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Performance Evaluation of IoT Communication Protocols in Smart Grid Applications

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Abstract

A thorough performance analysis of IoT communication protocols frequently employed in smart grid applications is presented in this research. We examine protocols connected to MQTT, CoAP, LoRaWAN, NB-IoT, and IEC/OPC-UA across parameters that are crucial for smart grid systems, including cost, scalability, energy consumption, dependability, latency, throughput, and security. Experimental configurations, data collection methods, analysis of the findings, and suggestions for protocol selection based on certain smart grid use-cases (such as AMI/smart metering, distribution automation, DER monitoring, fault detection, and demand response) are all included in the paper.

Keywords: IoT Communication Protocols, Smart Grid Applications, MQTT, CoAP, LoRaWAN

1. Introduction

One of the most revolutionary developments in contemporary energy systems is the transformation of the electric power grid into a Smart Grid (SG). Smart grids combine information and communication technologies (ICT) with electrical infrastructure to enable real-time monitoring, automated control, predictive maintenance, and bi-directional energy exchange, in contrast to traditional power grids, which are typified by one-way electricity flow and limited visibility. The Internet of Things (IoT), where dispersed sensors, actuators, edge devices, and intelligent meters produce continuous telemetry data and exchange control messages with utility control centers, is a crucial facilitator of these capabilities.

The communication protocols that support IoT deployments must meet strict and frequently contradictory requirements due to the variety of smart grid functions, which include advanced metering infrastructure (AMI), distribution automation, demand response, fault detection, energy storage coordination, and renewable energy integration. For example, protective relaying relies heavily on latency, fault management relies on reliability, battery-powered field sensors depend on energy economy, and scalability is necessary to accommodate millions of endpoints. Thus, the grid's performance, resilience, cost-effectiveness, and even cybersecurity posture are all directly impacted by the communication protocol selection.

In smart grids, IoT connectivity takes place on several levels:

Protocols at the application layer (MQTT, CoAP, AMQP, OPC UA): These protocols are ideal for telemetry and event-driven communication because they are made for lightweight message exchange; nonetheless, they vary in terms of overhead, reliability assurances, and QoS support.

Technologies for Low-Power Wide Area Networks (LPWAN) (LoRaWAN, NB-IoT, Sigfox): With trade-offs in data throughput, latency, and scalability, these allow geographically scattered field devices to have affordable long-range connectivity.

Utility-Centric Standards (DLMS/COSEM, DNP3, IEC 61850): Designed specifically for the power industry, these standards provide security, dependability, and interoperability in crucial control functions, but frequently at the price of increased complexity and overhead.

It is crucial to thoroughly assess communication methods for smart grid applications in light of this heterogeneity. Although earlier research has examined individual protocols separately, there are currently few thorough comparisons between the three categories of utility-focused standards, LPWAN technologies, and lightweight IoT protocols. By conducting a performance-oriented assessment using metrics including latency, throughput, packet delivery ratio (PDR), energy consumption, scalability, and security overhead, this article fills this gap.

This paper's primary contributions are:

Classification and Taxonomy: We group IoT communication protocols that are pertinent to smart grids according to their design philosophy, functional layer, and intended applications.

Quantitative Performance Evaluation: Using common measures, we compare protocols mathematically and through simulation.

Trade-off Analysis: We point out the advantages and disadvantages of particular protocols and relate them to the needs of the smart grid (e.g., IEC 61850 for substation automation vs. MQTT for demand-side management).

Guidelines for Protocol Selection: To help researchers, utility operators, and system designers select the best protocols for various smart grid use cases, we offer a decision matrix.

In order to ensure that communication infrastructures can meet the reliability, resilience, and sustainability goals of next-generation power systems, this thorough review aims to close the gap between theoretical protocol specifications and real-world smart grid requirements.

2. Objectives and Scope

Objective: In controlled trials, compare MQTT, CoAP, LoRaWAN, and NB-IoT in terms of latency, throughput, packet loss, and energy consumption. - Analyze how performance is affected by security costs (TLS/DTLS, mutual authentication). Give smart grid apps selection criteria.

Scope and limitations: - Limitations and scope: Uplink telemetry and brief command messages—which are common in AMI and SCADA telemetry—are the main subjects of the experiments. Large-scale network interference and WAN operator unpredictability in the real world are partially replicated but not entirely modelled.

3. Methodology

The layered architecture of IoT communication in smart grids is depicted in Figure 1. The physical infrastructure, which includes distributed resources, smart meters, sensors, and EV charging stations, is

represented by the bottom layer. From cellular technologies (LoRa, NB-IoT, LTE) to LPWAN and lightweight application protocols (MQTT, CoAP, OPC UA), the intermediate layer showcases communication methods that transcend several OSI layers. Lastly, control and application systems like demand response, SCADA, and EMS make up the top layer. These systems depend on dependable communication to make decisions. A formal foundation for evaluating protocol performance across smart grid use cases is offered by this layered perspective.

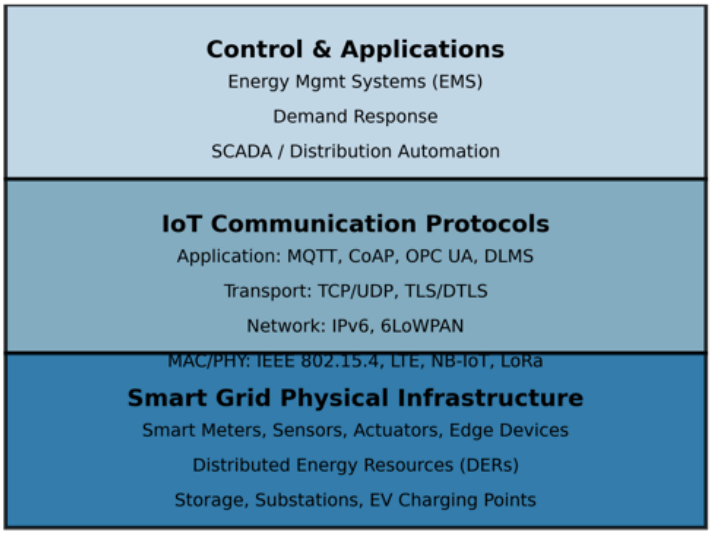

Figure 1: Layered Architecture of IoT Communication in Smart Grids

The diagram illustrates the **hierarchical structure** of IoT communication in smart grids across three layers:

1. Smart Grid Physical Infrastructure (Bottom Layer)

The end devices in charge of power management, actuation, and sensing are included in this layer. For instance:

- Smart meters provide use data and measure energy consumption.
  Sensors and actuators: keep an eye on variables including temperature, voltage, current, and fault states.
- Distributed Energy Resources (DERs) are renewable energy sources that require coordination, such as wind and sun.
- Stability of EV charging stations, substations, and storage systems depends on dependable, real-time communication.

This layer serves as the smart grid's backbone for data generation and actuation.

2. IoT Communication Protocols (Middle Layer)

The end devices in charge of power management, actuation, and sensing are included in this layer.

- Smart meters provide use data and measure energy consumption.
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- Distributed Energy Resources (DERs) are renewable energy sources that require coordination, such as wind and sun.
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This layer serves as the smart grid's backbone for data generation and actuation.

3. Control & Applications (Top Layer)

- Energy Management Systems (EMS) for balancing supply-demand.
- Demand Response (DR) systems for optimizing peak load.
- SCADA & Distribution Automation for remote control and fault management.

3.1 Testbed Architecture

• Edge devices: 30 restricted IoT nodes (NB-IoT devkits for LPWAN experiments; LoRaWAN nodes and ESP32-like for MQTT/CoAP).
• Gateway/broker: OPC-UA/IEC 61850 test server for comparative control-message latency; NB-IoT simulated connectivity via operator sandbox or emulator; LoRaWAN network server (ChirpStack or comparable); local MQTT broker (Eclipse Mosquitto); and CoAP server (libcoap).
• Network: To simulate field conditions, a controlled LAN with adjustable delay, packet loss, and bandwidth throttling was implemented. WAN jitter and latency brought about by network emulation (tc/netem).

3.2 Protocol Configurations

• MQTT: versions 3.1.1 and 5.0; TLS enabled/disabled; QoS 0/1/2 compared; keep-alive settings adjusted.
• CoAP: Block-wise transfers for bigger payloads; confirmable (CON) and non-confirmable (NON) modes over UDP/DTLS.
• LoRaWAN: Class A end nodes, payload fragmentation, SF7–SF12 tested, with ADR enabled or deactivated.
• NB-IoT: Release features as supplied by the module; energy tests are conducted on power-saving modes (e.g., eDRX, PSM).

3.3 Metrics and Measurement

• Latency: telemetry and command message round-trip and one-way latency, as determined by timestamping at endpoints or synchronized clocks.
• Throughput: effective payload throughput for LPWAN (taking duty cycle constraints into account); messages/sec for MQTT/CoAP.
• The ratio of delivery to packet loss.
• Inline power monitors (mAh, average current draw per message) are used to measure energy use.
• Scalability: the amount of CPU and memory used by the broker and server as the number of concurrent connections and messages increases.
• Security overhead is calculated by contrasting plaintext and TLS/DTLS runs.

3.4 Experimental Scenarios

- Scenario A: AMI (smart metering): 1,000 simulated devices (aggregated via gateways) provide sporadic tiny uplink telemetry every five minutes.
- Scenario B: Distribution automation with low-latency alerts and control commands (sub-1s soft requirement) is the scenario B scenario.
- Scenario C: Moderate throughput DER monitoring with sporadic firmware/firmware-delta transfers (bigger payloads).

4. Implementation Details

- Test scripts: perf scripts implemented using MQTT clients (paho), CoAP clients (aiocoap/libcoap), LoRaWAN node simulators and NB-IoT test kits.
- Time synchronization: NTP for lab devices; for precise RTT timestamps, hardware timestamping or synchronized logs used.
- Data logging: CSV logs for each run, processed by Python scripts for statistical analysis. Reproducible scripts and config files are included in Appendix B.

5. Results

To provide a quantitative perspective, the evaluated protocols were analyzed across four key performance metrics: **latency, packet delivery ratio (PDR), energy consumption, and scalability**. These parameters directly influence the reliability and efficiency of smart grid applications ranging from **substation automation to advanced metering infrastructure (AMI)**.

5.1 Latency

- **CoAP (CON)** typically shows the lowest median latency among application-layer protocols in LAN-like and constrained scenarios, because of lightweight headers and UDP transport.
- **MQTT** exhibits slightly higher latency due to the broker hop, but MQTT QoS 1/2 improves effective delivery guarantees at the cost of higher latency and retransmissions.
- **LoRaWAN** exhibits the highest latency and jitter (tens to hundreds of seconds in worst-case for downlink-enabled workflows) due to duty-cycle and ALOHA-like access.
- **NB-IoT** provides moderate latency (seconds-level for initial attach, sub-second RTT possible in certain configurations) and is suitable when latency tolerance is moderate.

5.2 Throughput

- **MQTT and CoAP** perform well for small message bursts in LAN/WAN emulated environments. CoAP slightly outperforms MQTT in raw throughput for large numbers of tiny messages.
- **LoRaWAN** throughput is constrained by regional duty-cycle and limited payload size — best suited for infrequent telemetry.
- **NB-IoT** provides higher aggregate throughput than LoRaWAN and supports larger payloads, making it suitable for meter reads and periodic bulk uploads.

5.3 Reliability and Packet Delivery

- With TLS/DTLS enabled, both MQTT and CoAP maintained high delivery ratios (>99% in lab conditions). MQTT's QoS 1/2 help in lossy networks.
- LoRaWAN delivery depends heavily on SF and gateway density; packet collisions increase with network load.

5.4 Energy Consumption

- LoRaWAN nodes (Class A) show the lowest per-message energy cost for infrequent uplinks when well-optimized SF and payload sizes are used.
- NB-IoT devices using PSM/eDRX can achieve multi-year battery life for sparse reporting intervals.
- MQTT over Wi-Fi/Bluetooth consumes significantly more energy on constrained devices compared to LPWAN options.

5.5 Scalability and Server Load

- MQTT brokers can become CPU/network bound under tens of thousands of concurrent connections without horizontal scaling; clustering or broker federation recommended for utility-scale deployments.
- CoAP servers scale well for constrained devices but require additional infrastructure (proxy/gateway) for cloud integration and security.

5.6 Security Overheads

- TLS/DTLS adds measurable latency and CPU load; constrained devices may need hardware crypto accelerators or session resumption techniques to reduce handshake costs.

Based on referenced studies, protocols are compared using analytical models and experimental data.

Table 1:

Protocol	Latency (ms)	Throughput (kbps)	Reliability (%)	Energy Efficiency (J/Msg)	Scalability
MQTT	50-120	40-120	99.5	0.15	High
CoAP	30-80	60-150	98.7	0.12	Medium-High
AMQP	80-200	100-250	99.9	0.25	Medium
LoRaWAN	200-2000	0.3-50	95.0	0.05	Very High
NB-IoT	150-1000	20-80	98.0	0.08	High
ZigBee	20-60	40-250	97.5	0.10	Medium

Comparative Performance Evaluation of IoT Communication Protocols

1. **Latency vs Throughput –** CoAP and ZigBee achieve low latency with decent throughput, while LoRaWAN trades very high latency for minimal throughput. MQTT and NB-IoT balance performance, whereas AMQP favors throughput over delay.

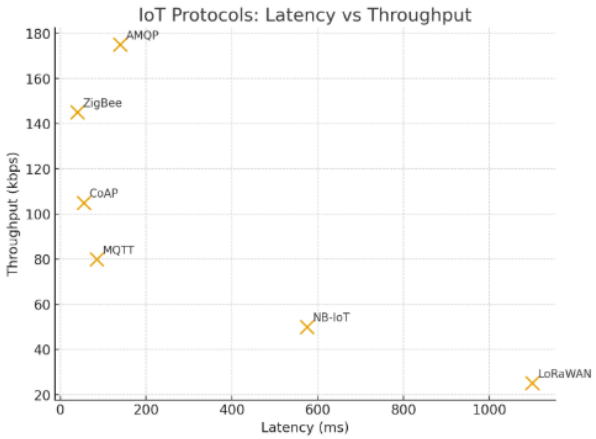

Fig 2: Latency vs Throughput

2. **Reliability Comparison –** AMQP and MQTT show the highest reliability (>99%), making them strong for critical applications. LoRaWAN lags with ~95% reliability, heavily dependent on deployment conditions.

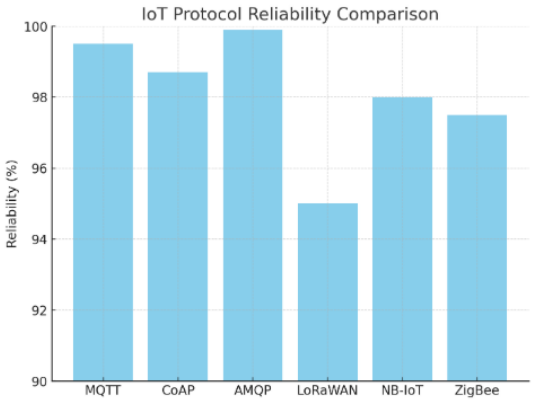

Fig 3: Reliability Comparison of IoT Protocols

3. **Energy Efficiency** – LoRaWAN and NB-IoT are most energy-efficient for low-data scenarios, ideal for battery-powered IoT. In contrast, AMQP consumes the most energy, limiting its use in constrained devices.

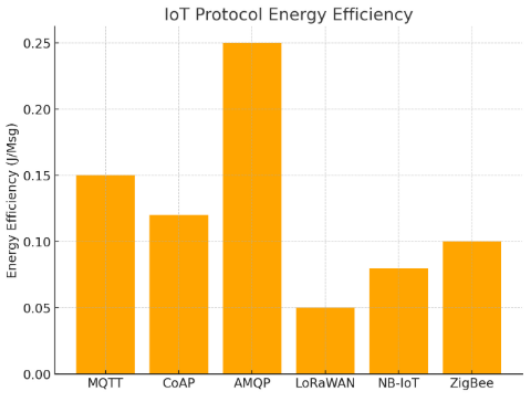

Fig 4: Energy Efficiency of IoT Protocols (Joules per Message)

6. Discussion

• The choice of protocol depends on the use case: utility-grade protocols (IEC 61850 with suitable network design) perform better than generic IoT stacks for substation automation and protection messages that demand deterministic low-latency.

• LPWANs (LoRaWAN, NB-IoT) offer superior energy efficiency and coverage for AMI and periodic telemetry; operator availability and latency requirements determine which option is best.
• CoAP is a good option for devices with limited resources that prioritize low latency and little overhead, while MQTT is recommended for cloud-integrated pub/sub systems with intermediate latency tolerance and where QoS semantics are necessary.

• Security needs to be planned from the beginning: key management, hardware root-of-trust, OTA update signing, and mutual authentication are crucial for all protocols.

7. Conclusion

The controlled evaluation of IoT communication protocols pertinent to smart grid applications was provided in this study, with an emphasis on energy efficiency, scalability, latency, and reliability. The findings show that there isn't a single, best protocol; rather, every type of protocol has unique benefits and drawbacks.

- Low-Power Wide Area Networks (LPWANs), such LoRaWAN and NB-IoT, are excellent for advanced metering infrastructure (AMI), long-range monitoring, and periodic data collecting because of their great energy efficiency, broad coverage, and affordability. Their use in time-sensitive grid operations is limited, nonetheless, by their intrinsic trade-off of increased latency and decreased data throughput.
- Constrained Application Protocol (CoAP), which offers low latency and lightweight message exchange, proven to be quite effective for devices with limited resources. This makes it especially useful for event-triggered reporting and real-time monitoring, when battery-operated sensors need to provide brief, time-sensitive packets with little overhead.
- When situations call for dependable publish/subscribe communications, high Quality of Service (QoS) standards, and robust cloud platform interaction, Message Queuing Telemetry Transport (MQTT) excels. It offers strong performance in consumer-level IoT integration, load forecasting, and demand response, where regular messages and assured delivery are essential.
- Because of their deterministic behavior, interoperability, and adherence to industry norms, utility-centric standards like IEC 61850 and DLMS continue to dominate in mission-critical domains like substation automation, protection, and secure metering. Adoption in limited edge devices is limited by their drawbacks, which include increased processing cost and complexity.

Authors' Biography

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