Lecture 3 - IoT Protocols Characteristics & Overview

Lecture Information

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Author	Prof. Marco Picone (marco.picone@unimore.it)
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3.1 Traditional Internet Protocol Stack (Overview)

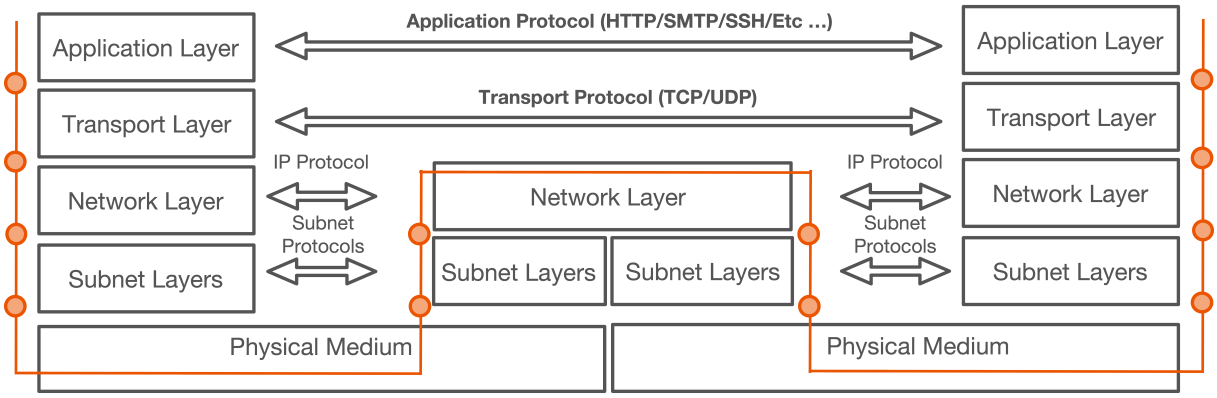


Figure 3.1: Traditional Internet Protocol Stack (Overview) with the different layers and their main protocols.

The **traditional protocol stack** is fundamental for modeling and understanding how digital communications work. By organizing network functions into **hierarchical layers**, each with specific responsibilities, the stack enables modular design and interoperability. The most common models are the **OSI** and **TCP/IP** stacks, which structure communication from the physical transmission of bits up to user-facing applications.

OSI vs. TCP/IP: Quick Differences and Similarities

- **OSI Model** has 7 layers (Physical, Data Link, Network, Transport, Session, Presentation, Application).
- **TCP/IP Model** has 4 layers (Link, Internet, Transport, Application).
- OSI separates presentation and session functions; TCP/IP combines them into the application layer.
- OSI is a theoretical reference model; TCP/IP is based on real-world protocols.
- Both models use layered architecture to promote modularity and interoperability.
- Each layer in both models serves specific functions and communicates with adjacent layers.
- Both models guide protocol design and troubleshooting in network engineering.

Protocol Stack Layer Overview

Each layer in the protocol stack abstracts and manages a distinct aspect of communication, relying on adjacent layers for data exchange. This layered modeling simplifies development, troubleshooting, and protocol evolution. In this overview, we focus on a simplified 5-layer model that captures the essential functions of both OSI and TCP/IP stacks:

Layer	Main Function	Common Protocols
Physical	Transmission of raw bits over physical medium	Ethernet (PHY), Wi-Fi (PHY)
Data Link	Framing, error detection/correction, MAC addressing	Ethernet, Wi-Fi (MAC), PPP
Network	Routing, addressing, packet forwarding	IP (Internet Protocol), ICMP
Transport	Reliable delivery, sequencing, flow control	TCP, UDP
Application	End-user services and protocols	HTTP, HTTPS, SMTP, SSH

- **Physical Layer**: The base layer, responsible for the actual transmission of data as electrical signals, light pulses, or radio waves over cables, fiber optics, or wireless channels.
- **Data Link Layer**: Handles framing, error detection/correction, and local addressing (MAC). It ensures reliable communication within a local network segment.
- **Network Layer**: Manages logical addressing and routing, enabling data packets to traverse multiple interconnected networks. The **IP protocol** is central here.
- **Transport Layer**: Provides end-to-end communication, reliability, and flow control. **TCP** ensures ordered, reliable delivery; **UDP** offers faster, connectionless transmission.
- **Application Layer**: Hosts protocols for user-facing services, such as **HTTP** for web, **SMTP** for email, and **SSH** for secure remote access.

Protocol and Communication Flow

Data originates at the **application layer**, then is **encapsulated** as it passes down through the transport, network, and data link layers, each adding its own header (and sometimes trailer) information. This encapsulation process is called **packet encapsulation**. At the sender, each layer wraps the data from the layer above, forming a protocol data unit (PDU) for transmission. The physical layer then transmits the bits over the medium.

On the receiving side, the process is reversed: each layer removes its header/trailer, passing the remaining data up to the next layer until the original application data is reconstructed.

Encapsulation Example:

```
Application Data
  ↓
Transport Layer (adds TCP/UDP header)
  ↓
Network Layer (adds IP header)
  ↓
```

```
Data Link Layer (adds Ethernet/Wi-Fi frame)
  ↓
Physical Layer (transmits bits)
```

This **layered encapsulation** ensures modularity, interoperability, and reliable communication across diverse networks and devices.

3.1.1 TCP & UDP Protocols (Quick Overview)

TCP (Transmission Control Protocol) and **UDP (User Datagram Protocol)** are two fundamental transport layer protocols in the Internet protocol suite, each with distinct characteristics, strengths, and application scenarios.

3.1.1.1 TCP (Transmission Control Protocol)

Characteristics:

- Connection-oriented protocol establishing a reliable connection between sender and receiver.
- Provides guaranteed data delivery through acknowledgments (ACKs), retransmissions, and sequence ordering.
- Ensures in-order delivery of packets and error detection/correction.
- Implements flow control and congestion control to optimize network usage.
- Suitable for applications where data integrity and reliability are crucial.

Internet Usage:

- Web browsing (HTTP/HTTPS), email (SMTP, IMAP), file transfer (FTP), and other use cases needing reliable communication.
- Ensures all data reaches the destination intact and in the correct sequence.

IoT Usage:

- Used for IoT devices requiring reliable commands and data, such as firmware updates, configuration, secure communications.
- Common in smart home devices, industrial control systems where data loss is unacceptable.

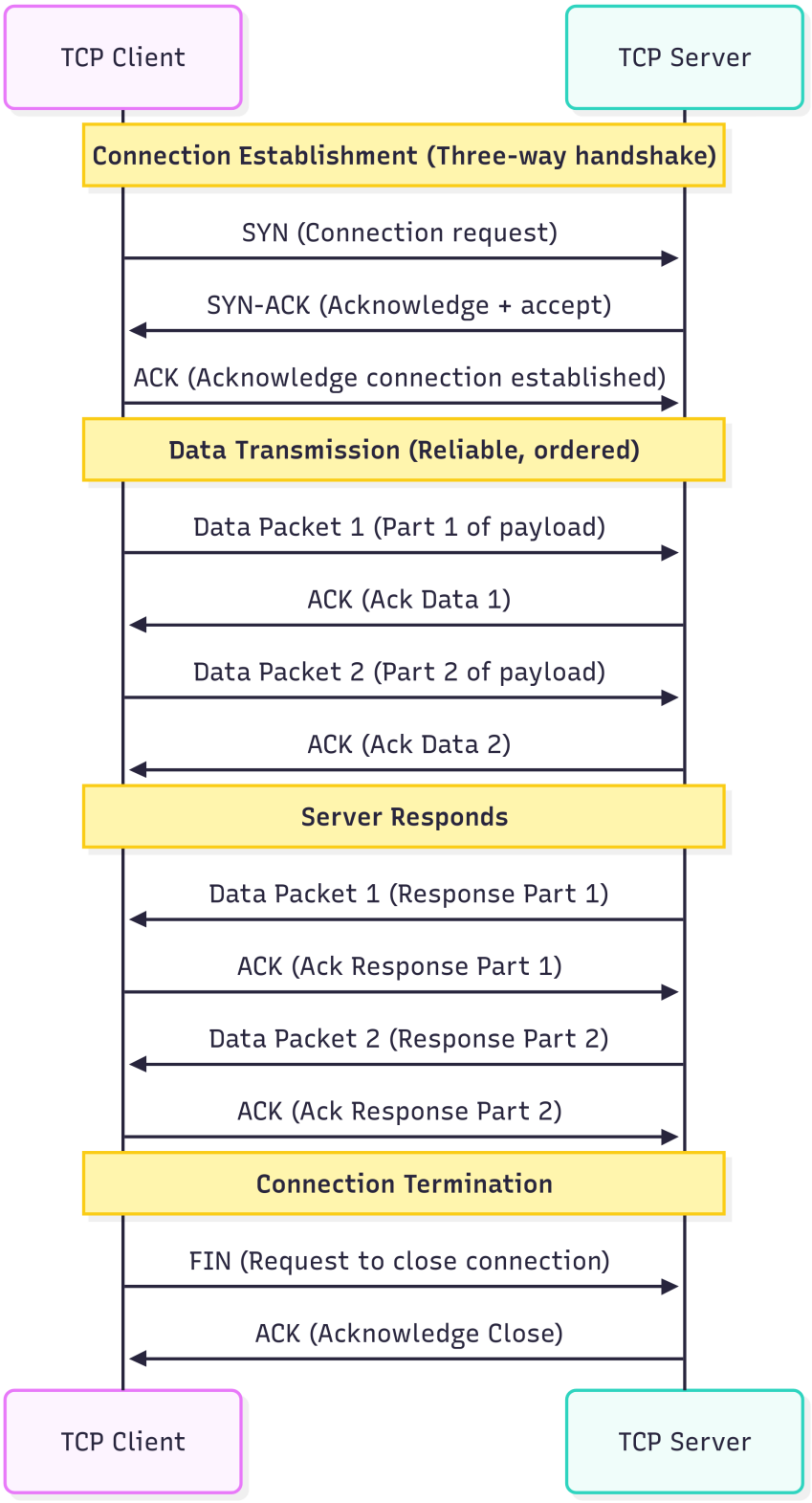

TCP Client
TCP Server
Connection Establishment (Three-way handshake)
SYN (Connection request)
SYN-ACK (Acknowledge + accept)
ACK (Acknowledge connection established)
Data Transmission (Reliable, ordered)
Data Packet 1 (Part 1 of payload)
ACK (Ack Data 1)
Data Packet 2 (Part 2 of payload)
ACK (Ack Data 2)
Server Responds
Data Packet 1 (Response Part 1)
ACK (Ack Response Part 1)
Data Packet 2 (Response Part 2)
ACK (Ack Response Part 2)
Connection Termination
FIN (Request to close connection)
ACK (Acknowledge Close)
TCP Client
TCP Server

Figure 3.2: TCP Communication Schema Example.

3.1.1.2 UDP (User Datagram Protocol)

Characteristics:

- Connectionless protocol that sends datagrams without ensuring delivery or order.
- No acknowledgments or retransmission mechanisms; minimal overhead.
- Faster and more efficient for time-sensitive applications.
- Suitable where occasional data loss is tolerable or where application-layer protocols handle reliability.

Internet Usage:

- Streaming media (audio/video), online gaming, DNS, VoIP where low latency is prioritized over reliability.
- Enables faster transmission by avoiding handshake and retransmission delays.

IoT Usage:

- Favored in resource-constrained devices and networks for lightweight communication.
- Used for telemetry, sensor data, where frequent updates make occasional loss acceptable.
- Protocols like CoAP and MQTT-SN are built on UDP for efficiency, especially in battery-powered or low-bandwidth scenarios.

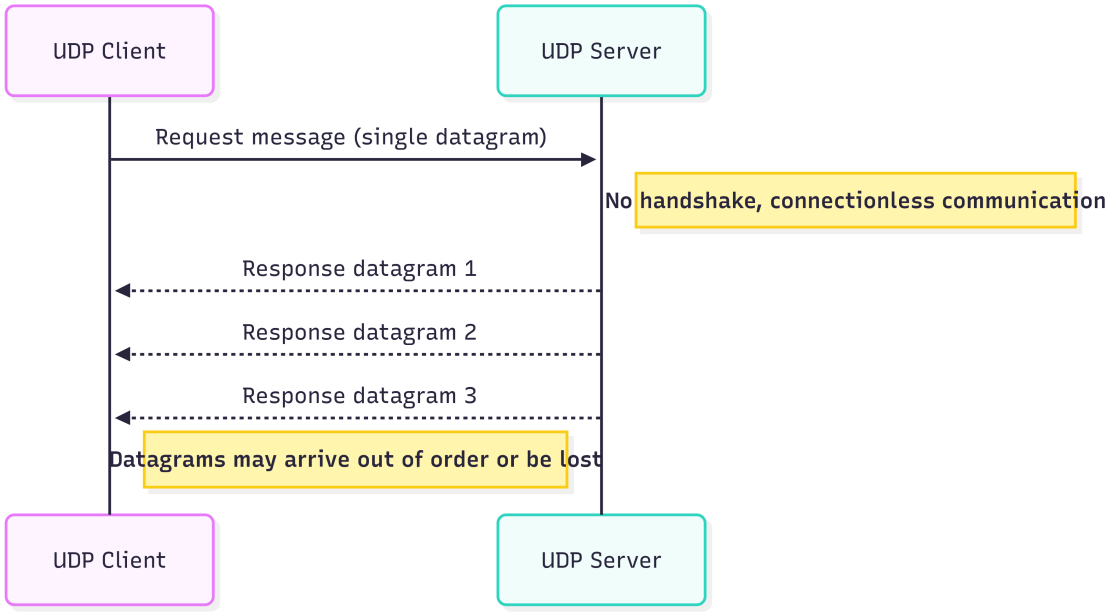


Figure 3.3: UDP Communication Schema Example.

3.1.1.3 TCP/UDP Comparison Summary Table

Feature	TCP	UDP
Connection type	Connection-oriented	Connectionless
Reliability	Guaranteed delivery with retransmissions	No guarantee, best effort
Ordering	Ensures data order	No ordering
Overhead	Higher (ACKs, flow/congestion control)	Lower, minimal
Latency	Higher due to connection setup	Low latency
Usage scenarios	Web, email, file transfers	Streaming, gaming, IoT telemetry
IoT use cases	Reliable command/control data	Sensor telemetry, lightweight data

3.1.1.4 The Need for Application Layer Protocols

While **transport protocols** such as **TCP** and **UDP** are responsible for the reliable delivery, packaging, and ordering of data between devices, they do not address how the actual application data should be **structured**, **interpreted**, or **managed**. This gap is filled by **application layer protocols**, which are crucial for modeling robust and interoperable systems.

Key modeling characteristics of application layer protocols:

- **Standardized Communication**: Define how applications exchange information, ensuring consistency across diverse platforms and devices.
- **Message Structure & Semantics**: Specify the format, encoding, and meaning of messages, so both clients and servers can correctly interpret commands and data.
- **Interaction Patterns**: Establish rules for request/response, publish/subscribe, and other communication paradigms, supporting scalable and flexible architectures.
- **Domain-Specific Logic**: Enable modeling of commands, queries, and resource manipulation tailored to the application's requirements.

> In summary, when modeling distributed systems, **application layer protocols** provide the essential framework for meaningful, standardized, and interoperable communication on top of transport protocols, enabling applications to understand and process exchanged data reliably.

3.2 IoT Protocol Stack (Overview)

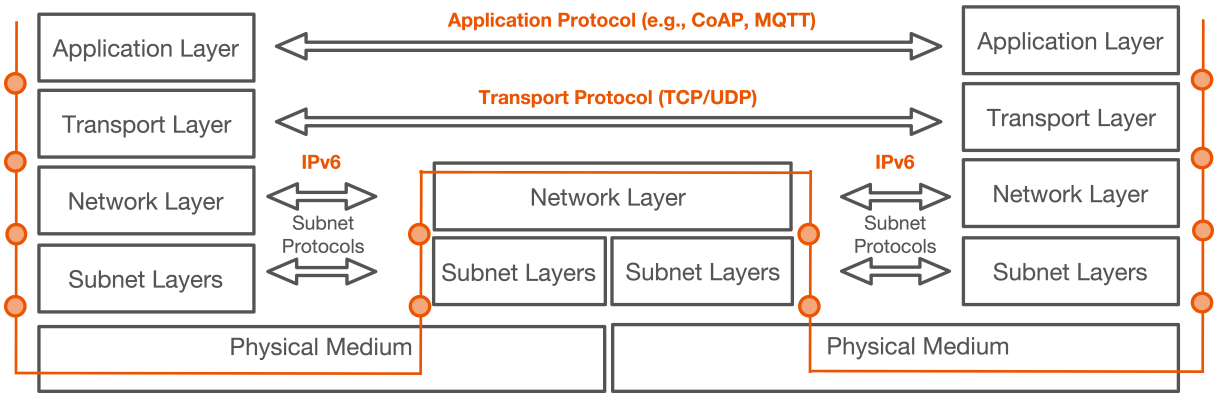


Figure 3.4: IoT Protocol Stack (Overview) with the different layers and their main protocols.

The **IoT protocol stack** builds upon the **traditional networking model** but introduces specialized layers, protocols, and adaptations to address the unique requirements of **resource-constrained devices**, **heterogeneous networks**, and **intermittent connectivity**. Modeling the IoT stack involves understanding how each layer is tailored for efficiency, scalability, and interoperability, while still

maintaining the modularity and abstraction principles of classic protocol stacks. **Key Layers and Protocols in IoT Stack Modeling**

- **Physical and Data Link Layers**: IoT networks often use low-power wireless technologies such as **ZigBee**, **LoRa**, **NB-IoT**, and **Bluetooth Low Energy (BLE)**, chosen for their energy efficiency, range, and suitability for large-scale deployments. Standards like **IEEE 802.15.4** provide the foundation for these technologies, supporting minimal energy consumption and cost-effective connectivity for battery-powered devices.
- **Network Layer**: To accommodate massive numbers of devices, IoT stacks typically adopt **IPv6** for its large address space. Protocols like **6LoWPAN** enable efficient transmission of IPv6 packets over constrained links, ensuring seamless integration with global networks while maintaining scalability and efficiency.
- **Transport Layer**: IoT environments require a balance between reliability and efficiency. While **TCP** and **UDP** are still used, adaptations such as **DTLS** (for secure UDP communication) are common to address low-latency and lossy network conditions, ensuring robust communication in challenging scenarios.
- **Application Layer**: Protocols like **MQTT**, **CoAP**, and **LwM2M** are designed for lightweight, efficient messaging, minimizing overhead and supporting intermittent connectivity. These protocols prioritize simplicity, low power consumption, and reliability, making them well-suited for resource-constrained IoT devices compared to traditional, heavier protocols like **HTTP**.

> Modeling the IoT protocol stack involves selecting and adapting layers and protocols to optimize for energy efficiency, scalability, and interoperability, addressing the unique requirements of diverse IoT environments.

Interoperability and Ecosystem Integration

- The IoT stack emphasizes **interoperability**, enabling seamless integration across diverse devices, vendors, and networks. **Protocol gateways** (e.g., ZigBee-to-IP converters) and **multi-stack solutions** facilitate communication between different technologies.
- **Open standards** and **unified APIs** are promoted to avoid vendor lock-in and foster ecosystem growth, ensuring that devices using specialized IoT protocols can participate in broader Internet-connected applications.

3.3 Simple Comparison Between Traditional Internet Protocol Stack and IoT Protocol Stack

Comparison: IoT Protocol Stack vs. Traditional Internet Protocol Stack

Layer	Traditional Stack	IoT Stack
Physical	Ethernet, Wi-Fi	ZigBee, LoRa, NB-IoT, BLE, Ethernet, Wi-Fi
Data Link	Ethernet (MAC), Wi-Fi (MAC), PPP	IEEE 802.15.4, ZigBee, Thread, BLE
Network	IPv4, IPv6, ICMP	IPv6, 6LoWPAN, RPL
Transport	TCP, UDP	UDP, TCP, DTLS (secure UDP), lightweight adaptations
Application	HTTP, HTTPS, SMTP, SSH	MQTT, CoAP, LwM2M, lightweight REST, custom IoT protocols
Modeling Focus	High throughput, reliability, modularity	Low power, scalability, interoperability, efficiency, resource constraints

The **IoT protocol stack** is modeled to optimize for **energy efficiency**, **scalability**, and **interoperability**, using lightweight protocols and specialized layers. In contrast, the **traditional stack** prioritizes **high throughput** and **reliability** for general-purpose computing and communication. Understanding these differences is essential for designing robust IoT systems that can seamlessly integrate with existing Internet infrastructure.

3.4 IoT Application Layer Protocols

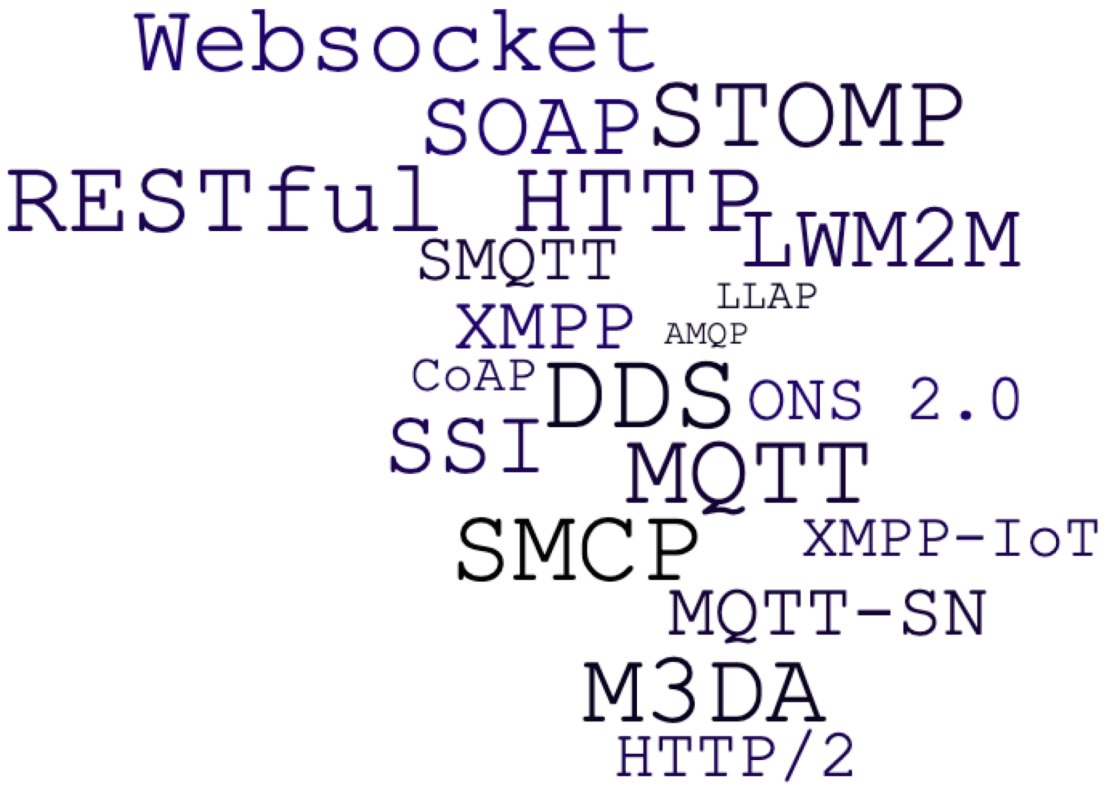


Figure 3.5: Some application layer protocols.

The **application layer** in networking models (OSI Levels 5, 6, and 7; TCP/IP application layer) is the **topmost layer** that interfaces between **end devices**, the **network**, and **user applications**. It is implemented via dedicated software at the device level and is responsible for **data formatting**, **presentation**, and **protocol-specific communication**. In traditional Internet services, protocols such as **HTTP**, **HTTPS**, **SMTP**, and **FTP** operate at this layer, enabling web browsing, secure transactions, email, and file transfers.

When **modeling IoT systems**, the application layer plays a crucial role in defining how devices interact, exchange data, and integrate with broader networks. However, **traditional protocols** are often **unsuitable for IoT environments** due to their **heavyweight nature** and **high parsing overhead**. IoT devices are typically **resource-constrained**—with limited CPU, memory, and energy—making it essential to use **lightweight protocols** that minimize computational and transmission demands.

Key modeling considerations for IoT application layer protocols:

- **CPU Processing:** IoT devices have **limited computational capabilities**, making it difficult to

process large or complex messages. **Reducing processing requirements** leads to **lower energy consumption** and longer device lifespans.

- **Data Transmission:** Large messages result in more **fragments**, increasing **overhead** and the likelihood of **retransmissions**—especially in **Low-power and Lossy Networks (LLNs)**. This can cause **higher delays** and further drain energy resources.
- **Efficiency and Scalability:** Lightweight protocols such as **MQTT**, **CoAP**, and **LwM2M** are specifically designed for IoT, focusing on **minimal overhead**, **efficient parsing**, and **robustness** in unreliable network conditions.

> In summary, modeling the application layer for IoT involves selecting protocols that optimize for **efficiency**, **scalability**, and **interoperability**, ensuring reliable communication while respecting the constraints of IoT devices and networks.

3.5 Main Protocols Interaction Models

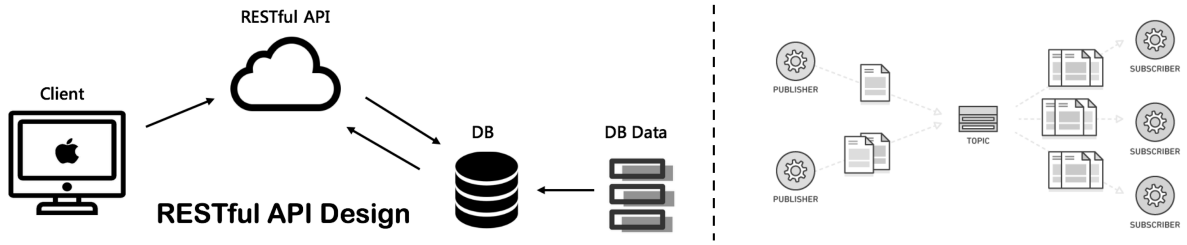


Figure 3.6: Quick comparison of main protocols interaction models among Request/Response and Publish/Subscribe.

When modeling IoT systems, **protocols** are designed around specific **communication paradigms** such as **request/response** and **publish/subscribe**. Each paradigm introduces distinct **requirements** that influence the selection of the most suitable protocol and **architectural style** for a given scenario.

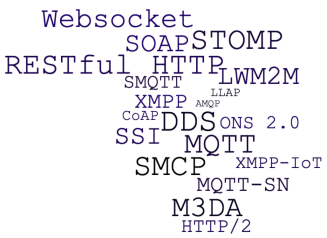
- The **request/response** paradigm is commonly used in **RESTful architectures**, where a client sends a request and the server responds with the required data. This model is straightforward and fits well for scenarios where devices need to **retrieve or update resources** on demand.
- The **publish/subscribe** paradigm enables **asynchronous communication**, allowing devices to **publish data** to topics and other devices to **subscribe** and receive updates automatically. This model is ideal for **event-driven** IoT applications, such as sensor networks and real-time monitoring.

Modeling the communication architecture involves analyzing the specific needs of your scenario—such as **latency**, **scalability**, **energy efficiency**, and **data flow patterns**—to determine which paradigm and protocol best fit. While there is no universal solution, the **IoT ecosystem** is predominantly built around the **REST architectural style** (mirroring the traditional Internet) and **publish/subscribe approaches** for flexibility and scalability.

> **Key takeaway:** Select the communication paradigm and protocol that align with your application's requirements, considering factors like device constraints, network reliability, and integration needs. Both **REST** and **Pub/Sub** are foundational to modern IoT system modeling.

> **Note:** There are several protocols belonging to both paradigms, but in this lecture, we will focus on **HTTP** (request/response) and **MQTT** (publish/subscribe) as representative examples. Additionally, we will briefly mention **CoAP**, which, despite being a request/response protocol, is specifically designed for constrained environments. We will not cover **AMQP** and **DDS** in this lecture, but they are also important protocols in the IoT landscape.

3.6 Protocols Objectives - Towards Standardization and Interoperability



Target IoT Application Layer Protocols
(Standard, Interoperable, Web of Things)

MQTT, AMQP, CoAP & HTTP …

Figure 3.7: The objective of IoT application layer protocols is to achieve standardization and interoperability.

When **modeling IoT systems**, protocols such as **MQTT**, **AMQP**, **CoAP**, and **HTTP** are chosen for their **wide adoption** and **design principles** that enable **cross-device** and **cross-vendor communication**.

- **Interoperability**: Adopting **standard protocols** ensures that devices from different manufacturers and domains can interact seamlessly, which is essential for building unified IoT solutions and ecosystems. This interoperability is a key modeling objective, as it allows diverse devices to exchange data reliably and efficiently.
- **Standard Usage**: Relying on **established, well-documented protocols** helps prevent fragmentation and vendor lock-in, supporting **large-scale deployments** and **future-proof integration**. Modeling with these protocols provides a stable foundation for expanding and maintaining IoT systems over time.

> The success of IoT modeling depends on selecting **standard, interoperable protocols** to build robust, scalable, and maintainable connected systems. The figure below illustrates that the primary goal of IoT application layer protocols is to achieve **standardization** and **interoperability**, laying the groundwork for the "**Web of Things**" where diverse devices and platforms can communicate easily and reliably.

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