 0's and 1's that are used to communicate data. In contrast, in shallow water (orange plot of Fig. 1(b)), the backscatter response is highly distorted and the transitions are significantly obscured.[5] It is worth noting that the difference between these two scenarios is not due to difference in the signal-to-noise ratio, since the distance separation between the backscatter node and the receiver is the same in both cases.

Instead, the difference between the two different scenarios arises from the multipath reflections mentioned earlier. Specifically, in deep water, the direct path is much stronger than the reflected paths because it travels a smaller distance and experiences less attenuation (4m vs 200m). In contrast, in shallow water, the direct path and reflected paths have similar lengths and thus have similar amplitudes; this leads to interference between subsequent symbols (i.e., between different backscatter states). Unless this distortion is accounted for, it will be difficult to estimate the wireless channel in the frequency domain (which UBL needs for localization).

This inter-symbol interference (ISI) is unique to underwater backscatter and does not exhibit in RF backscatter.[6] The difference between RF and acoustic backscatter arises from significant disparity between the speed of RF in air (3×10^8m/s) and that of sound in water (1, 500m/s). In RF backscatter, the nearest reflector that may cause ISI is more than 3 km away (i.e., significantly attenuated), while in acoustic backscatter even a reflector that is 1.5 m away can cause ISI. This difference motivates a new principled approach for underwater localization that differs from standard RF backscatter localization techniques.

3 UBL

UBL is an accurate underwater localization system for ultra-low-power and battery-free nodes. The system can achieve centimeter-scale positioning even in multipath-rich underwater environments. To locate a backscatter sensor, UBL performs the following steps:

- A UBL reader sends a query searching for backscatter nodes in the environment.
- When a node replies, UBL sends a downlink commands specifying the backscatter bitrate.
- As the node replies, the reader performs frequency hopping to estimate the node's channel over a wide frequency.
- Finally, UBL uses the acquired bandwidth to estimate the time-of-arrival (ToA) to the backscatter node and uses the ToA for localization.

Since prior work has demonstrated the ability to query and command an underwater backscatter node [20], in this section, we focus on how UBL uses frequency hopping to estimate the ToA (§3.1) and how it selects the bitrate and hopping sequence (§3.2).

[5]We observed similar behavior when empirically testing our system in a real river.

[6]Note that ISI is known in wireless communication, and standard protocols like OFDM can be used to address it [39]. However, OFDM is too complex for battery-free underwater nodes.

3.1 Backscatter ToA Estimation

UBL performs localization by estimating the time-of-arrival (ToA) of a backscatter node's signal. ToA estimation is particularly useful in multipath-rich environments. Specifically, in the presence of multiple reflections, a receiver can determine the direct path as the one having smallest ToA (since it travels along the shortest path).

The main challenge in backscatter ToA estimation arises from the random wake-up time of battery-free nodes. Specifically, recall from §1 that battery-free nodes need to harvest energy in order to power up before they can start backscattering. Moreover, this wake-up delay varies with distance and environment; thus, it cannot be determined a priori.

To overcome this challenge, instead of estimating ToA directly in the time domain, UBL does so in the frequency domain. Since time and frequency are inversely related, a wide bandwidth can be used to separate different paths and identify the direct path as the one that arrives earliest. Specifically, the resolution to determine the direct path is given by the following equation:

$$\text{resolution} = \frac{speed}{Bandwidth}$$

Thus, for a bandwidth of 10kHz, UBL can localize the node to within 10 cm. In the rest of this section, we describe the different steps of UBL's ToA estimation approach.[7]

Stage 1: Wideband Channel Estimation. UBL estimates the backscatter channel over a wide bandwidth by performing frequency hopping. Specifically, it transmits a downlink signal at a frequency k and obtains the backscatter response. Once the receiver obtains the response y_t, it performs the following two steps:

(1) First, it cross-correlates the received signal with the known backscatter packet preamble to determine the beginning of a packet, denoted τ^*, using the following equation:

$$\tau^* = \arg\max_{\tau} \sum_{t \in T} y_{t+\tau} p_t \tag{1}$$

where p_t is the known preamble and T is the length of the preamble. By identifying the beginning of the packet, this correlation can be used to eliminate the wake-up lag.

(2) Subsequently, UBL estimates the backscatter channel H_k using the packet's preamble. This can be done using standard channel estimation as per the following equation:

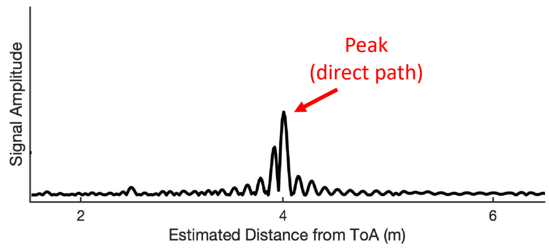
$$H_k = \frac{1}{T} \sum_{t \in T} y_{t+\tau^*} p_t \tag{2}$$

where $y_{t+\tau^*}$ corresponds to the received signal shifted to the beginning of a packet.

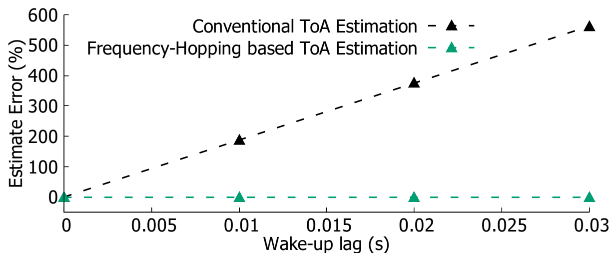
UBL repeats the above procedure for different frequencies (each time hopping to a different frequency and computing the corresponding channel) until is has obtained the channels for across a wide bandwidth $[H_1, H_2, \ldots H_N]$.

Stage 2: Obtaining the Time-Domain Channel. After concatenating the different frequencies, UBL performs an inverse Fourier transform (IFFT) on the channels. This allows it to obtain an expression of the channel in the time domain. Importantly, this time-domain representation is independent of the random wake-up time since it is obtained entirely from the channel estimates.

[7]We note that this technique is similar to that employed in [26] and will be adapted in §3.2 to underwater backscatter.



(a) Time-domain channel from frequency hopping



(b) Wake-up lag effect of localization

Figure 2—Range estimation via frequency hopping. (a) shows how UBL can isolate the direct path in the time domain using the frequency-hopping localization method and (b) shows the effect of the wake-up lag on conventional ToA based localization schemes.

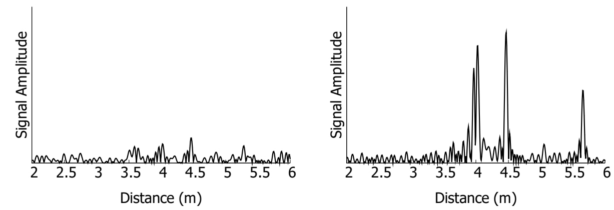
One might wonder whether eliminating the wake-up lag would also eliminate the impact of the round-trip delay on the channel estimates. In practice, this does not happen because UBL estimates the channel in the frequency domain. To see why this is true, consider a simple setup with a single line-of-sight path from the backscatter node to the receiver. Here, the baseband received signal y_t can be expressed as:

$$y_t = e^{j2\pi f_c \tau_r} b(t - \tau_r - \tau_w) \tag{3}$$

where τ_r and τ_w correspond to the round-trip delay and wakeup lag respectively. By shifting the received signal in the time domain (by $\tau_r + \tau_w$), UBL eliminates the delays in the time domain but not the impact of the round-trip delay on the frequency-domain channel. Hence, it is able to recover this delay upon performing an IFFT.

To demonstrate this idea in practice, we simulated the localization problem where a UBL reader and a backscatter node were separated by 4 m in a deep underwater environment. Fig.2(a) plots the channel amplitude as a function of distance after performing the above procedures. The plot demonstrates a clear peak amplitude in the channel around 4 m, which is aligned with the actual distance of backscatter node. Note that because the simulated environment corresponds to a deep sea where multipath is distance with respect to the line of sight, the plot does not show other peaks from nearby reflections in the environment.

Next, to investigate the effect of wake-up lag on UBL's ToA estimation approach, we simulated localization after introducing different time delays (betweem 0-30 ms), and compared the outcome of UBL with that of conventional time-domain methods for localization. Fig. 2(b) plots the percentage error in distance estimation as a function of the wake-up lag for both schemes. The figure shows that while UBL's error remains small irrespective of the wake-up lag, conventional (time-based) ToA estimation systems are significantly affected by this delay and suffer from a large margin of error. This demonstrates that UBL's ToA estimation approach



(a) Shallow water, Bit-rate: 2 kbits/s (b) Shallow water, Bit-rate: 100 bits/s

Figure 3—ToA Estimation in shallow water. This figure shows how multipath affects the localization ability for UBL. (a) shows that at a high bit-rate of 2 kbits/s, UBL fails to localize the object. (b) shows that operating at a lower bit-rate of 100 bits/s in multipath rich environments yields better performance.

is robust to the random wake-up lags of battery-free backscatter sensors. In §4, we empirically verify this result as well.

3.2 Adaptive Backscatter Localization

So far, we have described how UBL can estimate the ToA robustly despite a random wake-up lag. However, the above description focused on deep sea environments with little multipath. In this section, we describe how UBL's design can be extended to deal with extreme multipath and mobility in underwater environments.

3.2.1 Dealing with Extreme Multipath. To understand the impact of extreme multipath, we repeated the same simulation of as our earlier experiment but this time in shallow water (depth of 4 m) rather than in deep water. Fig. 3(a) plots the signal amplitude as a function distance. Unlike the previous experiment, we are unable to see a sharp peak around 4 m, making it difficult to robustly estimate the time-of-arrival in extreme multipath environments. This is because inter-symbol interference (ISI) makes it difficult to obtain accurate channel estimates. This challenge can be seen visually in the orange plot of Fig. 1(b).

To mitigate the impact ISI on ToA estimation, UBL can command the backscatter node to lower its bitrate. Intuitively, doing so increases the separation between any two backscatter symbols, thus reducing the interference between the reflection of the former with the direct path of the latter. From a communication perspective, reducing the bitrate results in a more narrowband channel, which increases robustness to frequency selectivity [39].

To test this idea, we repeated the same simulation, but this time at a bitrate of 100 bps instead of 2 kbps. Fig. 3(b) plots the resulting output for this experiment. The figure shows a much sharper peak around 4 m than that obtained when the same experiment was performed at a higher bitrate. The figure also shows a second peak around 4.5 m, which corresponds to the first (primary) multipath reflection off the surface and sediment. Note that both experiments used the same bandwidth and are simulated at the same distance (i.e., the latter did not benefit from more resolution or higher SNR). Rather the difference is localization robustness arises from the lower bitrate. Formally, we can prove the following lemma.

Lemma 3.1. *To ensure the inter-symbol interference from any single path is no larger than k dB, the backscatter bitrate must be less than* $\frac{c}{(10^{0.05k}-1)\ 4r}$

To prove this lemma, let us denote the largest delay caused by the reflected path as T_r and the delay caused by the direct path as T_l. We further assume that the power of the reflected path is attenuated by k dB compared to the power of the direct path. This gives us the following relation:[8]

$$T_r = 10^{0.05k}\ T_l$$

Since T_l corresponds to the round trip distance, it can be written as a function of the separation r and the speed of sound c as $T_l = 2r/c$. To ensure that any strong symbol reflection arrives before the next symbol is received, the symbol period T_s (or bit period) should be greater than twice the largest delay T_d, which gives an upper bound for bitrate R:

$$R \leq \frac{c}{(10^{0.05k} - 1)\ 4r}$$

3.2.2 Dealing with Mobility. Next, we are interested in extending UBL to deal with mobility of underwater backscatter (e.g., in tracking fish, AUVs). To understand the impact of mobility on localization, we simulated the localization process in deep water for a node moving at a speed of 0.3m/s. Fig. 4 plots the signal amplitude as a function of distance. Unlike the earlier experiment in deep water (i.e., Fig. 2(b)), we are unable to see a sharp peak around 4 m, making it difficult to robustly estimate the time-of-arrival in the presence of mobility. This is because mobility causes a change in the channel estimates over time. As a result, the resulting channel estimates $[H_1(t_1), H_2(t_2), \ldots H_N(t_N)]$ cannot be coherently combined to obtain an accurate location estimate.

To mitigate the impact of mobility on ToA estimation, UBL needs to reduce the overall time required for localization. This can be done by commanding the backscatter node to increase its bitrate and the reducing the number of frequencies in the frequency hopping sequence. We can formalize the mobility constraint through the following lemma.

LEMMA 3.2. *To localize a mobile node moving with the speed of v, backscatter and frequency hopping properties should satisfy the condition of :* $\frac{R}{N_f L_p} \geq \frac{2vB}{c}$ *where R is the backscatter bitrate, N_f is the number of frequency in frequency hopping, L_p is the bit length of the preamble, v is the relative speed of the mobile node , B is the bandwidth and c denotes the speed of sound.*

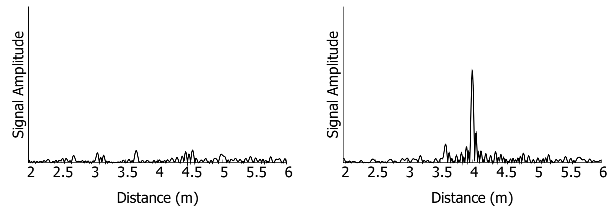
Lemma 3.2 is derived considering the fact that to localize a mobile node with the resolution of x, frequency hopping process must be accomplished before the node get displaced more than x. Assuming the backscatter bitrate of R and preamble bit length of L_p, the minimum required time to estimate the channel for each frequency is $\frac{L_p}{R}$ and the minimum required time for frequency hopping duration is $\frac{N_f L_p}{R}$. To localize the node, The duration of frequency hopping should be less than the time it takes for the node move more than x. This gives us the following relation:

$$\frac{N_f L_p}{R} \leq \frac{x}{v} \tag{4}$$

Additionally, the resolution x is function of bandwidth and may be written as $x = \frac{c}{2B}$, completing the lemma. □

To test the relationship, we repeat the same experiment as above, but this time with a backscatter bitrate of 10kbps. (Here, $B = 10KHz$, $L_p = 20$, $N_f = 100$, this requiring a minimum bitrate of 8kbps according to the lemma). Fig. 3(b) plots the resulting output for this experiment. The figure shows a much sharper peak around 4 m than that obtained when the same experiment was performed at a lower bitrate, demonstrating that UBL's adaptation enables it to accurately localize despite mobility.

[8]This comes from standard spherical loss $P \propto 20\log_{10}(1/T)$.



(a) Deep water, Bit-rate: 1 kbits/s (b) Deep water, Bit-rate: 10 kbits/s

Figure 4—ToA Estimation in deep water with mobility. This figure shows how UBL can adapt to mobility in deep water environments . (a) shows that at a bit-rate of 1 kbits, UBL is unable to localize the object while the object is moving with a speed of 0.3 m/s, so for better accuracy, it is desirable to operate at a higher bit-rates to deal with mobility as shown in (b).

We make few additional remarks about how UBL chooses its backscatter bitrate and hopping sequence:

- Lowering the bandwidth (B), decreases the resolution of localization. Therefore, UBL always tries to exploit the full bandwidth allowed by the backscatter node's mechanical characteristics.
- Decreasing the bit length of the preamble (L_p), leads to the lower SNR. UBL utilize the preamble length of at least 20 bit to ensure the channel is estimated reliably.
- The longest distance that can be localized is determined by the length of the IFFT. Therefore, decreasing the N_f, limits the range of the localization

4 FEASIBILITY STUDY

In this section, we explain how we implemented and validated the feasibility of UBL for underwater localization. Similar to our prior work on underwater backscatter [2, 13, 20], UBL's implementation leverages a projector to transmit an acoustic signal on the downlink, a backscatter node that decodes the downlink signal and transmits a backscatter packet on the uplink, and a hydrophone (Omnidirectional Reson TC 4014 hydrophone [37]) that receives and decodes the backscatter packets. The projector and backscatter node were fabricated in house from piezoceramic cylinders, following the procedure elaborated in our prior work [20].

In our experiment, the projector was programmed to hop its carrier frequency from 7.5 kHz to 15 kHz (at 75 Hz intervals, each for 6 seconds). This range of frequency is selected based on bandwidth of the backscatter node [20] and, subsequently, the expected resolution is 10cm. To account for the effect of multipath in such shallow environment, the backscatter bitrate of 100 bit/s is adopted. Notably, since the node was relatively stationary in the water, the bitrate of 100 bit/s was sufficient to estimate the channel. The received signal recorded by the hydrophone was then processed by first estimating the channel at each of the frequencies, and subsequently, the time-domain channel is computed to estimate ToA per our discussion in §3.1.

The outputs of UBL for three different node locations are shown in Fig.5. The x-axis corresponds to distance and the y-axis represents the normalized time-domain channel amplitude. In this result, the ground truth is marked using red vertical lines and the peak amplitude for each distance is within 10 cm from the ground truth.

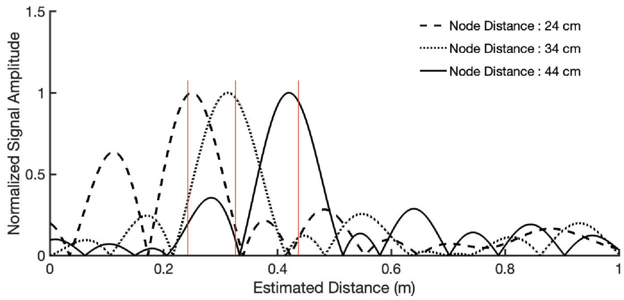


Figure 5—Preliminary Results for UBL. The system was tested for three different ranges i.e. 24 cm, 34 cm and 44 cm respectively.

Note that, due to the limited bandwidth , our resolution was 10 cm and to achieve finer precision, UBL can emulate a wider bandwidth.

5 RELATED WORK

Underwater localization dates back to the early 20^{th} century. The first underwater positioning system was developed to search for a missing American nuclear submarine, the USS *Thresher* [3]. Since then, the vast majority of the underwater positioning systems have relied on acoustic beaconing (since GPS and radio signals do not work underwater).

Early localization systems were based on detection: a node localizes itself to a specific area by detecting the signal of a reference node within that area; such methods are referred to as the Area Localization Scheme (ALS) or Direct Beaconing Localization system (UDB) [5, 24]. Later designs refined the accuracy of these systems by using the received signal strength (RSSI) or the angle-of-arrival (AoA) to perform triangulation or trilateration [17, 35]. However, all of these systems had poor accuracy in multipath-rich underwater environments [18, 29].

State-of-the-art underwater localization systems localize using ToA-ranging methods; these are typically referred to as Long Baseline (LBL) and Ultra-Short Baseline (USBL) methods [19, 30]. Such systems (described in §1) can achieve high accuracy (around 1 m) even in multipath rich deep-sea environments. However, all of today's systems require batteries or a dedicated power source, limiting their battery-life or the ping rate (i.e., ability to deal with mobility). Similar to these systems, UBL also computes the ToA and can deal with underwater multipath. In contrast to these systems, UBL nodes/anchors do not require any batteries and thus can be used for long-term deployments.

Our design of UBL is motivated by recent work in underwater backscatter networking [13, 20]. These systems have demonstrated the ability to achieve ultra-low-power and battery-free underwater communication; however, they have not shown the ability to localize. UBL builds on these designs and extends them to enable accurate localization.

Finally, prior work has explored other (non-acoustic) methods for underwater positioning including using visual odometry and geo-magnetism [8, 15, 21, 44]. Such designs typically require large AUVs and submarines with high sensitivity and cannot work with low power sensors; in contrast, UBL is more suitable for distributed low-power networks.

6 OPEN PROBLEMS & OPPORTUNITIES

This paper introduces underwater backscatter localization, a technology for ultra-low-power and scalable underwater positioning. Below, we highlight a number of open challenges and opportunities that would enable underwater backscatter localization to realize its full potential:

- *From 1D to 3D:* In this paper, we demonstrated the feasibility of 1D localization by estimating the distance between two nodes. There are various avenues to extend UBL's design to 3D localization. Potential solutions include adding two or more nodes (e.g., hydrophones) to perform trilateration or incorporating phased-array transmitters or receivers for obtaining the angle-of-arrival (and combining it with distance information).
- *Mobility in Shallow Water:* In §3.2, we described how UBL can adapt its bitrate and hopping sequence to deal with challenges arising from extreme multipath (in shallow water) or from mobility. Unfortunately, addressing both types of challenges simultaneously leads to competing design requirements (as the former requires designs with a lower bitrate, while the latter requires higher bitrate). Developing underwater backscatter localization systems for such environments is an important open problem to explore in the future.
- *Long-range Backscatter Localization:* UBL inherits the range limitation of prior underwater backscatter systems. Specifically, in contrast to traditional acoustic communication which incurs one-way path-loss, backscatter suffers from a combination of path-loss on the downlink and the uplink. The signal degradation from round-trip path-loss has limited state-of-the-art designs to an operational range of around 60 meters [13]. As underwater backscatter evolves to operate over longer ranges, we expect new challenges to arise in the context of localization, which would need to be addressed in future designs.
- *Towards Tracking, Navigation, and Robotic Manipulation:* UBL's ability to localize batteryless nodes is a fundamental primitive for a variety of other tasks such as tracking, navigation, and robotic manipulation. For example, backscatter nodes can be used to tag underwater objects or marine animals and track them in real-time to understand mobility and migration patterns. Alternatively, UBL's localization primitive can enable novel navigation systems for underwater drones (AUVs and ROVs) using batteryless GPS anchors. A third application involves tagging underwater assets with backscatter nodes, and using their location to enable complex robotic manipulation tasks (e.g., grasping) in underwater environments. Realizing this capabilities will require addressing an exciting array of challenges with tools from a variety of disciplines ranging from networking to robotic perception, learning, and control.

To conclude, this paper takes a first step toward ultra-low-power and batteryless underwater localization and highlights open challenges and opportunities to realize this vision. As the UBL evolves, we envision it will enable various applications in environmental monitoring, marine life understanding, and underwater exploration.

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REFERENCES

[1] F. Adib, Z. Kabelac, D. Katabi, and R. C. Miller. 3d tracking via body radio reflections. In *Usenix NSDI*, 2014.

[2] S. S. Afzal, R. Ghaffarivardavagh, W. Akbar, O. Rodriguez, and F. Adib. Enabling higher-order modulation for underwater backscatter communication. In *Global Oceans 2020: Singapore - U.S. Gulf Coast*, 2020.

[3] APOMAB. Underwater Acoustic Positioning System. http://www.hydro-international.com/files/3fb82f3961d1f9890fc2a475cf56d9ed.pdf, 2020.

[4] T. Casey, B. Guimond, and J. Hu. Underwater vehicle positioning based on time of arrival measurements from a single beacon. In *OCEANS 2007*, pages 1–8, 2007.

[5] V. Chandrasekhar and W. Seah. An area localization scheme for underwater sensor networks. In *OCEANS 2006 - Asia Pacific*, pages 1–8, 2006.

[6] X. Cheng, H. Shu, Q. Liang, and D. H.-C. Du. Silent positioning in underwater acoustic sensor networks. *IEEE Transactions on vehicular technology*, 57(3):1756–1766, 2008.

[7] J. H. Christensen, L. V. Mogensen, R. Galeazzi, and J. C. Andersen. Detection, localization and classification of fish and fish species in poor conditions using convolutional neural networks. In *2018 IEEE/OES Autonomous Underwater Vehicle Workshop (AUV)*, pages 1–6, 2018.

[8] S. S. da Costa Botelho, P. Drews, G. L. Oliveira, and M. d. S. Figueiredo. Visual odometry and mapping for underwater autonomous vehicles. In *2009 6th Latin American Robotics Symposium (LARS 2009)*, pages 1–6, 2009.

[9] DARPA. Angler. https://www.darpa.mil/program/angler, 2020.

[10] Dukane. Ulb-362b,ulb362/pl series underwater locator beacon. https://www.rjeint.com/wp-content/uploads/2017/01/ULB-362-ULB-362PL-Users-Manual-JAN-2018.pdf, 2020.

[11] Dukane. Underwater acoustic beacons. https://shop.boeing.com/medias/2598.pdf, 2020. Part No. 8102007K.

[12] X. Feng, Z. Wang, X. Liu, and J. Liu. Adcnc-mac: asynchronous duty cycle with network-coding mac protocol for underwater acoustic sensor networks. *EURASIP Journal on Wireless Communications and Networking*, 2015(1):1–10, 2015.

[13] R. Ghaffarivardavagh, S. S. Afzal, O. Rodriguez, and F. Adib. Ultra-wideband underwater backscatter via piezoelectric metamaterials. In *Proceedings of the ACM Special Interest Group on Data Communication*. ACM, 2020.

[14] D. Hahnel, W. Burgard, D. Fox, K. Fishkin, and M. Philipose. Mapping and localization with rfid technology. In *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA'04. 2004*, volume 1, pages 1015–1020. IEEE, 2004.

[15] S. Hu, J. Tang, Z. Ren, C. Chen, C. Zhou, X. Xiao, and T. Zhao. Multiple underwater objects localization with magnetic gradiometry. *IEEE Geoscience and Remote Sensing Letters*, 16(2):296–300, 2018.

[16] H. Huang and Y. R. Zheng. Node localization with aoa assistance in multi-hop underwater sensor networks. *Ad Hoc Networks*, 78:32–41, 2018.

[17] H. Huang and Y. R. Zheng. Node localization with aoa assistance in multi-hop underwater sensor networks. *Ad Hoc Networks*, 78:32–41, 2018.

[18] E. A. Iscar Ruland, A. Shree, N. Goumas, and M. Johnson-Roberson. Low cost underwater acoustic localization. In *Proceedings of Meetings on Acoustics 173EAA*, volume 30, page 070006. Acoustical Society of America, 2017.

[19] iXblue. Lbl positioning systems. https://www.ixblue.com/products/range/lbl-positioning-systems, 2020.

[20] J. Jang and F. Adib. Underwater backscatter networking. In *Proceedings of the ACM Special Interest Group on Data Communication*, pages 187–199. ACM, 2019.

[21] D. Kim, D. Lee, H. Myung, and H.-T. Choi. Artificial landmark-based underwater localization for auvs using weighted template matching. *Intelligent Service Robotics*, 7(3):175–184, 2014.

[22] H. Li, C. Tian, J. Lu, M. Myjak, J. Martinez, R. Brown, and D. Z.D. An energy harvesting underwater acoustic transmitter for aquatic animals. *Scientific Reports*, 6(33804), 2016.

[23] C.-C. Liang. A study of a short-baseline acoustic positioning system for offshore vessels. *Marine Geodesy*, 22(1):19–30, 1999.

[24] H. Luo, Y. Zhao, Z. Guo, S. Liu, P. Chen, and L. M. Ni. Udb: Using directional beacons for localization in underwater sensor networks. In *2008 14th IEEE International Conference on Parallel and Distributed Systems*, pages 551–558, 2008.

[25] Z. Luo, Q. Zhang, Y. Ma, M. Singh, and F. Adib. 3d backscatter localization for fine-grained robotics. In *16th {USENIX} Symposium on Networked Systems Design and Implementation ({NSDI} 19)*, pages 765–782, 2019.

[26] Y. Ma, N. Selby, and F. Adib. Minding the billions: Ultra-wideband localization for deployed rfid tags. In *Proceedings of the 23rd Annual International Conference on Mobile Computing and Networking*, pages 248–260. ACM, 2017.

[27] Markets and Markets. Autonomous Underwater Vehicle (AUV) Market worth $1,638 million by 2025. https://www.marketsandmarkets.com/PressReleases/autonomous-underwater-vehicles.asp, 2020.

[28] C. R. McMahon, E. Autret, J. D. Houghton, P. Lovell, A. E. Myers, and G. C. Hays. Animal-borne sensors successfully capture the real-time thermal properties of ocean basins. *Limnology and Oceanography: Methods*, 3(9):392–398, 2005.

[29] J. Ming, N. Hu, X. Niu, and Y. Zhang. Study on the personnel localization algorithm of the underground mine based on rssi technology. In *2017 IEEE 9th International Conference on Communication Software and Networks (ICCSN)*, pages 408–411. IEEE, 2017.

[30] J. Opderbecke. At-sea calibration of a usbl underwater vehicle positioning system. In *Oceans' 97. MTS/IEEE Conference Proceedings*, volume 1, pages 721–726. IEEE, 1997.

[31] A. Palmeiro, M. Martín, I. Crowther, and M. Rhodes. Underwater radio frequency communications. In *OCEANS 2011 IEEE - Spain*, pages 1–8, 2011.

[32] D. Roemmich, G. C. Johnson, S. Riser, R. Davis, J. Gilson, W. B. Owens, S. L. Garzoli, C. Schmid, and M. Ignaszewski. The argo program: Observing the global ocean with profiling floats. *Oceanography*, 22(2):34–43, 2009.

[33] M. S. Schwendeman and J. Thomson. Sharp-crested breaking surface waves observed from a ship-based stereo video system. *Journal of Physical Oceanography*, 47(4):775–792, 2017.

[34] M. Stojanovic. Underwater acoustic communication. *Wiley Encyclopedia of Electrical and Electronics Engineering*, pages 1–12, 1999.

[35] Y. Sun, Y. Yuan, Q. Xu, C. Hua, and X. Guan. A mobile anchor node assisted rssi localization scheme in underwater wireless sensor networks. *Sensors*, 19(20):4369, 2019.

[36] H.-P. Tan, R. Diamant, W. K. Seah, and M. Waldmeyer. A survey of techniques and challenges in underwater localization. *Ocean Engineering*, 38(14-15):1663–1676, 2011.

[37] TELEDYNEMARINE. Reson TC-4014 Hydrophone. Part No. TC-4014 http://www.teledynemarine.com/reson-tc-4014.

[38] The Verge. Alphabet's Tidal moonshot tracks individual fish to help sustainably feed humanity. https://www.theverge.com/2020/3/2/21161029/tidal-moonshot-sustainable-fish-farms, 2020.

[39] D. Tse and P. Viswanath. *Fundamentals of wireless communication*. Cambridge university press, 2005.

[40] D. Vasisht, S. Kumar, and D. Katabi. Decimeter-level localization with a single wifi access point. In *13th {USENIX} Symposium on Networked Systems Design and Implementation ({NSDI} 16)*, pages 165–178, 2016.

[41] J. Wang and D. Katabi. Dude, where's my card? rfid positioning that works with multipath and non-line of sight. In *Proceedings of the ACM SIGCOMM 2013 conference on SIGCOMM*, pages 51–62, 2013.

[42] M. A. Yaqub, S. H. Ahmed, S. H. Bouk, and D. Kim. Towards energy efficient duty cycling in underwater wireless sensor networks. *Multimedia Tools and Applications*, 78(21):30057–30079, 2019.

[43] C. H. Yu, S. H. Min, and J. W. Choi. Performance evaluation of toa-based sensor localization system in underwater sensor networks. In *2015 15th International Conference on Control, Automation and Systems (ICCAS)*, pages 493–498, 2015.

[44] T. Zhao, J. Tang, S. Hu, G. Lu, X. Zhou, and Y. Zhong. State-transition-algorithm-based underwater multiple objects localization with gravitational field and its gradient tensor. *IEEE Geoscience and Remote Sensing Letters*, 2019.