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Subsea Internet of Things (SIoT): Emerging Technologies for Marine Environmental Monitoring and Offshore Infrastructure Safety — A Critical Review

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ABSTRACT

The Subsea Internet of Things (SIoT)—often framed within the broader Internet of Underwater Things (IoUT)—is moving from pilot trials to targeted deployments for ecological sensing, offshore asset integrity, and safety-critical operations. This review critically examines enabling communications (acoustic, optical, radio-frequency, and magnetic induction), networking and MAC design, localization, energy autonomy, embedded intelligence at the edge, security, and standardization. We evaluate trade-offs that shape real systems and highlight gaps that still impede reliability at scale: brittle channels, fragmented standards, fragile energy budgets, and limited cross-vendor interoperability. We argue that multi-modal links, adaptive stacks co-designed with environment-aware models, and pragmatic standards (e.g., JANUS-family profiles) are near-term levers for progress, while longer-term success hinges on trustworthy autonomy, explainable anomaly detection, and lifecycle sustainability of subsea devices.

KEYWORDS: *Subsea Internet of Things, Internet of Underwater Things, underwater acoustic communication, underwater optical wireless, magnetic induction, marine monitoring, offshore safety, energy harvesting, underwater localization, JANUS.*

INTRODUCTION

The ocean is data-poor relative to its importance for climate, biodiversity, energy, and trade. SIoT aims to change that by interlinking fixed sensor nodes, autonomous underwater vehicles (AUVs), gliders, moorings, and gateways into resilient observatories. Unlike terrestrial IoT, SIoT must contend with extreme propagation variability, sparse bandwidth, long delays, biofouling, and finite energy. The communications triad—acoustic, optical, and (to a limited extent) RF/magnetic induction—defines the feasible envelope for range, rate, and latency. Recent surveys and system papers underscore both progress and persistent bottlenecks across the stack, from physical layer physics to security and interoperability.

ENABLING COMMUNICATION TECHNOLOGIES: A CRITICAL COMPARISON

Acoustic Links (Workhorse of SIoT)

Acoustics remains the only practical option for kilometer-scale links, but channels are band-limited, time-varying, and strongly multipath, with coherence sensitive to sea state, internal waves, bubbles, and bathymetry. Consequences include Doppler, frequency-selective fading, and high latency (sound travels ~1500 m/s). Modern physical layers adopt OFDM variants with adaptive channel prediction/equalization; however, model mismatch and outdated CSI under long delays are chronic issues.

Critical view: Acoustic solutions are mature enough for command/control and low-bit telemetry, but reliability is environment-bound. Overengineering with heavy redundancy wastes scarce bandwidth; underengineering risks unsafe gaps.

Underwater Optical Wireless (UOWC)

Blue-green optical links deliver Mbps–Gbps at meter-to-tens-of-meters ranges with low latency, ideal for data mule/AUV offload or local clusters. Sensitivity to turbidity, alignment, and bio-growth limits robustness; hybrid pointing, beamforming, and adaptive modulation alleviate some constraints. **Takeaway:** UOWC is a powerful complement rather than replacement for acoustics.

Radio Frequency (RF) and Magnetic Induction (MI)

Conventional RF attenuates quickly in seawater (especially above a few hundred kHz), confining use to very low frequencies or near-surface cases. Magnetic induction—near-field coupling via coils—offers short-range, low-latency links relatively immune to multipath and turbidity; recent work explores 3D coils and design optimizations, yet range typically remains within a few meters to tens of meters. **Use case:** structural monitoring inside/around steel/concrete where acoustics struggle.

Synthesis: No single carrier suffices. Practical SIoT will be **multi-modal**, switching among acoustic backbones, optical bursts, and MI/RF niches.

MAC AND NETWORKING: EFFICIENCY UNDER SEVERE CONSTRAINTS

MAC protocols for UWANs must manage long propagation delays, uncertain topology, and asymmetric energy budgets. Recent reviews catalog tone-Lohi, reservation-based, and hybrid contention/scheduling approaches; none dominate across conditions. Cross-layer design—letting physical layer SNR/coherence and mobility cues inform slotting and retransmission—improves goodput but complicates verification. Routing benefits from geography- and opportunity-aware strategies that exploit AUVs as ferries. **Gap:** Benchmarking across realistic ocean dynamics remains limited and fragmented across simulators.

4. LOCALIZATION, SYNCHRONIZATION, AND TIMING

SIoT functions depend on where data originate. Long-baseline (LBL) and ultra-short baseline (USBL) acoustics provide ground truth but add cost and deployment effort. Dead-reckoning drifts; cooperative localization using time-difference-of-arrival and Doppler aids helps, yet performance decays under internal wave activity and moving platforms. Temporal coherence studies show channel statistics—and thus ranging performance—change with internal waves and sea state, urging **adaptive localization filters** rather than fixed-parameter models.

5. EDGE INTELLIGENCE AND IN-SITU DATA REDUCTION

Bandwidth scarcity elevates **compute-then-communicate** pipelines: on-node ML compresses, denoises, and detects anomalies (e.g., leaks, scour, or marine mammal presence) before transmission. Emerging reviews envision AI-driven modality switching and adaptive coding; however, explainability, drift detection, and failure-safe behavior at the edge are under-studied. **Risk:** opaque models in safety-critical contexts (e.g., blowout preventer monitoring).

ENERGY AUTONOMY AND POWER BUDGETS

Energy is the master constraint. Batteries limit maintenance intervals; harvesting (wave, current, thermal gradients, microbial fuel cells) is promising but site-dependent and low-density. Communication modality choice impacts lifetime orders-of-magnitude more than compute in many deployments; MI and optical bursts are energy-lean per bit at short range, acoustics dominate long-range but draw more energy per delivered bit. **Research need:** co-optimizing duty-cycled sensing with event-triggered multi-hop relays and energy-aware MACs validated at sea. (See broad IoUT challenge surveys for energy/storage emphasis.)

INTEROPERABILITY AND STANDARDS

A key blocker in real deployments is **devices that don't talk**. The NATO-promulgated **JANUS** digital acoustic signaling (STANAG 4748) offers a common baseline for discovery, hailing, and low-rate messaging across vendors and platforms; industry profiles such as **SWiGacoustic** tailor parameters for oil & gas subsea operations. Wider adoption enables plug-and-work device discovery, emergency messaging, and gatewaying between proprietary high-rate links and a public control plane. **Critical view:** JANUS solves the "handshake" layer, not high-throughput transport; vendors must still implement robust higher-layer interoperability.

SECURITY AND TRUSTWORTHINESS

SIoT deployments increasingly face adversarial risks (spoofed telemetry, malicious control, privacy of ecological data). Acoustic channels allow **physical-layer fingerprints** and location-based proofs, but moving platforms and volatile channels complicate authentication. End-to-end crypto is necessary yet challenged by key distribution and energy costs. Resilience (graceful degradation, fail-safe states) is as important as confidentiality.

APPLICATION DOMAINS

Marine Environmental Monitoring

Networks track temperature/salinity, dissolved oxygen, acidification, harmful algal blooms, and noise pollution, often combining benthic nodes, moored profilers, and mobile AUV sampling. UOWC offloads rich payloads (video, hyperspectral) locally; acoustics provide backhaul. The literature highlights the need for long-term stability and calibrated sensing under fouling and drift. **Gap:** standardized metadata and provenance across multi-vendor systems.

Offshore Infrastructure Safety

Use cases include corrosion/CP measurements, leak detection on pipelines/risers, fatigue and scour monitoring, and integrity surveillance around platforms and wind farms. Metal structures and complex geometry often favor MI for embedded nodes, with acoustic beacons for alerts and JANUS/SWiG for cross-vendor messaging. **Gap:** end-to-end integrity KPIs that fuse structural models with sparse observations in real time.

CASE FOR HYBRID, ENVIRONMENT-AWARE SIoT

Multiple studies show ocean dynamics (surface waves, internal waves, rain, bubble plumes) reshuffle the acoustic link budget and temporal coherence. Static configurations underperform; **adaptive stacks** that (i) sense channel/state, (ii) predict near-term coherence, and (iii) switch carrier/modulation/MAC accordingly achieve superior reliability and energy efficiency. Pair this with **mission-aware** behavior: e.g., use UOWC bursts when an AUV docks, revert to JANUS-grade signaling in poor acoustic conditions, and keep MI for local intra-structure links.

OPEN CHALLENGES (CRITICAL GAPS)

1. **Channel Ground-Truthing at Scale:** Many algorithms are validated in simulators or short sea trials. Community datasets that couple oceanography, noise, and link performance are scarce; simulator diversity further fragments results.
2. **Energy-First Design:** Energy audits across sensing, compute, and multi-modal links are rarely published; reproducible lifetime models are needed for procurement-grade decisions.
3. **Interoperability Beyond Discovery:** JANUS/SWiG address discovery and minimal messaging. We need profiles for health reporting, time sync, localization beacons, and safe-state commands, plus compliance testbeds.
4. **Trustworthy Autonomy:** Edge AI is promising but fragile. Standards for dataset curation, model validation in dynamic oceans, and fail-safe fallbacks are largely missing.
5. **Localization Under Dynamics:** Internal waves and moving platforms degrade timing/ranging; robust cooperative schemes with real-time environment adaptation remain a frontier.

6. **Human-in-the-Loop Operations:** For safety-critical offshore assets, operators need interpretable alerts, not raw packets. HMI design and explainability deserve equal weight. (Inference based on surveyed needs.)

FUTURE DIRECTIONS

- **Predict-then-Communicate Stacks:** Fuse oceanographic forecasts and online channel prediction to pre-select carriers/parameters (e.g., adaptive OFDM with Kalman-like CSI prediction).
- **Standardized "Common Control Channel":** Widespread JANUS adoption as a universal hail/alert layer, with vendor-specific high-rate payloads tunneled above it; industrial profiles (e.g., SWiGacoustic) to harmonize frequencies, framing, and device discovery.
- **Energy-Sovereign Nodes:** Combine low-power sensing, event-triggered sampling, and hybrid links; quantify lifetime with site-specific harvest models before deployment.
- **Short-Range High-Bandwidth Islands:** UOWC/MI clusters embedded in structures (jackets, risers, monopiles), periodically drained by AUV data mules using optical docks.
- **Security by Design:** Physical-layer auth tied to channel fingerprints plus lightweight crypto, with contingency modes for lossy conditions.
- **Open Datasets & Benchmarking:** Shared sea trials linking environment, traffic, energy, and outcomes; agreed-upon KPIs for "five nines" where needed (e.g., blowout preventer telemetry).

IMPLICATIONS FOR PRACTICE

- **Marine Monitoring Programs:** Start hybrid: acoustic backbone + optical offload at service points; design for fouling mitigation and recalibration; plan energy budgets before sensor selection.
- **Offshore Safety & Integrity:** Use MI for in-structure sensing where metal blocks acoustics; use JANUS/SWiG for vendor-agnostic alarms; keep acoustic channels for ranged backhaul and emergency broadcast.
- **Procurement Checklists:** Require JANUS discovery support, documented energy per delivered bit at specified ranges, and evidence from at-sea trials under declared sea states.

CONCLUSION

SIoT is transitioning from bespoke, siloed pilots to **interoperable, hybrid networks** engineered around the ocean as it is—not as simulators assume. Acoustic links will remain the long-range workhorse; optical and magnetic induction provide crucial short-range, low-latency lanes. The path to reliable, safe, and sustainable SIoT systems runs through environment-aware adaptivity, energy-first design, baseline interoperability (JANUS and industry profiles), and trustworthy on-edge intelligence. With these pillars, SIoT can deliver continuous ecological insight and elevate offshore safety from periodic inspection to real-time assurance.

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