A Survey of Underwater Acoustic Backscatter Communication: BER–SNR Tradeoffs Across Range, Throughput, and Mobility-Focused Designs

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***Abstract*—The underwater acoustic backscatter is rising as a promising approach due to the ultra-low power sensing, however, its performance limits across the different system designs still remain poorly understood and evaluated. The existing approaches and evaluations report the disparate measures across spanning BER (Bit Error Rate), SNR (Signal to Noise Ratio), and throughput – making cross-comparison difficult and obscuring the fundamental tradeoffs between communication distance, data rate, and mobility. To address this gap, we compiled and normalized the results from different backscatter systems and analyzed them across three major design categories: Range Focused System, Throughput Focused System, and Mobility Resilient Focused System. The evaluation reveals a consistent operating constraint: reliable communication is confined to a narrow SNR region (-5 dB to +5 dB) regardless of the architecture. Furthermore, we also observe that the non-overlapping performance envelopes, where the long-range links achieve hundreds of meters at sub-kilo rates, wideband systems deliver tens of kilobits per second within a short range, while the mobility designs occupy a mid-range zone. These limits expose the channel predictability and the intrinsic limits imposed by the underwater propagation thereby providing a unified reference that directly informs the design of future MAC protocols and the routing strategies for underwater backscatter networks.**

I. Introduction

The standard acoustic underwater wireless communication faces several unique challenges when compared with the standard terrestrial systems. The underwater wireless communication methods suffer from attenuation, multipath distortion, and Doppler effects (when the relative motion between the transmitter, receiver, or medium shifts the frequency of the acoustic signals then the Doppler effects occur). These impairments are compounded by several factors such as limited power availability, harsh propagation conditions, and other mobility constraints in the case of AUV (Autonomous Underwater Vehicles) & ROV (Remotely Operated Vehicles)[10]. The traditional acoustic systems rely on the active transmitters, requiring high energy supply and significant infrastructure. On the contrary, the acoustic backscatter communication offers an ultra-low power alternative via reflecting the incident acoustic signals and omits the need for any other active energy transmissions. Henceforth, this approach makes it highly reliable for the Internet of Things (IoT), environmental monitoring, and robotics applications.

This paper primitively explores three major categories of systems: range-focused, throughput-focused and mobility-resilient systems. Each category addresses the operational requirements, key tradeoffs evident with respect to BER, SNR, frequency range, and MAC/PHY protocol design.

Range-focused systems are heavily reliable for maximizing the communication range extending between 300-800 meters of distance by making use of low acoustic frequency ideally between 8-30 kHz[1]. It focuses on the design techniques such as Van Atta acoustic arrays, chirp signaling, and multi-reflector gain mechanisms to boost the link budgets. These systems show the evidence of tolerating very low SNR thresholds as low as -10 dB and achieve very low throughout between 0.4-1 kbps[6]. Furthermore, the MAC protocols minimize the handshakes in order to avoid any expensive round trip delays and also the BER increases with the increase in the distance.

The throughput-focused systems primitively focus on maximizing the data rates extending between 5-25 kbps and it is ideal for any short-range communication distance between 10-50 meters[9]. It makes use of the modulation techniques like QPSK, 8PSK to enhance the bandwidth and the spectral efficiency. The adaptive routing at the MAC and the bandwidth expansion at the PHY layer supports the dense deployments like the underwater ID tags and the real-time sensing.

The mobility-resilient systems primitively focus on enhancing and maintaining the communication of the bodies under water, when the bodies are in motion. Examples of such bodies include AUV, ROV, and drifting sensors. Their operating distance extends between 50-200 meters. To ensure that the communication is standard under water, they rely on the advanced signal techniques like the Doppler compensation, time frequency, Bayesian estimators and deep learning models[11]. The SNR typically ranges from -5 to 0 dB while the BER typically increases by tenfold if it is not compensated.

Therefore, together these categories highlight the key tradeoffs which shape the underwater acoustic backscatter communication via analyzing the BER, SNR, frequency ranges, and MAC/PHY protocols and also underscores the technical aspects and foundations driving the subsea connectivity.

II. Background

Underwater acoustic backscatter systems share a common architectural principle: a remote projector emits an interrogation signal, a piezoelectric tag modulates its impedance to encode information, and a hydrophone receives the reflected waveform. Fig. 1 shows a generic backscatter link diagram illustrating this illumination–reflection–detection pipeline. Regardless of the specific modulation or protocol used, all recent systems build on this foundation

A. Range-specific Backscatter Architectures

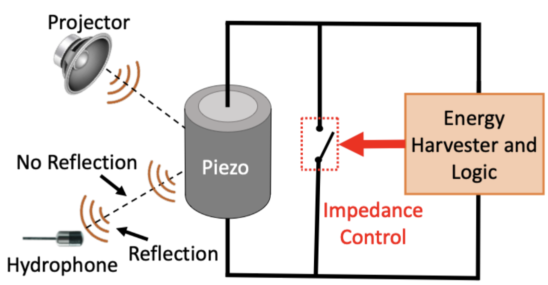

Fig. 1. Architecture - Underwater Backscatter Link [10]

A dominant research direction focuses on stretching the communication range of passive acoustic tags. Retrodirective Van Atta acoustic arrays enable passive beam steering, returning the incident wave back toward the projector without active phase control [1,19]. These arrays provide geometric gain and increase the effective aperture of passive tags.

Akbar et al. developed the most complete theoretical model of the underwater backscatter channel, incorporating frequency-dependent absorption, multipath reflections, surface/bottom losses, and coherent demodulation[2]. Their later experimental validation showed that even with large array gains, practical SNR collapses sharply at long distances [3]. The SIGCOMM link-budget tool formalizes these insights, mapping carrier frequency, projector power, aperture size, and ocean conditions to achievable SNR[5].

These works collectively demonstrate that range is fundamentally bounded by a narrow SNR window. Our dataset's "range-focused" category corresponds to these systems, reflecting the performance regimes.

B. High-Rate and Metasurface-Based Backscatter

A second line of work sacrifices range to push data rate using wideband excitations and richer modulation. Ghaffarivardavagh et al. use piezoelectric metamaterials to realize an ultra-wideband underwater backscatter link capable of tens of kilohertz of occupied bandwidth [4]. By exciting a broad frequency band and performing wideband correlation at the reader, their system achieves higher temporal resolution and supports higher symbol rates than narrowband designs.

Bhardwaj et al. extend this idea to broadband, battery-free acoustic identification tags and ultrasound-powered tags [6,8]. In both cases the tag implements multiple impedance states and the reader performs coherent combining across a wide spectrum, enabling multi-kbps links over tens of meters. Afzal et al. introduce higher-order modulation for underwater backscatter, demonstrating QPSK and 8-PSK constellations over reflected acoustic carriers [10]. Their work shows that once SNR is sufficient, spectral efficiency rather than raw bandwidth becomes the bottleneck.

Metasurface-based designs push rate even further. Raghavendra et al. apply generalized spatial modulation with acoustic metasurfaces, encoding bits in which sub-aperture of a programmable surface is activated [7]. Li et al. survey intelligent metasurfaces more broadly, highlighting how reconfigurable acoustic responses could shape beampatterns and frequency responses jointly for communication and sensing [21]. Together, these papers define our throughput-focused category: systems optimized for $\approx$2–25 kbps operation at short range, as reflected by the high-rate cluster in our range–throughput plots.

C. Mobility-Resilient Backscatter and Channel Learning

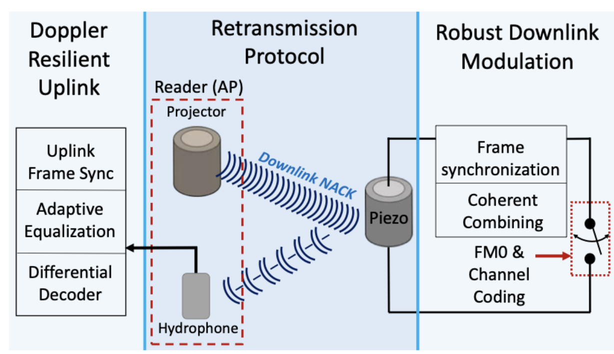

Fig. 2. Improvised Architecture: Energy-Efficient Robust Downlink [11]

Mobility and environmental dynamics introduce Doppler shifts and fast channel variations that are particularly problematic for backscatter, where the signal has already traversed a two-way path. Wang et al. propose mobile underwater backscatter networking, incorporating Doppler-resilient uplink processing, adaptive equalization, and a retransmission protocol tailored to long round-trip times [11]. Their design uses frame synchronization, per-frame equalizer updates, and differential decoding on the uplink, while the downlink employs frame combining and coding to maintain robustness.

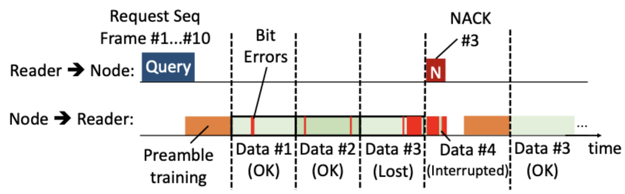

Fig. 3. Sample Retransmission Protocol [11]

The same work introduces a selective NACK-based ARQ protocol, where the reader issues negative acknowledgments only for frames detected as corrupted, rather than restarting an entire transfer. This mitigates the cost of long propagation delays.

Beyond protocol design, several papers target prediction and estimation of the time-varying channel. Liu et al. propose GKCformer, a transformer-based model that forecasts backscatter signal strength and SNR using spatial and temporal features [12]. Wang et al. use Bayesian clustered-sparse estimation to track multipath taps in time-varying OFDM acoustic channels, while Yang and Fang develop improved Doppler sonar velocity estimation methods [13,20]. Gong et al. introduce a multi-carrier excitation scheme to maintain stable SNR across frequency-selective fading [16]. Together, these works populate our mobility-resilient category: their design goal is not necessarily maximum range or rate, but stable BER under motion and environmental variation.

Localization and navigation applications further illustrate the need for mobility support. Afzal et al. show how time-of-flight measurements on backscattered signals can be used for battery-free underwater GPS [15]. Akbar et al. extend the link-budget analysis to realistic subsea IoT deployments, arguing that routing and MAC have to account for spatially varying channel reliability [22]. Our survey connects these PHY and link-layer techniques to higher-layer design choices.

III. Range-Focused System

The range-focused systems prove to be particularly critical for the applications that require the use of sparse sensing, long-distance sensing and remote oceanographic monitoring. The range-focused systems primarily prioritize the communication distance, often reaching the ranges between 300 – 800 meters. These systems are also ideal for operating under severe constraints of signal attenuation, multipath distortion, and low signal-to-noise ratios (SNR). Their design philosophy emphasizes on extending the link budgets, boosting the strength of the reflected signal, and careful selection of the frequency ranges in order to sustain the connectivity over extended distances[25].

A. Frequency Range and Signal Techniques

The range-focused systems typically exercise at very low acoustic frequencies, ideally between 8-30 kHz in order to minimize the absorption losses and extend the propagation distance. Albeit to the cost of the reduced bandwidth and throughput, the low-frequency acoustic operation allows the signals to travel nearly hundreds of meters. It makes use of the signaling techniques like passive steering (eg: Van Atta arrays) and chirp-based signaling. The passive steering makes use of the Van Atta arrays and directs the reflected gain and directional efficiency in a single direction without making use of any excessive power[21]. Another key approach, the chirp-based signaling offers resilience against the multipath fading and aids towards improving the detection at very low SNR levels. Furthermore, to boost the strength of the signals, it implements the multi-reflector gain mechanisms. The multi-reflector gain mechanisms help in amplifying the backscattered signals, focusing on compensating for the inherently weak reflection characteristics of the passive systems.

B. Performance Metrics: BER and SNR

The research reports indicate that these systems can sustain communication at SNR values as low as -10 dB, primarily highlighting their robustness in the noisy underwater channels. Whereas the BER typically ranges between 0.001 to 0.01, with the bit error rate significantly increasing with the increase in distance[23]. This tradeoff reflects the fundamental challenge of balancing the range extension with that of the reliable data delivery. For example, the experimental validations from the reports suggest that the underwater backscatter channels confirm that the BER performance deteriorates rapidly beyond several hundred meters, making it necessary for adaptive error correction and other lightweight strategies.

C. Throughput and Spectral Efficiency

A defining limitation of the range-focused systems is they offer very low throughput, typically between 0.4-1 kbps. This limitation arises because of the narrow bandwidth available at the low acoustic frequencies and the systems need to prioritize signal detectability over the data rate[17]. The range-focused systems are limited and unsuitable for the high-data applications like the video transmission or real-time sensing due to the limited spectral efficiency. Instead, these systems excel providing maximum communication distance in the environments like the monitoring, oceanographic surveys and the sparse sensor deployments focusing on the environments that require periodic and low-rate data collection[19].

D. MAC and PHY Protocol Considerations

At the MAC layer, the range-focused systems typically avoid heavy handshakes like the RTS/CTS (RTS: Request to Send, CTS: Clear to Send), because the long round-trip times (RTT) combined with the low SNR makes these exchanges prohibitively expensive[14]. Alternatively, the lightweight access protocols are favored, which reduces the overhead and ensures that the narrow bandwidth is allotted for the payload transmission. At the PHY layer, the design efforts to mainly focus on enhancing the link budget via frequency selection, reflection optimization, and signal processing techniques. The careful frequency selection helps in the detection and the timing of the signal and signal processing techniques help in boosting the strength of the signal[3]. For example, the

Van Atta acoustic array networks exhibited improved link reliability by redirecting the incident signals back towards the source.

E. Key Tradeoffs

The key tradeoffs in the range-focused systems centrally rely on the distance and throughput. While the communication distances for these systems concentrate up to 800 meters, the throughput remains extremely low, thereby limiting the applications to those only tolerant of sparse data[12]. Similarly, the rate of the BER is directly proportional to the distance i.e. as the distance increases, the BER also increases. Likewise, the spectral efficiency is constrained by the low-frequency operation. Furthermore, the reliance on the passive steering signaling techniques prohibits weak signal strength which requires careful optimization of the reflector design and the frequency selection.

F. Applications

The range-focused systems works very well for the environments which use minimal infrastructure such as the sparse, long-range sensing and the remote deployments [2]. These systems make use of the passive sensors that can communicate over large distances without the need for any active transmitters or batteries, thereby making it ideal for oceanographic monitoring, environmental sensing and subsea exploration. Furthermore, these systems are also ideal for the subsea environments where replacing or recharging of the devices is impractical. Besides, the range-focused systems also support scalable networks of passive nodes which enables wide-area coverage focusing on long-term monitoring campaigns.

IV. Throughput-Focused System

The throughput-focused underwater system primitively focus on maximizing the data rate and are ideal for the short-range applications. These systems operate only atBackscatter Networking a certain distance ideally between 10-50 meters with data rates between 5-25 kbps[22]. The examples of these underwater bodies include identification tags, battery-free camera, and real-time sensor networks. These are ideal for the conditions with dense deployments and rapid data exchanges. By leveraging the use of advanced signal modulation techniques, these systems address the growing demand for the subsea Internet of Things (IoT) applications which primarily uses richer data streams[5].

A. Frequency and Signal Techniques

The throughput-focused systems typically operate at high acoustic temperatures ideally between 100-500 kHz, thereby making it an excellent choice for short range underwater bodies. These high acoustic frequencies focus on providing greater bandwidth, however, suffer from higher absorption losses. These systems make use of the advanced and high modulation signal techniques such as OFDM (Orthogonal Frequency Division Multiplexing), QPSK (Quadrative Phase Shift Keying), 8PSK (Eight Phase Shift Keying), TR (Time-Reversal), GSM (Generalized Spatial Modulation) and Metasurface backscatter communication[24]. The OFDM is a signal modulation technique that splits or divides a single signal into multiple-sub signals as a counterfeit to reduce any interference. This technique improves the spectral efficiency and resilience against the multipath fading. The high modulation techniques such as the QPSK and 8PSK focus on increasing the data rates by encoding more bits per symbol. The QPSK uses four different key shifts by representing the data in the form of 2 bits (eg: 00, 01). Whereas the 8PSK uses eight different key shifts by representing the data in the form of 3 bits (eg: 000, 001)[16]. The Time-Reversal focuses on concentrating the energy back to the source thereby enhancing the signal detectability in the multipath rich environments. The GSM and the Metasurface backscatter communication support in improving the strength of the signals by focusing on spatial diversity and engineered reflectors. Therefore, these techniques enable the throughput-focused systems to achieve high data rates within short distances. However, for the throughput-focused systems to work reliably they require precise alignment and stable channels.

B. Performance Metrics: BER and SNR

By reflecting reliable communication under controlled conditions, these systems offer a BER rate of 0.001. The SNR values are often above 0 dB, but they are only operable within short ranges due to the frequency-dependent absorption. In the case of elevated frequencies, the BER performance can rapidly degrade if the alignment or the synchronization is lost and the SNR values become highly sensitive due to the channel variations[13]. Therefore, adaptive equalization and error corrections are critical to sustain the throughput under practical deployment scenarios.

C. Throughput and Spectral Efficiency

By exceeding the capabilities of the range-focused systems, the throughput-focused systems achieve throughput of about 5-25 kbps data rates. These systems focus on delivering improved spectral efficiency, support dense sensor networks and real time applications via exploiting the wide bandwidths under high frequencies. The OFDM and other higher-order modulation signal schemes are central to this efficiency, thereby allowing multiple subcarriers and symbols to be transmitted simultaneously. However, the spectral efficiency gains are hindered and limited through absorption losses and need precise synchronization ultimately limiting the operational range.

D. MAC and PHY Protocol Considerations

At the MAC layer, the throughput-focused systems mainly emphasize in adaptive routing and efficient scheduling in order to sustain the link quality in the dense environments. Furthermore, particularly in the networks of closely spaced sensors, the protocols are designed to minimize the collisions and optimize the channel utilization. On the contrary, at the

PHY layer, the bandwidth expansion and modulation diversity are prioritized. Some of the examples referring to the PHY innovations are OFDM subcarrier allocation, TR focusing, and metasurface reflectors[4]. These innovations support in enhancing the throughput and reliability of the systems. Together, the MAC and PHY designs ensure in high-rate communication which remain feasible and operable albeit the limitations of the short-range operation.

E. Key Tradeoffs

The central tradeoffs in the throughput-focused systems lies between the data rate and range. While the data rates of upto 25 kbps are achievable, the data communication distances are only constrained between 10-50 meters due to high-frequency absorption. Furthermore, the BER also raises under adverse conditions due to the increase in the sensitivity of the higher-order modulation signal schemes to the noise and alignment errors. Therefore, the prerequisites for the systems' reliable operation are precise synchronization and stable channels. These tradeoffs highlight the niche role of the throughput-focused systems: they excel in dense, short-range deployments but are unsuitable for sparse and long-range sensing.

F. Applications

The throughput-focused systems are ideally suitable for short-range and high-data communications. Some of these examples include underwater identification tags and battery free acoustic ID systems. These underwater bodies require rapid data exchange for authentication and tracking. The battery free cameras help in transmitting the real-time images or video snippets in the dense underwater environments. The dense sensor networks used for the environmental monitoring transmit the signals simultaneously through multiple nodes requiring efficient bandwidth utilization[7]. Overall, these applications focus on enabling richer data streams and real-time responsiveness.

V. Mobility-Resilient System

The mobility-resilient underwater acoustic backscatter systems are designed to maintain and enforce reliable communications in the dynamic environments where the nodes are subject to motion, drift, or in the cases of unpredictable flow. These systems aims to address the unique challenges posed by AUVs (Autonomous Underwater Vehicles), ROVs (Remotely Operated Vehicles) and drifting sensors. The factors such as Doppler shifts, time-varying multipath, and rapid fluctuations in the signal strength tends to degrade the communication quality. The BER usually tends to increase with the mobility resilient systems, and the SNR values typically are between -5 to 0 dB. These systems make use of advanced signal processing, adaptive MAC protocols, and robust PHY designs in order to sustain connectivity in mobile underwater networks.

A. Frequency Range and Signal Techniques

With reference to the operating distance, the mobility resilient systems typically operate within mid-range distances ideally between 50-200 meters, while balancing the frequency selection to mitigate the absorption and support the motion compensation. The advanced signal techniques include Doppler tracking and predication, Time-Frequency (TF), Bayesian estimators and deep learning models and Sparse channel estimation[8]. The Doppler tracking and prediction supports in estimating and maintaining the frequency shifts caused by relative motion. The Time-Frequency (TF) masking mainly isolates the usable signal components from the distorted multipath. The Bayesian estimators and the deep learning models help in adaptively predicting the channel variations and compensate for the motion-induced distortions. Finally, the sparse channel estimation techniques help in maintaining the strength of the signal while reducing the computational overhead accuracy in time-varying channels. Ultimately, these techniques aid the mobility-resilient systems to sustain the communication despite the rapid environmental changes.

B. Performance Metrics: BER and SNR

The mobility-resilient systems are known for maintaining acceptable BER and SNR ranges under motion. With reference to the BER rates, the BER can typically increase 10x without any Doppler compensation. Therefore, advanced and adaptive signal processing techniques are required to maintain the acceptable BER rates. The Doppler compensation introduces the techniques to reduce the interference in the BER rates under motion. However, with compensation, the BER range values are between 0.001 and 0.01[11]. The SNR typically ranges from -5 to 0 dB, which reflects the harsh conditions of the bodies present at mobile underwater channels. These metrics therefore highlight the fragility of the mobile links and the necessity for the implementation of the advanced PHY techniques in order to maintain the communication effectively.

C. Throughput and Spectral Efficiency

The throughput in the mobility-resilient systems reflects the tradeoffs between robustness and data rate while achieving range values between 0.5-2 kbps. Furthermore, these systems highlight the necessity for redundancy and adaptive coding in order to counteract the motion-induced errors with the help of spectral efficiency. Although, the throughput range values in the case of mobility-resilient systems is lower than the throughput-focused system, the mobility-resilient systems focus on prioritizing the link stability and reliability[17]. This is essential to ensure the critical control and telemetry data can be transmitted even under dynamic conditions.

D. MAC and PHY Protocol Considerations

At the MAC layer, the mobility-resilient systems deploy the motion-aware protocols that adapt to the Doppler shifts and fluctuating SNR. To ensure that the connectivity is maintained and established in the mobile networks at all times, these protocols help in minimizing the retransmissions and also adjust the access strategies[7]. The techniques such as adaptive channel estimation, Doppler compensation, and TF masking are central to sustaining communication at the PHY layer.

At the PHY layer, the deep learning-based designs such as transformer-based signal prediction models, enhances the resilience by forecasting channel variations. The innovations at the MAC and PHY layer ensure that communication is maintained at all times underwater when the bodies are in motion.

E. Key Tradeoffs

The primary tradeoffs in the mobility-resilient systems lies between the robustness and throughput. While these systems ensure to maintain connectivity of the bodies under motion, the throughput achieved is extremely low. The BER and the SNR performance values are highly dependent on the throughput range values of the mobility-resilient systems. Therefore, the SNR values remain near the threshold of detectability[15]. Furthermore, the advanced signal techniques aid towards increasing the computational complexity, which might limit the deployment in the resource-constrained devices. Furthermore, another key tradeoff is that these systems are only operable at certain mid-range distances in the dynamic environments and are unsuitable for high-data or long-range applications.

F. Applications

The primitive applications of the mobility-resilient systems include the AUVs, ROVs, drifting sensors and dynamic underwater robotics. The AUVs and ROVs help in navigating the dynamic subsea environments while utilizing reliable communication. The drifting sensors help in monitoring the ocean currents, temperature and salinity which are the factors subject to ocean motion. The dynamic underwater robotics ensure continuous telemetry and control the process of data exchange. These applications collectively make the mobility-resilient systems indispensable for the modern subsea networks since they depend on the ability to sustain communication under motion.

VI. Dataset

This study builds a unified dataset(publicly at my Github Link) by consolidating quantitative measurements reported across underwater acoustic backscatter papers published between 2020 and 2025. Although these works differ in frequency bands, test environments, and modulation methods, they collectively provide comparable metrics over range, received SNR, BER, and effective throughput, which form the basis of our analysis.

To construct a consistent dataset, numerical values were extracted from tables, measurement logs, and plotted curves in each paper; when only graphical data were available, values were digitized directly from figures. Because several papers reported performance qualitatively or without explicit axis values, missing points were approximated using the relative scale and slope indicated in the original plots, ensuring trend accuracy while maintaining cross-paper consistency. All SNR values were mapped to post-processing SNR at the detector input, and BER values were aligned to uncoded symbol-level BER for comparability.

Throughput values were normalized by accounting for guard intervals, pilot overhead, and backscatter duty cycle so that different protocols could be placed on a common scale. The resulting dataset supports the four quantitative relationships studied in this survey research: Range–BER, Range–Throughput, SNR–BER, and category-level performance —distributions, these reflects a view of measurements drawn from both analytical models and real experimental simulations.

This unified representation enables us to compare mechanisms that were originally evaluated under different conditions and to identify consistent operating limits that emerge across all systems.

VII. Results

This section presents the consolidated quantitative trends obtained from the survey dataset, which integrates 25 underwater acoustic backscatter systems published between 2020–2025. The four synthesized plots—Range vs BER, SNR vs BER, Range vs Throughput, and category-wise distribution boxplots—capture the dominant operating regimes, performance limits, and structural trade-offs present across the literature.

A. Range–BER Relationship

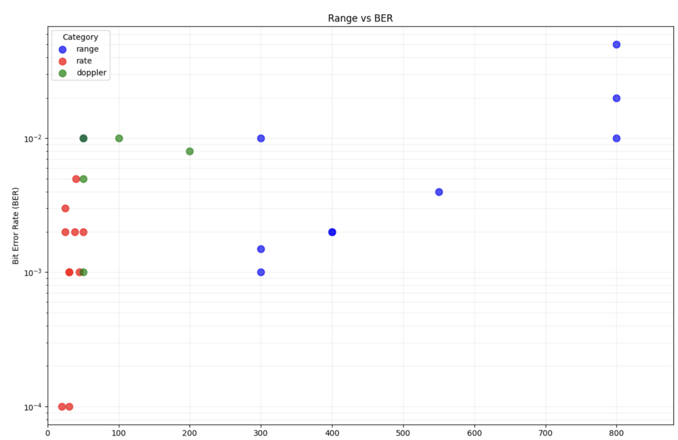

Fig. 4. Range VS BER Plot

The Range vs BER plot aggregates link-level measurements from systems optimized for long-range propagation, high throughput, or Doppler robustness. Across all architectural categories, BER increases exponentially with distance, but the gradient of degradation depends heavily on the system's operating capability.

Short-range wideband systems (typically operating below 80 m) maintain BER between 10^{-4} and 10^{-3} , reflecting operation in high-SNR, low-multipath conditions. These systems use large instantaneous bandwidths or high-frequency carriers, which is effective only while attenuation remains limited and coherence times remain relatively stable.

Mid-range systems (50–200 m), most of which implement Doppler compensation or time-varying channel estimation, exhibit BER in the range of 10^{-3} to 10^{-2}. Although their raw SNR is lower than short-range designs, the use of adaptive filters, symbol-timing correction, and frequency-drift mitigation enables them to maintain a usable error rate despite mobility and rapidly varying channels.

Long-range backscatter systems (300–850 m) cluster between 10^{-3} and 10^{-2} BER. These measurements are consistent with theoretical range scaling: absorption, geometric spreading, and extended multipath delay spreads reduce the effective SNR to the point where error floors become unavoidable. The transition beyond approximately 300 m represents a structural limit observed across the dataset, where propagation loss begins exceeding the detection capability of passive backscatter, regardless of the specific waveform or reflection mechanism used.

B. Range–Throughput

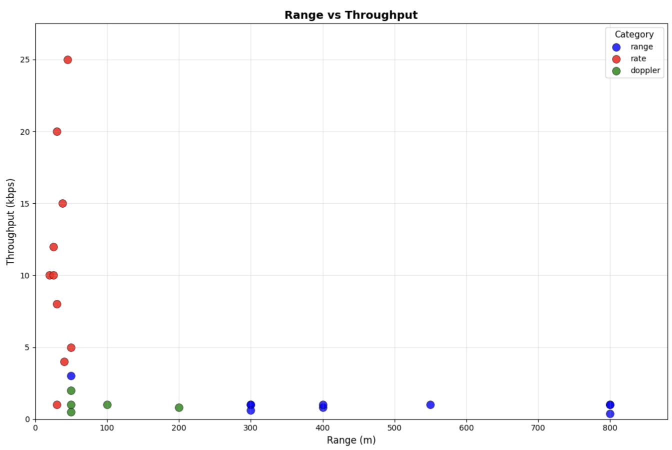

Fig. 5. Range VS Throughput plot

The Range vs Throughput plot consolidates data from all surveyed systems and highlights a clear structural coupling between achievable bandwidth and propagation distance in underwater acoustic backscatter. The distribution shows three distinct operating regimes: short-range high-throughput links, mid-range mobility-resilient links, and long-range low-rate links, each characterized by different physical and architectural constraints.

Across the dataset, throughput decreases rapidly as distance increases. At short distances (10–60 m), systems optimized for data rate consistently achieve between 2 and 25 kbps. These designs rely on wideband excitations, metasurface-assisted reflections, or multi-scatterer index modulation, all of which require high received SNR, limited multipath distortion, and stable coherence over the symbol duration. Their performance collapses beyond roughly 60 m because attenuation, frequency-selective fading, and temporal spreading degrade the spectral efficiency of high-bandwidth signals before they reach the receiver.

Mid-range systems (50–200 m) cluster tightly around 1–2 kbps. These architectures typically incorporate Doppler-aware synchronization, adaptive symbol-timing loops, or low-order modulation with redundancy to maintain tracking under platform motion and channel variation. Although these mechanisms stabilize links in dynamic environments, they consume available bandwidth and reduce effective throughput. As a result, these systems form a performance plateau(upper bound): they extend range through robustness rather than signal acceleration, and the additional processing overhead resulting limits in their data rate.

Beyond nearly 300 m, all systems shows similar performance regardless of waveform, reflection method, or hardware configuration. Long-range backscatter links typically achieve 0.5–1 kbps, reflecting fundamental propagation limits. At these distances, spherical spreading, absorption at moderate frequencies, and severe multipath cause the reflected signal to fall close to the noise floor. Designers compensate by using narrowband carriers, long symbols, and correlation-based detection, which inherently restrict throughput. The fact that multiple independent studies report nearly identical operating points indicates that long-range performance is dominated by physics rather than individual implementation choices.

The resulting curve shows a sharp transition zone, after which throughput decreases by an order of magnitude with every additional 100–150 m of range. This behavior aligns with classical acoustic link-budget predictions but is amplified in backscatter systems because the signal experiences two-way (source-to-tag and tag-to-receiver) attenuation. Overall, the plot reveals a consistent relationship: high throughput is feasible only in high-SNR, short-range regimes, whereas long-range connectivity is possible only at the expense of bandwidth. The empirical clustering across 25 papers suggests that these trade-offs are intrinsic and define the practical operating range of current underwater backscatter technology.

C. SNR–BER Behavior

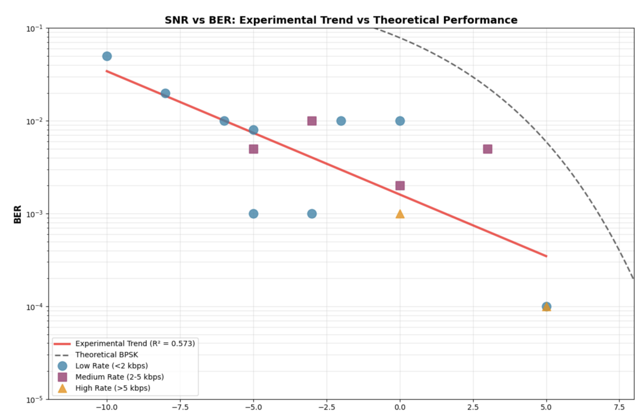

Fig. 6. SNR VS BER plot

The SNR–BER curve aggregates measured performance across the backscatter systems and compares it to the theoretical BER expression for theoretical BPSK, taken from Afzal et al. [10]. The experimental points form a dense cluster between

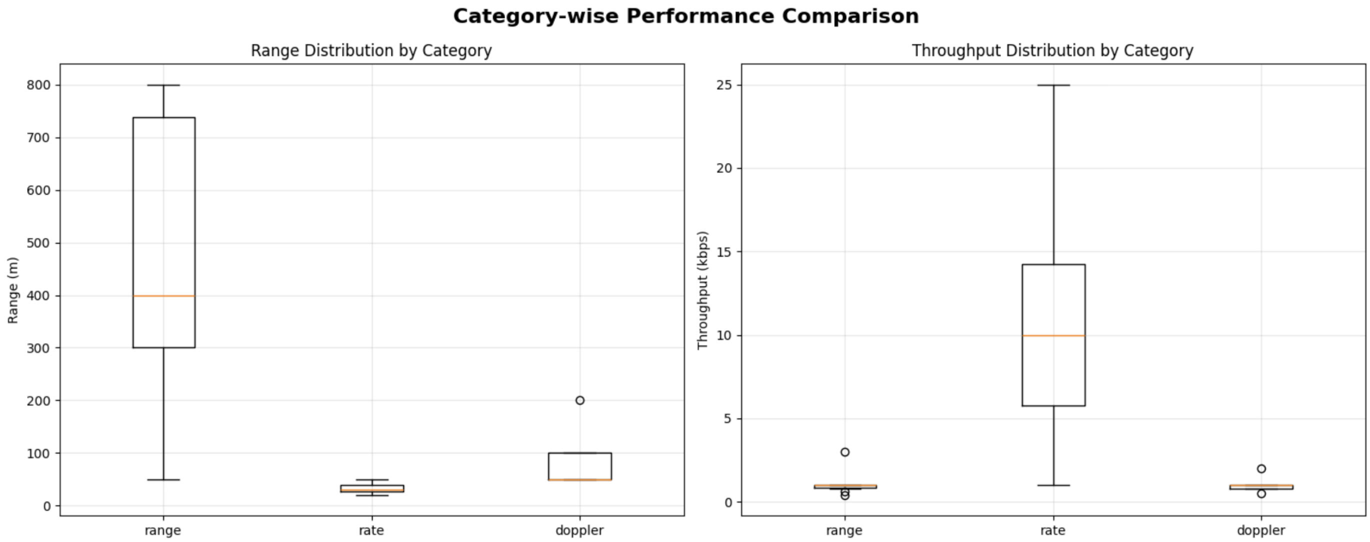

Fig. 7. Performance Comparison Box plot across the identified categories

–10 dB and +5 dB SNR and consistently show BER values in the range of 10^{-2} to 10^{-3}. Notably, almost all experimental points fall below the theoretical BPSK curve. This behavior indicates that many underwater backscatter receivers benefit from processing gains not captured in the ideal AWGN BPSK model.

Several factors explain the observed improvement relative to theory. Many backscatter systems use narrowband excitation, long symbol durations, chirp-based correlation, or matched filtering, which increase effective SNR by integrating energy over extended time windows. In addition, some architectures exploit retrodirective array responses or constructive multipath focusing, which further increases received signal strength. These mechanisms reduce BER beyond what the standard BPSK formula predicts, even though the raw acoustic SNR may be low.

Within the operational SNR window, high-rate systems occupy the upper-SNR region near 0–5 dB, while long-range narrowband systems operate near –10 to –5 dB. Across all categories, BER decreases steadily as SNR increases, but the slope of reduction is less steep than the theoretical model due to channel structure dominating over additive noise.

A consistent operating region emerges: *usable BER is achievable primarily within –5 dB to +5 dB SNR.* Below approximately –5 dB, BER increases sharply for all systems, indicating the onset of decoding instability. Above approximately +5 dB, most systems converge because of multipath, phase distortion, and Doppler effects, but its assumed to be due thermal noise.
Overall, the comparison shows that practical underwater backscatter systems can outperform the ideal BPSK bound due to correlation processing and structured reflections, but remain constrained by a narrow SNR region imposed by the underwater channel.

D. Category-Wise Performance Distributions

The boxplot comparison (Fig. 7) shows how the three design categories: range-focused, rate-focused, and Doppler-resilient systems, these naturally separate into distinct operating regions. In the range distribution, range-focused designs occupy the highest and broadest span, reflecting their ability to maintain connectivity over several hundred meters. Rate-focused systems remain limited to short distances, forming a tight cluster in the lower-range region. Doppler-resilient systems fall between these two extremes, consistent with their emphasis on stability under motion rather than maximizing distance.

The throughput boxplot shows the inverse relationship. Rate-focused systems dominate the upper-throughput region due to wideband and short-range operation. Doppler-resilient designs cluster around moderate throughput values, reflecting the overhead of synchronization and tracking. Range-focused architectures remain at the lower-throughput end because long-distance propagation restricts usable bandwidth.

Together, these distributions confirm that each category exhibits a characteristic performance envelope in both range and throughput, matching the separation shown in the previous plots. The boxplots therefore provide a concise summary of the "expected operating zone" for each system class, consistent with the trends highlighted in the earlier figures.

Conclusion

This survey integrates the last five years of underwater acoustic backscatter research and extracts a unified performance structure from 25 representative systems. By normalizing and comparing range, SNR, BER, and throughput across different architectures, the analysis exposes a set of recurring, channel-driven limits that shape all existing designs. The results show that reliable backscatter communication is limited to a narrow SNR region, that range and throughput occupy mutually exclusive domains, and Doppler-tolerant systems form an intermediate but bandwidth-limited domain. These patterns are consistent across independent experiments, modeling studies, and field trials, indicating that these limitations arise from the acoustic channel itself rather than from implementation differences.

The results shows two contributions to ongoing research. First, it establishes a clear operating range in SNR, range, and bandwidth within which underwater backscatter systems can be expected to function. Second, it identifies the structural trade-off surface separating long-range, high-rate, and mobility-robust designs. This understanding enables future work to target the true bottlenecks: improving channel predictability, incorporating adaptive waveform designs, and developing networking protocols that operate within the constrained SNR–range region observed across all systems. By revealing consistent behavior across different studies, this survey paper provides a clear baseline that researchers can use to design, evaluate, and compare next-generation underwater backscatter networks.

REFERENCES

[1] A. Eid, J. Rademacher, W. Akbar, P. Wang, A. Allam, and F. Adib, "Enabling Long-Range Underwater Backscatter via Van Atta Acoustic Networks," in *Proc. ACM SIGCOMM*, 2023.

[2] W. Akbar, A. Allam, and F. Adib, "The underwater backscatter channel: theory, link budget, and experimental validation," in *Proc. ACM SIGCOMM*, New York, NY, USA, 2023.

[3] W. Akbar, A. Allam, and F. Adib, "Underwater Backscatter: What is its Practical Communication Distance?," *GetMobile: Mobile Comp. and Comm.*, vol. 28, no. 1, pp. 35–39, May 2024.

[4] R. Ghaffarivardavagh, S. S. Afzal, O. Rodriguez, and F. Adib, "Ultra-Wideband Underwater Backscatter via Piezoelectric Metamaterials," in *Proc. ACM SIGCOMM*, 2020.

[5] A. Allam, W. Akbar, and F. Adib, "Demo: Underwater Backscatter Link Budget Tool," in *Proc. ACM SIGCOMM*, 2023.

[6] A. Bhardwaj, A. Erturk, and K. G. Sabra, "Broadband wireless battery-free acoustic identification tags for high data-rate underwater backscatter communication," *J. Acoust. Soc. Am.*, vol. 157, no. 1, pp. 445–458, 2025.

[7] A. H. Raghavendra, S. Gurugopinath, and S. Muhaidat, "Generalized spatial modulation for underwater backscatter communication using acoustic metasurfaces," *Sci. Rep.*, vol. 15, no. 1, Apr. 2025.

[8] A. Bhardwaj, A. Allam, A. Erturk, and K. G. Sabra, "Ultrasound-Powered Wireless Underwater Acoustic Identification Tags for Backscatter Communication," *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, vol. 71, no. 2, pp. 304–313, 2024.

[9] R. Mok and D. Katabi, "Battery-free wireless underwater camera using acoustic backscatter communication," in *Proc. ACM SIGCOMM*, 2022.

[10] S. S. Afzal, R. Ghaffarivardavagh, W. Akbar, O. Rodriguez, and F. Adib, "Enabling Higher-Order Modulation for Underwater Backscatter Communication," in *Proc. Global Oceans 2020*, pp. 1–6.

[11] P. Wang, S. S. Afzal, and F. Adib, "Mobile Underwater Backscatter Networking," in *Proc. ACM SIGCOMM*, 2025.

[12] J. Liu et al., "GKCformer: Transformer-Based Signal Strength Forecasting Model for Underwater Backscatter Communication," *IEEE Internet Things J.*, vol. 12, no. 17, pp. 35577–35588, Sept. 2025.

[13] S. Wang, M. Liu, and D. Li, "Bayesian Learning-Based Clustered-Sparse Channel Estimation for Time-Varying Underwater Acoustic OFDM Communication," *Sensors*, vol. 21, no. 14, p. 4889, 2021.

[14] K. Saijo et al., "TF-LOCOFORMER: Transformer with Local Modeling by Convolution for Speech Separation and Enhancement," *arXiv:2408.03440*, 2024.

[15] S. S. Afzal, R. Ghaffarivardavagh, W. Akbar, O. Rodriguez, and F. Adib, "Underwater Backscatter Localization: Toward a Battery-Free Underwater GPS," in *Proc. ACM SIGCOMM*, 2020.

[16] H. Gong, T. Zhang, Z. Zhao, H. Dong, and J. Tan, "A multi-carrier excitation system for stable underwater backscatter links," *Remote Sens.*, vol. 16, no. 19, p. 3635, 2024.

[17] Y. Song et al., "μMote: Enabling Passive Chirp De-spreading and μW-level Long-Range Downlink for Backscatter Devices," in *Proc. USENIX NSDI*, 2023, pp. 699–715.

[18] T. Govinda Waduge, Y. Yang, and B.-C. Seet, "A Review of Reconfigurable Intelligent Surfaces in Underwater Wireless Communication: Challenges and Future Directions," *J. Sensor Actuator Netw.*, vol. 14, no. 5, p. 97, 2025.

[19] A. Eid et al., "Enabling Long-Range Underwater Backscatter via Van Atta Acoustic Array," in *Proc. ACM SIGCOMM*, 2023, pp. 950–963.

[20] Y. Yang and S. Fang, "Improved Velocity Estimation Method for Doppler Sonar Based on Accuracy Evaluation and Selection," *J. Mar. Sci. Eng.*, vol. 9, no. 6, p. 576, 2021.

[21] L. Li, H. Zhao, C. Liu et al., "Intelligent metasurfaces: control, communication and computing," *eLight*, vol. 2, no. 7, 2022.

[22] W. Akbar, A. Allam, and F. Adib, "Underwater Backscatter Networking for Subsea IoT: A Link-Budget Analysis in Practical Ocean Channels," *IEEE J. Ocean. Eng.*, vol. 50, no. 3, pp. 1703–1717, July 2025.

[23] J. Wang and J. Lian, "Time-reversal waveform design for underwater wireless optical communication systems," *Opt. Express*, vol. 31, pp. 31447–31462, 2023.

[24] S. N. Daskalakis et al., "The New Era of Long-Range "Zero-Interception" Ambient Backscattering Systems: 130 m with 130 nA Front-End Consumption," *Sensors*, vol. 22, no. 11, p. 4151, 2022.

[25] S. Li et al., "Passive DSSS: Empowering the Downlink Communication for Backscatter Systems," Unpublished manuscript, Univ. Electronic Sci. Tech. China.