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at Northeastern University

EECE5155: Wireless Sensor Networks and the Internet of Things

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Module T5: Data Streaming

The Internet of Things

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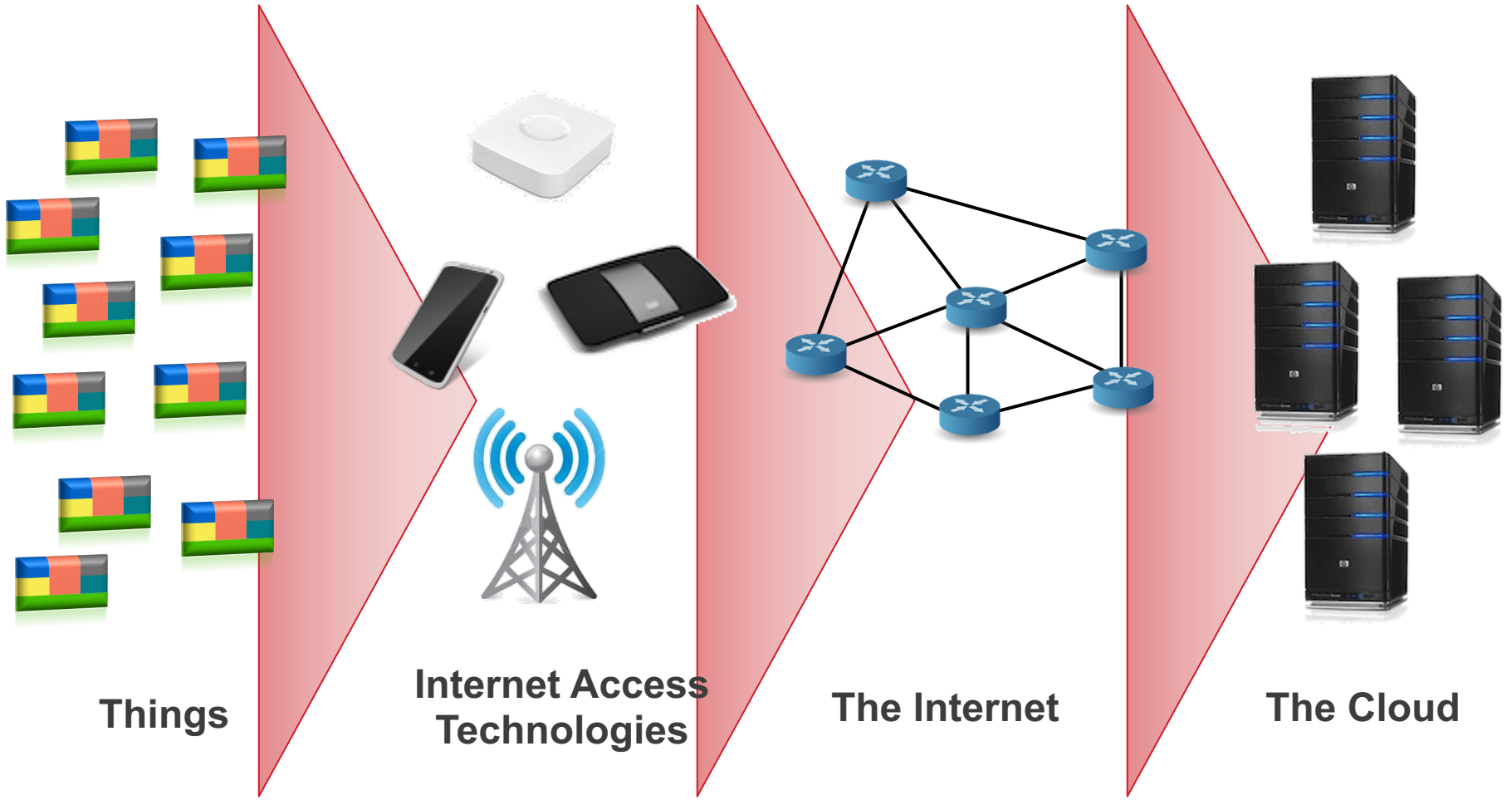

The Protocol Stack

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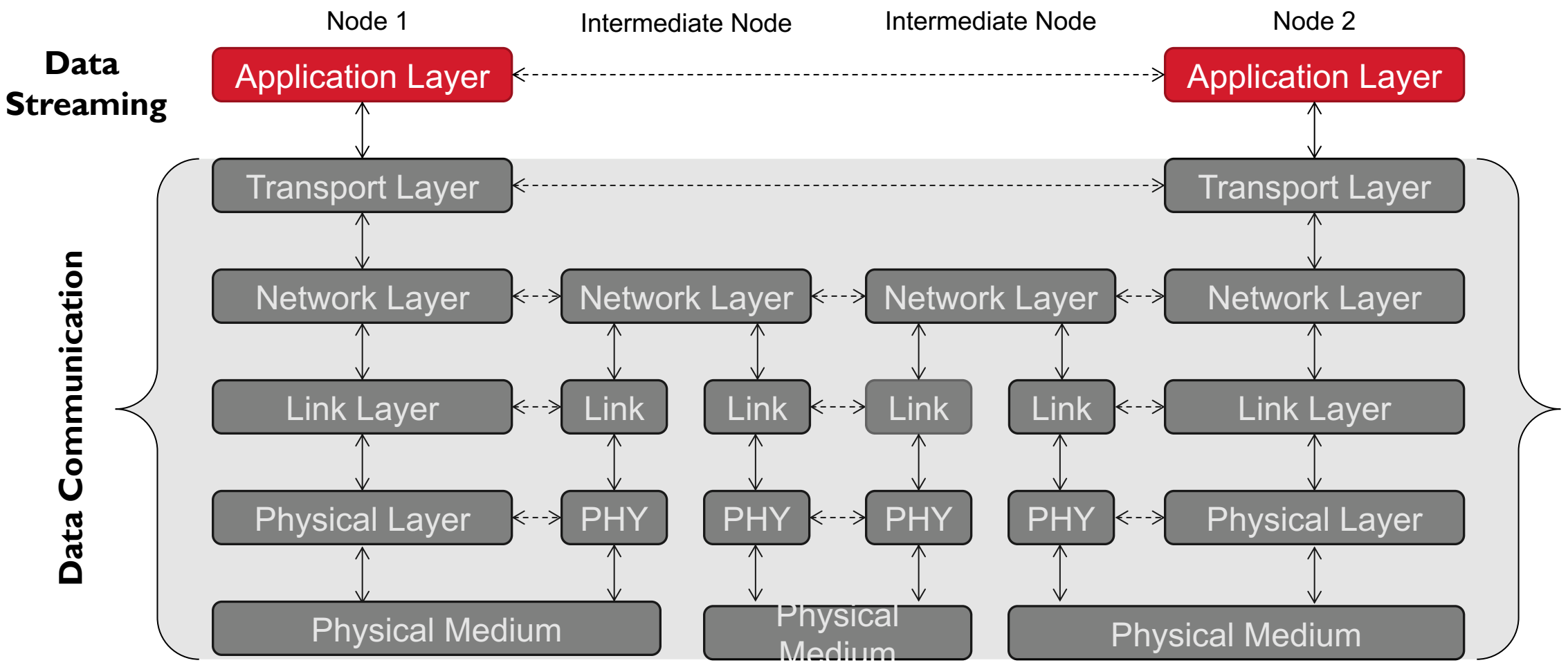

Data Streaming Protocols

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- At the application layer, we need to effectively transmit data:
  - From nodes to server
  - From server to nodes
  - Between nodes

- Why don't we use:
  - **FTP/SFTP** → Transfer files
    - Too complicated, unlikely needed
  - **POP3/SMTP/IMAP/Exchange** → Send emails
    - Too much burden for some simple data

Data Streaming Protocols

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- MQTT
- CoAP
- HTTP
- XMPP
- AMQP
- …

MQTT

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- A client-server **publish/subscribe** messaging protocol
  - It is lightweight, open, simple, and designed to be easy to implement
- Designed to handle high volumes of data in **low bandwidth networks**
  - Reduce operation cost
- **Small code footprint**
  - Reduce device cost
- Runs on top of **TCP/IP**
  - Some variations like MQTT- SN run over non-TCP/IP networks
- **Examples:**
  - Facebook Messenger
  - Supported by Amazon Web Services (AWS)
  - LoRaWAN gateways
  - Many others

MQTT History

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- Invented in 1999 by Andy Stanford-Clark (IBM) and Arlen Nipper
  - The original problem was to send sensor data from oil pipelines through a satellite link
  - The original acronym was **MQ Telemetry Transport**
    - MQ Series was an IBM product type for message queueing
      → But MQTT does not need to support message queueing
    - IBM released MQTT implementation in 2010
    - In 2013, **OASIS** standardized MQTT 3.1
      - *"A nonprofit consortium that drives the development, convergence and adoption of open standards for the global information society"*
      - http://docs.oasis-open.org/mqtt/mqtt/v3.1.1/mqtt-v3.1.1.html
    - In 2016, **ISO** standardized MQTT 3.1 as ISO/IEC PRF 20922
    - In 2018, **MQTT 5.0** is released.

MQTT Publish/Subscribe Model

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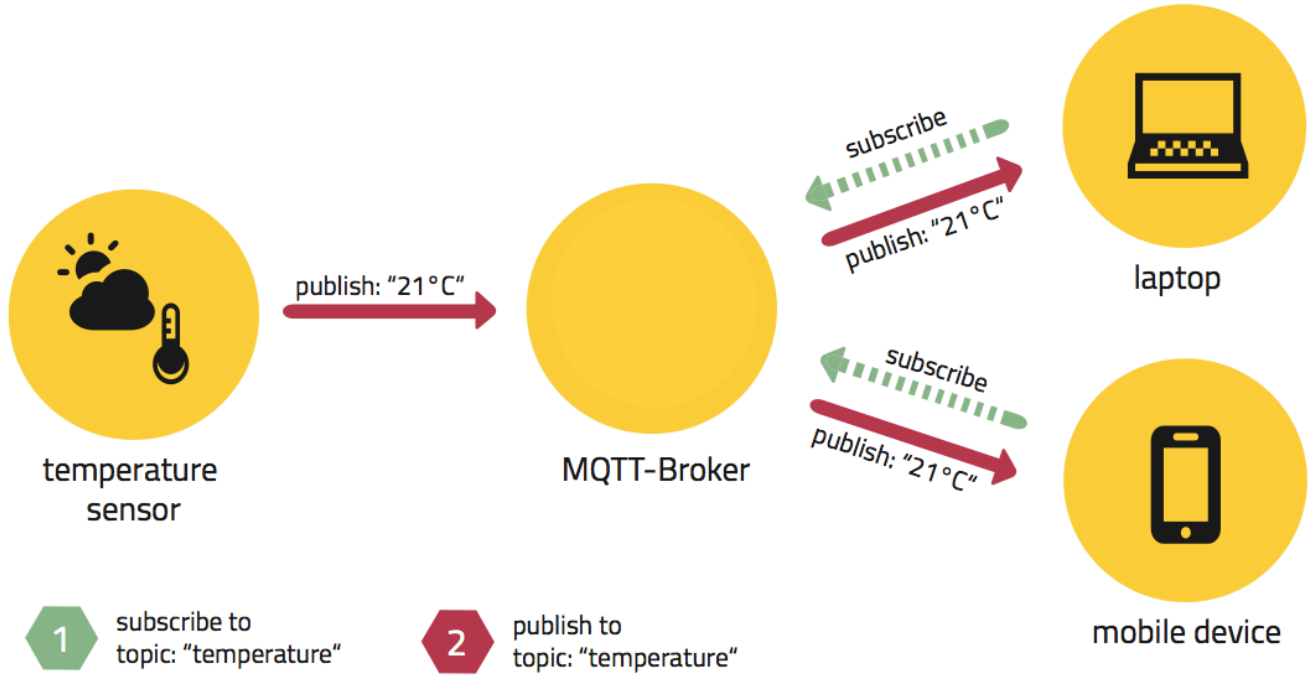
- MQTT allows devices to send (**publish**) information about a given topic to a server (MQTT message **broker**)
- The broker then **pushes** the information out to those clients that have previously **subscribed** to the topic
- A topic looks like a hierarchical file path:
  - Clients can subscribe to a specific level of a topic's hierarchy or
  - Use a wildcard character to subscribe to multiple levels



MQTT Topic Structure

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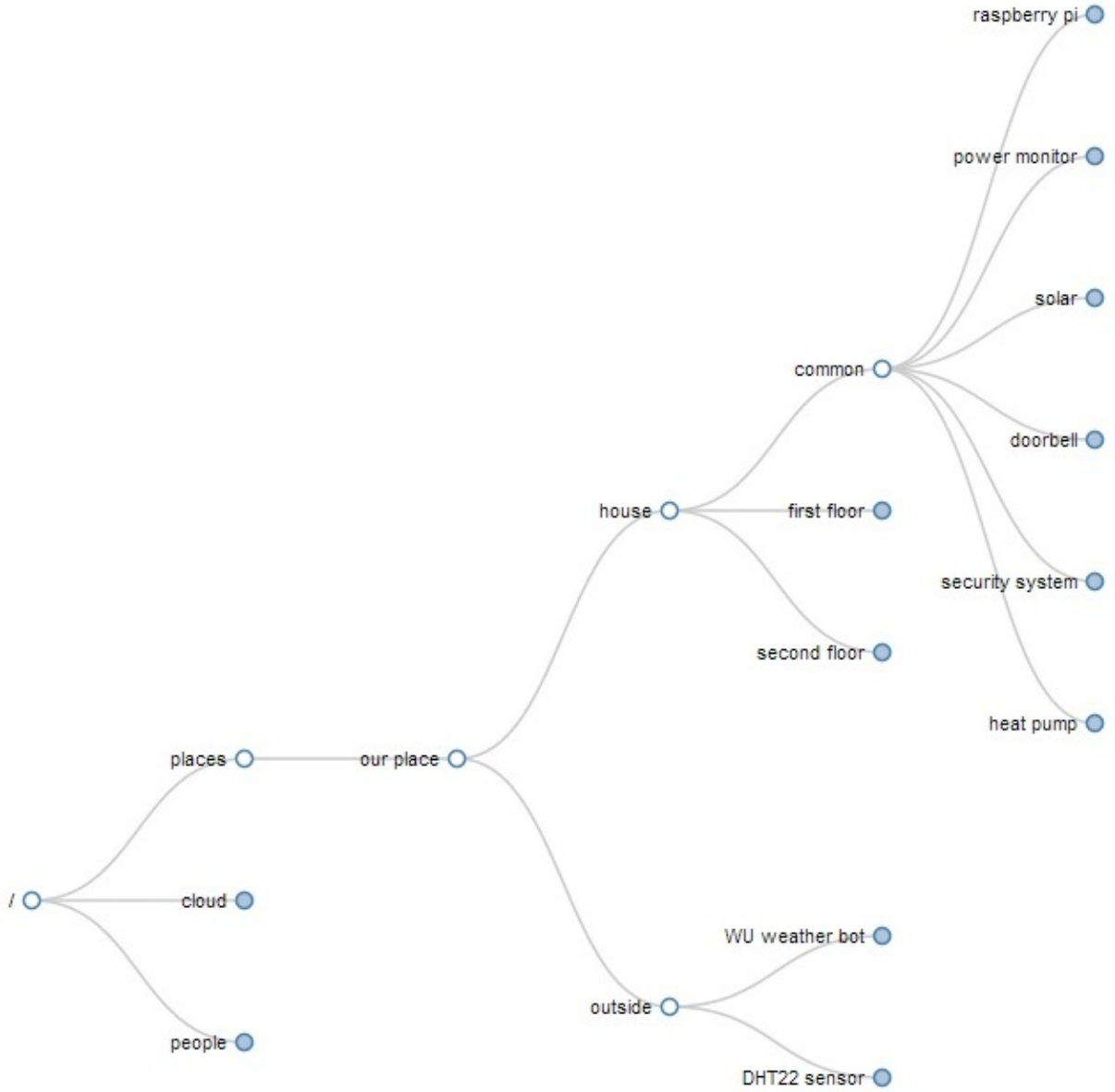

MQTT Protocol

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- An MQTT session is divided into four stages:
  1. **Connection:** CONNECT/CONNACK
     - A client starts by creating a TCP/IP connection to the broker by either using a standard port or a custom port defined by the broker's operators
       - 1883 for non-encrypted communication
       - 8883 for encrypted communication using SSL/TLS
  2. **Authentication:**
     - Without SSL/TLS:
       - Clear-text username and password are sent by the client to the server as part of the CONNECT/CONNACK packet sequence
     - With SSL/TLS handshake:
       - The client validates the server certificate to authenticate the server
       - The client may also provide a client certificate to the broker during the handshake which the broker can use to authenticate the client

MQTT Protocol

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- An MQTT session is divided into four stages:
  3. **Communication:** Three types of service
     - **Unacknowledged Service (*"at most once"*):** PUBLISH
       - The publisher sends a message one time to the broker and the broker passes the message one time to subscribers
       - There is no mechanism in place to make sure the message has been received correctly and the broker does not save the message
     - **Acknowledged Service ("*at least once*"):** PUBLISH/PUBACK
       - Packet/ACK packet sequence between the publisher and its broker, as well as between the broker and subscribers
       - Retransmit otherwise
     - **Assured Service (*"Exactly once"*):**
       - Two pairs of packets:
         - PUBLISH/PUBRECeived
         - PUBREL/PUBCOMPlete

MQTT Protocol

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- An MQTT session is divided into four stages:
  3. **Communication:** A client can perform 4 operations:
     - **Publish:**
       - The publish operation sends a binary block of data (the content) to a topic that is defined by the publisher
       - MQTT supports messages of up to 256 MB in size, 2 byte header
       - The format of the content is application specific
     - **Subscribe:** Topic subscriptions are made using a SUBSCRIBE/SUBACK packet pair
     - **Unsubscribe:** Un-subscription is similarly performed using a UBSUBSCRIBE/UNSUBACK packet pair
     - **Ping:** PINGREQ/PINGRESP is used to maintain the TCP connection alive
  4. **Termination:** DISCONNECT

Challenges for MQTT

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- **Scalability:** Topic structure can easily form a huge tree and there's no clear way how to divide a tree into smaller logical domains that can be federated:
  - This makes it difficult to create a globally scalable MQTT network, because as the size of the topic tree grows, complexity increases
- **Interoperability:** Message payloads are binary, with no information as to how they are encoded
  - Problems can arise in open architectures where different applications from different manufacturers are supposed to work seamlessly with each other
- **Security:** MQTT has minimal authentication features built into the protocol:
  - Username and passwords are sent in clear text and any form of secure use of MQTT must employ SSL/TLS, which unfortunately, is not a lightweight protocol
  - Authenticating clients with client-side certificates is not a simple process and there's no way in MQTT, except by proprietary out-of-band means, to control who owns a topic and who can publish information on it

HTTP: Hyper Text Transfer Protocol

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- Even though HTTP is old, it is still a perfectly valid protocol for transferring data between clients and servers:
  - HTTP is the most compatible with existing network infrastructure
    - If a web browser works, then nodes in this scenario should be able to send data to the cloud
  - Stateless HTTP will traverse firewalls and NAT systems easily

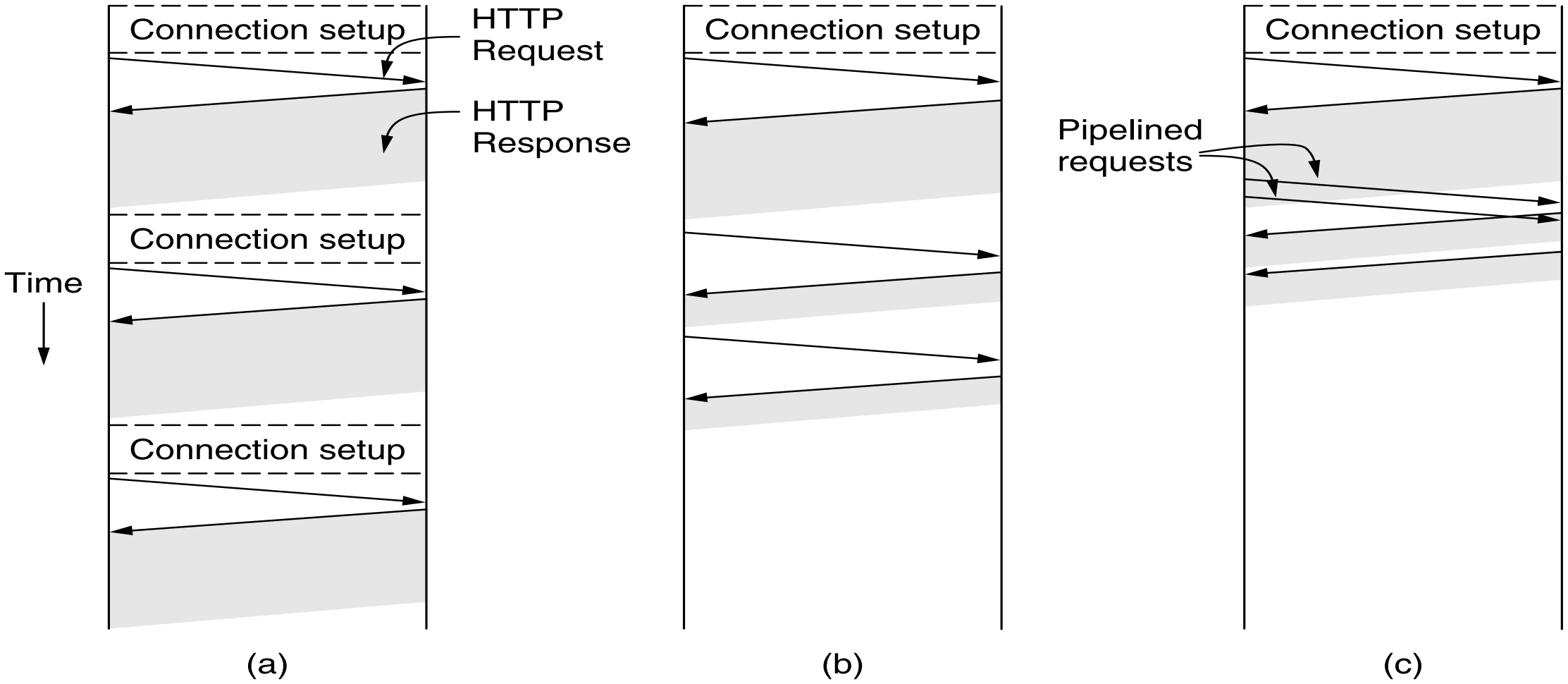
- Because the nodes initiate the connection to the server, the machines are much easier to secure
  - They don't even need any open ports
  - Most of the security effort in this system only needs to be focused in one place (cloud server)

- HTTP provides well understood authentication and encryption mechanisms

Reminder: HTTP

- HTTP is the protocol used to transport the web content from the web servers to the clients' browser
  - RFC 2616 (1999)
- The usual way for a browser to contact a server is to establish a TCP connection to port 80 on the server's machine
- The way in which TCP connections are handled in HTTP have changed since its creation:
  a) Multiple sequential TCP connections, each containing a single HTTP request
     - Too much overhead (connection establishment and release)
  b) Single persistent TCP connection, over which multiple HTTP requests are sent one after the other, sequentially
     - No need to go again through the slow-start process
  c) Single persistent TCP connection, over which multiple HTTP requests are sent simultaneously
     - The server is idling for a shorter time

HTTP: TCP Connections



HTTP: Methods

- Type of requests that can be sent over an HTTP connection

Method	Description
GET	Read a Web page
HEAD	Read a Web page's header
POST	Append to a Web page
PUT	Store a Web page
DELETE	Remove the Web page
TRACE	Echo the incoming request
CONNECT	Connect through a proxy
OPTIONS	Query options for a page

HTTP: Message Headers

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- The “parameters” of the request

Header	Type	Contents
Accept	Request	The type of pages the client can handle
Accept-Encoding	Request	The page encodings the client can handle
If-Modified-Since	Request	Time and date to check freshness
Authorization	Request	A list of the client’s credentials
Host	Request	The server’s DNS name
Last-Modified	Response	Time and date the page was last changed
Content-Type	Response	The page’s type
…		

CoAP: Constrained Application Protocol

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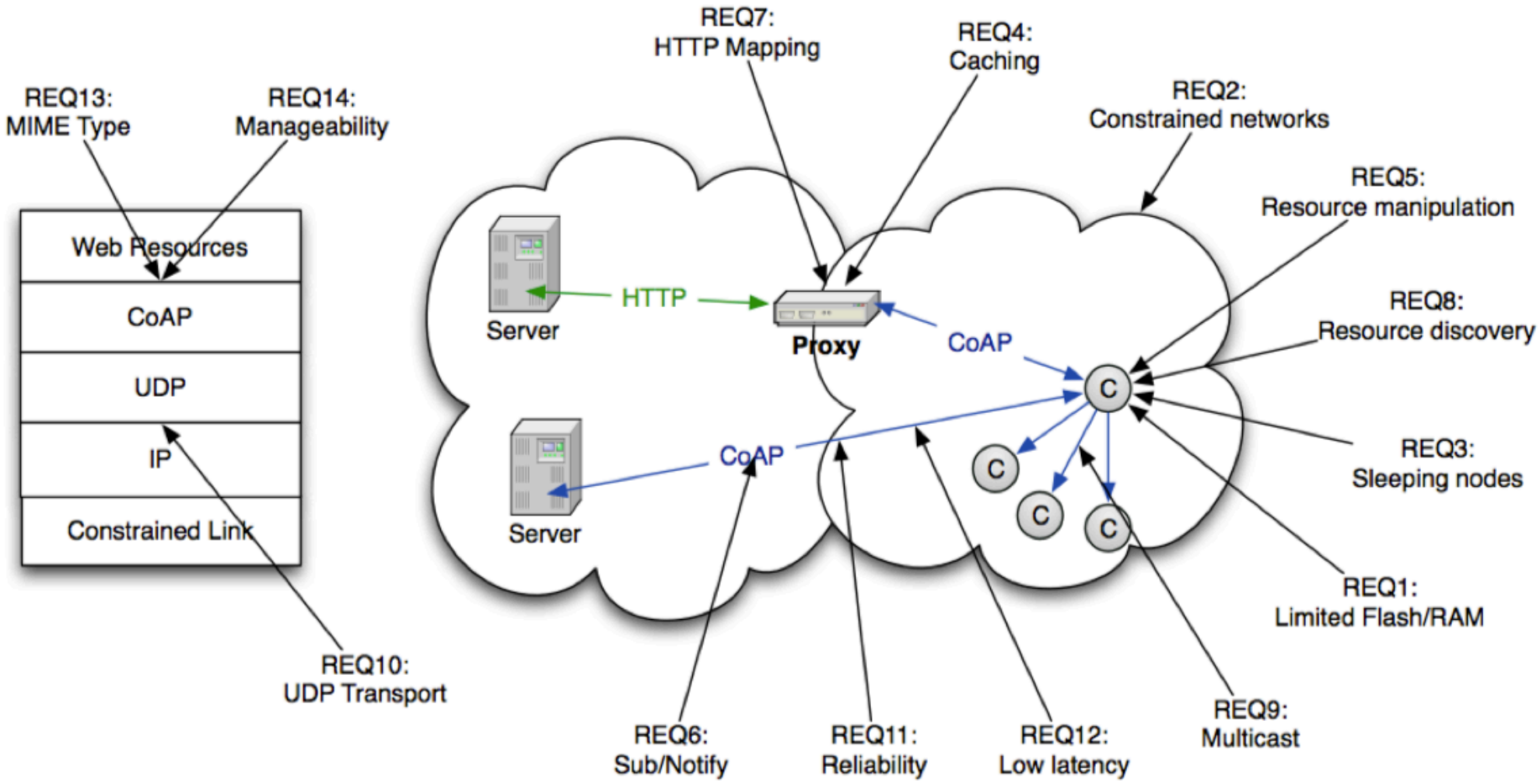
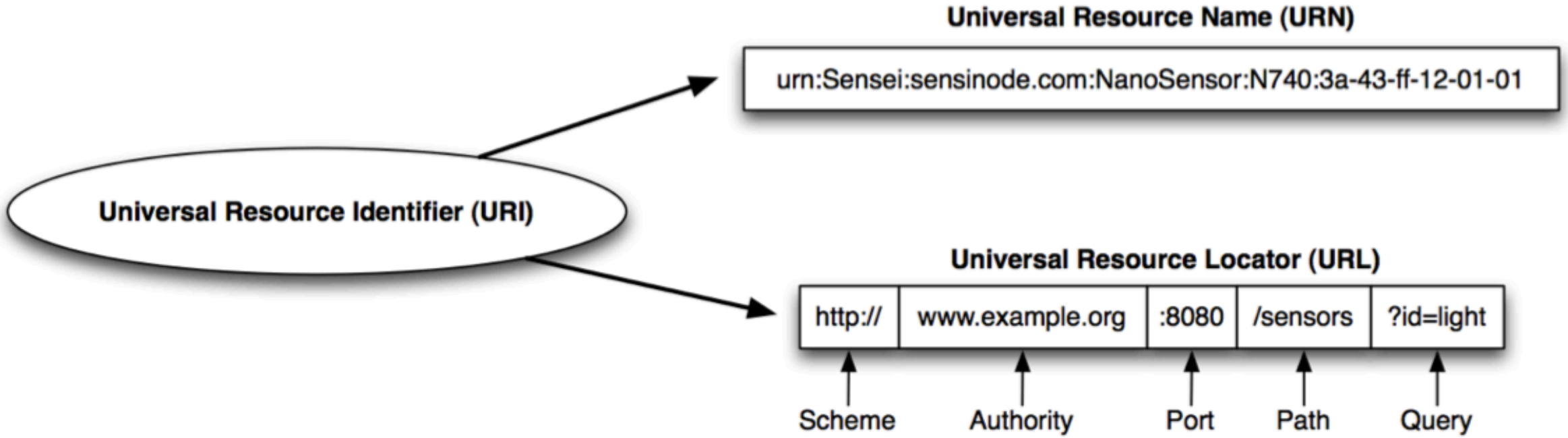
- Described in the RFC 7252, developed by the **IETF Constrained RESTful Environments (CoRE) working group**
- A specialized web transfer protocol that is suitable for:
  - **Constrained nodes** (low processing power, limited memory)
  - **Constrained networks** (low bandwidth)
- Like HTTP, servers make resources available under a **URI**…
  - … clients can access these resources using methods such as GET, PUT, POST, and DELETE
- The close resemblance with HTTP makes it very **user-friendly**…
  - … and also makes it easier to connect CoAP and HTTP using application-agnostic **cross-protocol proxies**
- As opposed to HTTP, CoAP is built on top of UDP

CoAP


REQ13:
MIME Type
REQ14:
Manageability
Web Resources
CoAP
UDP
IP
Constrained Link
REQ10:
UDP Transport
REQ7:
HTTP Mapping
REQ4:
Caching
REQ2:
Constrained networks
REQ5:
Resource manipulation
REQ8:
Resource discovery
REQ3:
Sleeping nodes
REQ1:
Limited Flash/RAM
REQ9:
Multicast
REQ12:
Low latency
REQ11:
Reliability
REQ6:
Sub/Notify
Server
HTTP
Proxy
CoAP
Server
CoAP
C
C
C
C

URI: Universal Resource Identifier



CoAP Messaging Model

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- Simple message exchange between end-points
  - 4 bytes header, max payload 8 kB
  - Includes Message ID to detect duplicates, increase reliability

- Types of Message:
  - **CON** (Confirmable)
    - Message is retransmitted using a default timeout and exponential back-off between retransmissions, until the recipient sends an ACK with the same Message ID
  - **NON** (Non-confirmable)
    - Not acknowledged, but still have a Message ID for duplicate detection
  - **ACK** (Acknowledgement)
  - **RST** (Reset)

CoAP Request/Response Model

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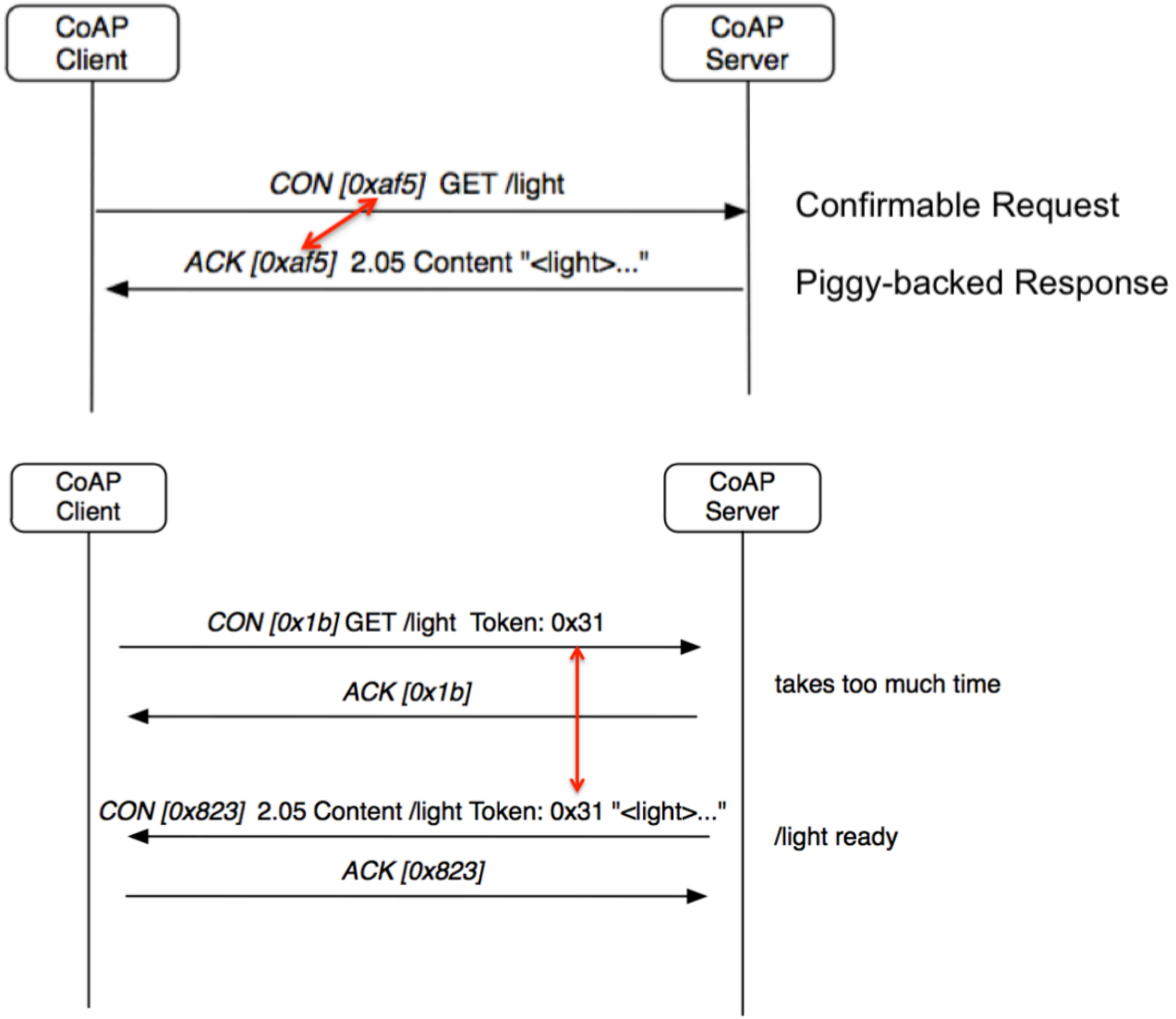
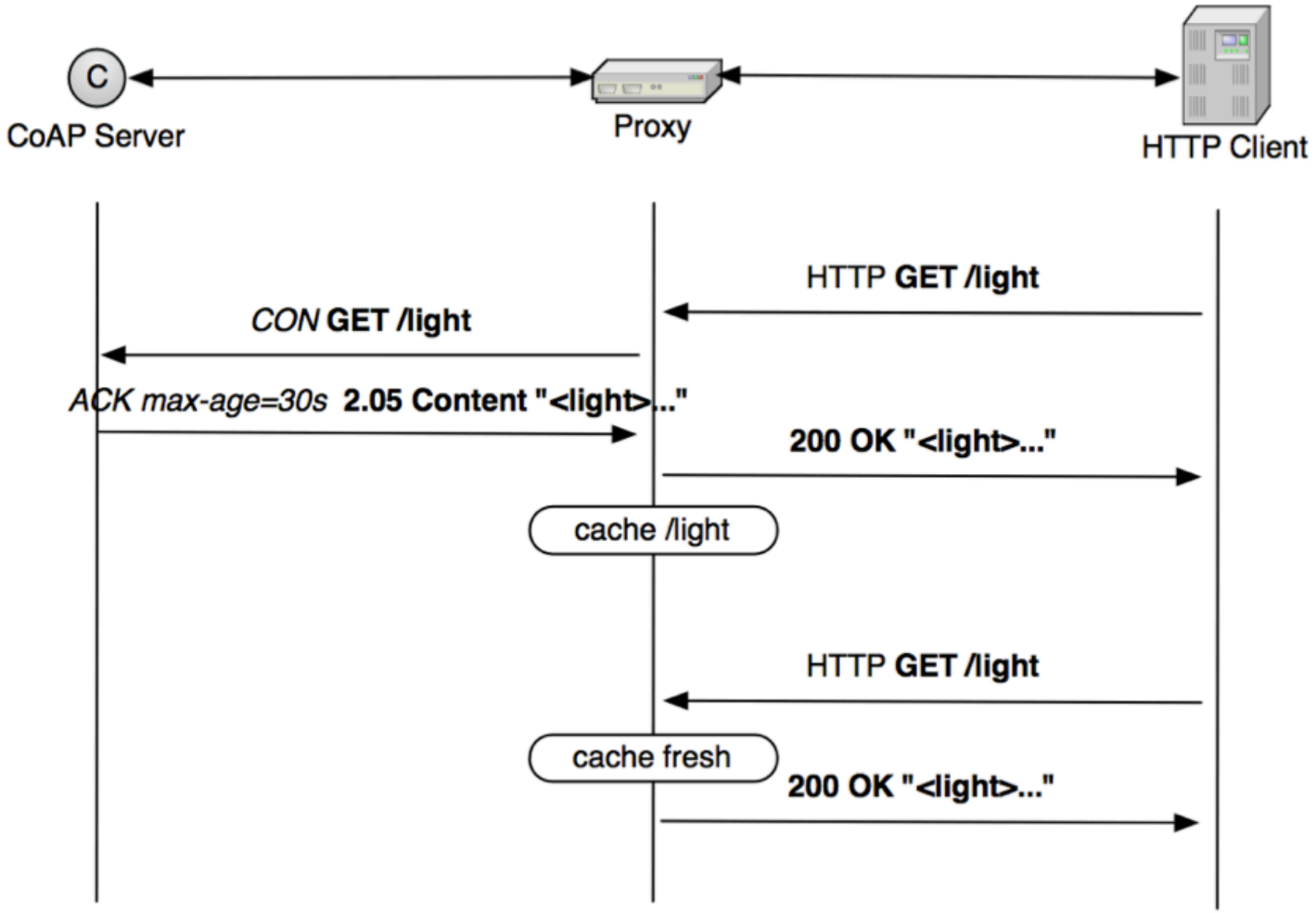
- CoAP request and response semantics are carried in CoAP messages, which include either a Method Code or Response Code, respectively
- If a request is carried in a CON message
  - If immediately available, the response to a request carried in a Confirmable message is carried in the resulting Acknowledgement (ACK) message
  - If the server is not able to respond immediately to a request carried in a Confirmable message, it responds with an Empty Acknowledgement message so that the client can stop retransmitting the request
    - When the response is ready, the server sends it in a new Confirmable message (which then in turn needs to be acknowledged by the client)
- If a request is sent in a NON message, then the response is sent using a new Non-confirmable message

CoAP Request/Response Model



CoAP/HTTP Proxy



XMPP: Extensible Messaging and Presence Protocol

- An application profile of the **Extensible Markup Language** (XML) that enables the near-real-time exchange of structured yet extensible data between any two or more network entities

- Standardized by **IETF**:
  - RFC 6120 (used to be 3920): Core
  - RFC 6121 (used to be 3921): Instant Messaging and Presence
  - RFC 7622 (used to be 6122): Address Format
  - RFC 3922: Mapping to CPIM
  - RFC 3923: End-to-end Signaling

- Developed originally by the **Jabber** open-source community (1999)
  - One of the ancient instant messaging platforms
    - At the basis of text messaging with Google Talk, Hangouts, etc.

XML

- A markup language that defines a set of rules for encoding documents in a format that is both human-readable and machine-readable
  - (Reminder: HTML: Hypertext Markup Language, you use it to write websites…)

- XML is not a replacement for HTML
  - XML was designed to **describe data and to focus on what data is**
    - HTML was designed to **display data and to focus on how data looks**
  - XML is about describing information
    - HTML is about displaying information

XMPP: Model

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- **Decentralized client–server architecture:**
  - Clients do not talk directly to one another
  - There is no central authoritative server
  - Anyone can run a server
  - Anyone may run their own XMPP server on their own domain

- **Implementation:**
  - Originally: XMPP on top of TCP
  - Currently: the majority of XMPP messages on top of HTTP
  - Alternative: WebSockets

WebSockets

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- An application-layer communication protocol that provides bidirectional full-duplex channels over a single TCP connection
  - **Bidirectionality:**
    - There are no pre-defined message patterns such as request/response
    - Either client or server can send a message to the other party
  - **Full-duplex:**
    - Client and server can talk independent of each other
  - **Single TCP:**
    - Client and server communicate over that same TCP connection for the lifecycle of WebSocket connection
  - **Efficient implementation**

WebSockets: Protocol

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- Designed to work well with the existing Web infrastructure (i.e., HTTP)
  - The connection starts its life as an HTTP connection, guaranteeing full backwards compatibility
  - The protocol switch from HTTP to WebSocket is referred to as a the WebSocket handshake
    - The browser sends a request to the server, indicating that it wants to switch protocols from HTTP to WebSocket
    - If the server understands the WebSocket protocol, it agrees to the protocol switch through the Upgrade header

XMPP: Addressing

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- Every user on the network has a unique XMPP address, called JID (for historical reasons)
  - The JID is structured like an email address with a username and a domain name (or IP address) for the server where that user resides, separated by an at sign (@) → username@example.com

- Since a user may wish to log in from multiple locations, they may specify a resource:
  - A resource identifies a particular client belonging to the user (for example home, work, or mobile)
  - This may be included in the JID by appending a slash followed by the name of the resource → username@example.com/mobile

- Each resource may have specified a numerical value called priority:
  - Messages simply sent to username@example.com will go to the client with highest priority
  - Those sent to username@example.com/mobile will go only to the mobile client

XMPP: Services

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- Channel Encryption
- Authentication
- Presence
- Contact lists
- One-to-one messaging
- Multi-party messaging
- Notifications
- Service discovery
- Capabilities advertisement
- Structured data forms
- Workflow management
- Peer-to-peer media sessions

XMPP: XML Stanzas

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- The basic unit of communication, similar to a packet or message in other network protocols
- Defined by:
  - The stanza element name, which is **message**, **presence**, or **iq**
    - Each kind of stanza is routed differently by servers and handled differently by clients.
  - The value of the type **attribute**, which varies depending on the kind of stanza in question
    - This value further differentiates how each kind of stanza is processed by the recipient.
  - The **child element(s)**, which define the payload of the stanza
    - The payload might be presented to a user or processed in some automated fashion as determined by the specification that defines the namespace of the payload.

Some thoughts about XMPP

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- XMPP is an IM protocol, and has a much, much higher overhead in handling presence messages between all the clients

- If you have a small memory footprint constraint, then having to handle the XML parser may make the use of XMPP impossible

- XMPP is an IM protocol which:
  - carefully defines all the message formats and requires that all messages be in XML
  - can be extended to support publish / subscribe procedures

AMQP: Advanced Message Queueing Protocol

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- An open internet protocol for business messaging:
  - It defines a **binary wire-level protocol** that allows for the reliable exchange of business messages between two parties
    - Utilized by many companies, e.g., banking and finance, defense, manufacturing, etc.
  - Developed by OASIS: http://docs.oasis-open.org/amqp/core/v1.0/os/amqp-core-complete-v1.0-os.pdf
  - Standardized as ISO/IEC 19464
- Used to transfer messages between two nodes:
  - Peer-to-peer
  - Peer-to-broker (server)
  - Broker-to-peer
- Usually on top of TCP

AMQP Frames

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- The basic unit of data in AMQP is a *frame*:
  - There are nine AMQP frame bodies defined that are used to initiate, control and tear down the transfer of messages between two peers:
    - open
    - begin
    - attach
    - transfer
    - flow
    - disposition
    - detach
    - end
    - close

AMQP Links

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- The link protocol is at the heart of AMQP.
  - An *attach* frame body is sent to initiate a new link
  - A *detach* frame is used to tear down a link
- Messages are sent over an established link using the *transfer* frame
- Messages on a link flow in only one direction
- Transfers are subject to a credit based flow control scheme, managed using flow frames
  - This allows a process to protect itself from being overwhelmed by too large a volume of messages
- Each transferred message must eventually be settled:
  - Settlement ensures that the sender and receiver agree on the state of the transfer, providing reliability guarantees.
- Multiple links, in both directions, can be grouped together in a session:
  - A session is a bidirectional, sequential conversation between two peers that is initiated with a begin frame and terminated with an end frame
  - A connection between two peers can have multiple sessions multiplexed over it, each logically independent

Some Thoughts

- **Which one is "the best"?**
  - Depends on your application
    - All these protocols provide general solutions, adaptable to your specific application
      - Widely adopted → Choose based on what your cloud supports
      - You might want to learn them ;)
    - Many times, you might want to define your data streaming protocol own..s

Next Steps

- Research paper:
  - Due on November 20

- First Quiz (up to Module T4):
  - December 1, 2020
    - On Canvas, open-book, multiple-choice questions
    - The exam will be available for 24h, but you will only have 60 minutes to complete it

- Coming soon:
  - Homework assignment (numerical)
  - Third (and last) laboratory assignment

Course Contents

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- **Module T5:** Data Streaming ✓
- **Module T6:** Data Storage & Cloud
- **Module T7:** Data Analytics