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A Novel Lightweight MQTT-Like Protocol for Bidirectional Command and Control in LPWAN Networks: Design, Implementation, and Performance Evaluation

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***Abstract*—Low Power Wide Area Networks (LPWAN) have emerged as a fundamental technology for Internet of Things (IoT) applications requiring long-range communication with minimal energy consumption. However, existing application-layer protocols such as MQTT-SN and CoAP were not specifically designed for the unique constraints of LPWAN, including strict duty cycle limitations (typically 1% in EU868 band), asymmetric uplink/downlink capacity, and limited downlink opportunities. This paper presents a novel lightweight MQTT-like protocol specifically designed for bidirectional command and control in LPWAN networks. The proposed protocol introduces six key innovations: (1) Micro-Session Token mechanism for stateless device operation reducing state storage to 20–32 bytes, (2) Windowed Bitmap ACK scheme enabling acknowledgment aggregation of up to 16 messages in a single downlink, (3) Deadline-Probability based QoS semantics replacing traditional QoS 0/1/2 with probabilistic guarantees, (4) Command Pull Slot mechanism exploiting receive windows opportunistically, (5) Compact 5-byte header format reducing overhead by 40%, and (6) Epoch-based idempotent commanding eliminating duplicate processing. We implement and evaluate the protocol using discrete-event simulation across three comprehensive experimental scenarios comprising 660 configurations: Command Control Timing, Network Scalability, and Duty Cycle Compliance. Results demonstrate that the proposed protocol achieves comparable delivery rates (96.46%–98.18%) to baseline protocols while reducing energy consumption by 11.1% compared to CoAP and 3.0% compared to MQTT-SN. The protocol successfully handles command latencies in the range of 407–600 seconds under realistic LPWAN conditions with 1% duty cycle constraints, validating its suitability for delay-tolerant command and control applications such as smart agriculture, infrastructure monitoring, and industrial IoT.**

***Keywords*—LPWAN, MQTT-SN, CoAP, IoT Protocol, Command and Control, Low Power, Bidirectional Communication, LoRaWAN, NB-IoT**

I. Introduction

The proliferation of Internet of Things (IoT) devices has driven significant interest in Low Power Wide Area Network (LPWAN) technologies such as LoRaWAN, NB-IoT, and Sigfox [1]. These technologies enable long-range communication (up to 15 km in rural areas) while maintaining extremely low power consumption, making them ideal for battery-operated sensors and actuators in smart city, agriculture, and industrial monitoring applications [2]. Notably, LPWAN technologies are increasingly deployed for distributed control systems, including agricultural robotics, Supervisory Control and Data Acquisition (SCADA)-based infrastructure monitoring, and remote actuator control in Industrial Internet of Things (IIoT) environments where reliable bidirectional Command and Control (C&C) is essential. The global LPWAN market is projected to grow substantially, with billions of devices expected to be deployed by 2030 [3].

A. LPWAN Characteristics and Challenges

Unlike traditional wireless networks, LPWAN systems are characterized by unique constraints that fundamentally affect protocol design:

- **Strict duty cycle limitations**: Regulatory constraints (e.g., 1% duty cycle in EU868 band for LoRaWAN, 10% for some sub-bands) severely limit transmission opportunities [4]–[6]. This means devices can transmit only 36 seconds per hour, necessitating careful resource allocation.
- **Asymmetric uplink/downlink capacity**: Downlink is typically more constrained than uplink due to gateway limitations and regulatory requirements. For LoRaWAN Class A devices, downlink is only possible in two short receive windows (RX1, RX2) immediately following an uplink transmission [4], [7].
- **Long round-trip times**: Round-Trip Time (RTT) can range from seconds to minutes depending on the duty cycle and network configuration. NB-IoT exhibits latencies of 1–10 seconds for Connection Setup procedures [8], [9], while LoRaWAN command delivery can take hundreds of seconds [10].

- **Limited payload sizes**: Maximum payload sizes are typically 51–222 bytes for LoRaWAN (depending on spreading factor SF7–SF12) and 1600 bytes for NB-IoT [11], [12].
- **Energy constraints**: Battery-operated devices must operate for 5–10 years on a single battery charge [13]–[15], requiring energy consumption in the range of 10–50 mJ per message.

B. Limitations of Existing Protocols

Existing application-layer protocols were not designed with these LPWAN constraints in mind. Recent comparative studies reveal significant limitations:

MQTT over TCP: The standard MQTT protocol requires persistent TCP connections and stateful session management with periodic keepalive messages [16], [17]. Studies on NB-IoT and LTE-M consistently show that MQTT/TCP incurs significant overhead—up to 2x higher energy consumption compared to UDP-based alternatives [8], [18]–[20]. The TCP three-way handshake alone can consume 20–30% of total transmission energy [21].

MQTT-SN: While MQTT-SN (MQTT for Sensor Networks) provides a more lightweight alternative with compact headers (7+ bytes), numeric topic IDs, and support for sleeping clients [22]–[24], it still maintains per-message QoS acknowledgments that are inefficient under strict duty cycle constraints [25]. MQTT-SN uses standard QoS 0/1/2 semantics which do not map well to LPWAN probabilistic delivery characteristics [26], [27].

CoAP: The Constrained Application Protocol (CoAP), though UDP-based and lightweight with 4-byte headers, uses confirmable (CON) messages that require individual acknowledgments [28], [29]. Comparative studies show CoAP generates higher control overhead than MQTT-SN in dense IoT networks [27], [30], [31] and exhibits 10–20% higher energy consumption per message compared to optimized solutions [32], [33].

C. Research Gap and Motivation

Recent literature reviews [3], [22], [34] reveal that despite extensive research on IoT protocols, no application protocol has been specifically designed for LPWAN bidirectional command and control with:

- **Minimal device-side state**: Existing protocols require 100s–1000s of bytes for session state, subscriptions, and message tracking [25].
- **Gateway-centric intelligence**: Current designs distribute complexity across devices and brokers, unsuitable for resource-constrained endpoints.
- **Aggregate acknowledgments**: Per-message ACKs waste precious downlink capacity [8].
- **LPWAN-aware QoS**: Traditional QoS 0/1/2 semantics do not account for duty cycle constraints and probabilistic delivery [35].
- **Opportunistic downlink utilization**: Existing protocols do not explicitly optimize for RX window exploitation [4].

D. Contributions

This paper addresses the identified research gap by proposing a novel lightweight protocol specifically designed for bidirectional command and control in LPWAN networks. Our contributions are:

1) **Micro-Session Token mechanism**: Eliminates device-side session state (reducing to 20–32 bytes total) while maintaining security and identity through long-lived cryptographic tokens.
2) **Windowed Bitmap ACK scheme**: Aggregates acknowledgments for up to 16 messages in a single downlink, reducing ACK traffic by 93.75% compared to per-message acknowledgments.
3) **Deadline-Probability QoS semantics**: Replaces traditional QoS 0/1/2 with tuples $(P_{delivery}, T_{deadline})$ that naturally express LPWAN probabilistic guarantees.
4) **Command Pull Slot mechanism**: Exploits receive windows opportunistically, allowing devices to “pull” pending commands only during scheduled uplinks.
5) **Compact header format**: 5-byte fixed header for 90% of messages, reducing overhead by 40% compared to MQTT-SN.
6) **Epoch-based commanding**: Idempotent command delivery using version epochs, eliminating the need for expensive “exactly once” semantics.
7) **Comprehensive evaluation**: Discrete-event simulation across 660 configurations demonstrating 11.1% energy improvement over CoAP and 3.0% over MQTT-SN.

E. Paper Organization

The remainder of this paper is organized as follows. Section II reviews related work on LPWAN application protocols. Section III presents the detailed protocol design. Section IV describes the simulation methodology. Section V presents experimental results. Section VI discusses findings and limitations. Section VII concludes the paper.

II. Related Work

A. LPWAN Application Layer Protocol Evaluations

Extensive research has evaluated existing protocols on LPWAN technologies, particularly NB-IoT and LTE-M.

NB-IoT Studies: Larmo et al. [8] conducted one of the first comprehensive studies comparing CoAP/UDP and MQTT/TCP over NB-IoT. Their findings show that CoAP consistently outperforms MQTT in latency (30–50% lower), coverage (better performance at cell edge), and system capacity (2x more devices supported).

Parmigiani and Dettmar [18] extended this comparison to include LwM2M, evaluating over-the-air traffic and energy consumption. Their measurements reveal that LwM2M and MQTT influence operational time differently—MQTT persistent connections can be more energy-efficient for frequent transmissions (>1 per hour), while LwM2M excels for infrequent reporting.

Khan and Pirak [32] performed experimental analysis using commercial NB-IoT smart meters with SIM7020E modems. Results show environment-dependent performance: CoAP achieves 15–20% lower packet loss in poor signal conditions (<-110 dBm).

B. IoT Protocol Comparisons

General IoT Protocol Surveys: Wytrębowicz et al. [22] provided a pragmatic comparison of messaging protocols for IoT systems, evaluating MQTT, MQTT-SN, CoAP, AMQP, and others. They identified MQTT-SN's compact headers, numeric topic IDs, QoS -1 fire-and-forget mode, and sleeping client support as particularly relevant for constrained devices.

Dizdarević et al. [3] surveyed communication protocols for fog-to-cloud IoT integration, analyzing latency, energy consumption, and network throughput. They concluded that protocol selection is highly deployment-dependent, with no single protocol dominating across all metrics.

Martí et al. [30] evaluated CoAP and MQTT-SN energy consumption in Wireless Sensor Networks (WSN). Simulations showed MQTT-SN achieves 10% lower power consumption and 30% lower latency compared to CoAP for 40-node networks.

C. MQTT-SN Specific Research

MQTT-SN Enhancements: Palmese et al. [35] proposed an adaptive QoS controller for MQTT-SN that dynamically assigns QoS levels based on network conditions. Their ns-3 simulations demonstrate adaptive QoS improves delivery ratio by 15–25% compared to fixed QoS assignments.

Nast et al. [36] designed a standalone MQTT-SN broker implementation decoupled from standard MQTT, enabling UDP-based pub/sub without MQTT dependency. Performance measurements show their implementation is 3x faster than specification-compliant MQTT-SN-to-MQTT gateways.

D. Bidirectional Command and Control

Smart Home Applications: Esposito et al. [37] implemented a complete smart home framework using NB-IoT + MQTT + serverless functions. Their prototype demonstrates voice command transmission from cloud to device via MQTT topics with acceptable NB-IoT latency (2–5 seconds).

Takruri et al. [38] designed a real-time street light dimming system using NB-IoT with UDP for bidirectional control. The system achieves real-time response (subsecond) through local microcontroller control with cloud monitoring, resulting in 55% energy savings.

E. Gap Analysis and Positioning

The comprehensive literature review reveals:

1) **Protocol Evaluation Focus:** Most research evaluates existing protocols rather than designing new LPWAN-specific protocols [8], [14], [18], [21].
2) **MQTT-SN as Best Current Option:** MQTT-SN emerges as most suitable existing protocol for constrained devices [22], [30], [39], but it still uses per-message ACKs and QoS 0/1/2 semantics not optimized for LPWAN.
3) **Energy Efficiency Gap:** Studies show 10–45% energy variations between protocols [11], [19], [40], indicating room for LPWAN-specific optimization.
4) **No Stateless Device Protocols:** All existing protocols maintain session state at devices.
5) **No Aggregate Acknowledgments:** Existing protocols use per-message or per-transaction ACKs, wasting downlink capacity.

Our proposed protocol fills this gap by specifically designing for LPWAN bidirectional operations with device statelessness, aggregate ACKs, opportunistic downlink, and probabilistic QoS semantics.

III. Protocol Design

A. Design Principles

The proposed protocol is built on four core principles:

1) **Device Statelessness**: All session state resides at the gateway; devices maintain only a minimal token and sequence numbers.
2) **Gateway Intelligence**: Complex scheduling, QoS management, and protocol translation are handled by the gateway.
3) **Opportunistic Downlink**: Commands are delivered only during receive windows following uplink transmissions.
4) **Aggregate Acknowledgment**: Multiple messages are acknowledged in a single downlink frame.

B. Micro-Session Token Mechanism

Unlike MQTT's CONNECT/CONNACK handshake, devices are provisioned with a micro-session token during initial setup:

- **Token size**: 64–96 bits (8–12 bytes)
- **Token lifetime**: Very long (monthly renewal)
- **Device state**: Only token + sequence counters (total ∼20–32 bytes)

The token is included in every uplink and downlink message, providing identity and context without connection establishment overhead.

C. Windowed Bitmap ACK Scheme

Instead of per-message acknowledgments, the protocol uses a bitmap-based aggregated ACK:

- Each uplink carries `seq_u` (12–16 bit sequence number)
- Downlink ACK carries:
  - `ack_base_u`: Base sequence number
  - `ack_bitmap_u`: 16-bit bitmap acknowledging up to 16 uplinks

This reduces downlink ACK traffic by up to 16x compared to per-message acknowledgments.

D. Deadline-Probability QoS

Traditional MQTT QoS levels (0/1/2) are replaced with deadline-probability tuples:

$$QoS_{DP} = (P_{delivery}, T_{deadline}) \tag{1}$$

For example, $(0.9, 1h)$ indicates 90% delivery probability within 1 hour. This semantic better matches LPWAN characteristics where:

- Exact delivery timing is unpredictable due to duty cycle
- Probabilistic reliability is more practical than guaranteed delivery
- Application deadlines vary significantly

E. Compact Header Format

The protocol uses a fixed 5-byte header for 90% of messages:

TABLE I
COMPACT HEADER FORMAT

Byte	Bits	Field
0	7..5 4..3 2..0	msg_type (3 bits) prio_class (2 bits) topic_class (3 bits)
1–2	15..0	seq_u (16 bits)
3	7..0	flags (8 bits)
4	7..0	token_short (8 bits)

F. Gateway Overhead Analysis

The proposed protocol shifts complexity from resource-constrained devices to the gateway:

Memory Requirements per Device:

- Token management: 16 bytes
- Sequence tracking: 8 bytes
- Command queue: 64–256 bytes
- QoS state: 8 bytes
- **Total per device**: $\sim$96–288 bytes

For comparison, MQTT-SN gateway requires $\sim$200–500 bytes per device, and CoAP server requires $\sim$150–400 bytes per device.

G. Security Considerations

Token Generation and Distribution:

- Tokens generated using Cryptographically Secure Pseudo-Random Number Generator (CSPRNG) during device provisioning
- Token entropy: 64–96 bits provides 2^{64}–2^{96} possible values
- Default lifetime: 30 days (configurable)

Threat Model and Mitigation: Table II summarizes the threat model, mitigation mechanisms, and associated overhead.

TABLE II
SECURITY THREAT ANALYSIS

Threat	Mitigation	Overhead
Replay attack	Monotonic seq_u; gateway rejects seq $\leq$ last_seen	2B per msg (seq field)
Token theft	LoRaWAN AES-128 MAC encryption; NB-IoT LTE security	0B (link layer)
Spoofing	Token validation + device-specific seq tracking	1B (token_short)
DoS flooding	Per-device rate limit at gateway (default: 10 msg/min)	0B (gateway CPU)
Eavesdropping	LoRaWAN: AES-128-CTR; NB-IoT: SNOW3G/AES	0B (link layer)
Man-in-middle	MIC verification at MAC layer	4B (LoRaWAN MIC)

Security Trade-offs and Limitations:

- **Forward secrecy**: Not provided. Compromised long-term token enables decryption of past captured traffic. Mitigation: periodic token rotation (configurable 7–90 days).
- **Application-layer encryption**: Protocol relies on link-layer security (LoRaWAN/NB-IoT). For end-to-end encryption, applications can encrypt payload before transmission (+16B for AES-128-GCM tag).
- **Formal verification**: Security properties not formally verified; future work includes ProVerif/Tamarin modeling.

H. Implementation Feasibility

To demonstrate practical implementability, we present byte-level message structures and overhead analysis mapped to LoRaWAN and NB-IoT constraints.

Uplink Message Structure (Sensor Data):

```
Byte 0:    [TTT|PP|CCC] msg_type|prio|topic
Byte 1-2:  [SSSSSSSS SSSSSSSS] seq_u (16-bit)
Byte 3:    [FFFFFFFF] flags
Byte 4:    [TTTTTTTT] token_short
Byte 5-N:  [payload...] sensor data
```

Example Uplink (20-byte sensor payload):

- Novel LPWAN: 5B header + 20B payload = **25 bytes**
- MQTT-SN: 7B header + 2B topic ID + 20B = 29 bytes
- CoAP: 4B header + 4B token + 3B options + 20B = 31 bytes

Protocol Comparison Assumptions: To ensure fair comparison, we specify the following implementation assumptions:

- **MQTT-SN**: PUBLISH with QoS 1, 2-byte topic ID (pre-registered), 7-byte header (length=1B, msg_type=1B, flags=1B, topic_id=2B, msg_id=2B). Does not include DTLS/UDP overhead.

- **CoAP**: Confirmable (CON) message, 4-byte base header (Ver=2b, Type=2b, TKL=4b, Code=8b, MID=16b), 4-byte token (recommended length per RFC 7252), 3-byte options (Uri-Path). ACK is 4B (empty ACK with matching MID). Does not include DTLS overhead.
- **Security layer**: All comparisons exclude transport security overhead. Illustrative range: DTLS 1.2 record header adds 13B (ContentType=1B, Version=2B, Epoch=2B, SeqNum=6B, Length=2B) plus 8–16B authentication tag; LoRaWAN adds 4B MIC per frame. These overheads (13–21B) apply symmetrically to uplink and downlink but were *not modeled* in our simulation to isolate application-layer protocol efficiency.

Downlink ACK + Command Structure:

```
Byte 0:     [TTT|PP|CCC] msg_type=ACK_CMD
Byte 1-2:   [ack_base_u] base sequence
Byte 3-4:   [ack_bitmap] 16-bit bitmap
Byte 5:     [cmd_epoch] command version
Byte 6-M:   [command payload...]
```

Overhead per Transaction:

TABLE III
PER-TRANSACTION OVERHEAD COMPARISON

Transaction	Novel	MQTT-SN	CoAP
Uplink (20B payload)	25B	29B	31B
Downlink ACK only†	5B	7B	4B
Downlink ACK + Bitmap‡	7B	N/A	N/A
Downlink ACK + Cmd	11B+	14B+	12B+
Round-trip total	**36B**	43B	43B

†5B: type+base+flags+token. ‡7B: header+bitmap (16 ACKs).

ACK Format Clarification: Both ACK modes reuse the standard 5-byte header structure (Table I). The *Minimal ACK* (5B) acknowledges a single uplink by setting msg_type=ACK and repurposing seq_u as ack_base (the sequence number being acknowledged). The *Bitmap ACK* (7B) extends this by appending a 2-byte bitmap field, enabling acknowledgment of up to 16 consecutive uplinks in a single downlink frame. The bitmap ACK achieves 16:1 aggregation ratio, amortizing the 7B cost to 0.44B effective overhead per acknowledged message.

LoRaWAN Payload Mapping:

- SF12 (51B max): Novel LPWAN fits 46B payload; MQTT-SN fits 42B
- SF7 (222B max): All protocols fit comfortably
- Bitmap ACK aggregates 16 uplinks in single 7B downlink (5B header + 2B bitmap)

NB-IoT Payload Mapping:

- Maximum Transport Block Size: 680–1000 bits (85–125B) per 3GPP TS 36.213 [6], [11]
- Novel LPWAN header (5B) consumes 4–6% of payload capacity
- CoAP+DTLS overhead can consume 30–50B additional [5], [21]

IV. SIMULATION METHODOLOGY

A. Simulator Implementation

We implemented a discrete-event simulator using SimPy 4.0 framework in Python. The simulator models:

- **Device behavior**: Uplink transmission, receive window management, command processing
- **Gateway behavior**: Downlink scheduling, command queuing, ACK aggregation
- **Channel model**: Packet loss, propagation delay, duty cycle enforcement
- **Protocol stacks**: Novel LPWAN protocol, MQTT-SN, and CoAP

B. MAC/PHY Layer Model

LoRaWAN Model:

- **Collision model**: Pure ALOHA with capture effect; capture threshold 6 dB based on empirical studies [41]
- **Multi-channel operation**: 8 uplink channels (EU868), 1 downlink channel (RX2)
- **Spreading factor allocation**: SF7–SF12 assigned based on link budget
- **Duty cycle enforcement**: 1% duty cycle (EU868 regulation)
- **Receive windows**: RX1 opens 1 second after uplink; RX2 opens 2 seconds after uplink

NB-IoT Model:

- **Random Access Channel (RACH)**: Contention-based access with exponential backoff
- **Coverage enhancement**: Three coverage levels with repetition factors 1, 8, 128
- **Extended Discontinuous Reception (eDRX) cycles**: 10.24 s modeled for idle mode

C. Model Validation

We validated key model behaviors against published measurements:

LoRaWAN Delivery Rate Validation:

TABLE IV
LORAWAN MODEL VALIDATION: PACKET DELIVERY RATE (PDR) VS DEVICE COUNT

Devices	Literature	Our Sim	Error
100	98.2% [41]	97.8%	0.4%
500	94.5% [42]	93.1%	1.5%
1000	86.3% [42]	84.7%	1.8%

Our simulator achieves $<2\%$ error compared to published results.

D. Simulation Parameters

E. Experimental Scenarios

Three comprehensive experiments were conducted:

TABLE V
SIMULATION PARAMETERS SUMMARY

Parameter	Value	Source
Frequency band	EU868	[41]
Bandwidth	125 kHz	LoRaWAN spec
Spreading factors	SF7–SF12	LoRaWAN spec
Tx power	14 dBm	[41]
Capture threshold	6 dB	[42]
Duty cycle	1%	EU regulation
Simulation duration	24–72 hours	–
Random seed	42	–

1) Command Control Timing Experiment:

- Device counts: 10, 50, 100
- Command intervals: 60, 300, 600 seconds
- Payload sizes: 20, 50, 100 bytes
- Total configurations: 210

2) Network Comparison Experiment:

- Network sizes: Small (10), Medium (50), Large (100)
- Gateway configurations: Single, Dual
- Traffic patterns: Periodic, Burst, Mixed
- Total configurations: 180

3) Duty Cycle Compliance Experiment:

- Duty cycles: 0.1%, 1%, 10%
- Spreading factors: SF7, SF9, SF12
- Transmission intervals: 60, 300, 900 seconds
- Total configurations: 270

V. EXPERIMENTAL RESULTS

A. Command Control Timing Results

Table VI presents aggregated results from the Command Control experiment across 210 configurations.

TABLE VI
COMMAND CONTROL TIMING EXPERIMENT RESULTS

Metric	Novel LPWAN	MQTT-SN	CoAP
Delivery Rate (%)	96.48 ± 0.15	96.46 ± 0.16	96.47 ± 0.15
Cmd Latency (s)	595.80 ± 4.0	599.12 ± 1.3	599.82 ± 1.3
Energy/Msg (mJ)	$\mathbf{9.59 \pm 0.09}$	9.86 ± 0.10	10.74 ± 0.14
Uplink (MB)	**75.33**	81.36	102.45
Downlink (MB)	50.83	34.94	37.93

Key observations:

- All protocols achieve similar delivery rates ($\sim$96.5%)
- **Energy efficiency**: Novel LPWAN uses 10.7% less energy than CoAP and 2.8% less than MQTT-SN
- **Uplink efficiency**: Novel LPWAN transmits 26.5% fewer uplink bytes than CoAP

B. Network Comparison Results

Key observations:

- Higher delivery rates ($\sim$98.2%) due to varied network configurations

TABLE VII
NETWORK COMPARISON EXPERIMENT RESULTS

Metric	Novel LPWAN	MQTT-SN	CoAP
Delivery Rate (%)	98.18 ± 1.73	98.17 ± 1.74	98.20 ± 1.71
Cmd Latency (s)	547.56 ± 49.3	407.08 ± 192.7	592.41 ± 7.7
Energy/Msg (mJ)	$\mathbf{4.92 \pm 4.68}$	5.06 ± 4.82	5.52 ± 5.27

- Novel LPWAN maintains consistent latency (547s, std 49.3s)
- **Energy efficiency**: Novel LPWAN achieves 10.9% improvement over CoAP

C. Duty Cycle Compliance Results

TABLE VIII
DUTY CYCLE COMPLIANCE EXPERIMENT RESULTS

Metric	Novel LPWAN	MQTT-SN	CoAP
Delivery Rate (%)	96.46 ± 0.18	96.44 ± 0.17	96.49 ± 0.15
Cmd Latency (s)	596.15 ± 2.9	599.19 ± 0.7	599.94 ± 0.5
Energy/Msg (mJ)	$\mathbf{9.59 \pm 0.09}$	9.87 ± 0.10	10.77 ± 0.09

Key observations:

- Consistent delivery rates across all duty cycle configurations
- **Energy efficiency**: 10.9% improvement over CoAP, 2.8% over MQTT-SN

D. QoS Deadline-Probability Comparison

TABLE IX
QOS DP VS TRADITIONAL QOS COMPARISON

QoS Config	Delivery (%)	Energy (mJ/msg)	Deadline Met (%)
Novel LPWAN QoS DP:			
Best-effort	51.2	**0.82**	N/A
Standard (0.9, 1h)	91.4	1.14	94.2
Reliable (0.99, 4h)	98.7	1.83	97.8
Time-critical	88.6	1.31	91.3
MQTT-SN Traditional QoS:			
QoS 0	67.3	0.91	N/A
QoS 1	99.1	2.47	N/A
QoS 2	99.8	4.12	N/A

Key findings:

- QoS DP enables fine-grained control unavailable in traditional QoS
- "Standard" class achieves 91.4% delivery with 54% energy reduction vs QoS 1
- "Reliable" class achieves 98.7% with 55% energy savings vs QoS 2

Generalization Limits: The QoS DP results in Table IX were obtained under specific conditions: 1% duty cycle

(EU868), 5% baseline packet loss rate, and 100-device network density. These represent typical LoRaWAN deployment scenarios.

Sensitivity Analysis: To assess robustness, we evaluated QoS DP "Standard (0.9, 1h)" class against MQTT-SN QoS 1 under varying loss rates:

TABLE X
QoS DP SENSITIVITY TO PACKET LOSS RATE

Loss Rate	Standard (0.9, 1h)		MQTT-SN QoS 1	
	Delivery	Energy	Delivery	Energy
5%	91.4%	1.14 mJ	99.1%	2.47 mJ
10%	88.7%	1.28 mJ	98.4%	2.89 mJ
15%	85.2%	1.41 mJ	97.6%	3.31 mJ
20%	81.1%	1.53 mJ	96.5%	3.78 mJ

Key insight: QoS DP "Standard" maintains 53–59% energy advantage over QoS 1 across all tested loss rates (5–20%), demonstrating robustness. The energy gap widens under higher loss because QoS 1 requires more retransmissions, while QoS DP's probabilistic approach accepts graceful degradation.

E. Consolidated Performance Summary

TABLE XI
CONSOLIDATED PERFORMANCE SUMMARY (ALL EXPERIMENTS)

Protocol	Energy (mJ/msg)	Latency (s)	Delivery (%)
Novel LPWAN	**8.01**	579.84	97.04
MQTT-SN	8.26	535.13	97.02
CoAP	9.01	597.39	97.05
*Improvement vs CoAP: **11.1%***			
*Improvement vs MQTT-SN: **3.0%***			

F. Statistical Significance

All reported improvements were validated using Welch's t-test ($\alpha = 0.05$):

- Energy improvement vs CoAP: $p < 0.001$ (significant)
- Energy improvement vs MQTT-SN: $p < 0.01$ (significant)

G. Ablation Study

TABLE XII
ABLATION STUDY: FEATURE CONTRIBUTIONS

Configuration	Energy (mJ/msg)	Contribution
MQTT-SN baseline	8.26	–
+ Compact header (5B)	8.09	2.1%
+ Bitmap ACK only	7.91	4.2%
+ QoS DP only	8.18	1.0%
Full Novel LPWAN	**8.01**	**3.0%**

Key findings:

1) **Bitmap ACK** provides largest contribution (4.2% energy reduction)
2) **Compact header** contributes 2.1% through uplink byte savings
3) **QoS DP** contributes 1.0% through smarter retry decisions

VI. DISCUSSION

A. Energy Efficiency Analysis

The proposed protocol achieves consistent energy savings across all experimental scenarios. Primary contributors:

1) **Compact header format**: 5-byte header reduces per-message overhead
2) **Aggregated ACKs**: Bitmap ACK reduces downlink transmissions
3) **Opportunistic command delivery**: Commands delivered during scheduled receive windows

B. Latency Characteristics

All protocols exhibit command latencies in the 400–600 second range, acceptable for delay-tolerant C&C applications:

- Configuration updates for distributed sensor networks
- Firmware scheduling and remote maintenance
- Non-critical actuator control (irrigation valves, Heating, Ventilation, and Air Conditioning (HVAC) systems)
- Alert threshold adjustments for SCADA/supervisory control
- Agricultural robot task scheduling and waypoint updates
- Smart infrastructure control (street lighting, traffic signals)

These latency characteristics are particularly suitable for robotic and control systems where commands are not time-critical but require reliable delivery, such as autonomous agricultural robots receiving field navigation updates, or distributed SCADA systems adjusting operational parameters.

C. Scalability Observations

Network Comparison results demonstrate consistent performance across network sizes (10–100 devices). Stress testing showed effectiveness up to $\sim$800 devices per gateway.

D. Reproducibility

To enable independent verification and replication of our results, we provide complete reproducibility information.

Simulation Environment:

- **Simulator**: SimPy 4.0.1 discrete-event simulation framework
- **Python version**: 3.9.7 (tested on 3.8–3.11)
- **Dependencies**: NumPy 1.21.0, PyYAML 6.0, Pandas 1.3.0
- **Platform**: Ubuntu 20.04 LTS / Windows 10 (platform-independent)
- **Execution time**: $\sim$2–5 minutes per single run (Intel i7-10700, 8-core)
- **Total computation**: 660 configs $\times$ 3 runs = 1,980 runs; $\sim$22–55 hours sequential, $\sim$3–7 hours with 8-way parallelization

Code and Configuration Availability: The complete simulation framework is publicly available at:

https://github.com/vokasitibrawijaya/novel-lpwan-protocol

Repository Structure:

- `simulation/src/`: Core simulator (device.py, gateway.py, network.py, protocols/)
- `simulation/configs/`: All 660 experiment YAML configurations
- `analysis/`: Result aggregation and statistical analysis scripts
- `results/`: Raw CSV outputs and aggregated statistics
- `README.md`: Installation and execution instructions

Source code, configuration scripts, and raw experimental data are publicly available at the repository above to enable full reproducibility of all reported results.

Execution Instructions:

```
# Clone and setup
git clone https://github.com/vokasitibrawijaya/
    novel-lpwan-protocol.git
cd novel-lpwan-protocol
pip install -r requirements.txt

# Run single experiment
python simulation/run_sim.py \
    --config configs/ieee_experiments/cmd_ctrl_001.yaml

# Run full sweep (660 configurations)
python scripts/run_sweep_local.py --parallel 8
```

Randomization Policy: All experiments use consistent randomization to ensure fair comparison:

- Global random seed: 42 (configurable via `base_ieee.yaml`)
- Same seed applied to all three protocols per configuration
- Device arrival times, packet loss events, and channel conditions are deterministic given the seed
- Each configuration executed with 3 independent runs (seeds 42, 123, 456) for statistical validation

Core Algorithm Pseudocode: The bitmap ACK aggregation scheduler operates as follows:

```
def schedule_ack(pending_acks, max_bitmap=16):
    base_seq = min(pending_acks)
    bitmap = 0
    for seq in pending_acks:
        offset = seq - base_seq
        if offset < max_bitmap:
            bitmap |= (1 << offset)
    return (base_seq, bitmap)
```

E. Limitations

Simulation Methodology Scope: The simulation models were calibrated against published measurements, achieving <2% error. However, simulation cannot capture:

- Firmware bugs and hardware manufacturing variations
- Real radio propagation anomalies
- Operator-specific behaviors
- Long-term device degradation

Future Work:

1) Hardware implementation on LoRaWAN Class A
2) Field trials in representative environments
3) Security formalization using ProVerif/Tamarin
4) MQTT 5.0 bridge implementation

VII. Conclusion

This paper presented a novel lightweight MQTT-like protocol specifically designed for bidirectional command and control in LPWAN networks. Through comprehensive simulation across 660 configurations in three experimental scenarios (Command Control Timing, Network Scalability, and Duty Cycle Compliance), validated against published measurements with <2% error, we demonstrated that the proposed protocol:

- Achieves comparable delivery rates (96.5–98.2%) to established protocols
- Reduces energy consumption by 11.1% compared to CoAP and 3.0% compared to MQTT-SN
- Maintains acceptable command latencies for delay-tolerant C&C applications
- Reduces uplink overhead by 26.5% compared to CoAP

The protocol's design principles—device statelessness, gateway intelligence, opportunistic downlink, and aggregate acknowledgment—prove effective for LPWAN's unique constraints. Future work includes hardware implementation and field deployment trials.

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