

Mobile and Cyber Physical Systems - Appunti

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Course info

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Part I

Stefano Chessa

Chapter 1

Internet of Things

The main topics addressed aside from IoT itself are how it relates to *Machine Learning* and *Cloud* computing processes, but also *IoT interoperability*, known *Standards*, and the *security* concerns about IoT.

1.1 IoT introduction

Cyber and Physical Systems (CPS) operate in both the Physical and Cyber worlds, thus we can see IoT as an embodiment of CPSs.

In a *smart environment*, smart objects are both physical and cyber, hence they are subject to “physical experiences” such as being placed, moved, damaged and so on.

But actually...
What is a *smart environment*?

The answer actually ain’t trivial; a journal on IoT reports:

“*smart environments can be defined with a variety of different characteristics based on the applications they serve, their interaction models with humans, the practical system design aspects, as well as the multi-faceted conceptual and algorithmic considerations that would enable them to operate seamlessly and unobtrusively*”

1.2 Platforms for IoT

Sensors and actuators are the edge of the cloud. In general the purpose of IoT is to gather and send data, send it somewhere where it gets transformed into information ultimately used to provide some functionality for an end user, or it simply presented to them.

A **Platform for IoT** is essentially a —complex— software hosted on the cloud, which, first of all, collects data gathered by IoT devices, but *not only* that:

- ◊ Identification
- ◊ Discovery
- ◊ Device Management
- ◊ Abstraction/virtualization
- ◊ Service composition
 - Integrating services of different IoT devices and SW components into a composite service
- ◊ Semantics
- ◊ Data Flow management
 - *sensors* → *applications*
 - *applications* → *sensors*
 - Support for aggregation, processing, analytics

1.3 No-SQL Databases

No-SQL DBs address the problem of the several changes of data formats, sources, cardinality and so on, which happen throughout time.

A common example is **MongoDB**, which stores records in JSON-like objects called *documents*, which are stored in *collections*, the entity corresponding to tables in relational DBs, with the key difference that multiple documents in a single collection may be structured differently.

1.4 IoT Issues

- ◊ Performance
- ◊ Energy Efficiency
- ◊ Security
- ◊ Data analysis/processing
 - Adaptability/personalization

The course will cover the basics of signal processing, with mentions to machine learning

- ◊ Communication/brokerage/binding
- ◊ Data representation
- ◊ Interoperability
 - Standard discussed will be ZigBee, MQTT, and IEEE 802.15.4 (?)

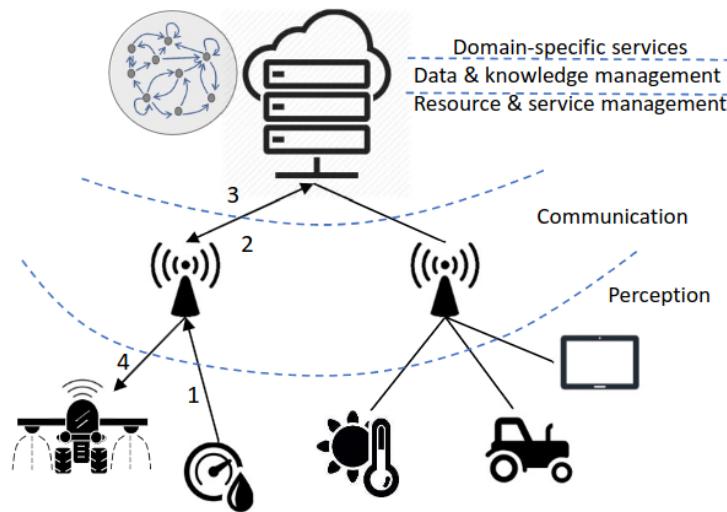


Figure 1.1: Communication outline in IoT

IoT systems are distributed, and servers may be dislocated around the globe, making room for latency and reliability issues.

To confine the problem displayed in Fig. 1.1 there are proposal to move the ability to make a decision on the data closer to the edge, but this in general isn't trivial.

Key Issues

1. Producing and handling fast-streaming heterogeneous sensed data
2. Make devices context-aware & allow them for continuous adaptation
3. Handle strong computing and energy constraints

1.4.1 Edge and Fog computing

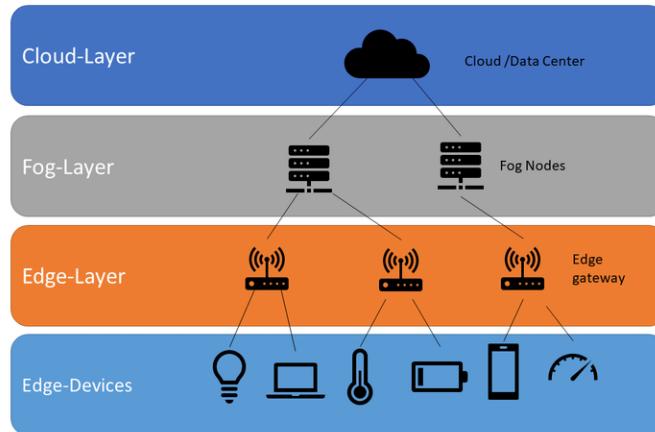


Figure 1.2: Layers scheme

A solution foresees to split the network in 4 layers, allowing for different response times and decisional capabilities.

A gateway on the **edge** interconnects the IoT-enabled devices with the higher-level communication networks, performing protocol translations.

A basic task performed at the fog layer is aggregating and collecting data, and then flushing it to the cloud periodically.

However, some decisions on the aggregated data may be taken at the fog node without querying the cloud, for instance determining where is a nest of tortoises, whether an explosion has occurred (by analyzing data from multiple sensors), and —maybe, one day in a not-so-far future— recognize human language.

prof. Chessa developed an 8 bit controller implementing a model for determining where is a nest of tortoises. Alexa and Google Home currently send audio samples to the cloud for processing, but in the future this may be done locally.

1.4.2 Artificial Intelligence

AI splits into **Machine Learning** and **Curated Knowledge**.

ML focuses on mimicking how humans learn on new knowledge, while *curated knowledge* focuses on mimicking how humans reason on a known set of data.

Machine Learning reveals itself to be particularly useful in aggregating multiple heterogeneous time-series sensed data about the same environment.

Supervised and Reinforcement learning are more promising than

1.4.3 Blockchain & IoT

A **blockchain** may act as a shared ledger between companies in a supply chain, with IoT devices to track goods and to monitor their quality along the chain, i.e. production stages, shipping and distribution.

With a blockchain each actor along the supply chain can query the ledger to check the —certified— state of the goods.

1.4.4 Interoperability

Vertical Silos: Developing a straight implementation of an IoT solution, starting from physical up to the application layer, is not a problem by itself.

In this way solution you implemented will work only on your devices, making your intervention needed for any change or update; besides, products by other vendors will be incompatible.

Vertical Silos business model leads to **vendor lock-ins**, which basically are service limitations which prevent the users from purchasing and using products from other vendors.

The solution to avoid —or limit— such issues is to introduce **standards**. Standards require common interests and agreements among different manufacturers, they are usually motivated by a reduction of the costs for development of a technology. There must be “*coopetition*” among manufacturers.

There is coopetition usually when a technology becomes mature:

- ◊ Big revenues are somewhere else
- ◊ No interest in investing big money in developing the technology
- ⇒ Without these conditions the standards will most likely fall

For what concerns wireless communication, standards are mainly differentiated by *Range* and *Data Rate*.

However, interoperability may be an issue not strictly related to vertical silos, but also to standards, in case there are *too many*.

The problem of interoperability shifts from low-level to application level.

To solve the problem, **gateways** are introduced, which translate different protocols.

- In type C configuration, how many mappings from one protocol to another (at the same level) the integration gateway should be able to manage?
- What about in type D configuration?

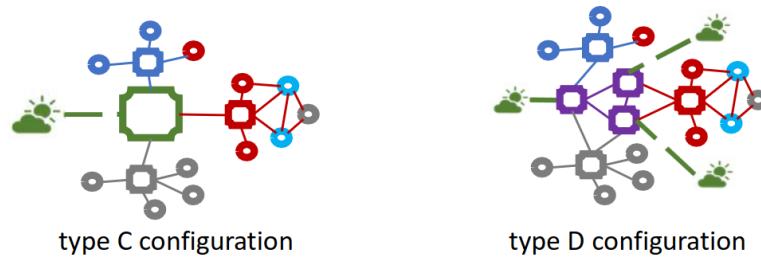


Figure 1.3: Gateway configs

Considering Fig 1.3 and assuming n protocol standards, the gateway in config C must be able to manage a mapping for every possible pair of standards, resulting in $n * n = n^2$ mappings. In configuration D instead every gateway translates *from* and *to* an **intermediate language** (purple in figure), resulting in a double translation process, but only $2 * n$ mappings, which is much less.

1.5 Security in IoT

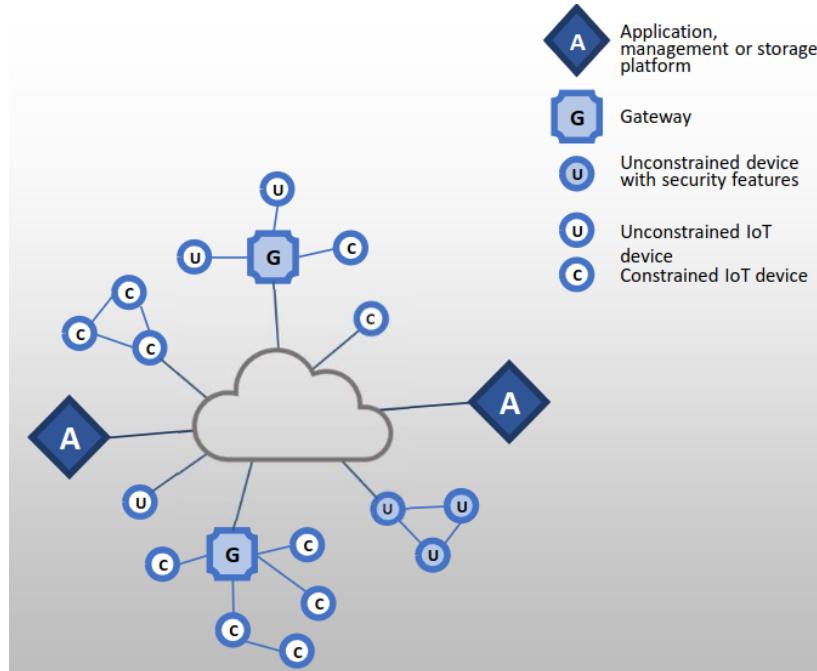


Figure 1.4: Security elements of interest

In an IoT environment there are various elements, each with its characteristics and vulnerabilities.

In general there are many issues concerning **patching vulnerabilities**, which poorly —or not at all— addressed.

- ◊ There is a crisis point with regard to the security of embedded systems, including IoT devices
- ◊ The embedded devices are riddled with vulnerabilities and there is no good way to patch them
- ◊ Chip manufacturers have strong incentives to produce their product as quickly and cheaply as possible
- ◊ The device manufacturers focus is the functionality of the device itself
- ◊ The end user may have no means of patching the system or, if so, little information about when and how to patch
- ◊ The result is that the hundreds of millions of Internet-connected devices in the IoT are vulnerable to attacks
- ◊ This is certainly a problem with sensors, allowing attackers to insert false data into the network

Not so critical for wristbands, but potentially harmful for water quality sensors, even worse for uranium enrichment, or aircraft sensors

- ◊ It is potentially a graver threat with actuators, where the attacker can affect the operation of machinery and other devices

What about **confidentiality**? Is it necessary?

The lecturer provided an example:

Assume that a wristband records the heartbeat without enforcing confidentiality, and assume that such heartbeat indicates a risk of heart disease in the owner. The owner may want to have a life insurance, but if a company had bought the unconfidential data on the black market, and recognized that the owner may suffer from a heart disease. Then the company could rise the price of the insurance for the unconfidential wristband owner.

Aside from these, laws introduce many requirements concerning security, which may be critical to satisfy in an IoT environment. In particular, The IUT-T standard Recommendation Y.2066 includes a list of security requirements for the IoT, which concern the following points, but note that the document does not define how to enforce and satisfy such requirements:

- ◊ Communication security
- ◊ Data management security
- ◊ Service provision security
- ◊ Integration of security policies and techniques
- ◊ Mutual authentication and authorization
- It is crucial for the authentication to work both directions, from the gateway to the device, and from the device to the gateway. It is needed because wireless networks are easily trickable by intruders.
- ◊ Security audit

Considering the points mentioned above, we must consider what is the role of **gateways** about security.

Sometimes instead of mutual one, weaker *one-way authentication* may be enforced: either the device authenticates itself to the gateway or the gateway authenticates itself to the device, but not both.

Also the security of the data is not trivial to achieve, especially if constrained devices are used, because they may not be able to enforce tasks such as encryption or authentication.

This makes **privacy** concerns arise especially regarding homes, cars and retail outlets, because with massive IoT, governments and private enterprises are able to collect massive amounts of data about individuals.

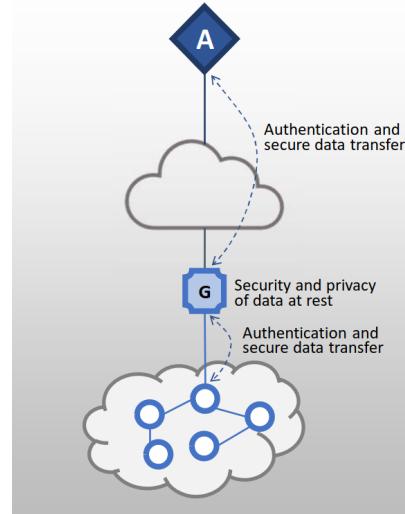


Figure 1.5: Gateways security functions

Chapter 2

MQTT

Things must be connected to the Internet to become “*IoT*” devices, and thus to adopt the internet protocol suite (TCP/IP + application, usually HTTP). However, the Internet stack is thought for *resource-rich* devices, not for IoT ones.

These led the canonical protocol stack to be modified for IoT environments, according to its needs and limitations.

MQTT is a publish-subscribe application protocol, which initially was not designed specifically for IoT. “MQTT” stands for “*Message Queuing Telemetry Transport*”, but “Queing” should not be intended literally as it usually is in the ICT world. MQTT is built upon TCP/IP. TCP isn’t the optimal choice for IoT, UDP is generally preferred, but as said before, MQTT was not designed for IoT:

- ◊ Port 1883
- ◊ Port 8883 for using MQTT over SSL
 - *SSL adds significant overhead!*

Lightweight

- ◊ Small code footprint
- ◊ Low network bandwidth
- ◊ Low packet overhead (guarantees better performances than HTTP)

2.1 Publish-Subscribe recalls

Publish/subscribe is a *loosely coupled*¹ interaction schema, where both publishers and subscribers act as “clients”. There is a third party called *event service* (aka **Broker**), which acts as the actual “server” (considering the client-server architecture), and which is known by both publishers and subscribers.

In this paradigm clients are simple, while the complexity resides in the broker.

Publishers, e.g. a sensor, produce events —or any data they wish to share by means of events— and interact only with the broker, while **subscribers** express the interest for an event, and receive an asynchronous notification whenever an event or a pattern of events is generated; also subscribers interact only with the broker.

Publishers and subscribers are **fully decoupled** in *time*, *space* and *synchronization*.

- ◊ Space decoupling:
 - Publisher and subscriber do not need to know each other and do not share anything
 - they don’t know the IP address and port of each other
 - they don’t know how many peers they have
- ◊ Time decoupling:
 - Publisher and subscriber do not need to run at the same time.
- ◊ Synchronization decoupling:
 - Operations on both pub. and sub. are not halted during publish or receiving.

The **Broker**:

- ◊ *Known* to publishers and subscribers
- ◊ *Receives* all incoming messages from the publishers
- ◊ *Filters* all incoming messages

¹i.e. peers don’t have to share “too much”

- ◊ Distributes all messages to the subscribers
- ◊ Manages the requests of *subscription/unsubscription*

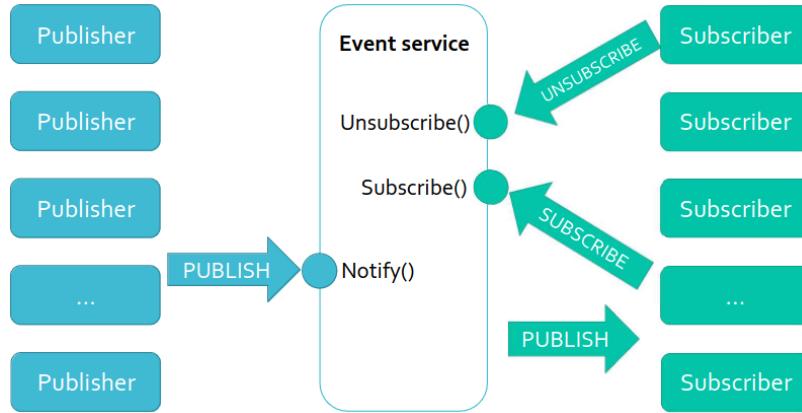


Figure 2.1: Broker management of events

2.1.1 Properties

Due its decoupling **properties**, compared to basic *client-server*, publish-subscribe is considered to be more **scalable**, even if it is implemented using an underlying client-server architecture.

First of all, everything is entirely up to the broker, does not depend on the direct interaction between endpoints. In case of a very large number of devices, the architecture can scale by **parallelizing** the (event-driven) operations on the broker.

Regarding the message filtering performed by the broker, it can happen depending on various fields:

- ◊ **Subject topic**
 - The subject (or topic) is a part of the messages
 - The clients subscribe for a specific topic
 - Typically topics are just strings (possibly organized in a taxonomy)
 - ◊ **Content**
 - The clients subscribe for a specific query (e.g. $Temp > 30^\circ$)
 - The broker filters messages based on a specific query
 - Data cannot be encrypted!
 - ◊ **Data type**
 - Filtering of events based on both content and structure
 - The type refers to the type/class of the data
 - Tight integration of the middleware and the language (!)
- The second and third approaches require increasing **integration** mechanisms to provide the desired features.

2.2 MQTT and Publish-Subscribe

MQTT provides a specific implementation of the PS paradigm. Since it relies on TCP/IP, Publishers and subscribers need to know the **hostname/ip** and port of the broker *beforehand*.

Thanks to its speed and to being lightweight, in most applications the delivery of messages is mostly in *near-real-time*, but in general this is *not* a guaranteed property.

In MQTT message filtering is based only **topics**, which is the most flexible filtering of the ones presented in the previous section.

2.3 Messages

A client connects to a broker by sending a **CONNECT** message. Since such message may be lost, the broker answers with a **CONNACK** message, indicating simply whether the connection was accepted, refused, and if there was a previously stored session with the client.

- ◊ Client ID

- A string that uniquely identifies the client at the broker.

If empty: the broker assigns a unique **clientID** and does not keep a status for the client.

In this case *Clean Session* must be TRUE.

Note also that in version 3.1.1 the servers replies with a CONNECTACK with *no* payload, so the assigned ID is not known to the client.

This has changed in version 5.0

ClientID Uniqueness - Digression

How can a client know if its Client ID is unique?

The answers is not completely addressed by the standard, and the scenario of a new client who wants to connect and have a persistent session is not clearly discussed. ClientIDs may be assigned beforehand, but this is possible only if the admin controls *entirely* the system, it is not possible if the broker is *public*, thus an owner of MQTT clients doesn't know whether there are other clients.

In reality, you can “take your chance”, because the ClientID is 23 byte long, so the chance of an overlap between multiple devices is low.

In general, standard specifications tend to omit everything that can be omitted, to avoid posing constraints which are not strictly necessary, by leaving room for personal implementations and needs.

optional

- ◊ Clean Session
 - Set to FALSE if the client requests a **persistent session**, allowing for session resuming and better QoS (storing missed messages).
- ◊ Username/Password
 - No encryption, unless security is used at transport layer
- ◊ Will¹ flags
 - If and when the client disconnects ungracefully, the broker will notify the other clients of the disconnection
- ◊ KeepAlive
 - The client commits itself to send a control packet (e.g. a ping message) to the broker within a keepalive interval expressed in seconds, allowing the broker to detect whether the client is still active (**detect disconnections**)

1

After CONNECT the publishers may send PUBLISH messages, which are later forwarded by the broker to the subscribers, and which are structured as follows:

PUBLISH

- ◊ **packetId**
 - An integer
 - It is 0 if the QoS level is 0
- ◊ **topicName**
 - a string possibly structured in a hierarchy with “/” as delimiters
 - Example: “home/bedroom/temperature”
- ◊ **qos** 0,1 or 2
- ◊ **payload**
 - The actual message in any form
- ◊ **retainFlag**
 - tells if the message is to be stored by the broker as the last known value for the topic
 - If a subscriber connects later, it will get this message
- ◊ **dupFlag**
 - Indicates that the message is a duplicate of a previous, unacked message
 - Meaningful only if the QoS level is > 0
- ◊ **packetId** an integer
- ◊ **topic_1** a string (see publish messages)
- ◊ **qos_1** 0,1 or 2

SUBSCRIBE

¹This refers to the *Last Will* (Testament), the document with the “wills” of someone dead.

SUBACK

- ◊ packetId the same of the SUBSCRIBE message
- ◊ returnCode one for each topic subscribed

There are also UNSUBSCRIBE and UNSUBACK messages which have a similar structure but are not described here.

2.4 Topics

TODO

2.5 QoS

The **QoS** is an agreement between the sender and the receiver of a message.

For example, in TCP the QoS includes guaranteed delivery and ordering of messages.

In MQTT the QoS is an agreement between the clients and the broker, and there are three levels:

level 0 At most once

- ◊ It is a “best effort” delivery and messages are *not* acknowledged by the receiver

level 1 At least once

- ◊ Messages are numbered and stored by the broker until they are delivered to all subscribers with QoS level 1. Each message is delivered at least once to the subscribers with QoS, but possibly also more.

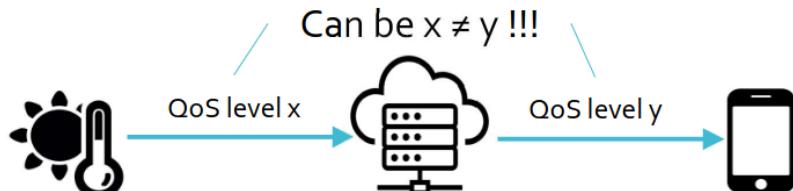
level 2 Exactly once

- ◊ guarantees that each message is received *exactly once* by the recipient, exploiting a double two-way handshake.

Note that QoS is used both:

- ◊ between publisher and broker
- ◊ between broker and subscriber

But the **QoS in the two communication may be different**.



2.5.1 Choosing the right QoS

- ◊ Use QoS level 0 when:
 - The connection is stable and reliable
 - Single message is not that important or get stale with time
 - Messages are updated frequently and old messages become stale
 - Don't need any queuing for offline receivers
- ◊ Use QoS level 1 when:
 - You need all messages and subscribers can handle duplicates
- ◊ Use QoS level 2 when:
 - You need all messages and subscribers cannot handle duplicates
 - Has much higher overhead!!!!

2.6 Persistent Sessions

Persistent sessions keep the state between a client and the broker: if a subscriber disconnects, when it connects again, it does not need to subscribe again the topics.

The session is associated to the clientId defined with the CONNECT message, and stores:

- ◊ All **subscriptions**
- ◊ All QoS 1&2 messages that are **not confirmed** yet

- ◊ All QoS 1&2 messages that arrived when the **client was offline**

Note that with **QoS = 0** persistent sessions are useless overhead.

2.7 Retained messages

A publisher has **no guarantee** whether its messages are —or *when*— actually delivered to the subscribers, it can only achieve guarantee on the delivery to the broker.

A **retained message** is a normal message with `retainFlag = True`; the message is stored by the broker, and if a new retained message of the same topic is published, the broker will keep only the last one. When a client subscribes the topic of the retained message the broker immediately sends the retained message, allowing subscribers to immediately get updated to the “state of the art”.

Note that retained messages are kept by the server even if they had already been delivered.

2.8 Last will & testament

Last Will & testament is used to notify other clients about the **ungraceful disconnection** of a client.

The broker stores the **last will message** attached to the `CONNECT` message, but if the client gracefully closes the connection by sending `DISCONNECT`, then the stored *last will message* gets discarded.

Often the Last Will message is used along with retained messages.

2.9 Packet Format

Structure of an MQTT control packet:

Fixed header, present in all MQTT control packets
Variable header, present in some MQTT Control Packets
Payload, present in some MQTT Control Packets

Fixed header (2 bytes):

Bit	7	6	5	4	3	2	1	0
byte 1	MQTT control packet type				Flags specific to each MQTT control packet type			
byte 2 ...	extra length				Remaining length			

Remaining length is the length of the variable header and payload.

- 1 byte encodes length of up to 127 bytes. The most significant bit specifies that there is another field of length (for packet longer than 127 bytes)

Control packet type:

Name	value	direction of flow
reserved	0	forbidden
CONNECT	1	client to server
CONNACK	2	server to client
PUBLISH	3	client to server or server to client
PUBACK	4	client to server or server to client
PUBREC	5	client to server or server to client
PUBREL	6	client to server or server to client
PUBCOMP	7	client to server or server to client
SUBSCRIBE	8	client to server
SUBACK	9	server to client
UNSUBSCRIBE	10	client to server
UNSUBACK	11	server to client
PINGREQ	12	client to server
PINGRESP	13	server to client
DISCONNECT	14	client to server
reserved	15	forbidden

Payload:

- Contains additional information
- E.g. the payload of `CONNECT` includes:
 - client identifier (mandatory)
 - will topic (optional)
 - will message (optional)
 - Username (optional)
 - Password (optional)

Control packet	payload
CONNECT	required
CONNACK	none
PUBLISH	optional
PUBACK	none
PUBREC	none
PUBREL	none
PUBCOMP	none
SUBSCRIBE	reserved
SUBACK	reserved
UNSUBSCRIBE	reserved
UNSUBACK	none
PINGREQ	none
PINGRESP	none
DISCONNECT	none

Figure 2.2: MQTT Packet headers

The —not displayed in Fig. 2.2— **Variable header**:

- ◊ Contains the packet identifier (encoded with two bytes)
 - Only `CONNECT` and `CONNACK` control packets do not include this information
 - The `PUBLISH` packet contains this information only if `QoS > 0`
- ◊ Contains other information depending on the control packet type

- For example, CONNECT packets include the protocol name and version, plus a number of flags (see CONNECT)

Chapter 3

ZigBee

ZigBee is widely used in various fields from home automation to Mars exploration; it is considered the “cousin” of Bluetooth: they are standardized by the same company and can coexist.

Aside from the application layer, ZigBee defines also a *Network Layer* which perfectly matches and maps to the underlying MAC and Physical Layers, standardized by IEEE 802.15.4; ZigBee is built on top of such IEEE standard.

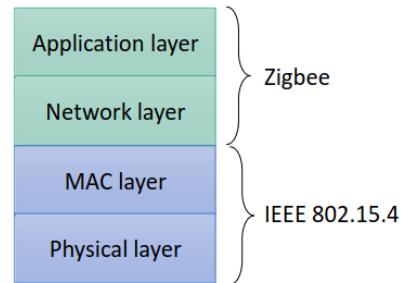


Figure 3.1: ZigBee layers

- Key Features*
- ◊ Specification of the physical and MAC layers for low-rate Wireless Personal Area Networks (PAN)
 - ◊ Infrastructure-less
 - ◊ Short range^a
 - ◊ Support for star and peer-to-peer topologies
 - ◊ Can coexist with IEEE 802.11 and IEEE 802.15.1 (Bluetooth)
 - ◊ Works on licence-free frequency bands

^a250m outdoors in ideal conditions

3.1 Architecture

APS provides *transport* services to the ZDO and the Objects in the Application Framework (APOs). It is some kind of Transport layer, similar to TCP but not the same.

APOs are the business logic of the business device, implemented by the user, and in a single device there may be instantiated up to APOs. We may say that for each APO provides a “functionality”.

The ZDO is an applicative object that defines and maintains the device behaviour in a ZigBee network.

An example of this behaviour, is replying to a device discovery message. Such reply is handled by the ZDO

The ZDO is provided by the third parties which are giving you the ZigBee stack. Manufacturers which produce devices compliant with ZigBee, sell them with a ZigBee stack already implemented, allowing for the buyer —e.g. a company which develops ZigBee solutions— to simply

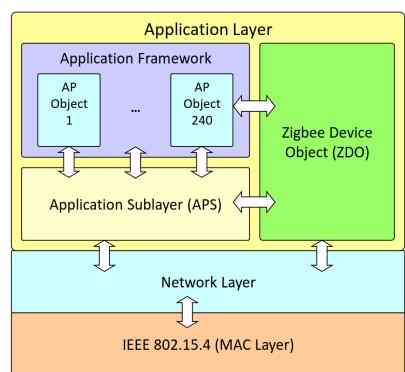


Figure 3.2: Zigbee architecture layers

implement the “functionalities” (i.e. APOs) they want.

3.2 Primitives

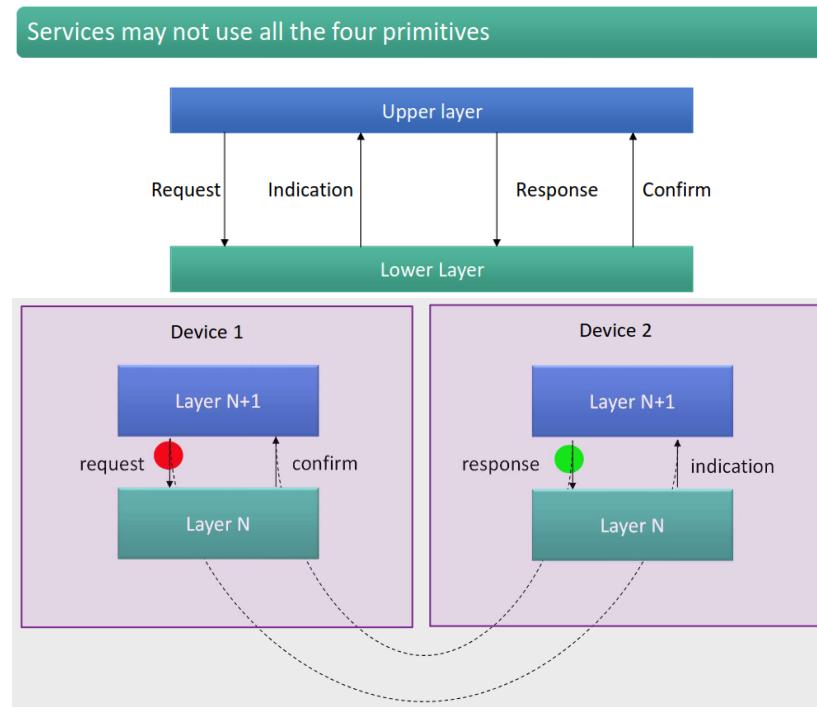


Figure 3.1: Mapping between zigbee primitives

Primitives

1. Request

It is invoked by the upper layer to request for a specific service

2. Indication

Is a sort of “*upcall*”, generated by the lower layer and is directed to the upper layer to notify the occurrence of an event related to a specific service

3. Response

It is invoked by the upper layer to complete a procedure previously initiated by an indication primitive

4. Confirm

It is generated by the lower layer and is directed to the upper layer to convey the results of one or more associated previous service requests.

3.3 Network Layer

The ZigBee network layer provides services for:

1. Data transmission (both unicast and multicast)
2. Network initialization
3. Devices addressing
4. Routes management & routing
5. Management of joins/leaves of devices

In a ZigBee network there are three kinds of devices:

1. **The Network coordinator**
A FFD¹ that creates and manages the entire network
2. **Routers**
A FFD with routing capabilities
3. **End-devices**
Correspond to a RFD² or to a FFD acting as simple devices

¹Full functional Device

²Reduced functional device

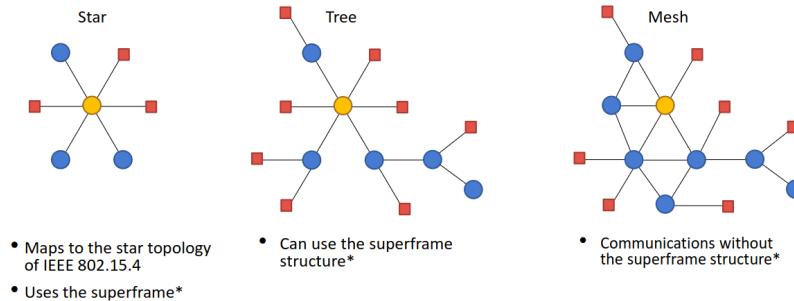


Figure 3.2: ZigBee Network topologies outline

The superframe mentioned above, is a feature used to obtain energy efficiency in ZigBee networks, but we will discuss it later on.

3.3.1 Network formation and joining

Before communicating on a network, a ZigBee device must either:

- ◊ Form a new network → *ZigBee Coordinator*
- ◊ Join an existing network → *ZigBee router* or *end-device*

The role of the device is chosen at compile-time

Formation

Network Formation is performed by a coordinator, which uses the MAC layer services to (**SCAN.request**) look for a channel that does not conflict with other existing networks, and then selects a PAN identifier which is not already in use by other PANs.

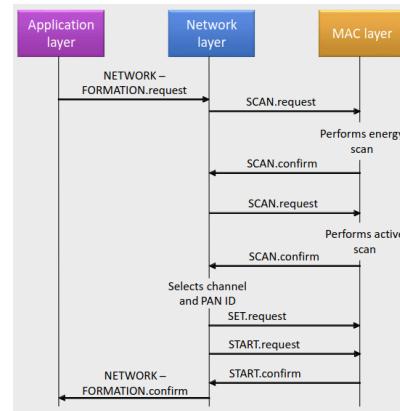


Figure 3.3: Network formation messages

Joining

Joining may happen in two ways, the first is to join through association: initiated by a device wishing to join an existing network.

Alternatively a device may perform a Direct join: requested by a router or by the coordinator to request a device to join its PAN.

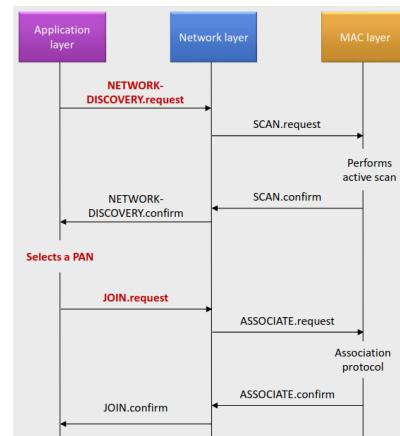


Figure 3.4: Network joining messages

3.4 Application Layer

Up to 240 APOs, each corresponding to an application **Endpoint**, with the Endpoint 0 reserved for the ZDO³. Each APO in the network is uniquely identified by its endpoint address and the network address of the hosting device.

3.4.1 APS - Application Support Sublayer

The APS frame uses the concepts of **endpoints**, **cluster IDs**, **profile IDs** and **device IDs**. It provides:

- ◊ Data service (a light transport layer)
 - Filtering out packets (non registered endpoints, profiles that do not match)
 - Generating end-to-end acknowledgments
- ◊ Management:
 - Local binding table
 - Local groups table
 - Local address map

Concepts and related IDs

³We could say that the ZDO is an “application object”, which would be true, but tailored to specific needs

A **cluster** may be, in the simplest case, a *message*. But this is not necessarily the case.

Informally, a cluster provides access to a service (a functionality) of an application object; Defines both *commands*, which cause actions on a device, and *attributes*, showing the state of a device in a given cluster.

Every cluster has a 16 bit identifier, which according to prof. Chessa is **not** sufficient.

Note that clusters are not related to the physical world interaction, because they must allow reuse.

Each cluster finds a possibly different meaning in each **application profile**. There is a mapping which defines such meanings mappings.

Using this schema, 16 bits become sufficient.

An **application profile** is the specification of the behaviour of a class of applications possibly operating on several ZigBee devices. Each profile is paired with a 16 bit identifier.

Every message sent (or received) is tagged with a profile ID. Different application profiles may co-exist in a single ZigBee network.

ZigBee **Device IDs** range from 0x0000 to 0xFFFF, and have two purposes:

1. To allow human-readable displays (e.g., an icon related to a device)
2. Allows ZigBee tools to be effective also for humans
 - i. a device may implement the on/off cluster, but you don't know whether it is a bulb or a oven ... you only know you can turn it on or off.
 - ii. The device ID tells you what it is, but it does not tell you how to communicate with it, which is given by the IDs of the clusters it implements!

ZigBee discovers services in a network based on profile IDs and cluster IDs, but **not** on device IDs

Cluster Name	Cluster ID
Basic Cluster	0x0000
Power Configuration Cluster	0x0001
Temperature Configuration Cluster	0x0002
Identify Cluster	0x0003
Group Cluster	0x0004
Scenes Cluster	0x0005
OnOff Cluster	0x0006
OnOff Configuration Cluster	0x0007
Level Control Cluster	0x0008
Time Cluster	0x000a
Location Cluster	0x000b
Profile ID	Profile name
0101	Industrial Plant Monitoring
0104	Home Automation
0105	Commercial Building Automation
0107	Telecom Applications
0108	Personal Home & Hospital Care
0109	Advanced Metering Initiative

Figure 3.5: ZigBee General Domain clusters and common Profile IDs

Name	Identifier	Name	Identifier
Range Extender	0x0008	Light Sensor	0x0106
Main Power Outlet	0x0009	Shade	0x0200
On/Off Light	0x0100	Shade Controller	0x0201
Dimmable Light	0x0101	Heating/Cooling Unit	0x0300
On/Off Light Switch	0x0103	Thermostat	0x0301
Dimmer Switch	0x0104	Temperature Sensor	0x0302

Figure 3.6: Device IDs from the *Home Automation* profiles

Back to APS Services

APS Provides:

- ◊ Data service to both the APOs and the ZDO.
- ◊ Binding service to the ZDO
- ◊ Group management services

The APS data service enables the exchange of messages between two or more devices within the network.

- ◊ The data service is defined in terms of the primitives:
- ◊ Request (**send**),
- ◊ Confirm (returns **status** of transmission) and
- ◊ Indication (**receive**).

APS provides also a **message reliability service**, which simply sends multiple times a message until an ACK is received (if it was needed in the first place).

The **group management** provides services to build and maintain groups of APOs, enabling multicast, with each group being identified by a 16-bits address.

MAC addresses in ZigBee contexts are meant to be permanent, even if in recent years FFDs provide functionalities to randomly generate MAC addresses in order to enforce privacy. This in general is not performed on low-end RFD devices.

3.5 Binding

Addresses are indirect, allowing to implicitly specify the destination of messages, which are no longer routed based on a pair $\langle \text{destination endpoint}, \text{destination network address} \rangle$ (*direct addressing*), but binding tables and address maps are used instead.

This is one of the key functions of the ZigBee Transport Layer, and is performed by the *APS*.

3.5.1 APS - Address Map

The APS layer contains the address map table, which associates the 16 bit NWK address with the 64 bit IEEE MAC address.

Zigbee end devices (ZED) may change their 16 bit NWK address (e.g. they leave and join again). In that case an announcement is sent on the network and every node updates its internal tables to preserve the bindings.

IEEE Addr	NWK Addr
0x0030D237B0230102	0x0000
0x0030B237B0235CA3	0x0001
0x0031C237b023A291	0x895B

Figure 3.3: Address Map

3.5.2 APS - Binding

We assume that typically the binding is performed by an admin who is —physically— deploying network nodes.

- Primitives*
- ◊ **BIND.request**
Creates a new entry in the local binding table taking as input $\langle \text{source address}, \text{source endpoint}, \text{cluster identifier}, \text{destination address}, \text{destination endpoint} \rangle$. The
 - ◊ **UNBIND.request**
deletes an entry from the local binding table.
- binding table associates sources and destinations based on MAC addresses, and is stored in the APS of the ZigBee coordinator (and/or of the routers); it gets updated on explicit request of the ZDO in the routers or in the coordinator, and is usually initialised at the network deployment. In general, it is *static*.

Indirect addressing is implemented exploiting the binding table and the address map:

Src Addr (64 bits)	Src EP	Cluster ID	Dest Addr (16/64 bits)	Addr/Grp	Dest EP
0x3232...	5	0x0006	0x1234...	A	12
0x3232...	6	0x0006	0x796F...	A	240
0x3232...	5	0x0006	0x9999	G	-
0x3232...	5	0x0006	0x5678...	A	44

Figure 3.4: Binding table

- ◊ matches *source address* \langle network addr, endpoint addr \rangle and the *cluster identifier* into the pair: \langle destination endpoint, destination \rangle

3.6 ZDO - ZigBee Device Object

ZDO is a special application attached to endpoint 0 and implements ZigBee End Devices, ZigBee Routers and ZigBee Coordinators.

It is specified by a special profile, the ZigBee Device Profile, which describes the clusters that must be supported by any ZigBee device; it defines also how the ZDO implements the services of discovery and binding and how it manages network and security.

- ZDO services*
- ◊ Device and service discovery
 - ◊ Binding management
 - ◊ Network management
 - ◊ Node management

3.6.1 Device and service discovery

The ZigBee Device Profile (ZDP) specifies the device and service discovery mechanisms. **Device discovery** allows a device to obtain the (network or MAC) address of other devices in the network:

- ◊ **Unicast** → directed to an individual device
- ◊ **Broadcast** → hierarchical implementation based on a tree and subtrees topology: a router returns to its parent its address and the address of all the end devices associated to itself and then the coordinator returns the address of its associated devices

Service discovery exploits queries based on profiles ID, cluster IDs, addresses, or device descriptors. Again may either be unicast or broadcast.

- ◊ **Unicast** → if directed to a single end device then the coordinator or the router to which it is connected respond on its behalf
- ◊ **broadcast** → The coordinator responds to service discovery queries returning lists of endpoint addresses matching with the query; It exploits a hierarchical implementation: each router collects information from its associated devices and forwards it to its parent

3.6.2 Binding management

The ZDO processes the binding requests received from local or remote EP To *add* or *delete* entries in the APS binding table.

3.6.3 Network and Node Management

- ◊ **Network management**
 - Implements the protocols of the coordinator, a router or an end device according to the configuration settings established either via a programmed application or at installation.
- ◊ **Node management**
 - The ZDO serves incoming requests aimed at performing network discovery, retrieving the routing and binding tables of the device and managing joins/leaves of nodes to the network.

3.7 ZigBee Cluster Library

ZCL is a repository for cluster functionalities, a “working library” with regular updates and new functionalities. ZigBee developers are expected to use the ZCL to find relevant cluster functionalities to use for their applications, in order to

- ◊ Avoid re-inventing the wheel
- ◊ Support interoperability
- ◊ Facilitate maintainability

A cluster is a collection of commands and attributes, which define an interface to a specific functionality of a device. Clusters refer to functional domains within the respective profile.

The ZCL foresees a Client-Server model.

- ◊ The device that *stores* the attributes is the *server* of the cluster
- ◊ The device that *manipulates* the attributes is the *client* of the cluster

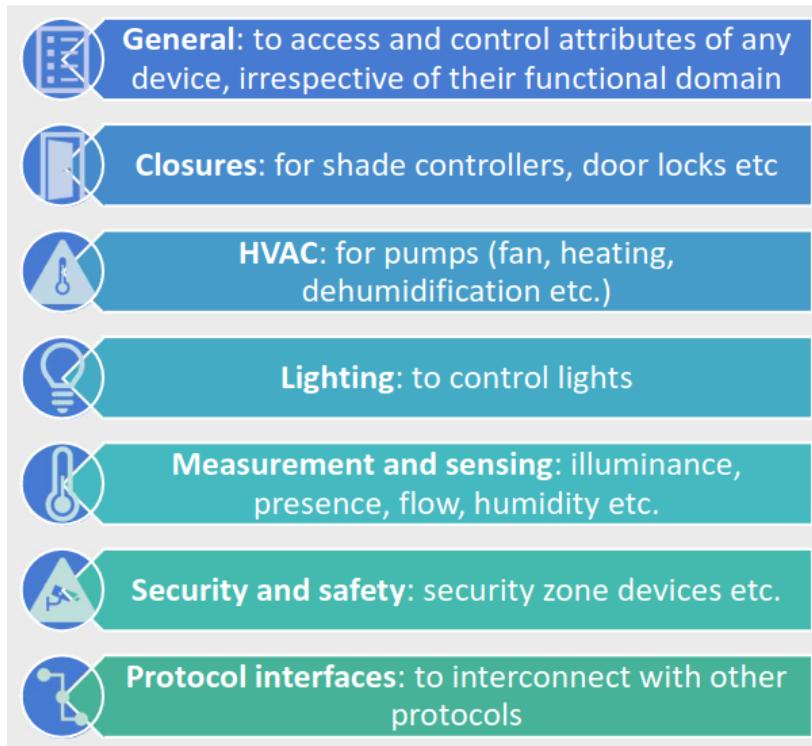


Figure 3.5: Functional domains

TODO integrate some slides

ZCL is built to allow combining simpler clusters into more complex ones, providing a hierarchical approach to define device functionalities.

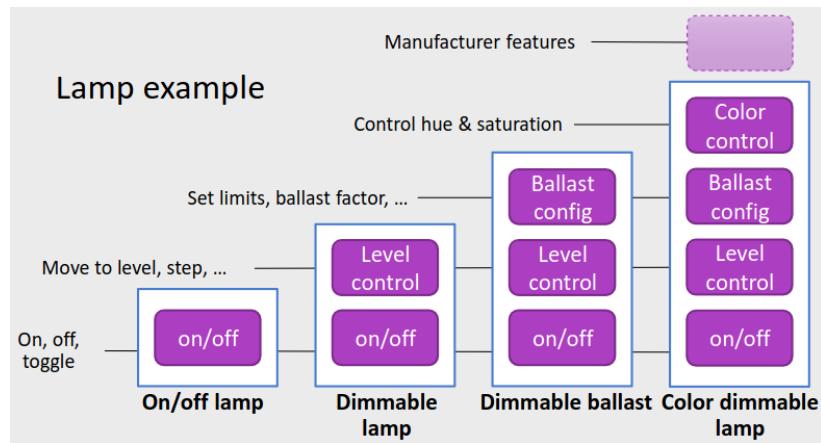


Figure 3.6: ZCL Hierarchical approach

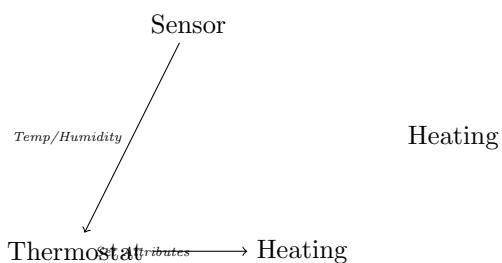


Figure 3.7: Heating System - exercise 2 Schema

Chapter 4

Use Cases

4.1 Industrial IoT in a smart GreenHouse

The topic discussed is a case study of a project funded by the Tucany Region and concluded in 2019 whose aim was to develop a technological **greenhouse** having specific objectives:

- ◊ Monitor drainage waters
- ◊ Control the root zone in terms of the presence of nutrients and waters
- ◊ Compare different cultivation substrates
- ◊ Develop new models based on AI to enable an intelligent control of the greenhouse

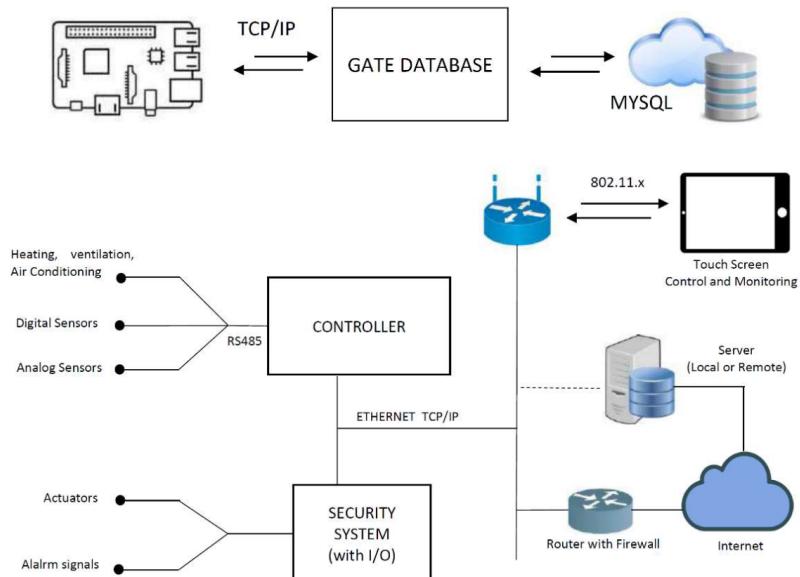


Figure 4.1: Greenhouse network architecture

There are some information concerning the architecture and structure of the greenhouse which are not reported here.

The problem is how to analyze data and integrate it with AI; there are two main aspects:

1. Need a control of the installation/systems that goes beyond the simple “timed logic”
 - i. E.g. the fertigation system may need to be controlled depending on the actual needs of the crops...
 - ii. ...that however change with the environmental conditions and with their growth
2. Need to forecast the crops growth to optimize the greenhouse (power/water/fertilizers consumption)

The parameters concerning **crops growth** are:

- ◊ Leaf area index(LAI)
- ◊ Dry weight (DW)
- ◊ Evotranspiration (ET)

The idea is to use AI models for growth prediction using a data driven approach. There a period of data acquisition of $35 + 52 + 37$ days (each in a different season) focused on salad.

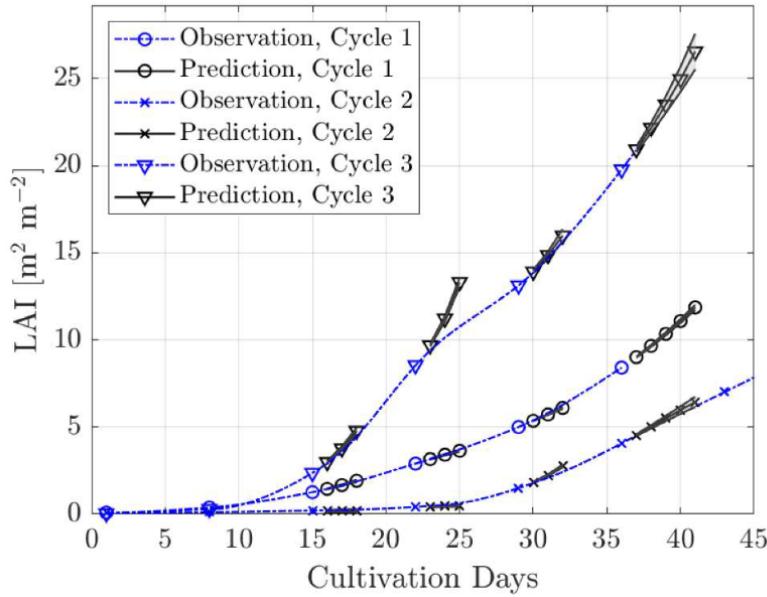


Figure 4.2: Crops growth AI prediction against acquired data

4.2 IoT in Ambient Assisted Living

The first topic discussed is the DOREMI project, which stands for *Decrease of cOgnitive decline, malnutRition and sedEntariness by elderly empowerment in lifestyle Management and social Inclusion*

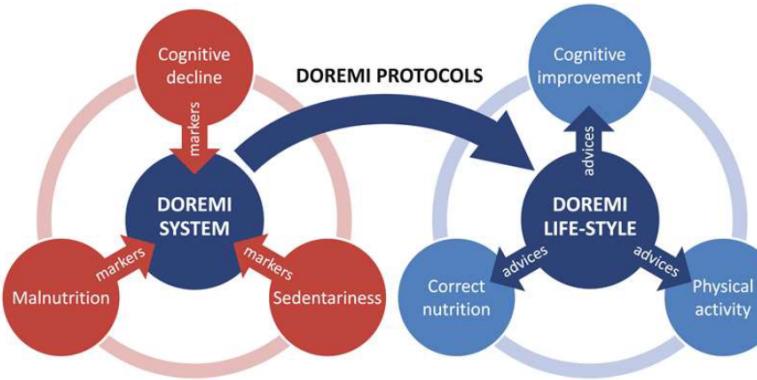


Figure 4.3: DOREMI project

The idea is to gather data from various sources, in order to obtain a profile of an elder.

1. Wristband
 - i. assess physical activities, hearth rate, calories expenditure, ...
2. Balance board
 - i. assess user balance according to the Berg scale
3. Environmental sensors
 - i. Indoor localization
 - ii. Socialization assessment
4. App for tablet
 - i. Enter dietary data
 - ii. Play cognitive, social, exer-games
 - iii. Receive feedbacks

KPI type	KPI	Data	Device
Clinical	Vital parameters	Weight	Balance board
		Balance	
	Physical activity	Heart rate	
		Wrist acceleration	
		Number of steps	
Social	Indoor position	Indoor position	DOREMI wristband
		Sensors activations	
Social	Number of interactions	GPS	Environmental WSN
			Smartphone

Figure 4.4: DOREMI Sensors and related data

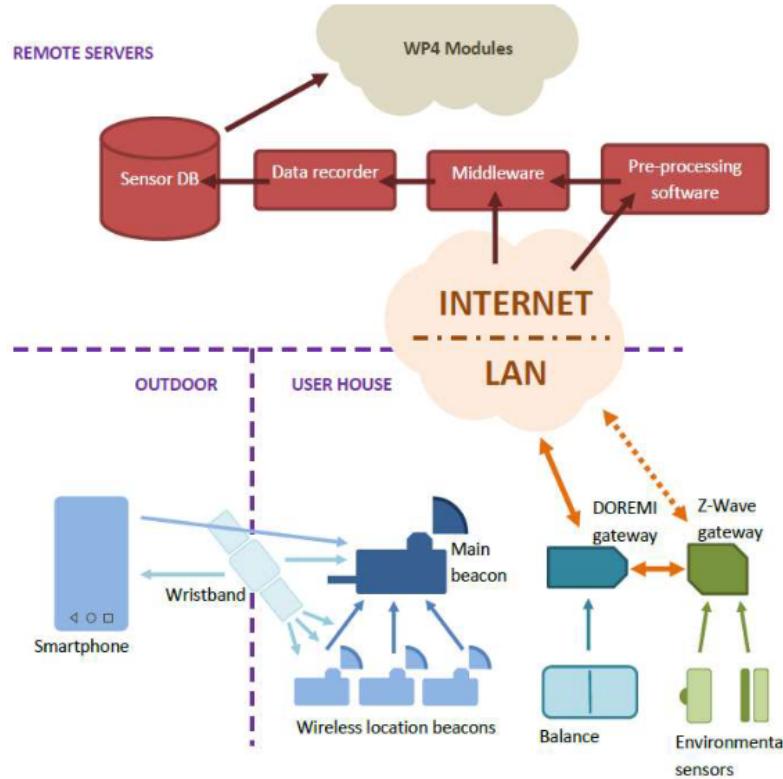


Figure 4.4: Wireless sensor network and Cloud architecture

They used Chinese Wii Balance Board replicas to assess data on balance and weight of the elderly. Wristbands were needed to measure the Heart Rate, which was later used to establish the calories consumption by applying a Fourier transform to it.

Some sensors instead when activated in a given sequence could indicate a human entering or leaving the house. Overall about 20 devices per user were used. For the “pilots” 400 devices were used in total.

They had to use two distinct databases, because some sensors provided time-series data, while more complex ones, such as the balance board, provided measurements.

32 **pilots** were chosen ranging in 65 to 80 years, half living in Italy and half in the UK, all having

- ◊ Mild to moderate cognitive impairment
- ◊ At risk of malnutrition
- ◊ Low physical activity

The pilots were divided into a *control group* and an *intervention group* made up of 7 and 25 users respectively.

The pilots were forced to follow some rules each day and each, such as wearing the wristband, play the cognitive games, perform suggested exercises etcetera.

4.2.1 Human Factor

When a system is developed for humans it is difficult to predict and handle all possible scenarios. The human factor in this example impact very much, especially the lack of motivation.

Other issues were related to inserting the food intake, picking up people spread around Genoa for social meetings, people not wanting sensors in their houses etc.

Chapter 5

IoT Design Aspects

Each device is usually low power and low cost small and autonomous system, equipped with processor, memory and radio transceiver along with sensing and/or actuating elements, with everything being powered by a battery (or something equivalent such as solar cells).

The main limitations in the design of IoT devices are due to the abovementioned components —aside from the sensors/actuators— and it is not clear whether technology improvements will overcome such constraints.

5.1 Issues

1. Energy efficiency
 - i. sensors are battery-powered or use energy harvesting
 - ii. need for HW/SW energy efficient solutions
2. Adaptability to changing conditions
 - i. need for dynamic network management and programming
3. Low-complexity, low overhead protocols
 - i. need at any level of the protocol stack due to limitation of nodes' resources
4. Security
 - i. at all layers of the stack
5. Multihop communications
 - i. need for protocol stacks and routing protocols
6. Mobility
 - i. Need for dynamic routing protocols Data storage and (pre-)processing

5.1.1 Moore's law

“The number of transistors that can be (inexpensively) embedded in a chip grows exponentially”

In other words, “it doubles every two years”

Three different—but equally true—interpretations may be given to such law:

1. The performance doubles every two years at the same cost
Up to now this is true for processors of servers/desktops
2. The chip's size halves every two years at the same cost
Consequently also the energy consumption is reduced
3. The size and the processing power remain the same but the cost halves every two years

5.2 Battery consumption

In the previous decades the focus was on minimizing the number of bytes sent to optimize network performance. For IoT instead, the focus is to keep the radio off most of the time, since it consumes about 40% of the battery.

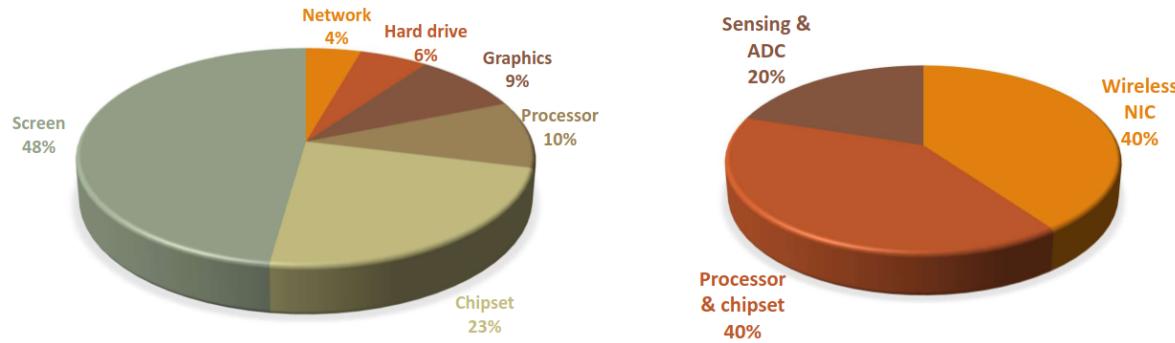


Figure 5.1: Laptop and IoT Sensor battery consumption percentages

5.2.1 Duty Cycle

Also turning off CPU and radio is battery consuming, so it must be done according to some criteria. Since the activity of an IoT device is (mostly) repetitive, it may define a **duty cycle** by alternating periods of activity to periods of inactivity.

The duty cycle of a system (or a component / device) is defined as the fraction of one period in which the system is active.

100% means always active, while 1% means active only 1% of its period

Note that even if the duty cycle of the whole device may be defined at application level, each component has its own duty cycle, adding some "unpredictability" to the power consumption equation.

```
void loop() {
    // reads the input from analog pin 0:
    turnOn(analogSensor);
    int sensorValue = analogRead(A0);
    turnOff(analogSensor);
    // converts value into a voltage (0-5V):
    float voltage = sensorValue * (5.0 /
        1023.0);
    // transmits voltage over the radio
    turnOn(radioInterface);
    Serial.println(voltage);
    turnOff(radioInterface);
    // waits for next loop
    idle(380);
}
```

Sometimes the specification of an IoT device indicates the power consumption expressed in mA for each component in each state it may be (idle/read/write/etc.). Even if not completely precise, the specification may provide a good approximation of the consumption.

It is also important to note that there should be a record in the specs indicating how much capacity the battery loses over time. Most batteries lose a low percentage (e.g. 3%) capacity each year.

Consider this program and the table of energy consumption in the different states. Compute:

- the energy consumption of the device per single hour
- the expected lifetime of the device (disregard battery leak...)

```
...
void loop() {
    turnOn(analogSensor);
    4 milliseconds int sensorValue = analogRead(A0);
    turnOff(analogSensor);

    1 milliseconds float voltage = sensorValue*
        (5.0 / 1023.0);

    15 milliseconds turnOn(radioInterface);
    Serial.println(voltage);
    turnOff(radioInterface);

    380 milliseconds idle(380);
}
```

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	μA
Radio		
current xmit	20	mA
current sleep	20	μA
Sensor Board		
current (full operation)	5	mA
current sleep	5	μA
Battery Specifications		
Capacity	2000	mAh

Figure 5.2: Exercise on energy consumption and duty cycling

For what concerns the exercise, these are the calculations

CPU	5	$0.05 * 8$	$0.95 * 0.015$	0.41425
Radio	3,75	$0.0375 * 20$	$0.9625 * 0.020$	0.9425
Sensor	1	$0.01 * 5$	$0.99 * 0.005$	0.05495

Table 5.1: Exercise calculations and solutions

5.2.2 MAC Protocols

In general they are Low-level communication protocols to send/receive packets to/from in-range sensors, but in IoT they also implement strategies for energy efficiency, by synchronize devices and turning off the radio when it is not needed¹.

Exercise 1

Exercise 2

Consider the sensor specs in the table.
The device measures the hearth-rate (HR) of a person:

- Samples a photodiode on the wrist at 20 Hz
 - sampling the sensor takes 0.5 ms
 - it requires both the processor and the sensor active
- HR is computed every 2 s (based on 40 samples)
 - Computing HR in the device takes 5 ms
- Transmit a data packet to the server:
 - The average time required to transmit is 2 ms
 - Requires both processor and radio active

Compute the energy consumption and the lifetime of the device if it computes HR itself:

- Transmits every 5 values of HR computed (1 packet every 10 seconds)

Disregard battery leaks

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	µA
Radio		
current xmit	20	mA
current sleep	20	µA
Sensor Board		
current (full operation)	5	mA
current sleep	5	µA
Battery Specifications		
Capacity	2000	mAh

$$\text{Duty cycle sensor} = 0.01$$

$$\text{Duty cycle radio} = 0.008$$

$$\text{Duty cycle CPU} = (0.5 * 5 + 2)/250ms = 0.018 = 0.01 + 0.008$$

Radio energyON	$=20mA * 0.008$	$= 0.16mA$
Radio energyIDLE	$=20\mu A * 0.992$	$= 0.01984mA$
Sensor energyON	$=5mA * 0.01$	$= 0.05mA$
Sensor energyIDLE	$=5\mu A * 0.99$	$= 0.00495mA$
CPU energyON	$=8mA * 0.018$	$= 0.144mA$
CPU energyIDLE	$=15\mu A * 0.982$	$= 0.0147mA$

$$\text{Total energy per hour} =$$

$$0.16 + 0.01984 + 0.05 + 0.00495 + 0.144 + 0.0147 = 0.39349mA$$

$$\text{Total energy available} = 2000mAH$$

$$\text{Expected lifetime} = 2000/0.39349 = 5084.5h = 212d$$

Exercise 2

Exercise 1

Consider the sensor specs in the table.
The device measures the hearth-rate (HR) of a person:

- Samples a photo-diode on the wrist at 20 Hz
 - sampling the sensor takes 0.5 ms
 - it requires both the processor and the sensor active
- HR is computed every 2 s (based on 40 samples)
- Transmit (from time to time... see below) a data packet to the server:
 - The average time required to transit is 2 ms
 - Requires both processor and radio active

Compute the energy consumption and the lifetime of the device if it sends all the samples to a server:

- Stores 5 consecutive samples from the photodiode
- Transmits the stored 5 samples to the server
- The server computes HR (hence the device **does not compute HR**)

Disregard battery leaks.

	value	units
Micro Processor (Atmega128L)		
current (full operation)	8	mA
current sleep	15	µA
Radio		
current xmit	20	mA
current sleep	20	µA
Sensor Board		
current (full operation)	5	mA
current sleep	5	µA
Battery Specifications		
Capacity	2000	mAh

$$\text{Duty cycle sensor} = 0.01$$

$$\text{Duty cycle radio} = 2/10000ms = 0.0002$$

¹Equivalent to excluding a device from the network

$$\text{Duty cycle processor} = (0.5 * 200 + 2 + 5 * 5) / 10000 = 0.0127$$

Radio energyON	$= 20mA * 0.0002$	$= 0.004mA$
Radio energyIDLE	$= 20\mu A * 0.9998$	$= 0.01998mA$
Sensor energyON	$= 5mA * 0.01$	$= 0.05mA$
Sensor energyIDLE	$= 5\mu A * 0.99$	$= 0.00495mA$
CPU energyON	$= 8mA * 0.0127$	$= 0.1016mA$
CPU energyIDLE	$= 15\mu A * 0.9873$	$= 0.0148mA$

Total energy per hour =

$$0.004 + 0.01998 + 0.05 + 0.00495 + 0.1016 + 0.0148 = 0.19533mA$$

Total energy available = 2000mAh

$$\underline{\text{Expected lifetime} = 2000 / 0.19533 = 10238.5h = 426d}$$

The expected lifetime doubled! This is due to the fact that the radio is on for a very short time, and the CPU is on for a longer time but with a lower consumption.

“Sending 1 bit costs 1000 times more than computing it” -cit. Anon

Part II

Federica Paganelli

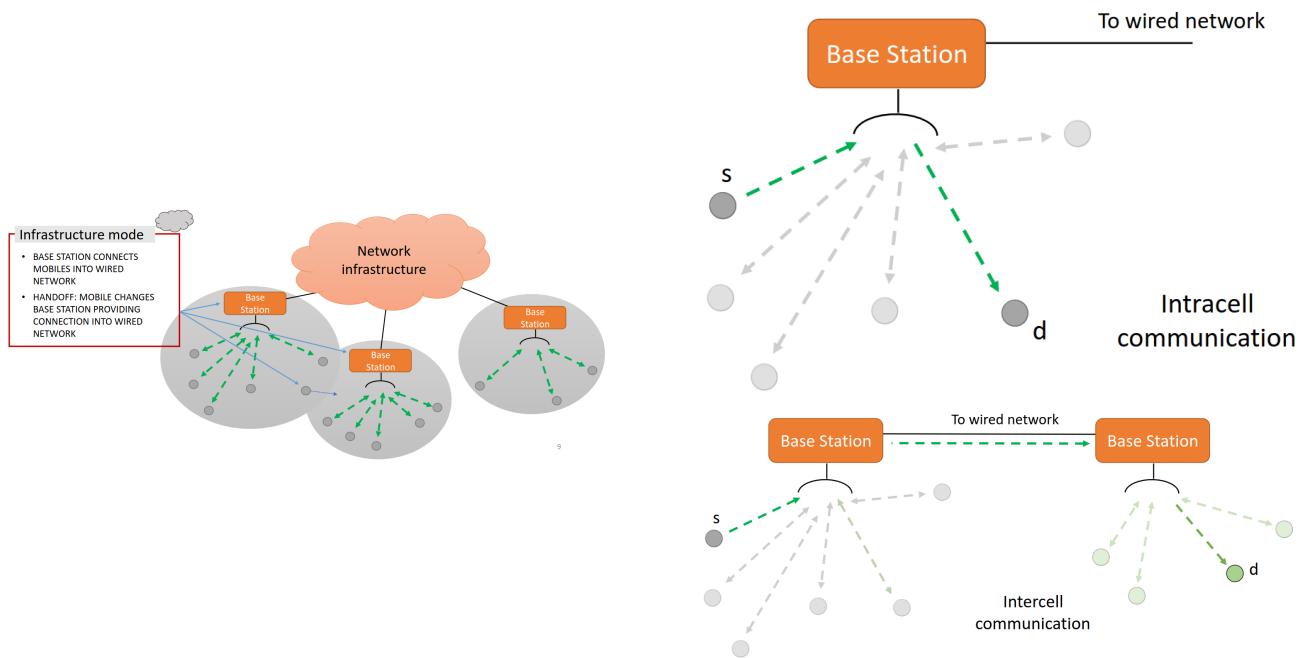
Chapter 6

Wireless Networks

Wireless Networks are composed of **hosts**, which are end-system devices that run applications, typically battery powered.

Recall that wireless \neq mobility

In general Wireless Networks may be based on the interaction *hosts longrightarrow base station* —or access point— or *hosts longrightarrow hosts*. The two resulting functioning modes are called *Infrastructure* and *Ad hoc networking*.



6.1 Link Layer

6.1.1 CSMA/CD

Basic idea of CSMA/CD:

1. When a station has a frame to send it listens to the channel to see if anyone else is transmitting
2. if the channel is busy, the station waits until it becomes idle
3. when channel is idle, the station transmits the frame
4. if a collision occurs the station waits a random amount of time and repeats the procedure.

Refer to the slides of 21 February for more in depth usage examples

In short: CSMA/CD performs poorly in wireless networks. Firstly because CSMA/CD detects collisions while transmitting, which is ok for wired networks, but not for wireless ones. Secondly, what truly matters is the interference at the *receiver*, **not** at the *sender*, causing the two problems known as hidden terminal and exposed terminal problems; to

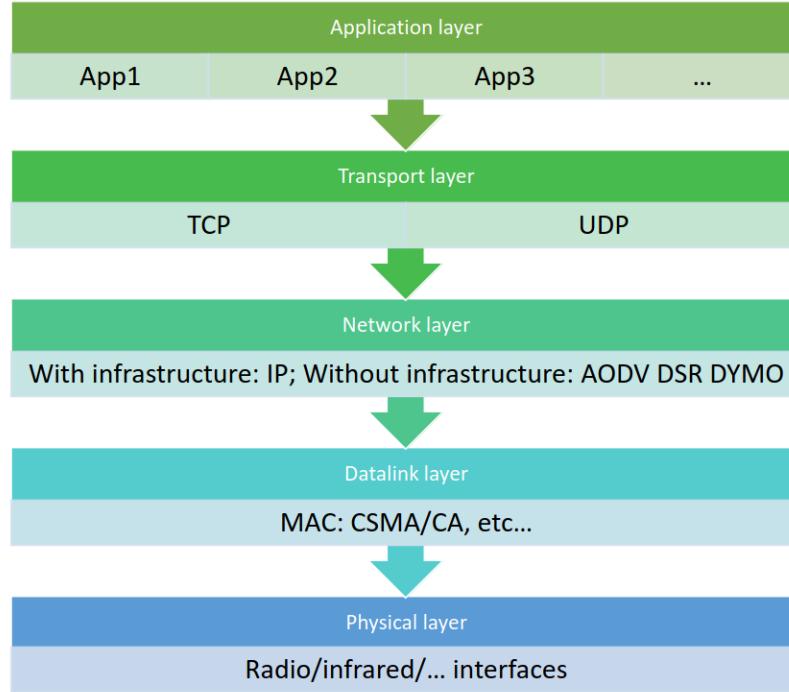


Figure 6.1: Protocol stack

better understand this point, look at the following figure, consider that at the sender, the signal strength of its own transmission (self-signal) would be too strong to detect a collision by another transmitter, making collisions happen at the receiver.

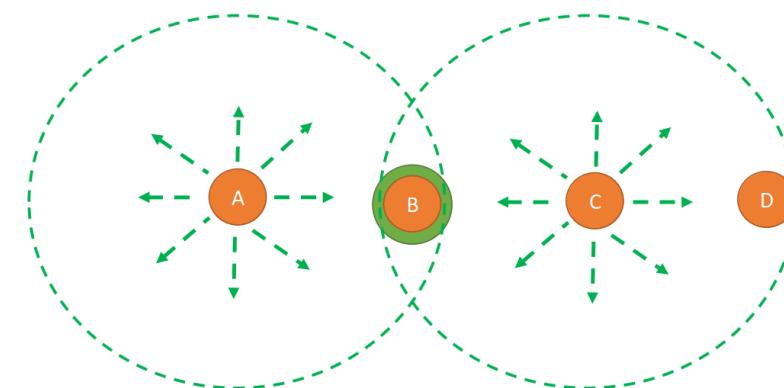
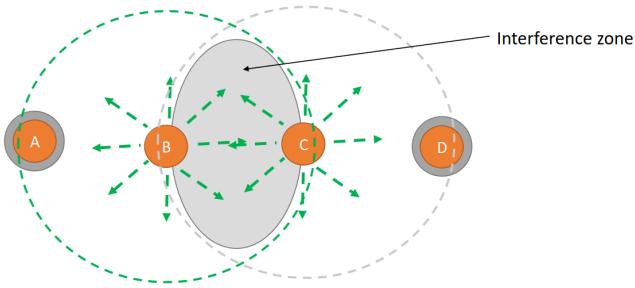


Figure 6.2: **Hidden Terminal** problem

Two or more stations which are out of range of each other transmit simultaneously to a common recipient



1. B is transmitting to A, C wants to transmit to D
2. C senses the medium, concludes: **cannot transmit** to D
3. The two transmissions can actually happen in parallel.

Figure 6.3: **Exposed Terminal** problem

A transmitting station is prevented from sending frames due to interference with another transmitting station

6.1.2 MACA

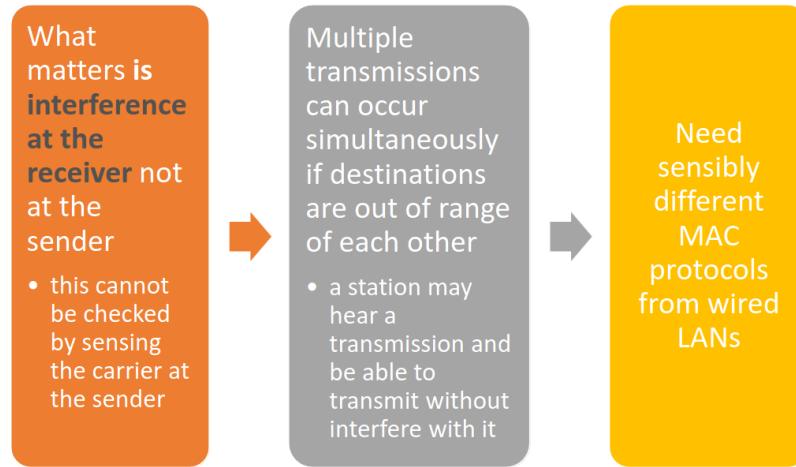


Figure 6.4: MACA Motivations

MACA stands for *Multiple Access with Collision Avoidance*

1. stimulate the receiver into transmitting a short frame first
2. then transmit a (long) data frame
3. stations hearing the short frame refrain from transmitting during the transmission of the subsequent data frame

Basically, a transmitting node sends a *Request to Send RTS* and a receiving node answers with *Clear to Send CTS*. Other nodes which hear RTS or CTS must stay silent until the transmission is over.

Further details and examples on how the protocol works are on the slides.

MACAW implements some improvements to MACA:

- ◊ ACK frame to acknowledge a successful data frame
 - ◊ added Carrier Sensing to keep a station from transmitting RTS when a nearby station is also transmitting an RTS to the same destination
 - ◊ mechanisms to exchange information among stations and recognize temporary congestion problems
- CSMA/CA used in IEEE 802.11 is based on MACAW

Chapter 7

IEEE 802.11

IEEE 802.11 standard	Year	Max data rate	Range	Frequency
802.11b	1999	11 Mbps	30 m	2.4 Ghz
802.11g	2003	54 Mbps	30m	2.4 Ghz
802.11n (WiFi 4)	2009	600	70m	2.4, 5 Ghz
802.11ac (WiFi 5)	2013	3.47Gbps	70m	5 Ghz
802.11ax (WiFi 6)	2020 (exp.)	14 Gbps	70m	2.4, 5 Ghz
802.11af	2014	35 – 560 Mbps	1 Km	unused TV bands (54-790 MHz)
802.11ah	2017	347Mbps	1 Km	900 Mhz

Figure 7.1: IEEE 802.11 standards

All these standards use CSMA/CA for multiple access, and have base-station and ad-hoc network versions

TODO

Chapter 8

Mobile Networks

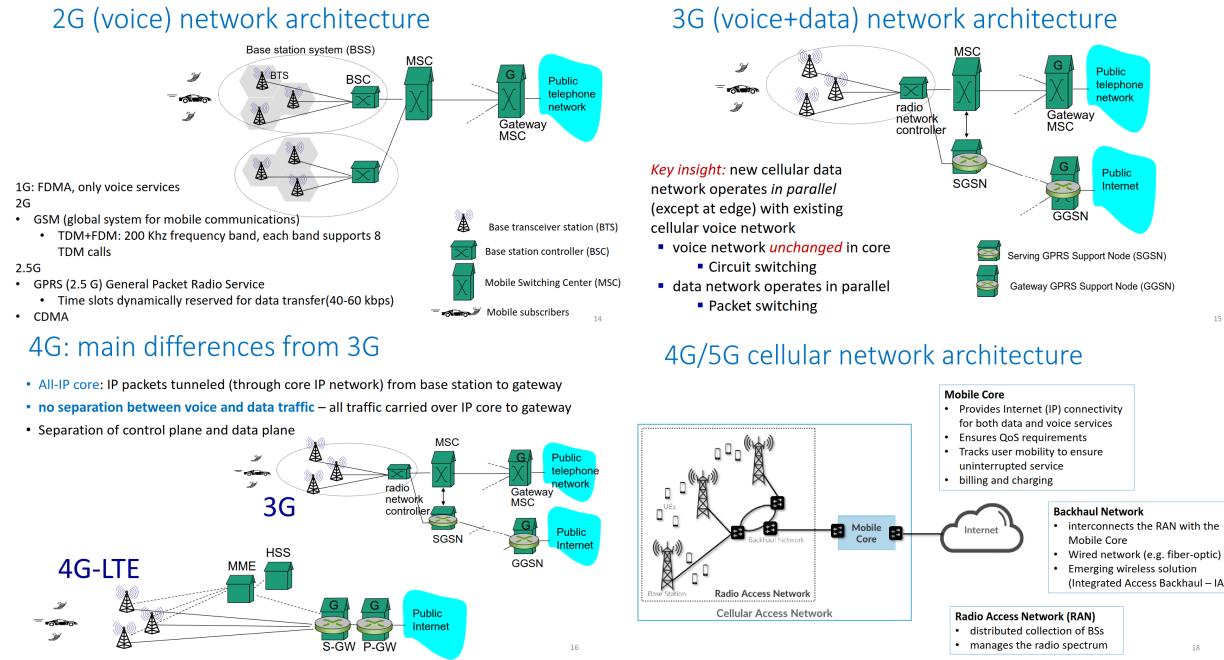


Figure 8.1: Mobile Networks architectures

The key point in **3G** is the introduction of a data service, operating in parallel with voice network, which forced the important modifications to the architecture.

In **4G** also the voice traffic uses *packet switching*, instead of circuit switching.

Control vs Data plane

Control plane includes routing protocols such as BGP and all the processes which handle and determine how data packets should be forwarded.

Data plane instead handles the transport of host/application data, and performs the actual forwarding of packets.

"Think of the control plane as being like the stoplights that operate at the intersections of a city. Meanwhile, the data plane (or the forwarding plane) is more like the cars that drive on the roads, stop at the intersections, and obey the stoplights" [Cloudflare Data/Control plane](#)

To handle devices' mobility there must be home network to rely onto.

With respect to the questions posed in the third image in Fig. 8.3, data being sent from a device to a mobile one may be routed in three ways.

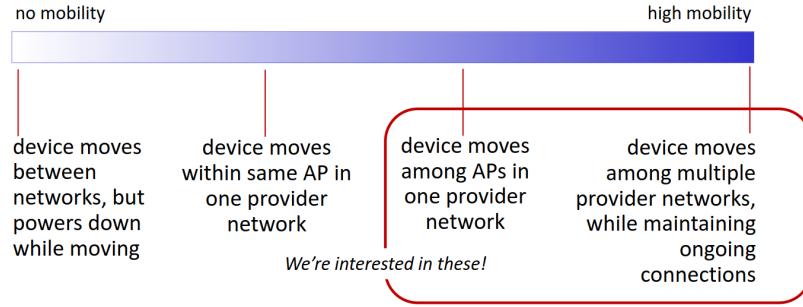


Figure 8.2: Mobility

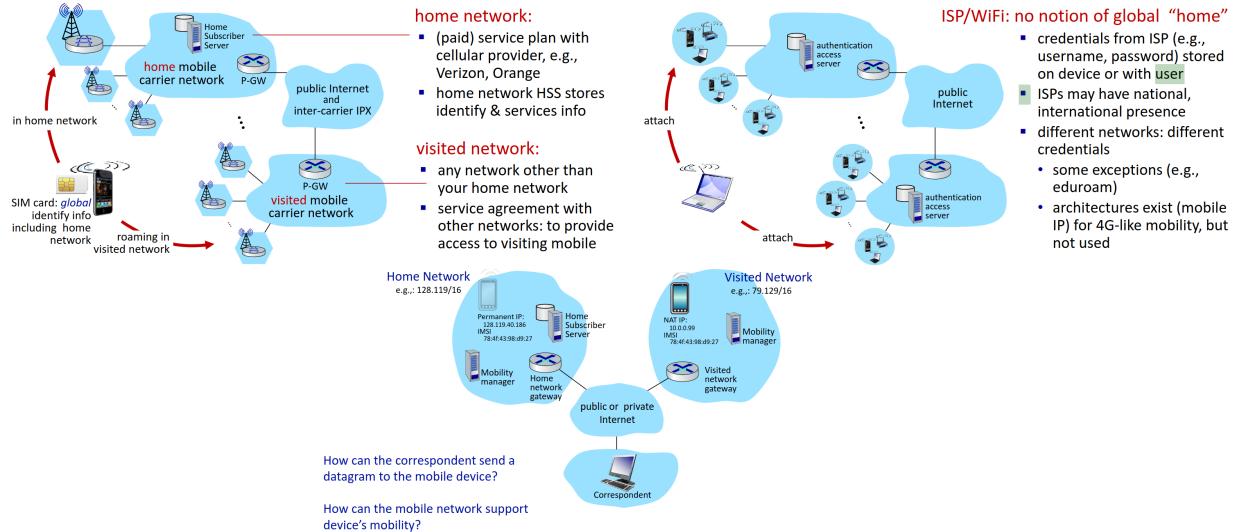


Figure 8.3: Home and visited Networks

1. The first is the canonical routing, using IP addresses and routing tables, but it is not a feasible scenario for billions of devices.
2. The other possibility is to rely on the edge of home and visited networks instead.
 - Direct routing**
Sender gets foreign address of mobile, send directly to mobile
 - Indirect routing**
Communication from sender to mobile goes through home network, then forwarded to remote mobile

Many things are missing here. Refer to the slides or to chapter 7 of the course book (Kurose) for more information.

Chapter 9

Software Defined Networking

SDN is often referred to as a “radical new idea of networking”. It has been made to overcome many requirements and current network technology limitations which arose in the last years:

The demand is increasing

1. Cloud computing
2. Big Data
3. Mobile traffic
4. IoT

Supply also increasing

5. Network technologies capable of absorbing high load
6. Performance of network devices increased
 - i. CPU speed
 - ii. Buffer capacity and speed
 - iii. etc...

Traffic patterns¹ have changed and became more dynamic and complex

This is the most critical aspect

9.1 Traffic Patterns

Modern distributed applications typically access multiple databases and servers that must communicate with each other, creating a lot of “horizontal” traffic between servers—in addition to the “vertical” client/server one—which was initially neglectable, but now it is not.

Unified communications (UC) services are increasingly used within enterprises. Many communication services such as instant messaging (chat), presence information, voice, mobility, audio, web and video traffic, must be *integrated* into a unique service delivery platform

TODO

9.2 Layering

Layering, as it is applied in TCP/IP stack, implies decomposing delivery into fundamental components, allowing independent but compatible innovation at each layer; it revealed itself to be pretty successful, however, many issues reside in the *Network Control/Management Plane*.

If in computer science usually many clean and elegant abstractions are used, network control instead is strongly related to hardware and verbose protocols, there are *no* principles or abstractions guiding the process, making in general difficult managing traffic flows.

SDN helps providing some abstraction through a centralized view of the network.

¹Traffic patterns measure how traffic varies in time and space

9.2.1 Network Layer

- ◊ **Forwarding** move packets from router's input to appropriate router output
Data Plane
- ◊ **Routing** determine route taken by packets from source to destination
Control Plane

These are the two key tasks. In Fig. a comparison between the traditional and the SDN approaches.

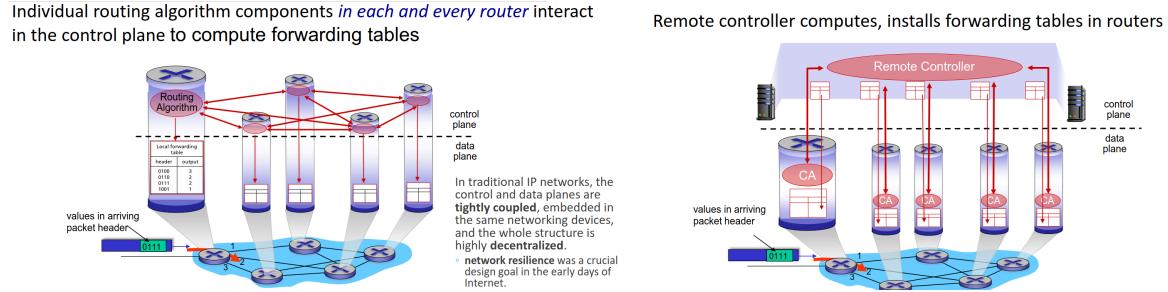


Figure 9.1: Traditional vs SDN

Data-plane switches are fast, simple, commodity switches implementing generalized data-plane forwarding in hardware, and generally provide API for table-based switch control, e.g. `OpenFlow`.

SDN controller (network OS) maintain network state information and interacts with network control applications “above” via northbound API, and with switches using “below” via southbound API. They are implemented as distributed system for performance, scalability, fault-tolerance, robustness.

Network-control apps are “brains” of control, they implement control functions using lower-level services. They are *unbundled*, meaning that they may be provided by a 3rd party different from routing vendor or SDN controller

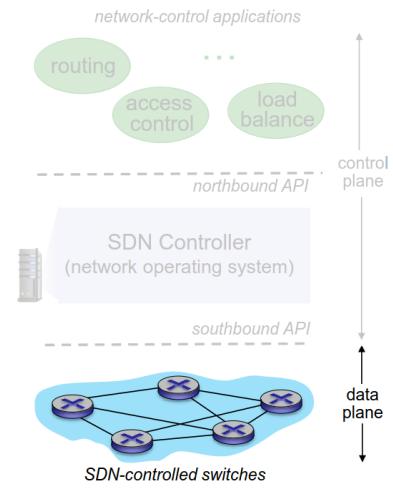


Figure 9.2: SDN Layer Architectures

9.3 Data Plane

Resource or infrastructure layer providing a *Forwarding Abstraction* made up of **forwarding devices** —without embedded software to make autonomous decisions— which perform the transport and processing of data according to decisions made by the SDN control plane.

Inside the routers there is an **OpenFlow flow¹ table**.

Some simple forwarding rules are defined:

- ◊ *Match*: Pattern values to be matched in packet header fields
- ◊ *Actions*: Actions to be performed for matched packet: **drop**, **forward**, **modify**
- ◊ *Priority*: Used to disambiguate overlapping matching patterns
- ◊ *Counters*: Typically used for #bytes and #packets

Destination-based forwarding:													
Switch	Port	MAC src	MAC dst	Eth type	VLAN ID	VLAN Prio	IP Src	IP Dst	IP Prot	IP TOS	TCP s-port	TCP d-port	Action
*	*	*	*	*	*	*	*	*	*	*	*	*	port6
IP datagrams destined to IP address 51.6.0.8 should be forwarded to router output port 6													
Switch	Port	MAC src	MAC dst	Eth type	VLAN ID	VLAN Prio	IP Src	IP Dst	IP Prot	IP TOS	TCP s-port	TCP d-port	Action
*	*	*	*	*	*	*	*	*	*	*	*	*	22 drop
Block (do not forward) all datagrams destined to TCP port 22 (ssh port #)													
Switch	Port	MAC src	MAC dst	Eth type	VLAN ID	VLAN Prio	IP Src	IP Dst	IP Prot	IP TOS	TCP s-port	TCP d-port	Action
*	*	*	*	*	*	*	*	*	*	*	*	*	drop
Block (do not forward) all datagrams sent by host 128.119.1.1													
Layer 2 destination-based forwarding:													
Switch	Port	MAC src	MAC dst	Eth type	VLAN ID	VLAN Prio	IP Src	IP Dst	IP Prot	IP TOS	TCP s-port	TCP d-port	Action
*	*	*	*	*	*	*	*	*	*	*	*	*	port3
layer 2 frames with destination MAC address 22:A7:23:11:E1:02 should be forwarded to output port 3													

Figure 9.3: OpenFlow rules examples

Router	Firewall
• match : longest destination IP prefix	• match : IP addresses and TCP/UDP port numbers
• action : forward out a link	• action : permit or deny
Switch	
• match : destination MAC address	• match : IP address and port
• action : forward or flood	• action : rewrite address and port

The abstraction of **match+action** unifies different kinds of devices

9.3.1 OpenFlow to control the Network Device

Data Plane Network devices support, alongside the abovementioned rule-based forwarding capabilities, interaction with the SDN controller for management of forwarding rules, through OpenFlow switch protocol.

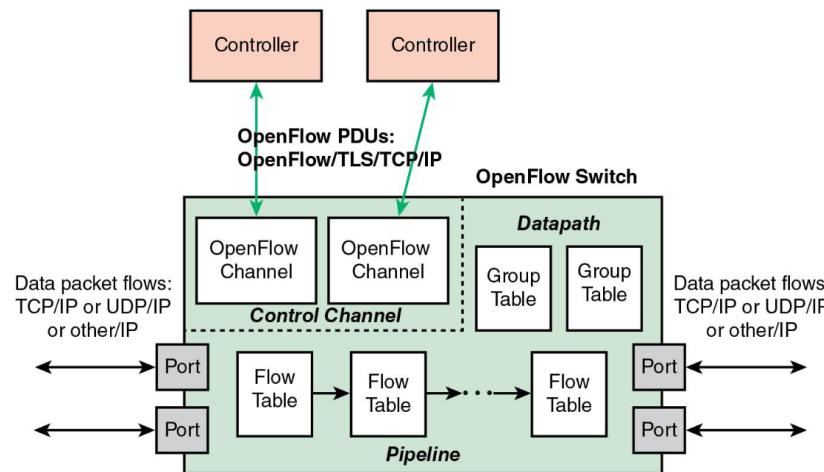


Figure 9.2: OpenFlow switch

Through OpenFlow, the controller can add, update, and delete flow entries in tables, both reactively (in response to packets) and proactively.

A switch is made up of one or multiple pipelined flow tables, possibly allowing for considerable flexibility. Instructions

¹Defined by *link*, *network* and *transport* layer fields

performed on a packet may explicitly direct it to another flow table (`Goto` instruction) and so on, until it is forwarded to an output port.

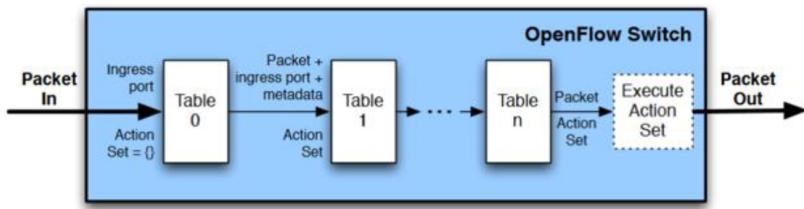


Figure 9.3: Multiple tables inside switch

9.4 Control Plane

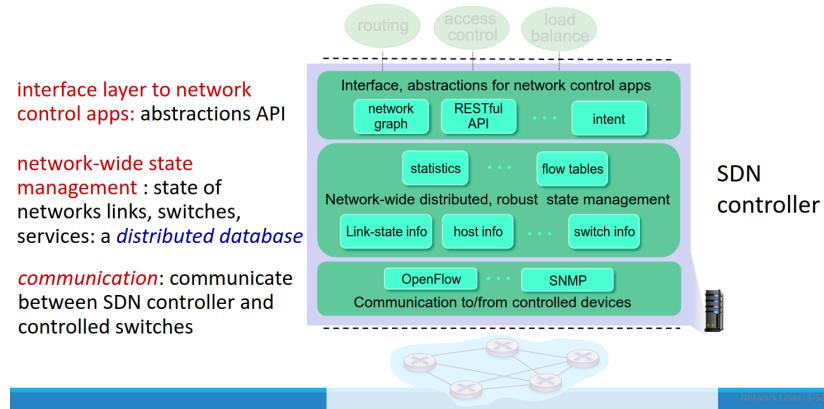


Figure 9.4: Inside an OpenFlow controller

The Openflow protocol operates between a controller and switches using TCP (optional encryption). There are three classes of OpenFlow messages:

1. Controller-to-switch
 - i. *Features*: controller queries switch features, switch replies
 - ii. *Configure*: controller queries/sets switch configuration parameters
 - iii. *Modify-state (FlowMod)*: add, delete, modify flow entries in the OpenFlow tables
 - iv. *Packet-out*: controller can send this packet out of specific switch port
2. Asynchronous (switch to controller)
 - i. *Packet-in*: transfer packet (and its control) to controller. See packet-out message from controller
 - ii. *Flow-removed*: flow table entry deleted at switch
 - iii. *Port status*: inform controller of a change on a port.
3. Symmetric (misc.)

Fortunately, network operators don't "program" switches by creating/sending OpenFlow messages directly; they use instead use higher-level abstraction at controller.

9.5 Topology discovery and forwarding in the SDNs

9.5.1 Routing

While traditionally the routing function is *distributed* among the routers in a network, in an SDN controlled network, it makes sense to centralize the routing function within the SDN controller, allowing it develop a consistent view of the network state for calculating shortest paths and implementing application-aware routing policies.

Thus, data plane switches are relieved of the processing and storage burden associated with routing, leading to improved performance.

The centralized routing application performs two tasks

- ◊ **Link/Topology discovery**
 - The routing function needs to be aware of links between data plane switches

- The topology discovery in OpenFlow domains currently is not standardized
- ◊ **Topology manager**
 - Maintains the topology information for the network
 - calculates routes in the network (the shortest path between two data plane nodes or between a data plane node and a host)

Every OF switch has initially set the IP address and TCP port of a controller to establish a connection as soon as the device is turned on; it also has preinstalled flow rules to route directly to the controller via a Packet-In message any message of the **Link Layer Discovery Protocol (LLDP)**, which is a neighbor discovery protocol of a single jump, i.e. it advertises its identity and capabilities and receives the same information from the adjacent switches.

LLDP is vendor neutral and works at layer 2, using *Ethernet* as “transport” protocol.

Switches send the LLDP messages (“*frames*”) —periodically at a given interval of time— to discover the underlying topology by request of the controller.

9.6 Google B4 WAN

There are two **backend backbones**, B2 carrying internet facing traffic, and B4 moving inter-datacenter traffic; the latter has grown a lot in the recent years.

B4 was needed for various reasons:

- ◊ Not on the public Internet
- ◊ Cost effective network for high volume traffic
- ◊ Bursty/bulk traffic²

Flow types traversing backend backbones are:

- ◊ User data copies
- ◊ Remote storage access
- ◊ Large-Scale data push synchronizing state across multiple data centers

² “Burst”: a group of packets with shorter interpacket gaps than packets arriving before or after that burst