Proceedings Paper:
Tang, N., Liu, Y., Chu, X. et al. (2026) Poster: Energy efficiency maximization for underwater acoustic backscatter communications. In: Proceedings of the 24th Annual International Conference on Mobile Systems, Applications and Services Companion. MobiSys Companion '26: 24th Annual International Conference on Mobile Systems, Applications and Services Companion, 21-25 Jun 2026, Cambridge, United Kingdom. ACM, pp. 62-63.

https://doi.org/10.1145/3812835.3814880

Poster: Energy Efficiency Maximization for Underwater Acoustic Backscatter Communications

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Abstract

Backscatter communication enables battery-less IoT devices by modulating ambient electromagnetic waves (terrestrial) or acoustic (underwater) waves without active transmission. This paper presents an energy-efficient design framework for underwater acoustic backscatter systems, where high-power transceivers emit acoustic signals and piezoelectric nodes modulate and reflect them back. Our work establishes a comprehensive analytical model that integrates three critical aspects: the electromechanical behavior of piezoelectric nodes, the underwater acoustic channel, and transceiver placement. Leveraging a circuit-theoretic approach to piezoelectric behavior, this framework enables the systematic optimization of key material and communication parameters, including vibration mode selection, circuit loading, and modulation scheme, to maximize energy efficiency. Simulation results validate the effectiveness of the proposed models and optimization strategies, and identify the dominant parameters that govern system energy efficiency.

CCS Concepts

• **Networks** → **Mobile networks**; **Network performance modeling**.

Keywords

Backscatter communications, energy efficiency, Internet-of-Things, piezoelectric materials, underwater acoustics

1 Introduction

The Internet of Things (IoT) has expanded beyond terrestrial environments into challenging domains such as underwater monitoring, environmental sensing, and marine exploration. However, underwater networks face unique constraints, particularly in terms of energy availability, communication range, and hardware durability. Traditional wireless communication methods using electromagnetic waves are severely limited in underwater environments due to the high attenuation of radio frequency signals in water [5, 7].

Underwater acoustic backscatter communication (UABC) emerges as a promising alternative. UABC systems enable battery-free or ultra-low-power operation by leveraging externally generated acoustic carrier waves. Passive sensor nodes can reflect and modulate incident signals without generating new waves, relying on the piezoelectric effect [1–3]. This backscattering process significantly reduces the complexity and energy consumption of underwater nodes, making it ideal for long-term deployment in deep-sea or hard-to-reach areas. Despite its potential, UABC technology is still in its early stages, with limited work integrating electromechanical behavior modeling of UABC nodes with system-level communication and control optimization. Existing approaches (e.g., [4, 6, 8–10]) overlook the influence of piezoelectric materials and vibration modes on reflection efficiency. Furthermore, little attention has been paid to the coordination strategies between node-level attributes and system-level parameters such as node vibration mode, transmit power, node scheduling, modulation, and receiver positioning.

This work bridges these gaps by proposing a UABC system involving an underwater vehicle (AUV) as a high-power transceiver and multiple fixed piezoelectric backscatter nodes. We establish a comprehensive design and optimization framework that integrates circuit-based reflected-power modeling across piezoelectric vibration modes, circuit-based electrical-load optimization at the node, bit error rate (BER) characterization, and joint optimization of AUV positioning, node scheduling, modulation parameters, and vibration-mode selection to maximize system energy efficiency.

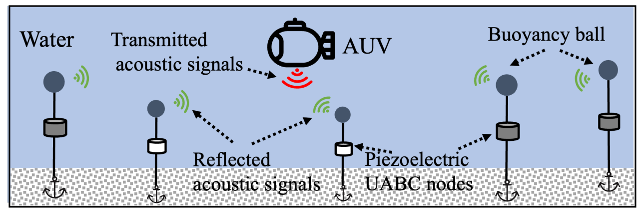

Figure 1: The architecture of a UABC system.

2 System Design and Modeling

The proposed UABC system consists of a mobile AUV equipped with a directional acoustic transceiver and multiple underwater backscatter nodes anchored at fixed locations, as illustrated in Fig. 1(a). The AUV moves horizontally above the node field and communicates with the nodes in a time-division multiple access (TDMA) manner. During each time slot, the AUV transmits a single-tone acoustic signal matched to a node's resonant frequency. The target node then modulates and reflects the signal by adjusting its impedance, embedding its sensed data into the reflected wave via the piezoelectric effect.

As shown in Fig. 2, each UABC node comprises a receiver unit, a backscatter unit, and a data unit. The receiver extracts initialization parameters broadcast by the AUV. The backscatter unit toggles the reflection coefficient by controlling a MOSFET connected to the piezoelectric material, enabling binary modulation. We develop simplified Mason-equivalent circuit models for piezoelectric–acoustic

MobiSys Companion '26, Cambridge, United Kingdom

ACM ISBN 979-8-4007-2711-5/2026/08
https://doi.org/10.1145/3812835.3814880

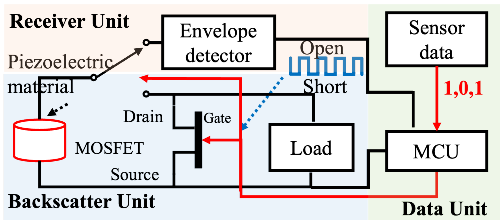

Figure 2: A UABC node.

coupling in both thickness and length modes. The circuit model bridges the mechanical and electrical domains by representing the piezoelectric transducer as a coupled electromechanical system, where the mechanical impedance of the resonator is mapped to an equivalent electrical circuit. By connecting the circuit model to a controlled MOSFET switch, we can characterize how toggling the impedance impacts the reflection coefficient and backscattered signal power. The circuit model serves two main purposes:

- It enables mode-aware analysis of reflection efficiency for each node , which varies between the high-frequency thickness mode and low-frequency length mode.
- It provides closed-form expressions for frequency selective impedance under toggling operations, which are critical for evaluating the backscatter link budget and optimizing transmit pressure.

Based on the circuit model and signal modulation scheme, we derive a closed-form expression for BER under frequency-shift keying with reflection-based modulation, which incorporates node mode selection, acoustic power, and frequency separation. The BER model captures the impact of piezoelectric impedance variation on reflection efficiency and is incorporated as constraints in the optimization problem.

3 Problem Formulation and Optimization

The objective is to maximize the energy efficiency of the UABC system by jointly optimizing the AUV's horizontal position, the node scheduling decisions, the acoustic transmit pressure, the frequency separations used for frequency-shift modulation, the symbol durations for two vibration modes, and the binary selection of the vibration mode at each node. To ensure system performance and feasibility, several constraints are imposed. First, the BER of each node must remain below a predefined threshold to ensure communication reliability. Second, each node must transmit a minimum amount of data during the scheduling window to satisfy data delivery requirements. Additionally, only one node is allowed to transmit per time slot under the TDMA scheme. Practical hardware constraints are also considered. The frequency separation, transmit pressure, and symbol durations are bounded within device-specific operating limits. Lastly, the AUV's movement is restricted to remain within the spatial region defined by the locations of the deployed backscatter nodes.

4 Simulation Results

Simulation results reveal that material choice is found to be critical, with PZT-4 providing broader bandwidth and better performance than $BaTiO_3$. The optimal selection of piezoelectric vibration modes is closely affected by the spatial distribution of nodes, as reflection efficiency declines with increasing distance from the network center. Nodes with shorter ranges perform best in the thickness mode, while the length mode is more suitable for longer communication distances. The proposed joint design achieves up to 16% energy savings compared to benchmark schemes. These findings confirm the importance of incorporating material-aware and distance-aware optimization into the system-level design.

5 Conclusion

We developed a UABC system-level framework that integrates piezoelectric circuit modeling, frequency-shift modulation, and energy-efficient transmission control. Our results demonstrate that considering electromechanical behavior in the design pipeline leads to better coordination between hardware and communication strategies. The proposed system is suitable for batteryless underwater IoT applications such as distributed sensing and infrastructure monitoring. Future work will extend the framework to mobile nodes with Doppler compensation and energy-harvesting integration, while incorporating tank-based experimental validation to assess its performance under realistic underwater acoustic conditions.

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