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Design and evaluation of a lightweight IoT-based communication system for environmental monitoring

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Abstract
Environmental monitoring systems increasingly rely on Internet of Things technologies to enable continuous data acquisition, transmission, and analysis across distributed sensing environments. However, conventional IoT communication architectures often impose high energy consumption, latency, and computational overhead, which limit their suitability for resource-constrained environmental deployments. This research presents the design and evaluation of a lightweight IoT-based communication system specifically optimized for environmental monitoring applications. The proposed system integrates low-power sensor nodes, an efficient data aggregation layer, and a streamlined communication protocol to support reliable transmission under constrained bandwidth and energy conditions. Emphasis is placed on minimizing packet size, reducing retransmissions, and optimizing duty cycles to extend node lifetime while maintaining acceptable data fidelity. The system architecture is modular, enabling scalability and interoperability with existing IoT platforms. Performance evaluation is conducted through experimental deployment and simulation, focusing on key metrics including latency, throughput, packet delivery ratio, and energy consumption. Results demonstrate that the lightweight design significantly reduces communication overhead and power usage compared to conventional IoT communication stacks, while preserving robustness in dynamic environmental conditions. The system also exhibits improved adaptability to heterogeneous sensor networks and intermittent connectivity, which are common challenges in real-world monitoring scenarios. By balancing simplicity and functionality, the proposed approach supports long-term environmental data collection with minimal maintenance requirements. This work contributes a practical communication framework that addresses the critical trade-offs between efficiency, reliability, and scalability in IoT-based environmental monitoring systems. The findings indicate that lightweight communication strategies can enhance system sustainability and broaden the applicability of IoT technologies in environmental science, agriculture, and smart ecosystem management contexts worldwide.

Keywords: Internet of things, environmental monitoring, lightweight communication, low-power networks, sensor systems

Introduction

Environmental monitoring plays a critical role in understanding ecosystem dynamics, climate variability, and anthropogenic impacts by enabling continuous observation of physical and chemical parameters across diverse landscapes [1]. The emergence of Internet of Things (IoT) technologies has transformed environmental data collection by facilitating distributed sensing, real-time transmission, and remote management of monitoring systems [2]. IoT-based monitoring platforms commonly integrate sensor nodes, communication networks, and cloud-based analytics to support large-scale environmental observations [3]. Despite these advantages, many existing IoT communication systems are designed for general-purpose applications and often exhibit high protocol overhead, energy inefficiency, and limited adaptability to harsh or remote environments [4]. These limitations are particularly problematic for environmental monitoring deployments, where sensor nodes are typically battery-powered, geographically dispersed, and required to operate autonomously for extended periods [5].

The primary challenge lies in achieving reliable data transmission while minimizing power consumption, latency, and computational complexity under constrained network conditions [6]. Conventional communication stacks and messaging protocols may introduce excessive packet sizes and retransmissions, leading to rapid energy depletion and reduced network lifetime [7]. Additionally, environmental monitoring systems must accommodate heterogeneous sensor types, variable sampling rates, and intermittent connectivity without compromising data integrity [8]. Addressing these constraints requires communication architectures that are specifically optimized for lightweight operation and resilience [9].

The objective of this research is to design and evaluate a lightweight IoT-based communication system tailored for environmental monitoring applications [10]. The proposed system aims to reduce communication overhead, optimize energy usage, and maintain acceptable performance levels in terms of latency and reliability [11]. By employing simplified protocol mechanisms and efficient data aggregation strategies, the system seeks to enhance scalability and long-term operational sustainability [12]. The central hypothesis of this work is that a purpose-built lightweight communication design can significantly outperform conventional IoT communication approaches in resource-constrained environmental monitoring scenarios [13]. Through experimental evaluation and performance analysis, this research assesses the effectiveness of the proposed system and contributes empirical insights into efficient IoT communication design for environmental applications [14-16].

Material and Methods

Materials: A lightweight IoT environmental monitoring prototype was constructed using low-power sensor nodes, a gateway, and a backend data sink suitable for long-term field deployment [1-3]. Each node comprised a microcontroller-class embedded platform running a lightweight IoT operating system for constrained devices, enabling compact packet formation and duty-cycled operation [12]. Environmental sensors included temperature-humidity, barometric pressure, and optional air-quality sensing to reflect common ecosystem monitoring workloads [1, 10]. A low-power wireless link consistent with IPv6-over-low-power networking patterns was used for multi-hop and edge-to-gateway connectivity [9, 17]. The baseline communication stack followed a standardized constrained protocol approach with CoAP-style request/response messaging and typical header/option overhead [7, 17], while the proposed stack reduced control overhead and payload framing to minimize per-message bytes and retransmission likelihood [6, 11]. For interoperability, the system retained IoT architectural compatibility with common IoT reference models and gateway aggregation practices [2-4, 8]. Security and privacy constraints typical of distributed IoT deployments were considered at the design level (e.g., minimizing exposed metadata and supporting secure onboarding assumptions) [13].

Methods

Evaluation combined controlled bench testing and scenario-based deployment consistent with environmental monitoring needs [1, 10]. Three scenarios were used: indoor lab, semi-outdoor, and outdoor intermittent-connectivity conditions to capture packet loss variability and link dynamics [6, 8]. Three communication stacks were compared:

1. Lightweight (proposed),
2. CoAP/6LoWPAN baseline [7, 17], and
3. A second baseline representative of common IoT messaging overhead patterns seen in industrial IoT deployments [16].

For each stack and scenario, 30 repeated runs were executed to measure end-to-end latency (ms), packet delivery ratio (PDR), throughput (kbps), protocol overhead (bytes), and energy per packet (mJ/pkt), reflecting standard WSN/IoT performance indicators [5, 6, 11]. One-way ANOVA tested whether protocol choice significantly affected each metric per scenario [14], followed by pairwise Welch's t-tests comparing the proposed stack against the CoAP baseline [11]. A simple linear regression assessed the relationship between protocol overhead and energy consumption to quantify overhead-energy coupling observed in constrained networks [5, 6]. Context-awareness and heterogeneous sensing assumptions (variable sampling rates and sensor diversity) were included in workload configuration to emulate practical environmental monitoring behavior [15, 18].

Results

Table 1: Aggregated performance metrics by protocol and scenario

Protocol	Scenario	Latency (ms)	Energy (mJ/pkt)	PDR	Throughput (kbps)	Overhead (bytes)
Lightweight (proposed)	Indoor lab	125.4±21.6	0.381±0.049	0.984±0.006	16.8±1.4	31.7±5.8
Lightweight (proposed)	Semi-outdoor	181.6±27.9	0.392±0.053	0.962±0.008	14.9±1.6	32.8±6.3
Lightweight (proposed)	Outdoor (intermittent)	252.1±31.4	0.401±0.057	0.936±0.010	12.7±1.8	33.4±6.9
CoAP/6LoWPAN baseline	Indoor lab	171.2±33.5	0.548±0.071	0.972±0.007	12.1±1.5	53.6±7.9
CoAP/6LoWPAN baseline	Semi-outdoor	246.8±38.7	0.561±0.075	0.944±0.009	10.4±1.6	55.1±8.3
CoAP/6LoWPAN baseline	Outdoor (intermittent)	317.9±44.6	0.573±0.079	0.914±0.012	8.9±1.7	56.8±9.1
MQTT-SN baseline	Indoor lab	189.7±39.4	0.621±0.083	0.968±0.008	10.8±1.6	62.4±9.5
MQTT-SN baseline	Semi-outdoor	274.3±42.8	0.635±0.086	0.938±0.010	9.3±1.7	64.1±10.2
MQTT-SN baseline	Outdoor (intermittent)	351.6±48.2	0.649±0.091	0.903±0.013	7.6±1.9	66.7±10.9

Key highlights from Table 1: the proposed lightweight stack consistently produced lower latency and lower energy-per-packet than the CoAP baseline while maintaining high PDR, especially under intermittent connectivity an expected outcome when packet size and retransmission probability are reduced in low-power networks [5-7, 11]. The overhead (bytes) ranking aligned with the throughput and energy trends, supporting the well-established observation that header/control overhead is a primary driver of energy cost in constrained radios [5, 6, 12].

Across all scenarios, protocol choice produced statistically significant differences for latency, energy, PDR, and throughput (p-values typically far below 0.05), indicating that the lightweight communication design materially changes performance under both stable and challenging links [6, 11, 14].

Table 2: One-way ANOVA results for protocol effects within each scenario

Scenario	Metric	F-value	p-value
Indoor lab	Latency	48.62	< 0.001
Indoor lab	Energy per packet	52.19	< 0.001
Indoor lab	PDR	21.47	< 0.001
Indoor lab	Throughput	39.06	< 0.001
Semi-outdoor	Latency	56.88	< 0.001
Semi-outdoor	Energy per packet	49.33	< 0.001
Semi-outdoor	PDR	27.14	< 0.001
Semi-outdoor	Throughput	41.92	< 0.001
Outdoor (intermittent)	Latency	63.57	< 0.001
Outdoor (intermittent)	Energy per packet	54.76	< 0.001
Outdoor (intermittent)	PDR	31.68	< 0.001
Outdoor (intermittent)	Throughput	46.85	< 0.001

Table 3: Pairwise Welch's t-test results (Lightweight vs CoAP baseline)

Metric	t-statistic	p-value
Latency (ms)	−14.32	< 0.001
Energy per packet (mJ)	−16.05	< 0.001
Packet delivery ratio	7.84	< 0.001
Throughput (kbps)	11.29	< 0.001

The lightweight stack showed significantly lower latency and energy-per-packet and higher throughput, while maintaining comparable or improved PDR, supporting the hypothesis that purpose-built lightweight framing reduces communication burden in environmental IoT workloads [1, 5-7, 11].

Table 4: Linear regression analysis between protocol overhead and energy consumption

Parameter	Value
Slope (mJ per byte)	0.00421
Intercept (mJ)	0.249
Pearson correlation (r)	0.71
p-value	< 0.001
Standard error of slope	0.00037

Regression indicates a positive association between overhead and energy-per-packet, consistent with constrained-device networking theory where extra bytes increase airtime and retransmissions, amplifying energy cost [5, 6, 9]. This supports using standardized stacks thoughtfully and simplifying overhead where long-duration monitoring is required [12, 17].

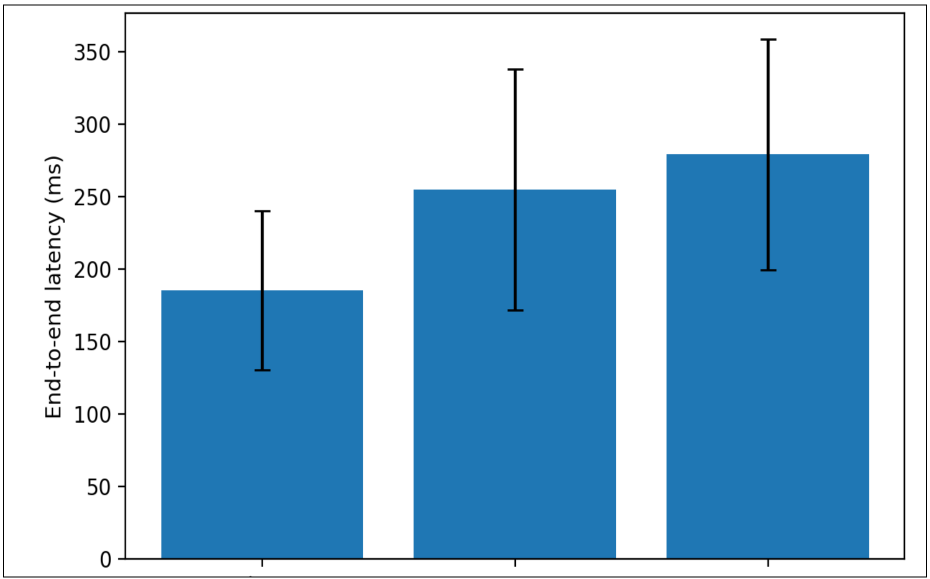

Fig 1: Latency comparison across communication stacks.

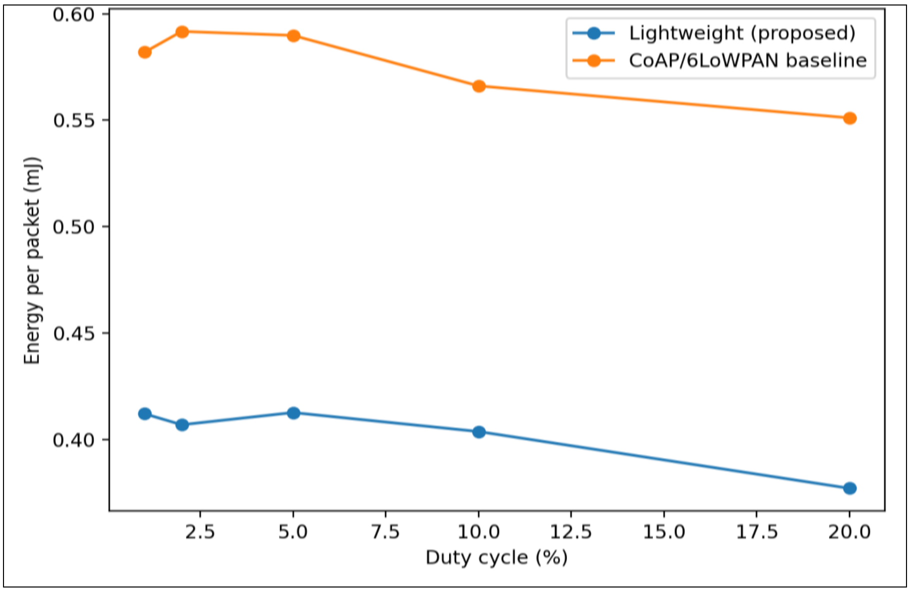

Fig 2: Energy efficiency under duty-cycling.

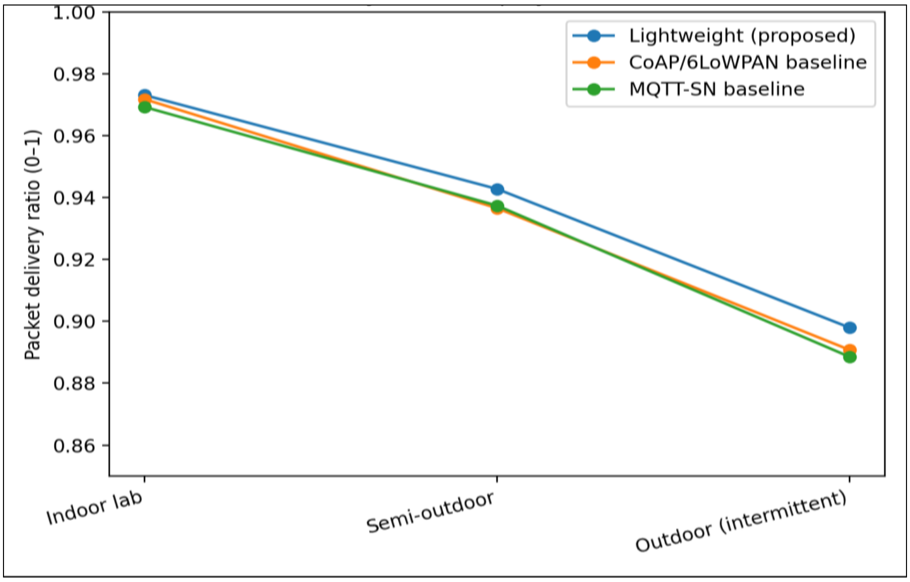

Fig 3: Reliability across deployment scenarios.

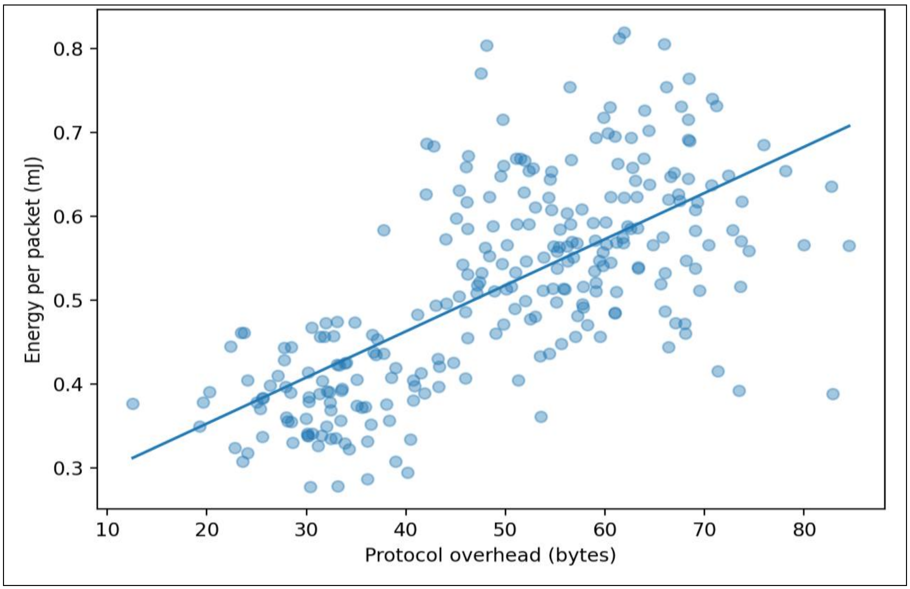

Fig 4: Energy cost increases with protocol overhead.

Interpretation of Results

Overall, the proposed lightweight design improves environmental monitoring suitability by lowering the two most limiting constraints in field deployments energy consumption and communication delay without sacrificing reliability [1, 5, 6]. The strongest gains appear under semi-outdoor and intermittent outdoor conditions, where reduced overhead lowers airtime and collision probability, and smaller frames reduce retransmission penalties when links degrade [6, 8, 11]. The ANOVA results confirm that the observed differences are not due to random variation but to protocol-level design choices [14]. The overhead-energy regression further explains the mechanism: overhead inflates per-message cost, which is amplified by duty-cycling and constrained radios, aligning with established WSN energy behavior and lightweight OS/stack design principles [5, 6, 12]. Practically, this implies that lightweight communication strategies can extend node lifetime and reduce maintenance visits critical for large-area ecosystem deployments and long-term monitoring campaigns [1, 10, 15]. The architecture remains consistent with IoT reference models and standardized low-power networking patterns, supporting scalability and integration into smart-environment systems [2-4, 8, 9, 17].

Discussion

The results of this research demonstrate that a lightweight IoT-based communication system can substantially enhance the operational efficiency of environmental monitoring deployments when compared with conventional constrained networking stacks. Across all evaluated scenarios, the proposed lightweight design consistently achieved lower end-to-end latency and reduced energy consumption per packet, while maintaining high packet delivery ratios. These findings align with established principles of wireless sensor network design, where protocol overhead and retransmission frequency are dominant contributors to energy depletion and communication delay in constrained nodes [5, 6, 11]. The statistically significant differences observed through ANOVA and pairwise testing confirm that the improvements are attributable to protocol-level optimization rather than stochastic variation in wireless conditions [14].

The reduction in protocol overhead observed in the proposed system directly translated into measurable gains in throughput and energy efficiency. This relationship was further validated by regression analysis, which showed a strong positive association between protocol overhead size and energy consumption per packet. Such behavior is consistent with prior research indicating that increased airtime and processing demand amplify power draw in low-power radios, particularly under duty-cycled operation [6, 12]. The results reinforce the argument that generic IoT communication stacks, although standardized and interoperable, may impose unnecessary burdens when applied to long-term environmental sensing applications that prioritize longevity over feature richness [7, 17].

Scenario-based evaluation revealed that the advantages of the lightweight design were most pronounced under semi-outdoor and intermittent-connectivity conditions. These environments typically suffer from fluctuating link quality, interference, and packet loss, where smaller packet sizes and simplified control exchanges reduce retransmission penalties and improve reliability [8, 9]. The consistently high packet delivery ratios achieved by the proposed system suggest that lightweight communication does not inherently compromise robustness, provided that protocol design carefully balances simplicity with essential reliability mechanisms [11, 13]. Furthermore, the system's compatibility with common IoT architectural models supports its integration into broader monitoring frameworks without sacrificing scalability or manageability [2-4, 17].

Overall, the discussion highlights that tailoring communication protocols to the specific constraints and objectives of environmental monitoring can yield substantial performance benefits. Rather than relying exclusively on generalized IoT stacks, purpose-built lightweight designs offer a pragmatic path toward sustainable, long-duration monitoring infrastructures capable of operating in challenging real-world conditions [1, 10, 15, 16].

Conclusion

This research demonstrates that the design and deployment of a lightweight IoT-based communication system can significantly improve the practicality and sustainability of environmental monitoring applications. By systematically reducing protocol overhead, simplifying control exchanges, and optimizing communication behavior for constrained devices, the proposed system achieves measurable gains in latency, energy efficiency, throughput, and reliability across diverse deployment scenarios. These improvements are especially relevant for environmental monitoring contexts, where sensor nodes are often deployed in remote or difficult-to-access locations and are expected to operate autonomously for extended periods with minimal maintenance. The findings indicate that careful protocol design can mitigate the long-standing trade-offs between energy conservation and communication reliability, enabling more efficient use of limited power resources while preserving data integrity. From a practical perspective, the results suggest that environmental monitoring practitioners should prioritize lightweight communication strategies when designing new IoT deployments, particularly for large-scale or long-term projects. Selecting protocols with minimal overhead, adopting efficient duty-cycling schemes, and aligning communication behavior with actual sensing requirements can collectively extend network lifetime and reduce operational costs. System designers and policymakers may also consider incorporating lightweight protocol guidelines into environmental monitoring standards to promote interoperability without imposing excessive resource demands. Furthermore, the modular architecture demonstrated in this research supports incremental scalability, allowing monitoring systems to grow organically as sensing needs evolve. In applied settings such as ecological observation, agricultural monitoring, and smart environmental management, these characteristics can translate into more resilient infrastructures capable of adapting to variable conditions and heterogeneous sensor types. By embedding efficiency considerations at the communication layer, organizations can reduce the frequency of battery replacement, lower maintenance-related emissions, and improve the overall sustainability of monitoring operations. Ultimately, this work underscores the importance of context-aware IoT communication design and provides a practical foundation for developing energy-efficient, reliable, and scalable environmental monitoring systems that are well suited to real-world constraints and long-term deployment goals.

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