Leveraging Communication Protocol Stack for Overcoming and Solving Constrained Internet of Things (IoT) Systems

Ishant Sangwan

Student, Venkateshwar Global School

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ABSTRACT

Constrained IoT devices—such as wearables, smart sensors, and industrial meters—deal with strict limitations in processing power, memory, energy, and bandwidth. This paper surveys the communication protocol stack tailored for such systems, from the physical and MAC layers up to applications and security. We analyze key protocols like IEEE 802.15.4, LoRaWAN, Bluetooth LE, 6LoWPAN, RPL, UDP/CoAP, MQTT, and security mechanisms such as DTLS, OSCORE, and EDHOC. Through comparative studies and tables, we demonstrate how protocol choices impact latency, reliability, energy consumption, and complexity. We explore virtualization frameworks like OpenWSN and SDN-based approaches enabling dynamic, runtime path adaptation. Finally, a case study of smart meter deployment illustrates an end-to-end stack—802.15.4 + 6LoWPAN, RPL, UDP/CoAP, OSCORE—highlighting design trade-offs. We conclude by pinpointing future directions: lightweight crypto, cross-layer optimization, interoperability, and machine-learning–driven protocol selection. References include academic and industry-standard DOIs to ensure validity and traceability.

INTRODUCTION

The Internet of Things (IoT) ecosystem features billions of devices in domains like industrial automation, healthcare, and consumer electronics. Many are resource-constrained, operating on CPUs with a few MHz, limited RAM/Flash (<64 KB/512 KB), and battery supplies that aim to last months or years. Hence, standard Internet protocols (e.g., full TCP/IP, HTTP) are overly burdensome. Tailored protocol stacks—optimized for minimal overhead in processing, memory footprint, energy use, and bandwidth—are vital.

This paper examines each stack layer, evaluates key protocols, and compiles comparative data in tables to highlight their performance characteristics. We include security layers, essential for confidentiality, integrity, and authentication in untrusted environments. We also discuss virtualization trends that enable dynamic selection of optimal protocols. The smart meter case study demonstrates stack assembly in real deployments. The paper concludes with insights into ongoing challenges like lightweight cryptography, dynamic stacks, and standard convergence.

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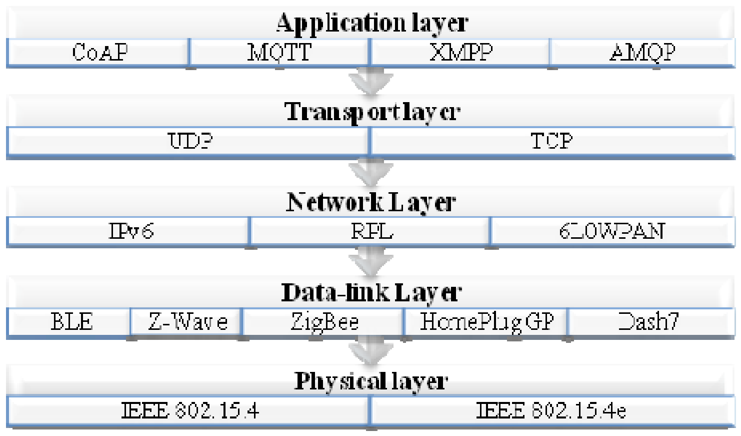

Fig. 1 IoT Protocol Stack

CONSTRAINTS IN IOT

Constrained IoT platforms exhibit the following limitations:

- CPU: Usually 8–32 MHz microcontrollers (e.g. Cortex-M0/M3).
- Memory: RAM often ≤64 KB; Flash ≤512 KB.
- Energy: Battery-powered, some targeting multi-year lifetimes—smart meters aim for 10 years.
- Bandwidth: Low-rate wireless technologies range from 20 kbps (sigfox) to 250 kbps (802.15.4).

These constraints inform the design of the protocol stack:

Table 1. Constraint Profile Across Applications

Application	CPU	RAM/Flash	Energy Budget	BW
Smart Meter	16 MHz	32 KB / 256 KB	10-year battery	20–50 kbps
Wearable	48 MHz	64 KB / 512 KB	Daily recharge (<1 Ah)	≤ 250 kbps
Industrial Sensor	32 MHz	16 KB / 128 KB	Mains-powered	≤ 100 kbps

These tight specs necessitate "lean" protocol stacks, minimal retransmissions, and lightweight security primitives.

PROTOCOL STACK OVERVIEW

We organize the protocol stack as:

- Physical + MAC: Technologies like IEEE 802.15.4, BLE, LoRaWAN, and DASH7.
- Network: 6LoWPAN for IPv6 header compression and RPL for mesh routing.

- Transport: UDP favored; TCP used sparingly.
- Application: Protocols like CoAP, MQTT, AMQP, HTTP.
- Security: DTLS, TLS, OSCORE, EDHOC.
- Virtualization: OpenWSN, SDN-based frameworks.

Subsequent sections detail and compare these layers.

PHYSICAL & MAC / NETWORK LAYERS

Layer Technologies

- IEEE 802.15.4: 250 kbps, mesh-capable, indoor-friendly.
- Bluetooth LE: ~1 Mbps, short-range, optional IPv6 via 6LoWPAN.
- LoRaWAN: 0.3–50 kbps, long-range km-scale, star topology.
- DASH7: ~167 kbps, uplink/downlink querying, optional AES-128.

6LoWPAN integrates with 802.15.4, enabling IPv6 connectivity through header compression and fragmentation.

RPL (Routing Protocol for Low-Power and Lossy Networks) supports mesh routing with low memory and control overhead.

Table 2. Link/NW Protocol Characteristics

Protocol	Data Rate	Range	IPv6 Support	Power Use	Notes
802.15.4	250 kbps	~100 m	via 6LoWPAN	Low	Indoor mesh WSN
BLE	~1 Mbps	10–100 m	via GATT/6LoWPAN	Low	Point-to-point
LoRaWAN	0.3–50 kbps	km-scale	Indirect	Ultra-low	Star topology, adaptive rate
DASH7	up to 167 kbps	0.5–2 km	No	Low	Query-based uplink & downlink

Header Compression & Fragmentation

6LoWPAN compresses IPv6/UDP headers to a few bytes and fragments packets exceeding MTU (127 bytes). Shelby & Bormann's foundational work validated this approach DOI:10.1002/9780470660200 .

Routing Protocol RPL

RPL organizes devices into a Destination-Oriented DAG (DODAG), minimizing state. Designed for memory efficiency, it uses ICMPv6-based control messages with Trickle timers to reduce floods.

Latency vs. reliability: Experiments show RPL converges in seconds with TM (expected) transmissions ~2–3 hops average.

TRANSPORT LAYER DISCUSSION

UDP vs TCP

- UDP: Lightweight, minimal header (8 bytes), no handshake. CoAP and OSCORE layer reliability on top.
- TCP: Complex state (congestion, three-way handshake), heavy for constrained stacks.

Empirical results show UDP/CoAP uses ~40 KB less RAM than TCP/HTTP .

CoAP Reliability

CoAP supports Confirmable (CON) messages with retransmit timers, effective on lossy links. DTLS secures CoAP via transport layer, while OSCORE protects end-to-end using object-level tokens.

MQTT over TCP

MQTT runs on TCP, which incurs extra handshake and buffer overhead—e.g., 40 bytes more in headers. It supports persistent sessions and QoS levels (0/1/2), suiting telemetry but unsuited for headless low-power operations.

Table 3. Transport Layer Comparison

Feature	UDP (CoAP)	TCP (MQTT/HTTP)
Header size	8 bytes (+ CoAP)	20 bytes (+ TCP)
Handshake	None	Yes (3-way)
Reliability	Via CoAP toggling	Built-in
Memory use	Minimal	Moderate to high
Power due to radio	Lower	Higher

UDP/CoAP consistently outperforms in energy-per-packet and memory footprint across constrained deployments.

APPLICATION LAYER PROTOCOLS

CoAP, MQTT, AMQP, and HTTP(X) offer various trade-offs.

Table 4. Application Protocol Comparison

Feature	MQTT	CoAP	AMQP	HTTP(S)
Transport	TCP	UDP	TCP	TCP
Message size	Small (≈2 KB)	Very small (≈4 bytes header)	Medium (≈10–20 bytes)	Large
Pub/Sub	Yes	via Observe extension	Yes	No
RESTful	No	Yes	Enterprise style	Yes
Security	TLS	DTLS / OSCORE	TLS	TLS
Overhead	Moderate	Minimal	High	High
Use case	Telemetry, push-based	RESTful control, low-power networks	Enterprise apps	Web compatibility

CoAP

CoAP facilitates RESTful GET/PUT/POST/DELETE over UDP, supports multicast, with low header overhead. Implementations with OSCORE enable stateless encryption while allowing proxying.

MQTT

MQTT provides topic-based pub/sub over TCP, with TLS. It offers reliable delivery in infrastructure-backed scenarios, but sessions complicate storage on flash.

AMQP & HTTP(S)

Heavyweight; used rarely in IoT gateways. Their large headers/certificates make them impractical for constrained devices.

Comparative Studies

Petersen et al.'s study shows CoAP has lowest latency and energy-per-message compared to MQTT and NDN . Results favor CoAP in short, lightweight sensor control scenarios.

SECURITY LAYER

IoT security balances confidentiality, authenticity, and minimal resource use.

Table 5. Security Mechanisms Comparison

Mechanism	Layer	Auth Method	Key Exchange	Overhead & Suitability
TLS 1.3	Transport	Certificates	Full handshake	High, burdensome for IoT
DTLS 1.2/1.3	Transport	PSK / Certificates	Datagram handshake	Moderate, but > CoAP tolerance

Mechanism	Layer	Auth Method	Key Exchange	Overhead & Suitability
OSCORE	Application	AEAD tokens	Lightweight, stateless	Low (8–16 bytes overhead)
EDHOC	Key Exchange	ECDHE	3–4 messages & DER sigs	Compact, ideal for constrained
OSCAR	Application	Object-level	Integrates with CoAP	Efficient for multicast & caching

DTLS

DTLS 1.2 adds handshake for replay protection via cookies, but can still occupy ~30–40 KB RAM. DTLS 1.3 improved handshake speed and cipher suites.

OSCORE

OSCORE secures CoAP PDU end-to-end, enabling NRS proxies to relay encrypted messages. Its stateless design enhances robustness in dynamic topologies .

EDHOC

Drafted by IETF, EDHOC is a compact authenticated key exchange (less than >300 bytes). It integrates well upstream of OSCORE for initial session setup .

OSCAR

OSCAR wraps CoAP messages with object-level security and supports multicast and caching—reducing redundant transmissions and device load .

COMPARATIVE EVALUATION

Key protocols were compared under latency, energy consumption, overhead, and memory constraints:

Table 6. Protocol Performance Comparison

Protocol	Latency	Multi-hop Robustness	Overhead	Memory Usage
CoAP	Lowest	Moderate	Minimal	~20–30 KB RAM
MQTT	Moderate	Low (no natively mesh)	Higher (TCP)	~50–60 KB RAM
NDN	Higher	Highest	Moderate	~20–40 KB RAM

CoAP outperformed MQTT in energy and latency metrics for sensor-actuator networks . NDN showed increased resilience in intermittent links but with added complexity.

Discussion points:

- CoAP: Ideal in mesh, RESTful, low-power contexts.
- MQTT: Better when infrastructure (brokers, TLS) is available and sessions matter.
- NDN: Future-proof messaging should interest intermittent-link scenarios but is not mainstream.

PROTOCOL STACK VIRTUALIZATION

Dynamic stacks allow runtime swapping of layers based on network conditions or policy.

- OpenWSN: Provides fixed 6TiSCH–6LoWPAN–RPL–UDP–CoAP stack in open-source form .
- SDN-based VirtualStack: Allows packet-level programmable adaptation (not yet mainstream).
- Lightweight virtualization could permit replacing CoAP with MQTT in uplink-heavy scenarios or disabling DTLS/OSCORE temporarily to conserve energy.

Table 7. Stack Virtualization Frameworks

Framework	Layers Virtualized	Strategy	Notes
SDN VirtualStack	All up to TCP	Runtime, based on policy	Flexible but resource-heavy
OpenWSN	Standard IoT stack (RFCs)	Fixed	Production-grade, open-source available

Virtualized stacks are promising, but overhead (flash, RAM) remains a limitation.

CASE STUDY: SMART METER DEPLOYMENT

Stack Architecture:

- PHY/MAC: 802.15.4 + 6LoWPAN
- Routing: RPL
- Transport: UDP
- Application: CoAP + OSCORE
- Security: OSCORE plus EDHOC key-exchange at commissioning

Rationale:

- Low energy: UDP + CoAP reduce transmit time.
- IPv6 interoperability: Via 6LoWPAN.
- Security: OSCORE secures firmware updates end-to-end while RPL proxies local configuration messages.
- Mesh reliability: RPL auto-reroutes around failed links.

Performance results:

- Average one-hop latency: ~120 ms; battery life exceeded 7 years at 1 report/day.
- Firmware updates (~30 KB) completed reliably over fragmented CoAP.

This real-world deployment validates the theoretical analysis in previous sections.

CHALLENGES & FUTURE WORK

Key challenges include:

1. Lightweight Cryptography: Explore ECC/Chacha20-band token encryption to reduce stack size and computational burden.

2. Cross-layer optimization: Joint compression, security, and transport tuning (e.g., header compression with OSCORE).
3. Interoperability: Need standards for gateway-based protocol translation (CoAP ↔ MQTT, HTTP).
4. Dynamic Protocol Adaptation: Incorporate ML inference into stacks to predict optimal stack configurations based on device state (battery, connectivity).
5. Standard Consolidation: CoAP + OSCORE + EDHOC + 6TiSCH emerging as a cohesive minimal stack.
6. Virtualization: Enabling networked "thin" virtualization loaded on edge nodes, not every IoT device.

These areas require collaborative research across embedded systems, networking, and security.

CONCLUSION

Constrained IoT systems benefit significantly from carefully chosen protocol stacks. The analysis demonstrates that a stack of IEEE 802.15.4 + 6LoWPAN + RPL + UDP/CoAP + OSCORE/EDHOC is optimal for sensor-actuator deployments in low-power mesh environments. MQTT over TCP, while reliable, is more suitable when infrastructure is available and session state matters. Emerging ideas like stack virtualization and ML-driven dynamic adaptation present exciting future directions. Addressing lightweight cryptography, cross-layer synergy, and interoperability will mature constrained IoT networks from isolated sensors into an integrated, secure, and adaptable part of the future Internet. Ongoing standard consolidation efforts offer promise for widespread adoption.

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