



University of Pisa

Computer Science Department

Master degree in Computer Science

Notes of Mobile and Cyber-Physical Systems

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Those notes have been written in Obsidian and automatically converted to LaTeX: there are several type of errors, missing labels and caption, wrong/absence of references and both grammarly and conceptually errors.

Chapter 1

IoT & Smart Environment

There is no universal accepted definition. According to Journal of Ambient Intelligence and Smart Environment: “*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*”

They are considered smart for the final user because can **recognize context, situations and activities, able to figure out use need at right time and provide services**. They also have in common several characteristic like **persasive, unobtrusive cyber-physical devices**.

For IoT or **Internet of Things** we mean physical objects embedded with electronics, software and sensor, with **network connectivity**. Generally, they are objects with **sensors** and **actuators**: they respectively represent the two flow of data in-and-out of the IoT system because **sensors** can receive input data and elaborate them by resulting in a performed physical action on the physical environment by **actuators**.

IoT Devices Each IoT devices is composed by 4 main components:

- Sensors/actuators
- Microcontroller
- Wireless interface
- Software for business logic

We can identify in IoT a *layered architecture* pictured in 1.1 And, by instantiating this model we can obtain the following scenario:

Sensors at perception layer can be of different type based on the nature of activity that need to be carried out:

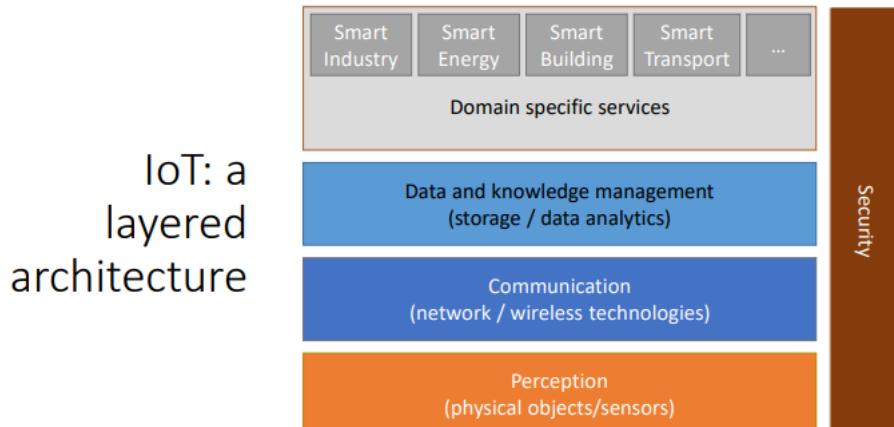


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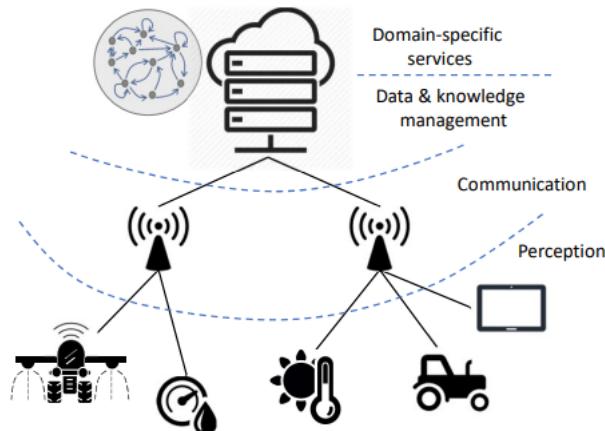


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- Specific: they're a fully-functional component and not need to be instantiated along other components to accomplish the desired task
- Aspecific: they're part of a chain of interaction with other component and this interaction (*e.g. Camera that effect facial recognition task*) allows to perform the intended task

Platforms for IoT Sensors and actuators are the edge of the cloud: behind internet, data is stored, processed and presented in the cloud. So **IoT Platforms** provide software layer between IoT devices and applications. Their functionalities may be distributed between devices themselves, gateways and server in the cloud or at the edge. Those platforms not only allow data collection but can perform several complex functionalities with a various range of activities (*as mentioned, facial recognition can be a service offered/Performed via AWS SageMaker connected to AWS IoT*). Those platforms allow a wide range of functionalities:

- **Identification:** provides a unique way to identify things in the platform. There are several established standards, based on context:
 - *IP Address*: for Internet
 - *MSISDN – Mobile Station International Subscriber Directory Number*: for telephony identification
 - *URI - Universal Resource Identifier*: on resources exposed to web
 - *UUID - Universally Unique Identifier*: in computer system and bluetooth-based communication system
- **Discovery:**
 - A mean to find devices, resources and/or services within an IoT deployment inside the same network of devices. This allows also to obtain properties, features and services and locate via identification.
- **Device Management:** as *initial setting* allows to pair, secure setting and key distribution, manage configuration and binding of devices with services, calibrate the sensors, localize devices etc. Managing involves also **Automatic Software Updates** (*both for software and firmware*), **device real-time monitoring** (*battery level, internal temperature, energy consumption*), **diagnostic/default detection**, **remote control of devices** (*by activating peripherals and remote rebooting, without human interaction*) and **system logging and audit management**. Clearly there are different standards based on a given context. The most popular are:
 - **OMA DM (Open Mobile Alliance Device Management)**: mainly for management activity of mobile terminals
 - **OMA LWM2M (Open Mobile Alliance Lightweight Machine2Machine)**: used for management of IoT devices

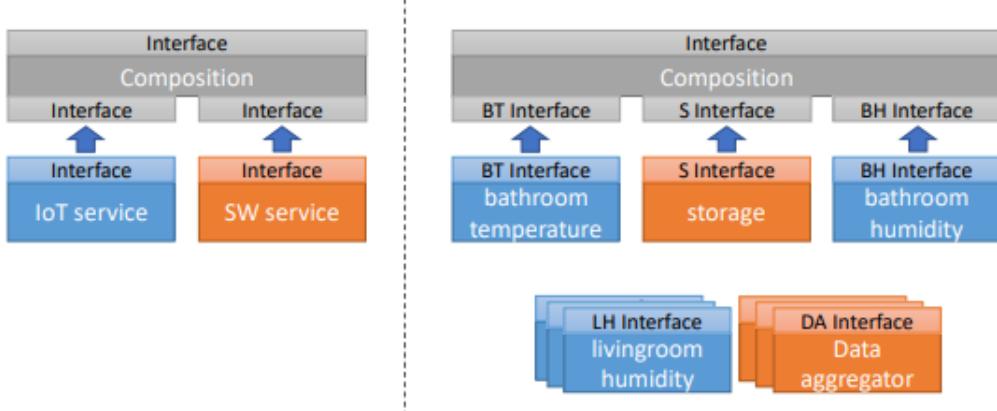


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- **BBF (Broadband Forum) TR-069:** management for end-users appliances (*e.g. DSL terminals, etc.**)
- **Abstraction/Virtualization:** an IoT device is seen as a service so the physical device is associated with its *digital twin*. This provide a way to represent IoT devices and their context, enabling a broad of function on the virtual-device like reasoning and AI-processing over data.
- **Service Composition:** build a composite service by integrating services of different IoT devices and SW components as sketched in 1.3

Based on the previous layered architecture model, we add the details just mentioned and provide a general picture on how those are distributed among the layers, obtaining the model pictured in 1.4

NoSQL databases

No-SQL databases are used in big data and real-time application: they're suitable to scale on horizontal cluster of machines.

As main example, we use **MongoDB**: what in SQL were *Records* in MongoDB are **documents**. Documents have a *JSON*-like data syntax: in the following snippet, they're all *fieldUnknown Node :: textDirective* entry.

```
{
  name: "sue",
```

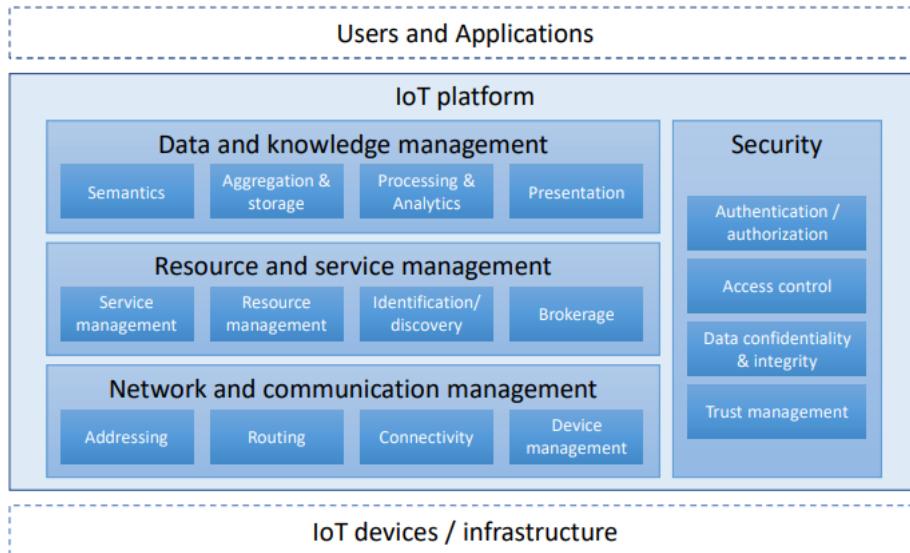


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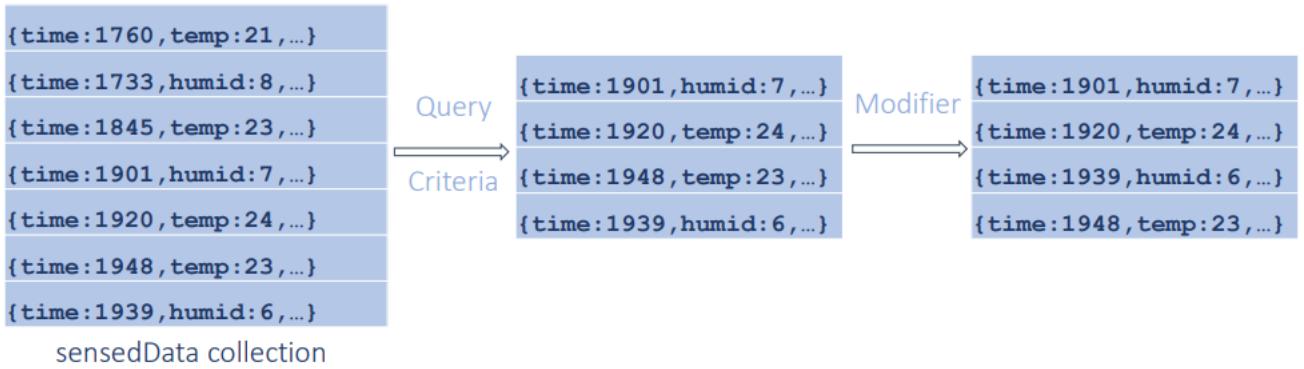


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```

age: 26,
status: "X";
group: ["news", "sport"]
}

```

A set of *name/value* pairs are separated by commas: a **value** can also be an array. So MongoDB **documents** correspond to **native data types** in many programming languages: can embed other documents and arrays to reduce the need for expensive joins.

What were **tables** in SQL, in *MongoDB* are **collections**: documents can be grouped in collection but, differently from SQL, different documents in the same collection can have different structure.

Queries Usually a **query** targets a specific **collection**: it specify criteria and conditions that identify a set of documents in the collection. As SQL, a query can also include a *projection* that specifies the fields to return or include modifier of the output (*like sorting of result, manipulating data format, etc*). Here an example:

```
db.sensedData.find({time:{$gt: 1900}}).sort({time:1})
```

which is represented by the image pictured in 1.5.

We can **modify the data** by update/create/delete: the **update** and **delete** operations can specify the criteria to select the documents to update or remove. Here an example of **insert** query (*referring the pictured in 1.6*):

```

db.sensedData.insert(
{
  time:2011,
  humid: 5,
  ...
})

```

Relevant issues in IoT

There are many issues in IoT and they're not easy to address:

- **Performance**: because microcontroller have a very low computation capacity there are physical and computational constraints to evaluate based on the type of activity to perform. This induces to optimize various parameters and metrics.
- **Energy efficiency**
- **Security**
- **Data analysis/processing**:
- **Communication/brokerage/binding**: How to bring together data producers (*sensors*) with consumers (*users/actuators/applications*).

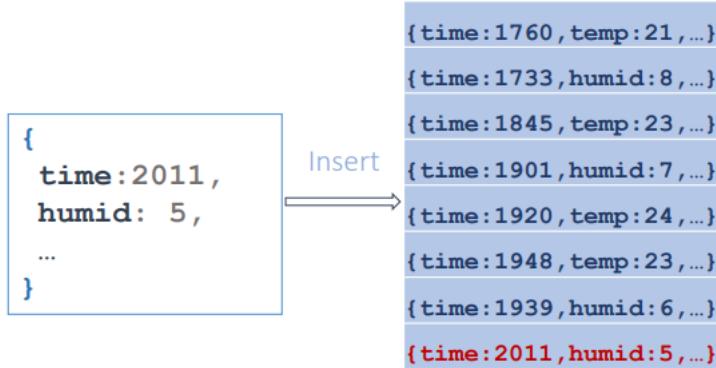


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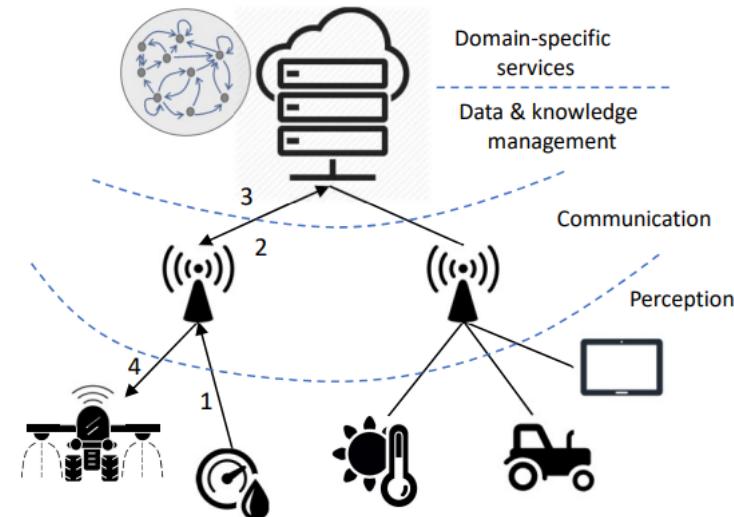


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- **Data representation:** data formats and standardization
- **Interoperability:** many standard already exists at different level, like:
 - **MAC Level:** *Bluetooth, IEEE 802.15.4*
 - **Network level:** *ZigBee, Bluetooth, 6LowPan,*
 - **Application level:** *MQTT, CoAP, oneM2M*

1.0.1 IoT issues

In IoT we can have **latency** and **reliability** issues: this happens because the physical devices can be (and they are) far from each other, this without any doubt adds latency to the iot network. With reliability we mean the process of the network to lose nodes or packets due to some type of **failure/incident**. We saw 2 approaches:

- **Everything is on the Cloud:** this means that all the processing is done in the cloud, the devices at the perception level are meant only to acquire data and send it to the cloud servers, where all the processing is done. Here latency impacts a lot, since the amount of data sent to the cloud can be huge.
- **Some Processing on the Edge:** We can adopt some perception devices (still sensors) with a little bit of computational power (small cpu) to process some of the input data, in this way we can reduce the amount of packets sent to the Cloud servers. It's not mandatory to use the cloud, if your devices can make all the processing alone, then you don't need any cloud.

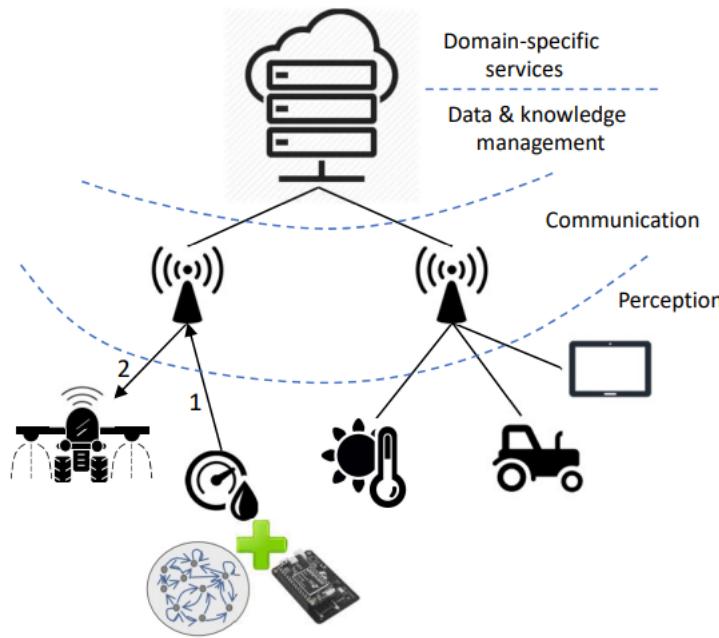


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Let's see what some terms means by referring the scenario pictured in 1.9:

1. **Edge**: the edge of a typical enterprise network is a network of IoT-enabled devices consisting of sensors and perhaps actuators, these devices may communicate with one another. A cluster of sensors can communicate with a central device that aggregate the data to be collected by a higher level entity. A **gateway** interconnects the IoT devices with the higher level communication networks, it performs the translation between the protocols used in the communication networks (on top of **perception** layer) and those used by devices. Perception layer uses some protocol that needs to be translated to enter the network. In **Poche Parole** in the edge we find the **physical** devices of the perception layer.
2. **Fog**: It's an infrastructure of local servers and access points, connected together to provide fast response time to the **edge devices** and to reduce the amount of data that goes to the cloud, typically the fog devices are deployed **physically near the edge**. So rather than storing data **permanently** or for **long period** in a central storage we do as much processing as possible on the **Fog** level. Processing elements at these levels may deal with high volumes of data and perform data transformation operations, resulting in the storage of much lower volumes of data. Examples: **Evaluation, Formatting, Expanding / decoding, Distillation / reduction, Assessment**. You can think of Fog as the opposite of Cloud: **Cloud: centralized storage and processing for a relatively small number of users** **Fog: distributed processing and storage resources close to the massive number of IoT devices**
3. **Core**: the core **network connects far fog networks and provides access to other networks**. The core network uses high-performance routers, high-capacity transmission lines and multiple interconnected routers for redundancy and capacity. It may connect to other type of devices, such as high performance servers and databases or private cloud capabilities. **This means that you can connect fog networks to the cloud.**

1.0.2 The AI approach to IOT

AI aims at getting computers to behave in a smarter manner, **either through curated knowledge or through machine learning**. **Curated Knowledge**:

Machine learning: Subfield of AI that deals with automatic systems that can learn from data. The system is fed by examples to learn to associate input with output, then when an input (**never seen**) is given, the model/system produces anyway an output. If **well trained** the output will mostly be correct, due to generalization capability of ML. **3 ML PARADIGMS: Unsupervised learning**: In

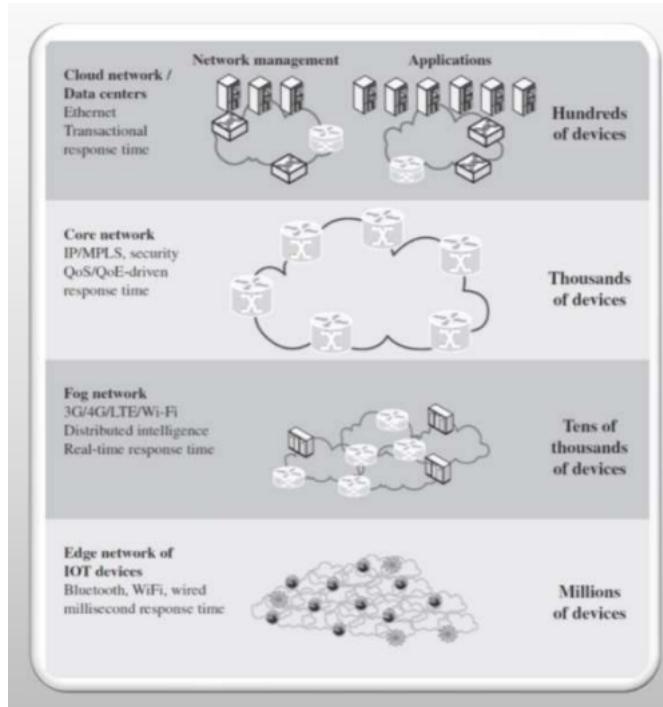


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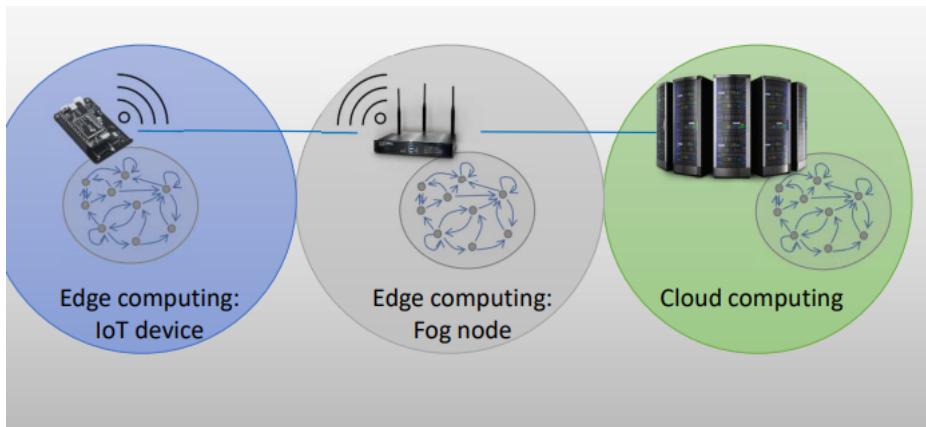


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AI through Curated knowledge

Many ways of representing knowledge, Often based on (a large number of) cause/effect rules

Examples:

- Propositional logic:
 $It\ is\ hot \rightarrow I\ wear\ shorts \wedge I\ drink\ ice\ tea$
- Predicate logic:
 $\forall x: day_of_week(x, wednesday) \vee day_of_week(x, friday)$
 $go(me, football_court) \wedge play(me, football)$

- Production rules:
if having a sandwitch then hungry
- Semantic networks:

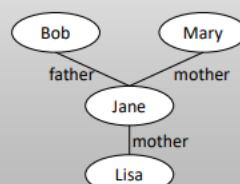


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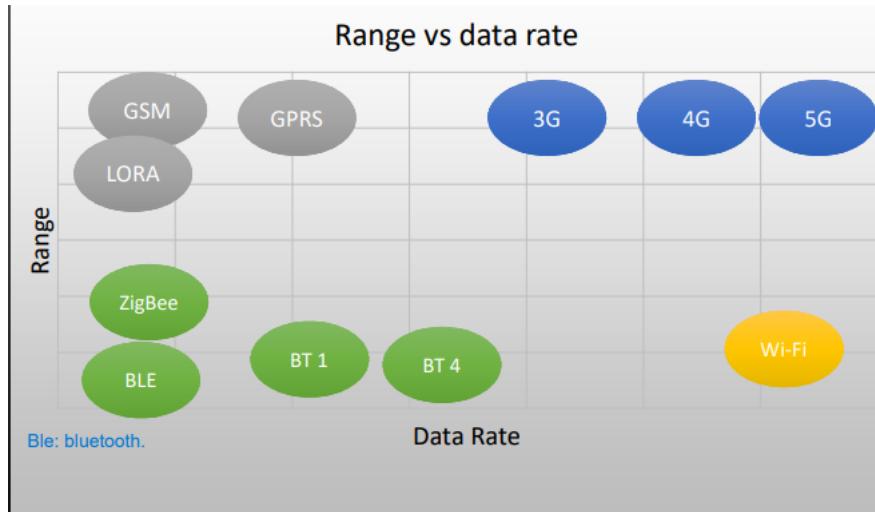


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unsupervised learning, the algorithm is presented with a dataset and must find structure or relationships within that dataset on its own. The goal is to identify underlying patterns or groupings within the data. **Without any type of labeled data.**

The following 2 are used in IoT:

- **Supervised learning:** learn from past examples, **every example is a pair input + desired output**, aims at predicting the future or interpret the present.
- **Reinforcement learning:** learn from examples, **but the main difference is that the example is a pair input + reward**, in this way the system knows that the answer is correct if there's a reward. (*E.g. to learn a game the reward can be +1 for winning, -1 for losing, 0 otherwise*).

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1.0.3 IoT and emerging Paradigms

Blockchain is a **shared and trusted public ledger** for making transactions, everyone can inspect and nobody can alter it. the blockchain thus provides a single point of truth: it is shared and **tamper-evident**, in case of tampering it's quickly noticed. Blockchains shifts the IoT paradigm from **centralized storage** to a **decentralized one** in a distributed ledger. Supports the expanding of the IoT Ecosystem. Since the **ledger is public** this implies a **reduce in maintenance costs** and provides trust in data produced. An implementation of this approach can be seen on having different companies that work in a supply chain, everyone of them needs to **check the quality of the product** along the chain. Each company in supply chain can **query the ledger** and check the latest transaction, thanks to **smart contracts** that are used to certify each intermediate transaction.

1.0.4 Interoperability & Reference Standards

A straight implementation of an IoT solution is not a problem by itself, you can design the solution from the bottom (Physical layer) up to the application layer. This approach is called **Vertical Silos** (No external communication, tutto quello che fa parte dell'infrastruttura è interno al silos) since this system only has your devices and every change/update requires **your intervention**. This creates a **Vendor Lock-in** for your clients because the silos prevent them to use devices from other vendors (Wii con crossfit, altri sono riusciti a crearlo e venderlo a prezzo più basso). Vendor lock-in forces high costs to **migrate** to another vendor, customer need to fully redesign and deploy a new solution. **Standards** are useful to fix this problem. The first standards we saw are for **Wireless technologies**:

1. **vIEE 802.11 aka WIFI:** is a **family of standards** useful for networks where devices are close to each other (Range = 100 meters) but need high data rate. There's a new standard IEEE 802.11A, B, AC. They added new features such as additional frequency bands (5GHz). Since Wi-Fi networks operate on specific frequency bands, with this band the network is faster and less congested. **Increasead trasmission range and bit rate.** Another useful feature is Roaming between access points, this means that a device changes to the nearest access point in the network.

Full vs. partial mesh networks

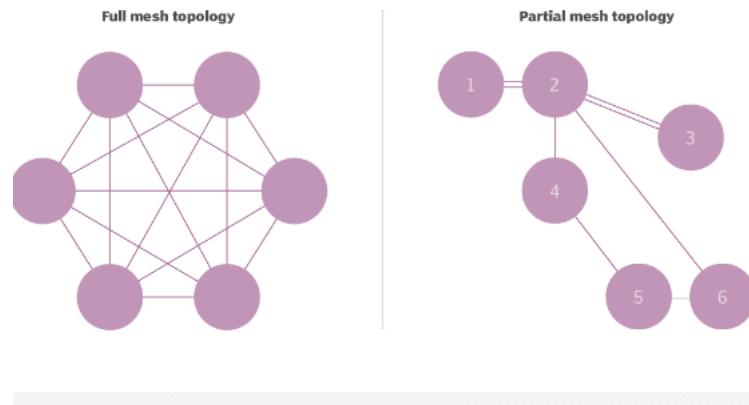


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2. **IEEE 802.15.4 and Zigbee:** is a wireless communication standard for low-rate wireless networks, where devices are very close to each other (low range). It defines **both physical and MAC layers**. Usually used when developing low-power sensor networks. Low power = Low throughput (115 Kbps, molto poco) and low duty cycle (percentage of time sensor is sensig). Thanks to the fact that Zigbee network can create a **mesh topology**, we can create larger range networks. In partial mesh topology, nodes basically forward the data to the desired node, in this way the network can grow. The general idea is pictured in 1.13.
3. **Bluetooth:** Higher data rate than ZigBee, but the range is basically the same. Used to make multimedia communication. Small networks with **master-slave communication**, master sends the data and the slave acquire it.

Why standards? Usually motivated by a reduction of the costs for development of a technology, the price for a new technology is high but as soon as other companies try to create the same one this will **instantly drop the price**. For instance think about a technology that has been developed on the lower layers, in this case communication layer (Wifi) the companies can move to higher layers in order to create their own technology and sell it at their price.(a quel livello non si guadagna più). **Coopetition** can be a good approach for companies, they work with eachother to develop a standard but still deploy their own technologies, built on top of those standards. **Usually happens when technology becomes mature, the big revenues are somewhere else.** As said before, this happened for wireless communications, we saw lot of different standards. **Interoperability problems moved to the higher layers.**

The problem of **interoperability** arises between consortium of standards. Nowadays, the problem of interoperability and thus of standarization is moving up at middleware/application layer. For ZigBee, it covers many layers: it defines a network, transport and application layer specific for ZigBee and incompatible with others.

When there are too many standard available and they are not compatible, the solution is to use the concepts of *endpoints* or **integration gateways**: allows to translate from a given standard to another. The gateway is limited to a single layer but they're able to translate a layer protocol to another one.

We have different scenarios/configurations as sketched in 1.14

In the left case, even if the same vendor with same protocol, the nodes need a communication to the service gateway that provides access to the internet. In the right case, we have different vendors that commonly use the same protocol, respecting a common standard: even in this case we need the service gateway to access the rest of the world. The service gateway allows to map *the rest of the world* to interact with it.

For devices that are not using internet, there is no need to provide external connectivity: differently for ZigBee or MQTT in which the service gateway provide the functionality of transmitting external data. Different scenario is pictured in 1.15

In the left scenario, we have 3 networks which talk using a common standard provided by the **integration gateway**: in each network, the nodes talk each other using specific protocols, different from network to network. A **integration gateway** is able to speak different languages/protocols and able to

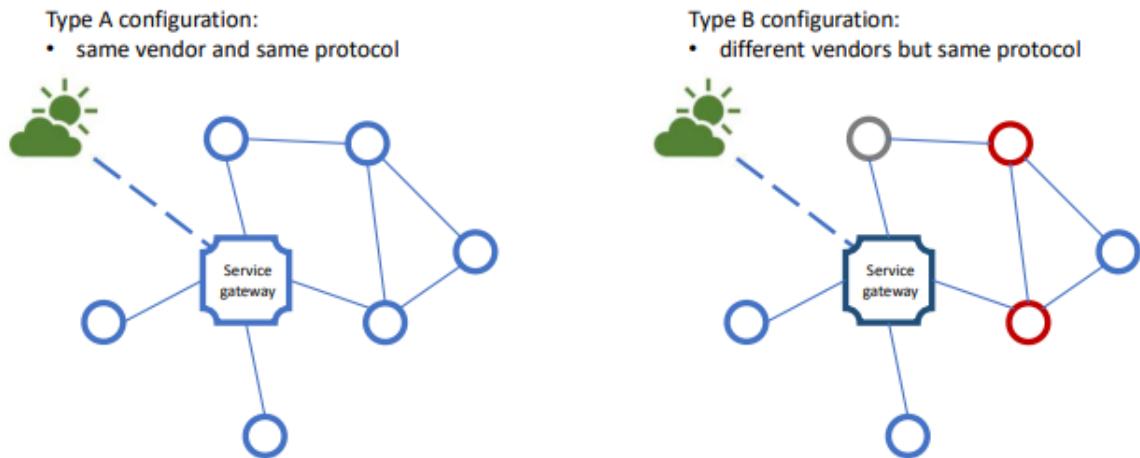


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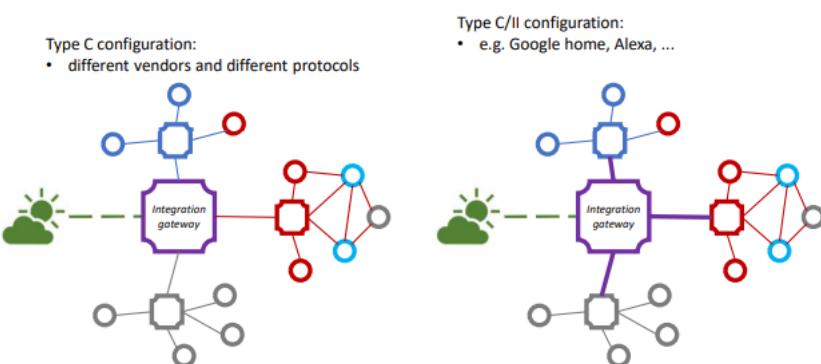


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map one protocol in another. The mapping can be complicated because we can define different behaviours of the devices: in case of a protocol that *push data* and other that differently *pop data* are not translatable in one another. So the integration gateway need to translate the *behaviour*: it also need to complete the packet structure, frame transmission, etc.

In type C/II scenario, the key idea is that the protocol standard or under-the-hood technology is driven by the players (*Google, Amazon*) that in practice determine the specific technology of *integration gateway*, pushing other players to develop in accordance to their technology to guarantee interoperability.

Provide a general purpose integration service is complex: a better solution is forming a *network* of integration gateway that allows to map one protocol to another one or subset of specific-translated protocol. So we obtain a network of **distributed integration gateways** as sketched in 1.16

- Type D configuration:
• Different vendors, different protocols, distributed integration gateways

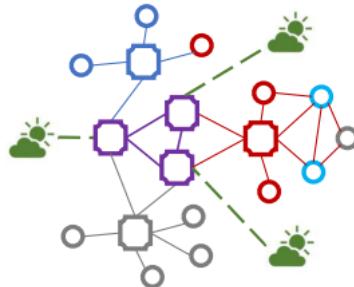


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Brief Security in IoT

The general context which we refer is pictured in 1.17

Some devices are constrained, unconstrained or provide security features: some of them, despite not having security features, they're connected directly with internet. A paper of 2014 poses to problem of security in IoT: the pressure of time-to-market and fasten development phases set the problem of security on devices that are constrained in terms of capabilities or powers so security sometimes became optional because it's not fittable in that types of devices.

Usually those devices are not capable to run a full-fledge OS but only a simple OS without security features that are necessary to implement policies, even during updating the software-specific features.

The problem arises in the topics of *confidentiality* and *authentication* (e.g. *wearable, physiological sensors*).

Security Standards The IUT-T standard recommendation includes a list of security requirements for the IoT: it describes functional requirements during capturing, storing and transferring⁷processing data of things as well as provision services. The requirements concern:

- **Communication security** (*secure, trusted, and privacy protected communication capabilities*): enforces confidentiality and integrity of data during data transmission or transfer
- **Mutual authentication and authorization**: mutual authentication and authorization between devices (or device/user) according to predefined security policies. Before a device (or an IoT user) can access the IoT. The authentication pattern can follow 2 main methods:
 - Remote: directly to the cloud but poses complexity due to device's constraints
 - Local: between devices or authentication service at most one-hop far way or with low overhead for devices. The mutual authentication is meant as *in both direction between devices and gateway*.

The **gateway** is the main building block of the security mechanism and the devices implement only a subset of logic in accordance to the security operations carried out by the gateway.

Authentication can happen at different levels: authenticate devices only at physical layer is important but itself it's not a guarantee that the behaviour at the application level is correct (e.g. *tampered device at physical layer*). There are also other features like protect privacy for devices and gateway, self-diagnosis and self-repair. A critical phase is the deployment of the devices because initially they're not fully configured and may have not been still identified the correct gateway to connect.

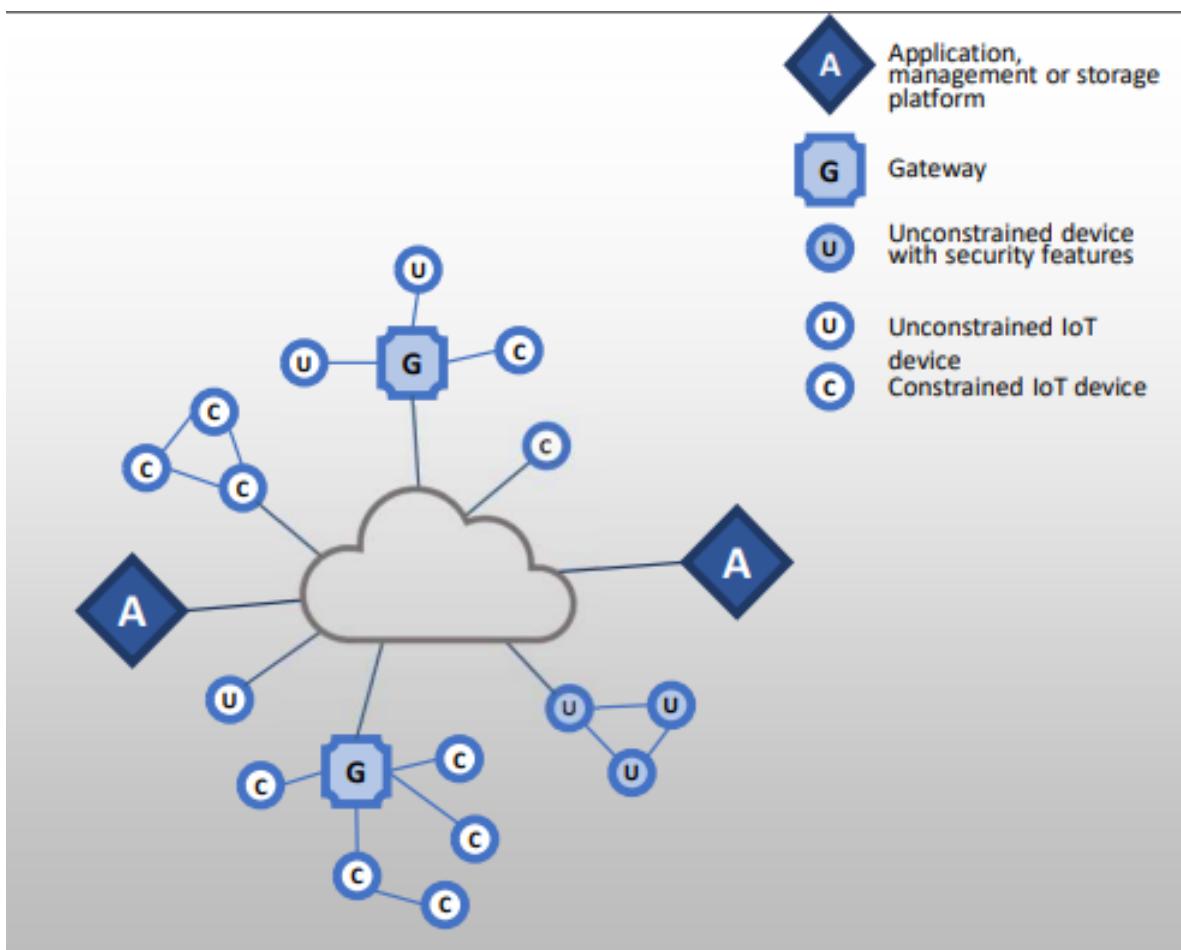


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Chapter 2

MQTT - Message Queueing Telemetry Transport

MQTT covers application, session and presentation layer (*both directly or indirectly by using middleware*). MQTT uses an instance of *publish-subscribe* model between users and consumer: internally, as we will see, is implemented as a client-server architecture. To connect to internet, the IoT devices must adopt internet protocol suite. However, internet stack is too resource-comsumptive respect to constrained IoT devices that usually are *lossy, low power, etc.*

IoT Requirements The IoT devices have different requirement based on given context and offered/requested features.

- *Multi-hop/Mesh networking* allows to provide a connectivity and communication among shared group of devices.
- Addressing:

MQTT it's a *lightweight publish/subscribe reliable messaging transport protocol*. Lightweigh thanks to small code footprint and low network bandwidth, with minimal packet overhead (slightly better than TCP). It builds upon *TCP/IP* with port 1883 or 8883 for using MQTT with SSL (*with overhead*).

Internally MQTT uses a **client/server** architecture: this bought the major complexities on the server side. Provide QoS and it's *data agnostic* so it's suitable both to M2M and IoT.

Publish/subscribe model The main components of the model are **publishers, subscribers** and **broker or event service**. The fist two are both seen as clients and do not know each other, the latter it's the serer known both by publishers and consumer. The **publisher** produce event or any data: interact only with the **broker** and does not know if the data is consumed/read by other entities. The **subscribes** express interest for an event (*or a pattern of events*): receive the notifications from the broker whenevr the event is generated. Publishers and subscribers never interact each other: they interact indirectly only by the *broker(s)*. Those pattern allows to be publisher and subscriber to be decoupled in **time, space and synchronization**.

The broker know publisher/subscribers and receive all incoming messages from the first, filter them all and distributed them to the interested subscriber. It also need to manage request of subscription/unsubscription.

A **publish/subscribe** interaction can be impleted in different ways: the boker is usually an *independent* agent and manage, coordinating with publishers/subscribers, the operations of **publish, subscribe, notify, unsubscribe** as briefly introduced in 2.1

The **broker** is delegated to storage and management of subscriptions.

In figure 2.2 example in which different subscribers register themself to one or more *topics* (*smartphone wubscribe to T&H or temperature and humidity while computer subscribe only to temperature topic*).

This model allow to **decouple the space** because pub/sub do not need to known each other and do not share anything (*they don't known the IP/port of each other and how many peers are subscribed*). It allows also the **time decoupling** because they don't need to run at the same time, guaranteeing the **asynchronicity** of the model. The asynchrnous model is pictured in 2.3.

The decoupling increments the **scalability** of the actors involved: the operations on the broker can be easily parallelized and are event-driven, allowing scalability to a very large number of devices by parallelizing the broker.

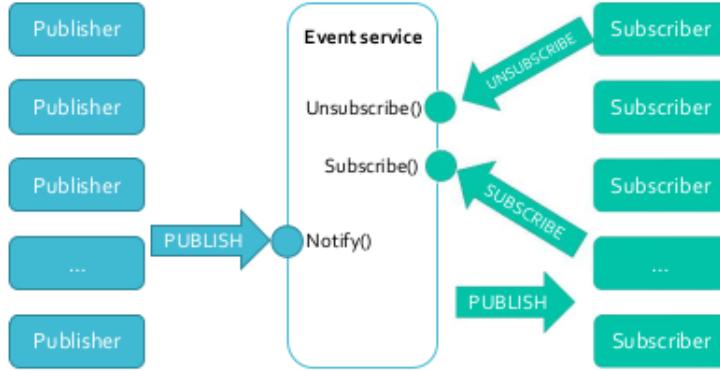


Figure 2.1: undefined undefined

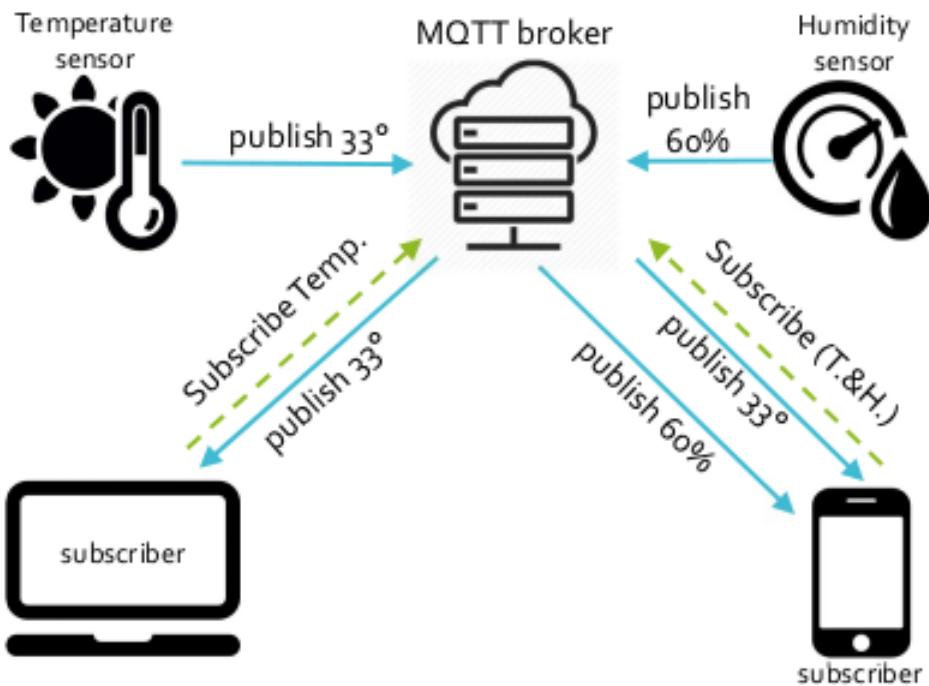


Figure 2.2: undefined undefined

Filtering The filtering features managed by the broker can be based on three different criteria:

- *Based on subject topic*: the subject (or topic) is a part of the message and clients subscribe only to a specific topic. They are usually represented by a string, possibly organized in a hierarchical taxonomy.
- *Based on content*: the client subscribes for a specific query (like `temperature > 30°`) and that query is used by the broker to filter the messages. This method involves understanding the semantics of the data transmitted or at least be able to *read* the data so as to add complexity and context in which security mechanisms (like *encryption*) are used to transmit/store data.
- *Based on type*: filtering of events is based on both *content* and *structure* so the type refers to the type/class of data that can be customized by the subscriber by defining in a strongly typed language the desired object structure. This method introduces complexities in case publishers and subscribers are written in different languages and there is no a unique *translation of type* because their type system is not uniquely determinate. In those scenarios tight integration of the middleware and language paradigms (like *Object Programming*) can ease the presented problem.

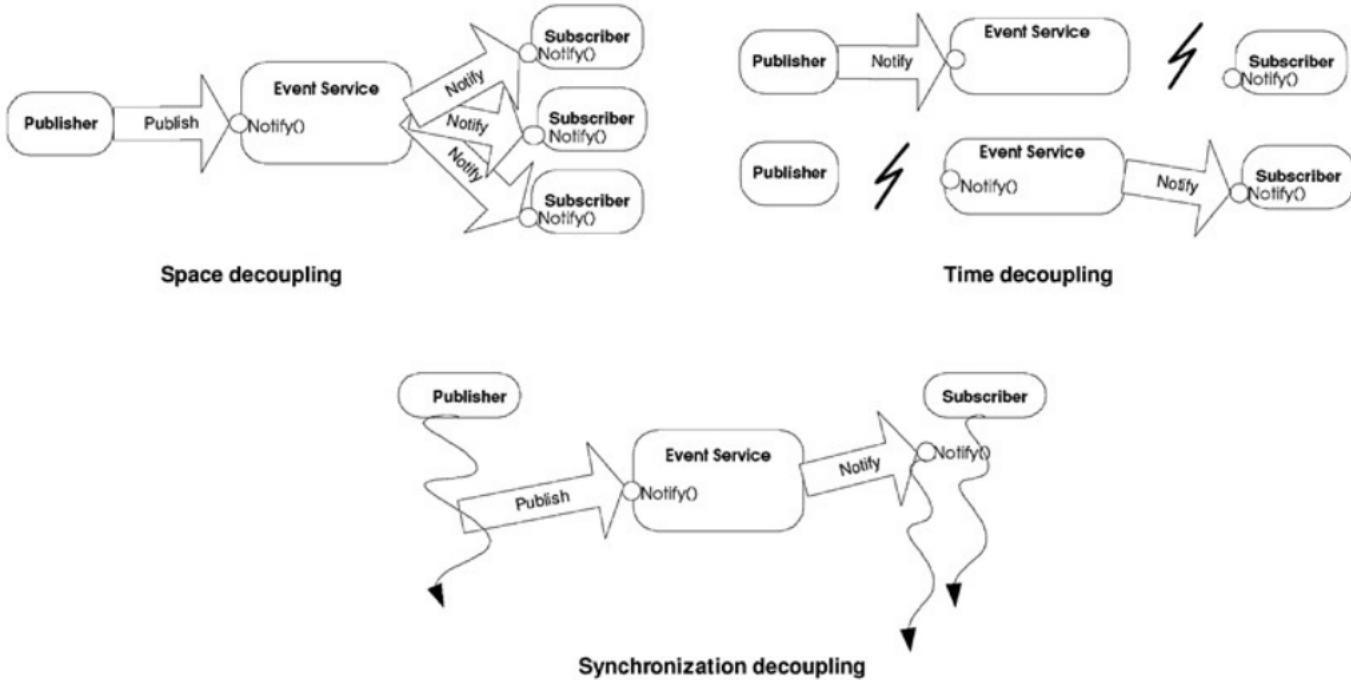


Figure 2.3: undefined undefined

Highlights In the proposed model (*sketched in 2.3*), publishers and subscriber **need to agree on topics beforehand** and publisher cannot assume that somebody is listening to the messages because there are no subscriber messages are not readed by anyone.

Despite pub/sub do not need to known each other, they need to known the *hostname/port* of the **broker** beforehand, to connect and establish a TCP connection to it. In most application, the delivery of messages is near-real-time but in cases when the subscribers are offline, the broker is able to store the messages *only if* subscribers have been connected with a **persistent session** and they're already subscribed to the *topic*. In case of delay or unreliable message the retrasmissons is necessary and the latency issues have to been taken into account. Also the deployment phase take time due to the time needed both by clients to connect to brokers.

MQTT decouples the synchronization allowing to obtain an *asynchronous model*: this model implies the use of callback functions on the subscriber side. Libraries that implements MQTT allows this async model by enabling callbacks. The complexities of the MQTT protocol are shifted to the broker work which in general represent a much more powerful machine respect to subscribers/clients.

As mentioned, the *subject-based* filtering of a message involves the use of *topic*: topic is based on a hierarchy of topics that are meaning to the purposes of the application. MQTT offers additional *QoS* in term of message reliability: it's based on top of TCP by adding an application level acknowledgement. It's expressed by 3 levels of QoS (0, 1, 2). The last two levels ensure the ACK at application level: the level 0 corresponds to TCP reliability level.

2.0.1 MQTT operations

MQTT includes operations at layer 5-6 of ISO/OSI layer, as indicated in 2.4.

CONNECT A client connects to a broker by sending a CONNECT message. This enstaurate a TC connection with the broker. The CONNECT Messages contains:

- *Client ID*: it's an optional identifier, if absent is setted to 1. It's necessary in case of persistent connection: allows to restore connection even in case the connection with the broker is broken, allowing to restore the session from the last *time* the exchange of the message happened. Using no client ID implicit declare the *no session state* so this setting the *Clean Session* flag to true.
- *Clean Session (Optional)*: it's FALSE if the client request a persistent session.

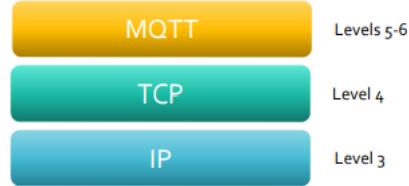


Figure 2.4: undefined undefined

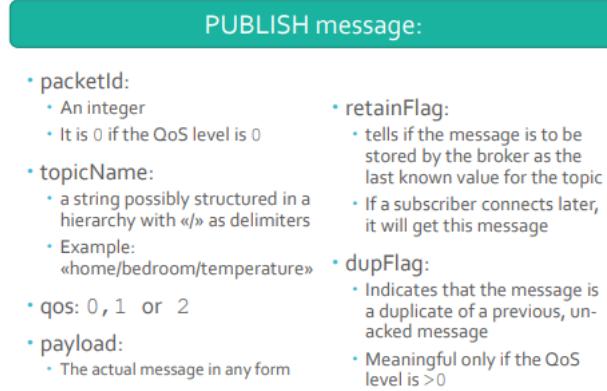


Figure 2.5: undefined undefined

- *Username/Password (optional):* No encryption unless used with SSL
- *Will flags (optional):* allows in case of disconnection ungracefully to sent a **last will message** to the subscribers by the broker (*in case of broken connection with the broker and/or damage*).
- *KeepAlive (optional):* the broker expect to receive from the client periodic message of alive. If not received, the broker can assume that the client is dead and close the TCP connection (*possibly sending the last will message to each subscriber*). The **KeepAlive = 0** turn off this mechanism, indicating that the subscriber will never send the alive messages to the broker.

The broker acknowledges to the CONNECT message with the CONNECTACK message that states if the connection is accepted or rejected and also informs the client (in case of persistent session) information about the previous session.

PUBLISH

Each message contains a **topic** and a **payload** of whatever type because it's managed as a bunch of bytes. Only the subscriber is able to understand the semantics of the payload.

The publish message is sent by the publisher to the broker and forgotten. Then it's forwarded by the broker to the subscriber. The PUBLISH message contains the following data (*summarized in 2.5*):

- **packetId:** an integer, is 0 if the QoS level is 0
- **topicName**: Unknown Node :: textDirective string possibly structured in a hierarchy with slash / delimiters
- **qos:** 0,1 or 2 (*see later*)
- **payload:** the actual message in any form (*usually interpreted as bytes*)
- **retainFlag:** tell 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 duplicate of a previous un-ACKed message. This field is meaningful only if the **qos** is greater than 0.

The **retainFlag** allows to send a specific message for later subscriber: store it to the broker.

When the **broker** receives a PUBLISH message, it:

- acknowledges the message (*if requested, QoS ≥ 0*)
- processes the message (*identify its subscribers*)
- delivers the message to its subscribers The **publisher**:
- leaves the message to the broker
- does not know whether there are any subscribers and whether or when they will receive the message

SUBSCRIBE There can be a difference of QoS between publisher and broker vs subscriber and broker: even in case of 3 different subscriber with different QoS, the broker will manage them independently. The structure of the SUBSCRIBE message is the following:

- **packetId**: an integer
- **topic1**: a string (*as in publish message*)
- **qos1**: 0,1 or 2 Usually a SUBSCRIBE message contains a list of (**topic**, **qos**) because a subscribe message can refer to multiple topics with the relative QoS.

The **broker** acknowledges the subscriber with a SUBACK message. It contains the following fields:

- **packetId**: the same integer of the relative SUBSCRIBE message
- **returnCode**: one for each topic subscribed. The value 128 indicates failures (*e.g. the subscriber is not allowed or the topic is malformed*) while 0,1,2 indicates success with the corresponding QoS granted (*that can be lesser than the QoS requested*).

UNSUBSCRIBE A client can unsubscribe a topic to stop receiving the related messages. The UNSUBSCRIBE message is composed by a **packetId** and a list of topics **topic1**, **topic2**, ..., **topic_n**. The UNSUBACK message have also a **packetId** and contains the same data of the UNSUBSCRIBE message.

2.0.2 Topics

Topics are strings that are organized into a hierarchy: each level is separated by a */ slash*. The subscriber can use **wildcards** to specify a group of topics:

- **home/firstfloor/+/presence**: select all presence sensors in all rooms of the first floor
- **home/firstfloor/#**: select all sensors in the first floor If using only a dash as a topic, you will subscribe to all topics, including the reserver one. Topics that begins with "\$" are reserved for internal statistics of MQTT so they cannot be published by clients. An HiveMQ example:

```
$SYS/broker/clients/connected $SYS/broker/clients/disconnected $SYS/broker/clients/total  
$SYS/broker/messages/sent  
$SYS/broker/uptime
```

Topics must do not contain space, are short for memory storage optimization and packet size, use ASCII char UTF-8. It's also common practice to embed the clientID in topic or an *unique identifier* like **sensor1/temperature** so that onlt the client with the same **clientID** can publish such a topic.

2.0.3 Quality of Service

The QoS is an agreement between the send and the receiver of a message: the underlying TCP allows the QoS to gurantee delivery and ordering of the messages. In MQTT the QoS is an agreement between the *clients (publishers/subscribers)* and the *broker*. MQTT define three levels of QoS:

- **At most once (level 0)**
- **At least once (level 1)**
- **Exactly once (level 2)**

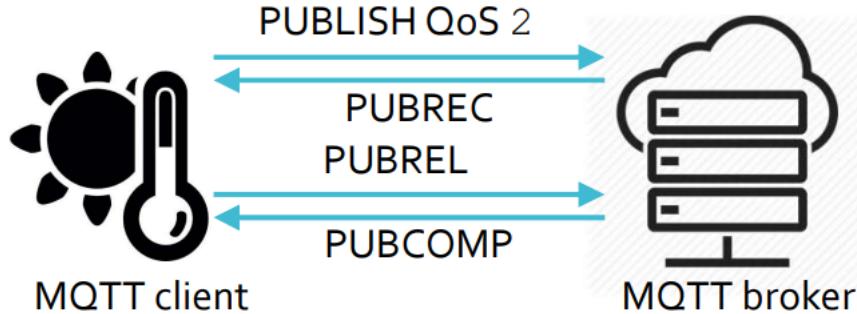


Figure 2.6: undefined undefined

So QoS is used both between publisher and broker and between broker and subscriber. It's called *best effort* delivery because messages are not acknowledged by the receiver. When used between publisher and broker messages are not stored by the broker and immediately forwarded. It provides the same guarantees as the TCP Protocol: it guarantees delivery as long as the connection remains. If one of the two peers disconnect there's no guarantee anymore.

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 1. A message may be delivered more than once so it's suitable when the subscribers can handle the management of duplicated messages. Subscribers send acknowledgements by sending PUBACK packets.

It's the slowest mechanism to guarantee QoS because it checks that each message is received exactly once by the recipient. It uses a **double two-way handshake** by sending PUBLISH and the relative ACK by the PUBREC Packet. Respectively, the client sends PUBREL to acknowledge the reception of the message: the broker now can drop the message from its storage and declare the transmission complete by sending a PUBCOMP packet. So for each message of QoS level 2 there is need four times the exchange of packets required by the level 0. To summarize QoS level 2, the figure 2.6, describes the entire exchange.

The **broker**:

1. receives the PUBLISH with a message
2. Process the PUBLISH
3. Sends back a PUBREC
4. Keeps a reference to the message until it receives PUBREL
5. Sends PUBLISH with a message
6. Waits for PUBREC and then store PUBREC and discards the message
7. Sends back a PUBREL to inform the broker
8. Waits for PUBCOMP and then discards the PUBREC

The *double two-way handshake* is necessary because the first handshake allows to send the message, the second is to agree to discard the state. The PUBREC message alone is not sufficient because if it's lost, the client will send again the message so the broker needs to keep a reference to the message to identify duplicates. With PUBCOMP the broker knows that it can discard the state associated to the message. This level of QoS is suitable when the clients *cannot manage duplicates* so the complexity to guarantee avoiding duplicates is managed by the broker that keeps tracks of ACK and stores messages, with high overhead.

2.0.4 Persistent sessions

Persistent sessions keep the state between the client and the broker: if a subscriber disconnects, when it connects again, it does not need to subscribe again to the topics. The session is associated with the `clientId` defined with the CONNECT message. In a persistent session the data stored are:

- All subscriptions to topics

- All QoS 1,2 messages that are not confirmed yet
- All QoS 1,2 messages that arrived when the client was offline A persistent session is requested at CONNECT time (*cleanSession flag setted to FALSE*): the CONNACK message confirms whether the session is persistent. Also clients have to **store state** in persistent session:
- Store all messages in QoS 1,2 flow, not ACKED By the broker
- All received QoS 2 messages not confirmed by the broker Messages of persistent sessions will be stored as long as the system allows it. The persistent mechanism can be avoided when refers to publishing-only clients that uses onlt QoS level 0 or if old messages are not important or when miss some data is not a problematic.

2.0.5 Retained messages

A publisher has to gurantee that its messages are actually delivered to the subscriber, even for later subscriber. When a client connects to the broker and subscrbes a topic, it does not known when it will get any message. For each topic, we can have **only one retained messages**, generally the *last one message* sent by the publisher. This way a new subscriber is immediately updated with the *state of the art*. A retained message is a normal message with the flag **retainFlag** setted to TRUE: the message is stored by the broker so if a new retained message is published, the broker will keep the last one received. When a *client* subscribes the topic of the retained message, the broker immediately sends the retained message for that topic: this can also works combined with **wildcards**.

The mechanism of **retained messages** and **persistent sessions** are completely decoupled: the second are messages kept by the server even if they had already been delivered. To delete a retained message is sufficient to publish a retained **empty** message of the same topic. This mechanism is usefull for *unfrequent updates* of a topic: for *example*, consider a device that update its status (ON/OFF) on topic `home/devices/device1/status` so if it publish ON, this status will remain for long time and if the message if retained, all subscribers will easily know the device is on.

2.0.6 Last will and testament

Last will and testament feature is used to **notify other clients about the ungraceful disconnection of a client**. At CONNECT tune, a client can request the broker a specific behavior about its last will: it's a normal message with **topic**, **retainFlag**, **QoS** and **payload** stored by the broker as a last will. When the broker detects the client is **abruptly disconnected**, it ends the last will message to all subscribers of the topic specific in the last will message. If the client send DISCONNECT, the stored last will message is discarded because the underlying assumption is that before correctly disconnect the clients has been already notified other clients. So, the broker sends a last will message if:

- Occurs an IO Network error
- The client does not send the **KeepAlive** message in time
- The client closes the network connection without sending DISCONNECT
- The broker closes the connection with the client because of a protocol error

The last will is specified in the CONNECT Message and contains 4 optional fields:

- **lastWillTopic**: a topic
- **lastWillQoS**: either 0,1,2
- **lastWillMessage**: a string
- **lastWillRetain**: a boolean flag
-

The last will message can be combined with **retained messages**: imagine a scenario in which a devices updates the status (ON/OFF) on topic `home/devices/device1/status` so it's powered and publish ON with a *retained message*. If the device crashes and then it abruptly disconnect, it does not publishes OFF: *last will message* can be useful here because could be a retained message with payload OFF so the **subscribers and the futues ones are properly informed**, even in case of unwanted disconnection.

KeepAlive

The KeepAlive mechanism assure that a client and its connection with the broker is still **alive**: the client sends periodics messages to the broker that prove its liveness. The *frequency* of these messages is declared in the CONNECT message. The keep alive message must be sent by the client before the connection expiration of the interval set with the CONNECT message. The entire process is sketched in 2.7

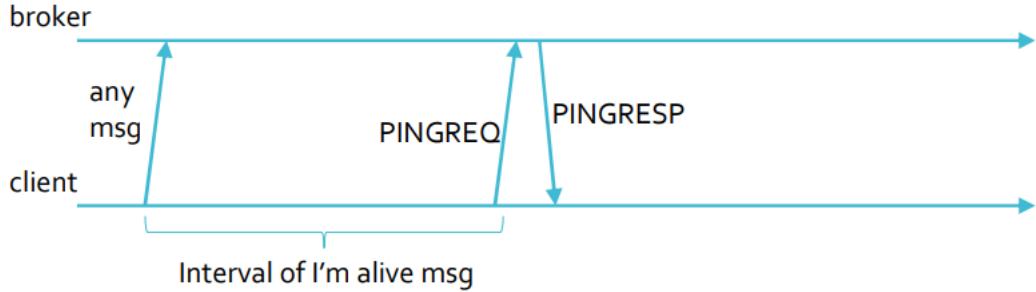


Figure 2.7: undefined undefined

KeepAlive timer (*managed by the broker to control the liveness*) is reseted by both PINGREQ messages and by publish a message on a topic: this allows to be considered alive by the broker. So if the client does not send PINGREQ in time or any other message, the broker turns off the TCP connection and sends the last will message.

2.0.7 Packet format

The structure of an MQTT **control packet** is the following:

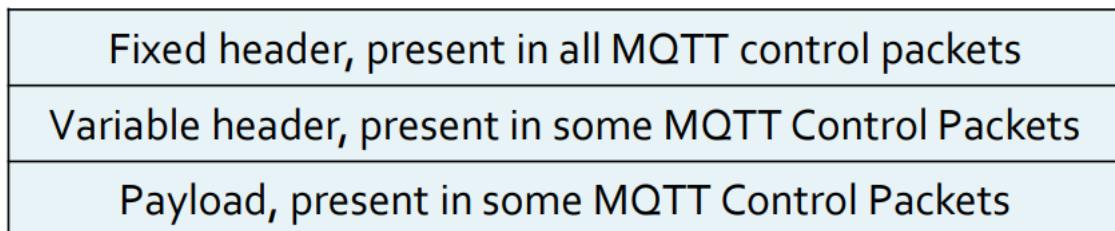


Figure 2.8: Control packet structure

The **fixed header** is composed by **2 bytes**, the first contains (2.9):

- *MQTT Control packet type*: 4 bit (range 7 to 4)
- *Flags specific to each MQTT control packet type*: 4 bit (range 3 to 0) The second byte contains the **remaining length** which is the **length** of the variable header and payload: 7 bits are used to encode the remaining length while one bit (*the MSB, index 7*) is a flag that specifies that there is another field.

The **control packet type** are pictured in 2.10

| 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 | | | | | |

Figure 2.9: Fixed header structure

| 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 |

Figure 2.10: Control packet type

The **variable header** contains the `packetId` (*encoded with 2 bytes*), only the packets regarding the CONNECT and CONNACK does not contain the `packetId` while the PUBLISH packet contains this information only if `qos > 0`. It can contain 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).* The **payload** can be empty or, in case of CONNECT message it contains data about the client or for PUBLISH can be optional (*empty payload are allowed, e.g. to reset retained message*). For example, for CONNECT Packet includes:

- client identifier (mandatory)
- will topic (optional)
- will message (optional)
- Username (optional)
- Password (optional)

In the table 2.11 is listed when the payload is required.

2.1 MQTT on Arduino

Include only a subset of MQTT specific, excluding:

- No SSL/TLS
- QS levlw 2
- Payload limited to 128 bytes

| 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 2.11: MQTT required payload commands

Constructors

- `PubSubClient()`
- `PubSubClient (server, port, [callback], client, [stream])`: create a fully configured client instance. The API includes other `PubSubClient` with lesser parameter. The parameters are:
 - Server address: IP address of the broker (*as an IPAddress object*)
 - Port: port used by the broker. Because SSL/TLS is absent, usually is the 1883.
 - Callback: a pointer to a function that allows to distinguish between subscriber, publisher or both. They are implemented on top of interrupts and allows to intercept publishing/invokation.
 - Client: an instance of the `Client` class that can connect to a specified internet IP address and `portClient` (*e.g. EthernetClient*)
 - Stream: an instance of `Stream`, used to store received messages (*e.g. mqtt_stream*)

Functions

- `boolean connect(clientId, username, password, willTopic, willQoS, willRetain, willMessage)`: connect the client, specifying the **will message**, username and password (*as basic authentication mechanism*)
- `void disconnect`
- `int publish(topic, payload, length, retained)`: publishes a message to the specified topic, with the **retained flag** as specified. Return FALSE if publish fails, either due to connection lost or message too long, while return TRUE if publish succeeds. The API includes other `publish()` with lesser methods.
- `boolean subscribe (topic, [qos])`: topic is a `const char []`, payload is a `byte []`, length is `byte`, retained is `boolean` and qos is an `int`.
- `boolean unsubscribe(topic)`:
- `boolean loop()`: to support the keepAlive features

| | MQTT | HTTP |
|------------------------|--------------------------|-------------------------------------|
| pattern | publish/subscribe | client/server |
| focus of communication | single data (byte array) | single document |
| size of messages | small and small header | large, details encoded in text form |
| service levels | 3 QoS levels | same service level for all messages |
| kind of interaction | 1 to 0; 1 to 1; 1 to N | 1 to 1 |

Figure 2.12: MQTT vs HTTP

- `int connected()`: check whether the client is connected to the server
- `int state()`: return the current state of the client. The following function configure the parameter to the server if still not initialized by the constructor:
- `PubSubClient setServer (server, port)`
- `PubSubClient setCallback (callback)`
- `PubSubClient setClient (client)`
- `PubSubClient setStream (stream)`

See more bootstrap example at <https://pubsubclient.knolleary.net/api>.

2.1.1 MQTT Competitors

HTTP is a valid alternative to MQTT, despite it's not specifically designed to operate for IoT devices at application level. A comparison is sketched in 2.12.

HTTP used in IoT device can be used in two different ways:

1. Clients are servers and accept connections from services
2. Service is the server and accept incoming connections from clients (devices). This paradigm poses problems on scalability, also considering the size of messages and the focus of communication (*because HTTP is not suitable for constrained devices*). In real world applications both solutions are deployed (e.g. TeamSpeak, AWS IoT) because nowadays devices are not entirely constrained on power/computation capacity.

There are several **limitations** on MQTT: the need for a centralized broker can be limiting in scenarios where we have several point-to-point communications because the overhead of a broker may easily become incompatible with end devices' capabilities as the network scales up. Also, the broker is a **single point of failure** and the underlying TCP protocol does not come for free: it's not cheap for low-end devices. There is also an MQTT based on UDP, not standardized nowadays.

2.1.2 Brief CoAP (Constrained Application Protocol)

Standardized in RFC-7252, it's specialized for **web transfer** and it's suitable for machine-to-machine use with constrained nodes and constrained networks. It uses under the hood the UDP Protocol. The general key idea is pictured in 2.13

CoAP also supports direct connections between devices, without relying on intermediate bridges to translate/support the communication.

CoAP is designed to work with nodes with *8 microcontrollers* with small amounts of ROM and RAM. Constrained networks such as IPv6 over 6LoWPANs: it concerns the size of the header, compressing addresses and header used in IPv6. The main strengths are:

- Native UDP
- Multicast
- Security embedded in the specification

- Asynchronous communication While, the weaks are:
 - Standard maturity
 - Message reliability noy quite sophisticated, similar to MQTT QoS

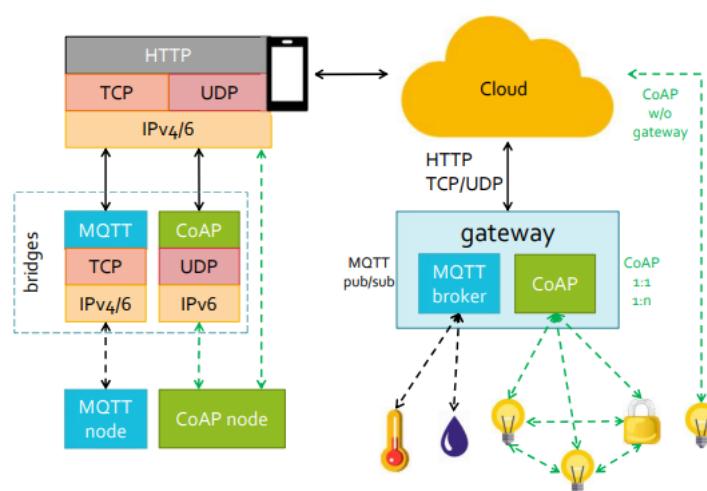


Figure 2.13: MQTT vs CoAP

Chapter 3

ZigBee

It covers almost all layer from physical to application layer. It's a standard for wireless sensors and actuators networks: it's considered an IOT standard even if use TCP/IP as its internal mechanism. The protocol is developed and promoted by industrial private alliance called ZigBee alliance.

It covers different application cases like *home automation, health care, consumer and industrial automation*. It's a competing standard with Bluetooth, especially in eHealth environment where ZigBee failed but had more successfull application in other sectors.

The main requirements that drove the designing of the protocol were:

- Network completely autonomous, self-organizing with minimal or nothing manual intervention
- Very long battery life: ideally a ZigBee device should last 10 years
- Low data rate: allows to guarantee a very long battery life by optimizing performances. This allows trading performances for battery life.
- Interoperability of ZigBee devices from different vendors

This criteria result in some main features, like:

- Standard based
- Low cost
- Can be used globally: it's complex to guarantee because in the range of private frequencies, there is a limit of power. This constraints are country-specific but almost all countries have a subset of frequencies in common.
- Reliable and self-healing
- Support large number of nodes: up to 30.000 devices that using short range (200m) communication. For larger distances there is the need to introduce *multi hops networks*.
- Easy to deploy (by definition)
- Very long battery life
- Secure embedded

Despite is not mentioned, the *transport layer* features are implemented by some sub-layers between network and MAC layer.

IEEE 801.15.4 Standard Define the specification of the physical and MAC layers for low rate PAN. It operates on top of the frequencies of WiFi and Bluetooth: using the same frequencies but not perceived or talk each other, just consider each other as *noise*. The frequency that are defined by the specification are:

- 868–868.6 MHz (e.g., Europe) with a data rate of 20 kbps;
- 902–928 MHz (e.g., North America) with a data rate of 40 kbps; or
- 2400–2483.5 MHz (worldwide) with a data rate of 250 kbps

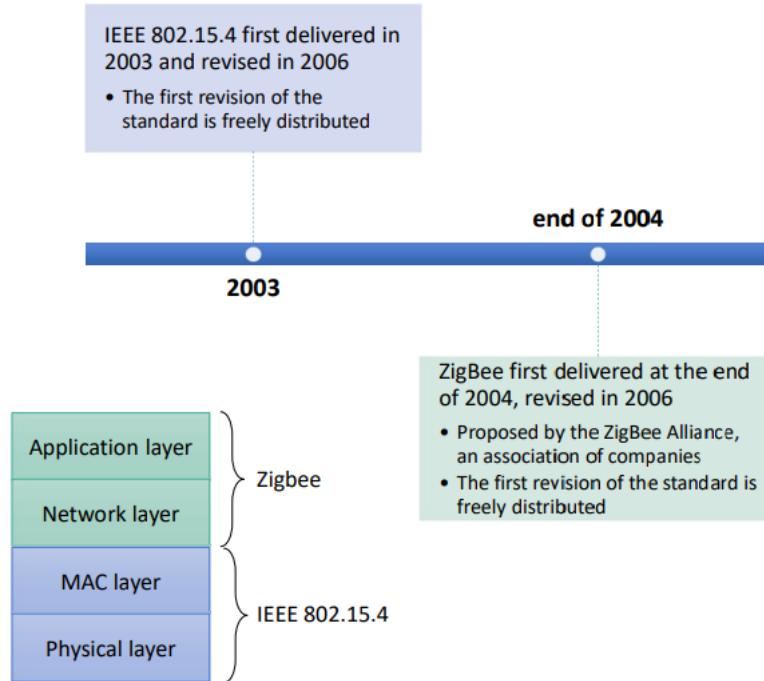


Figure 3.1: undefined undefined

3.0.1 ZigBee Standard

The components described in the ZigBee specification are pictured in 3.2.

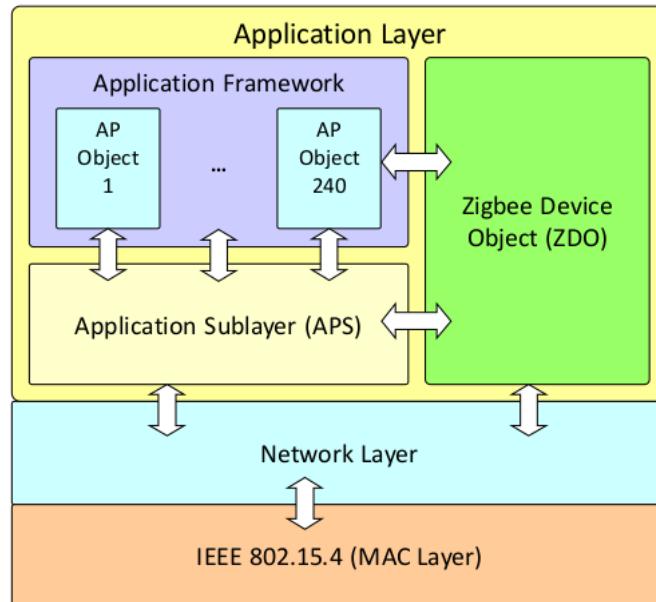


Figure 3.2: ZigBee Specification overview

The Application layer of ZigBee is defined by 3 sub-layer:

1. Application Framework: contains up to 240 **Application Objects (APO)** in which each APO is a user defined ZigBee application.
2. ZigBee Device Object (ZDO): provides services to let the APOs organize into a distributed application. Guarantee interoperability between different devices of different vendors
3. Application Support sublayer (APS): provides data and management services to the APOs and ZDO.

Service primitives

Each layer provides its data and management service to the upper layer so **each service** is specified by a set of primitives of four generic types. Between all the services and all the layers, only **4 primitives** are used/consumed between each layer as sketched in 3.3:

- **Request:** It is invoked by the upper layer to request for a specific service;
- **Indication:** It is generated by the lower layer and is directed to the upper layer to notify the occurrence of an event related to a specific service;
- **Response:** It is invoked by the upper layer to complete a procedure previously initiated by an indication primitive;
- **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. Services may not use all the four primitive (*see later*).

Here an example of *service primitives* that allows to visualize the flow: same levels of different nodes interact by means of those 4 primitives.

Data transfer The data transfer between node assume an uniform name called **Data Unit**, encapsulated at different level with different packet layers, here specified in 3.5.

For each layer:

- Application Protocol Data Unit
- Network Protocol Data Unit
- MAC Protocol Data Unit
- Physical Protocol Data Unit

3.0.2 Network Layer

At network level we identify 3 types of devices:

1. **Network coordinator:** Despite been a infrastructurless protocol, a coordinator have the function of create the network by taking decisions/interfacing with the rest of the network. Allows to bootstrap the network.
2. **Router:** provide routing features in a large network and can also have services capability. From the point of view of routing capabilities, they have the same capabilities or coordinator.
3. **End device:** they are not able to communicate alone with the rest of the network and use coordinators/routers to communicate. They must be attach to the coordinator to be able to communicate over the network. They do not need to implement the entire standrd, differently from router/coordinators that must have the capabilities to implement the standard fully. Generally they correspond to a RFD or FFD with simple features (**RFD**: Reduced Functional Interface, **FFD**: Full Functional Device)

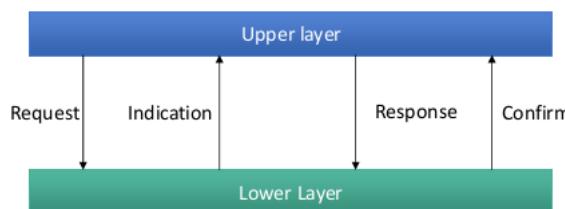


Figure 3.3: undefined undefined

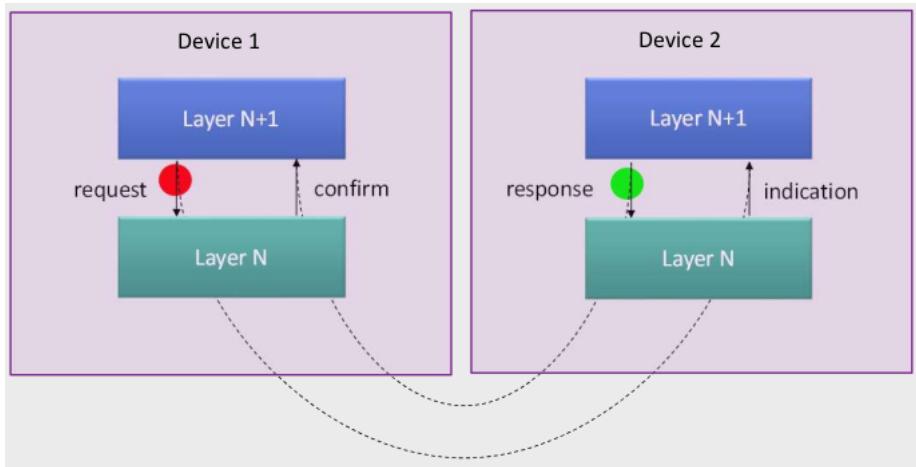


Figure 3.4: undefined undefined

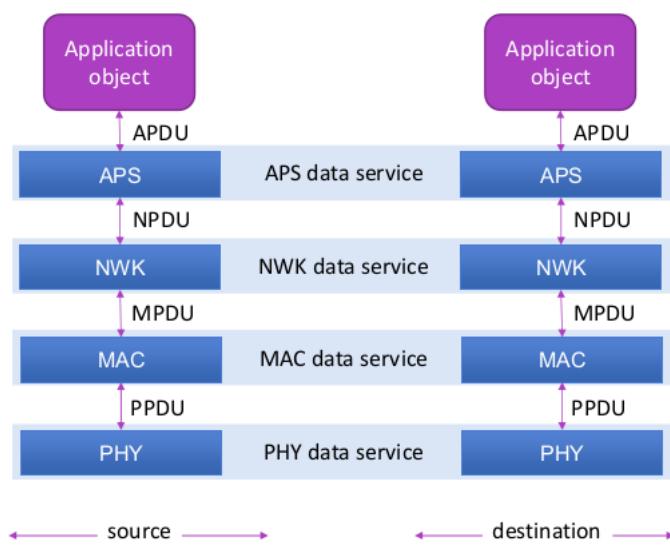


Figure 3.5: undefined undefined

We can have different **network topologies** as specified in 3.6.

In a **star shaped topology**, the router have the same roles as end device: they uses the *superframe*. In the **tree topology**, the *multi-hop network* (*not fully addressed in those notes*) functionalities are supported and the nodes can communicate only via the intermediary routers: they can or cannot use *superframes*. In **mesh networks**, the communication is possible even between nodes without relying on the *superframe infrastructure* (*superframe is the topic of the lecture on CSMA/CA, see later chapters*).

The network layer provides services for:

1. Data transmission (both unicast & multicast)
2. Network initialization
3. Devices addressing
4. Routes management & routing

5. *Management of joins/leaves of devices*: because the networks is formed incrementally, formed a network with an arbitrary topology.

In 3.7 table that summarizes which services uses the 4 primitives already mentioned:

As highlight the table, not all four primitives are used in the listed operations: particularly, the **GET** and **SET** are functionalities used **locally to set/get parameters of the network layer**, internally, without using communication means.

Before communicating over a network, a ZigBee must either:

1. Form a network so it's a **ZigBee coordinator**
2. Join an existing network so it's a **ZigBee router/end-device** The role of the device is chosen at **compile-time** by specifying the code ad application level when writing the **Application Object** code.

Network Formation The *network formation* is initiated by the **NETWORK-FORMATION.request** primitive: it's invoked by a device that acts as a **coordinator** and that is not already in another PAN. The operation uses the MAC layer services to **look for a channel** that doe snot conflict with other existing networks: it **selects a PAN identifier** which is not alredy in use by other PANs. The process is pictured in 3.8

1. At application layer is invoked the **NETWORK-FORMATION.request**
2. The network layer execute an *energy scan* to verify if there is noisy on the channel
3. The MAC layer return the result of the energy scan: at this point, the network layer request a second scan, differently from the first because it's an **actve scan** to lookup nearest PAN networks. This is due to avoid to have two different PAN with the same identifier so a preventive scan allows to select a PAN ID unique among the already existing.
4. The MAC Layer return a list of existing PAN ID and the Network Layer now can set the PAN ID.

The process of **NETWORK-FORMATION** continues as showed in 3.9

Now the Network later can configure the MAC Layer starting from the time the **START.request** is sent and the MAC Layer can start to send beacon frames. After that, the MAC layer can answer with a

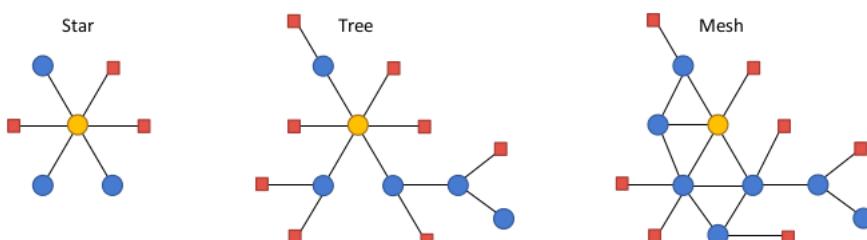


Figure 3.6: undefined undefined

| Name | Request | Indication | Confirm | Description |
|-------------------|---------|------------|---------|---|
| DATA | X | X | X | Data transmission service |
| NETWORK-DISCOVERY | X | | X | Look for existing PANs |
| NETWORK-FORMATION | X | | X | Create a new PAN (invoked by a router or by a coordinator) |
| PERMIT-JOINING | X | | X | Allows associations of new devices to the PAN (invoked by a router or by a coordinator) |
| START-ROUTER | X | | X | (Re-)Initializes the superframe of the PAN coordinator or of a router |
| JOIN | X | X | X | Request to join an existing PAN (invoked by any device) |
| DIRECT-JOIN | X | | X | Used by the coordinator or by the routers to force an end device to join their PAN |
| LEAVE | X | X | X | Leave a PAN |
| RESET | X | | X | Resets the network layer |
| SYNC | X | | X | Allows the application layer to synchronize with the coordinator or a router and/or to extract pending data from it |
| GET | X | | X | Reads the parameters of the network layer |
| SET | X | | X | Set parameters of the network layer |

Figure 3.7: undefined undefined

START.confirm that will be translated also by the network layer with a NETWORK-CONFIRMATION.confirm to the application layer to confirm that the PAN has been created.

To join inside a PAN network there are two ways:

1. The end-device or the router can communicate with the coordinator to request the access: this method is called **Join Through Association**
2. The coordinator request a device to join the network: this method is called **Direct Join**

Join through association (CHILD-SIDE) The protocol flow is pictured in 3.10

The device that wish to join a PAN:

1. Performs a NETWORK-DISCOVERY to look for existing PANs

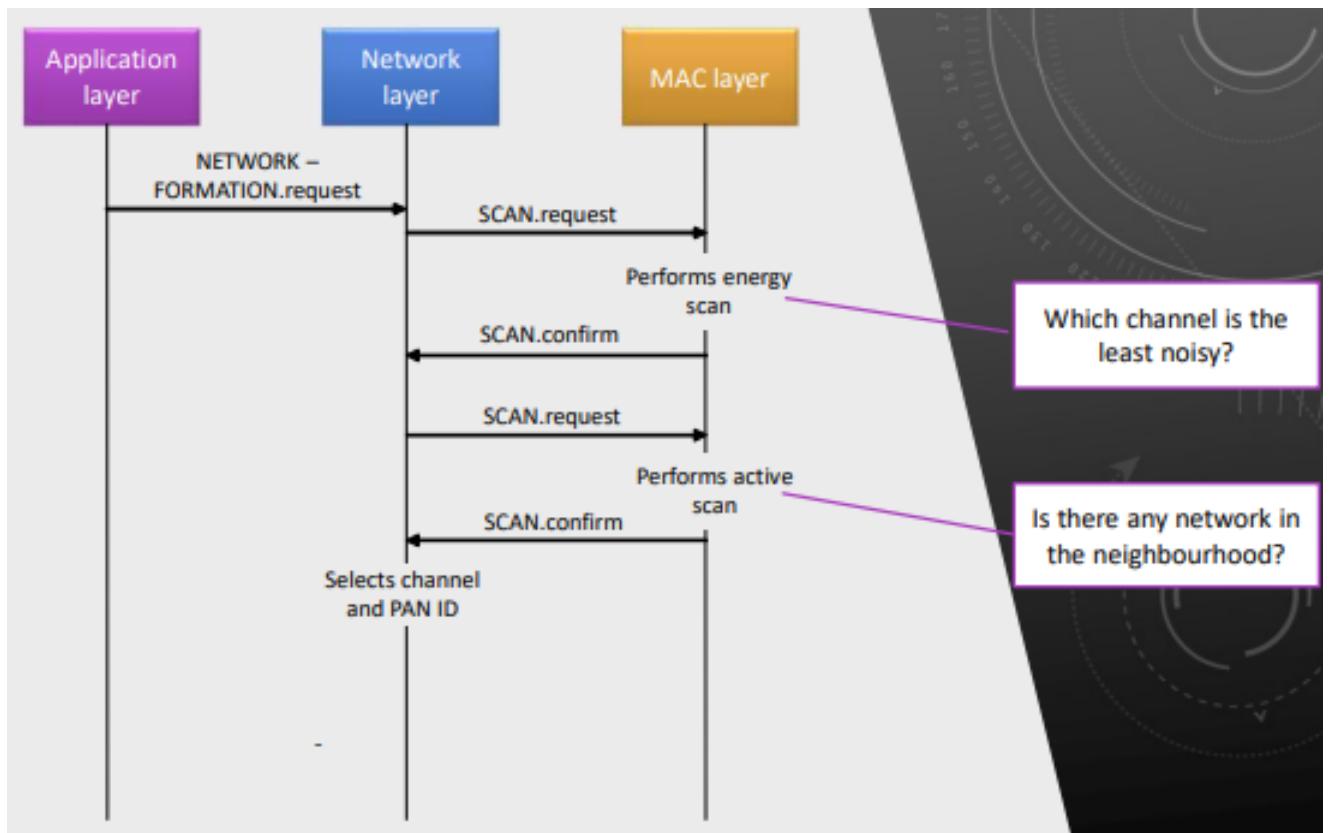


Figure 3.8: Network Formation exchange diagram

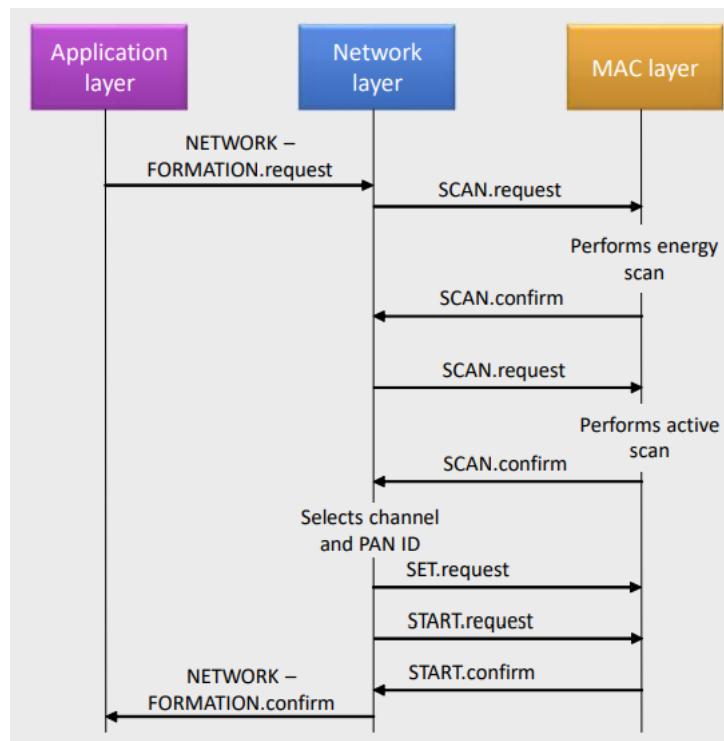


Figure 3.9: undefined undefined

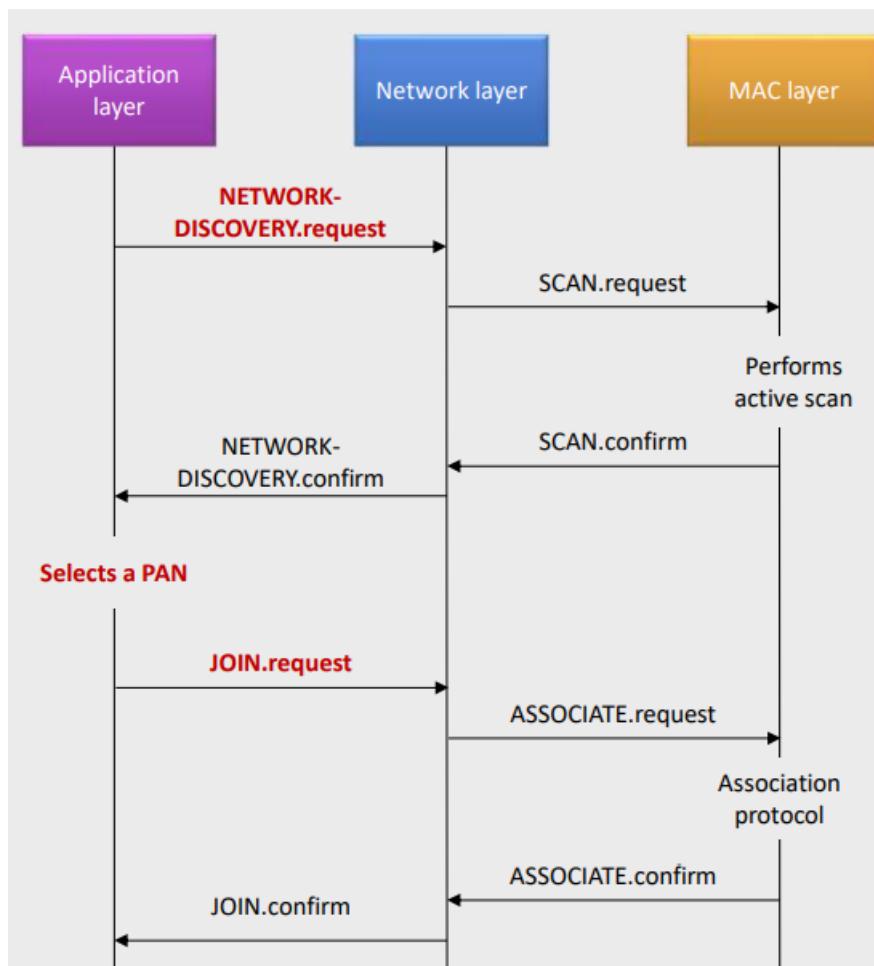


Figure 3.10: Join Through Association

2. Select a PAN
3. Invokes JOIN.request with parameters like the *PAN Identifier* of the selected network, a *flag* indicating whether it joins as a router or as an end device. This request in the *network layer* selects a "parent node P" (in the PAN) from its neighbourhood. In a **star topology** P is the coordinator and the device join as end-device, while in a **tree topology** P is the coordinator or a router and the device can join as a router or as an end-device.
4. The association protocol obtains from P a 16-bit **short address**: the ASSOCIATE.confirm returns to the netowkr layer the short address that will be used in any further communication over the network. The JOIN.request is triggered at application level: this require preliminarily to scan the network to find a free channel to communicate. The scan is perfomed troguht NETWORK-DISCOVERY which return a list of PAN network to connect: this allows to select the PAN and send the JOIN request. Depending on network topology, the association of a new device can be structured by identified implicitly a **root father** so the topology assume the form of a sort of a tree: the end-devices will be the leaves while the internal nodes are the router, the *coordinator* is the root node. This tree-structure topology is used to assign the addresses to new devices, coordinated by the *ZigBee coordinator* that decides and control parameters like *number of leaves*, *number of routers*, *depth of the tree* and so on. Each router have assigned its own set of addresses to assign to new joined devices: the assignment of the address is performed by ensuring that new devices are highest in the network and are at a lower number of hops from the root/parent router.

3.0.3 Application Layer

The application layer comprehends various components (*as shown in 3.11*):

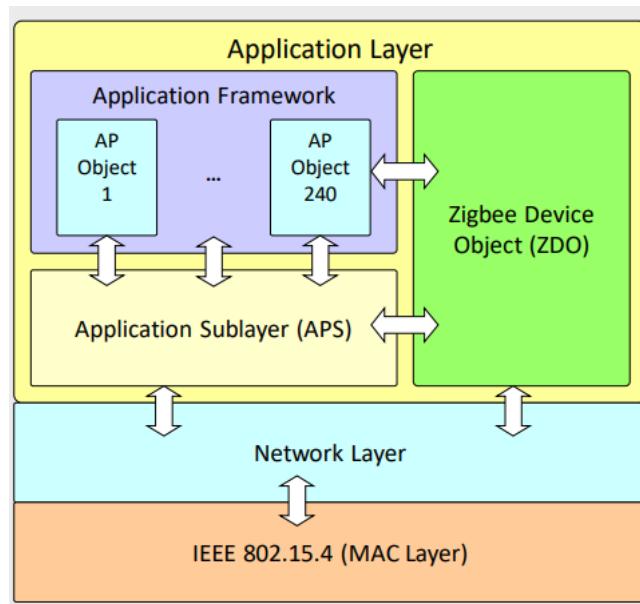


Figure 3.11: undefined undefined

1. **Application Framework**: contains up to 240 **Application Objects (APO)** in which each APO is a user defined ZigBee application.
 2. **ZigBee Device Object (ZDO)**: provides services to let the APOs organize into a distributed application. Guarantee interoperability between different devices of different vendors
 3. **Application Support sublayer (APS)**: provides data and managemnt services to the APOs and ZDO.
- 1. Application Framework** The application framework can contains up to 240 different *Appication Object (APO)*, each one uniquely identified inside the netowrk. Simplest APO can be queried with *Key Value Pair data service (KVP)* by using primitives like Set/Get/Event transactions on the APOs

attributes: native KVP disappeared in the second version of ZigBee but it's now present in the cluster library. Complex APO can have complex states and communicate with the *Message data Service*. In figure 3.12 an example of complex APO: we have two devices, the first with two endpoint, the second with three endpoint: the logic of this device can be easily implemented using two ON-OFF attribute and two endpoint in the device A. **APOs 5B, 6B, and 8B** have a single attribute containing the status of the bulbs (on/off) that is configured as servers at the application layer while **APO 10** and **APO 25** are switches, and they are configured as clients at the application layer. The attributes of **APOs 5B, 6B, and 8B** can be set remotely from the **APOs 10A** and **APO 25A**.

2. Application Support Sublayer (APS)

The APS define the **endpoint**, **cluster**, **profile IDs** and **device IDs**. It's responsible for:

- Data service (*light transport layer*) that provides support for the communication's reliability and packet filtering
- Management services which includes maintaining a local binding table, a local group table and a local addresss map.

The **endpoints** are identified by a number between 1 and 240: an endpoint can be seen as the equivalent of a Unix socket, connecting virtual wires to applications. The **cluster** is a protocol that can be used to implement the functionality of a given application: cluster defines the attribute that contains the information about the APO. A cluster is defined by an identifier of **16 bit**, local inside the **profile**. In ZigBee a **profile** defines a set of application layer protocols that enable interoperability between devices that perform specific functions or serve specific purposes. A profile specifies the standard ways in which devices should communicate and exchange information, making it easier for devices from different manufacturers to work together.

A profile consists of one or more **clusters**, which are groups of related functionality that can be supported by a device. Each cluster is identified by a unique ***cluster ID**, which is a 16-bit integer value.

A cluster defines a specific set of messages and commands that devices can use to communicate with each other. *For example, the ZigBee Home Automation profile includes clusters for controlling lights, thermostats, and door locks. Each cluster specifies the data format and message types that devices should use to exchange information related to that functionality.*

In the previous table, the *Basic Cluster* with ID 0x0000 allows to retrieve basic information about the device, the *Power Configuration Cluster* allows to set the *minimum and the maximum temperature* of the device. Also, the *OnOff Cluster* allows to set the *switch ON or OFF*, as expected.

The **APS Device IDs** range from 0x0000 to 0xFFFF: this value has two main purposes:

1. To allows human readable displays (*e.g. an icon is realted to a device*)
2. Allows ZigBee tooools to be effective also for humans:
 - (a) A device may implement the on/off cluster but you don't know whether it's a bulb or a oven so you only knwo you can turn it on or off. The DeviceID tells you what it is, but it does not tell you how you can communciat ewith it: this is given by the IDs of the cluste rit implements.

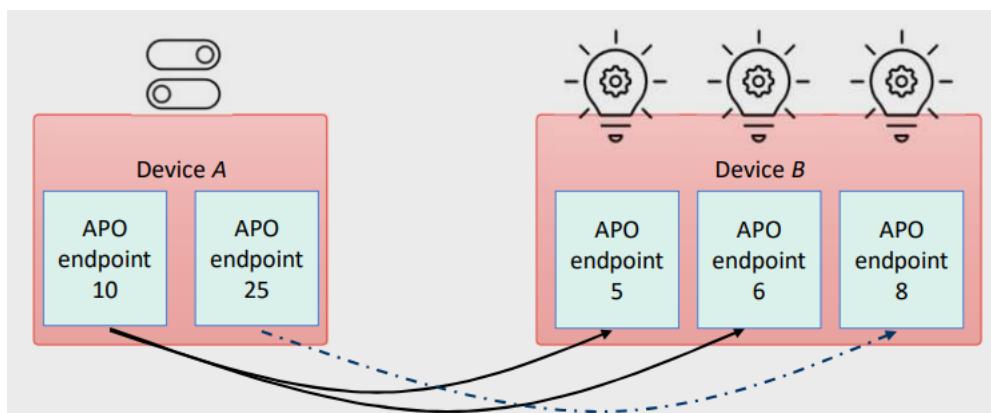


Figure 3.12: APO complex example

| 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 |

Figure 3.13: undefined undefined

| 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 |

example from the Home Automation Profile

Figure 3.14: undefined undefined

ZigBee discovers services in a network based on profile IDs and cluster IDs, but not on device IDs because each device is specified by the combination of Application profile and cluster ID. Here example of device IDs:

The **APS Services** provides data service to both APOs and ZDO: allows to *bind a service to the ZDO* and *group management services* (see later). APS data service enables the exchange of messages between two or more devices within the network: the data is defined in terms of primitives like `request(send)`, `confirm(return status of transmission)`, `indication(receive)`.

The reliability of a data service is ensured by using the **ACKNOWLEDGE** messages for data transmission as the schema 3.15 indicates.

The **APS Group Management** provides service to build and maintains groups of APOs: a group is identified by a 16-bit address and each APO in the group is identified by the pair network *address/endpoint*. The **ADD-GROUP** primitive allows to add an APO to a group and **REMOVE-GROUP** primitive to remove an APO from a group: takes group number and endpoint number; if the group does not exist it's created. The information about groups are stored in a *group table* in APSs.

APS Binding The binding operation allows an endpoint on a node to be connected (*bound*) to one or more endpoints on another nodes: the binding is **unidirectional** and can be configured only by the ZDO of the coordinator or of a router. So the binding provides a way to specify the destination address of the messages: this method is called **Indirect Addressing**. When a Message is routed to

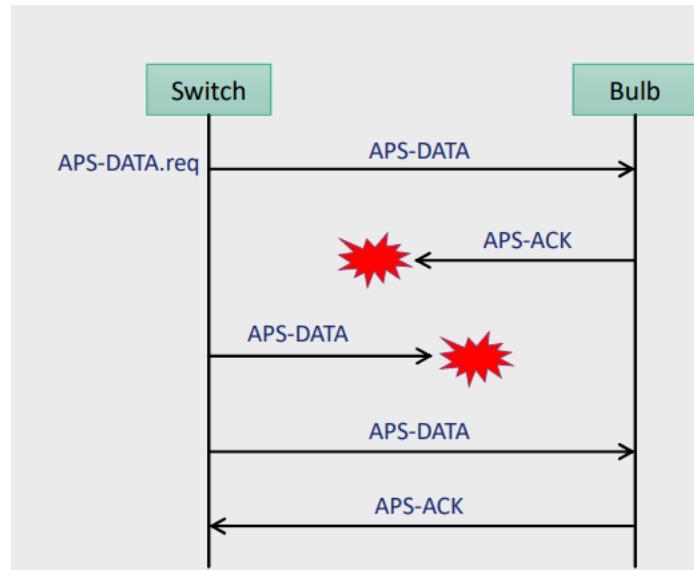


Figure 3.15: undefined undefined

the destination APO based on its pairs <destination endpoint, destination network address> the method is usually called **Direct Addressing**. Direct addressing might be unsuitable for extremely simple devices while *Indirect addressing* exploit the ***Binding table***.

Two main primitives are used for binding, respectively **BIND** and **UNBIND**:

1. **BIND.request** creates a new entry in the local binding table. It takes in input the table <source address, source endpoint, cluster identifier, destination address, destination endpoint>
2. **UNBIND.request** deletes an entry from the local binding table

In the **Indirect addressing**, the binding table matches the *source address* <*network addr, endpoint addr*> and the *cluster identifier* into the pair <destination endpoint, destination network address>. The binding table is stored in the APS of the ZigBee coordinator and/or of the other router: it's updated on explicit request of the ZDO in the routers or in the coordinator. It's usually initialised at the network deployment.

In the scenario of light bulb and a switch, can be complex from the switch side to know to which light bulb connect but, this information is known by the installer. Despite operating directly on the device, the installer can set an entry in the **coordinator's binding table** so that the messages arriving to the switch will be forwarded to the light bulb.

Here an example of **binding table** with a request **APS-DATA.req** of cluster 6 from EP 5 on node 0x3232 that in **indirect routing** will generate 4 data requests:

- Node 0x1234, endpoint 12
- Multicast to group 0x9999
- Node 0x5678, endpoint 44

In the binding table showed in 3.16, the **Src Addr** and the **Dest Addr** are formatted as a MAC address: this choice has been made because the devices can disconnect/re-connect to the network for many reasons, requiring a reconfiguration of the addresses in the binding table. The column **Addr/Grp** allows to tag as destination a group of devices (G). Also, the same devices can be the source of different messages (**Src EP = Endpoint**).

The **APS Address Map** 3.17 allows to associate the 16-bit network address with the 64-bit IEEE MAC address: ZigBee end devices (ZED) may change their 16 bit network address when they leave and join again. In that case, an announcement is sent on the network and every node updates its internal table to preserve the binding.

3. ZigBee Device Object (ZDO) ZDO is a *special application* attached to **endpoint 0**: it implements the basic functionalities expected by the devices. It also implements the end-device or router or coordinator based on the specific configuration given by the **ZigBee Device Profile** that describes the cluster that

must be supported by any ZigBee device, defines how the ZDO implements the services of discovery and binding and how it manages the network and security. So the main ZDO services are:

- Device and service discovery
- Binding management
- Network management
- Node management

Device and service discovery The **ZigBee Device Profile** specifies the device and the *service discovery mechanisms* to obtain any information about devices and services in the network. The **device discovery** allows a device to obtain the (*network or MAC*) address of other devices in the network: starting from an unknown address it allows to identify the relative device inside the network. It follows an **hierarchical implementation** in which a router returns to its parent its address and the address of all the end-devices is associated to itself. Then the coordinator returns the address of its associated devices.

A newly joined device does not know anything about the network: to provide a service it must also know, require and use the services offered by other devices. These actions are performed thanks to **ZigBee Device Profile** that allows the service discovery of other devices. The service discovery sends queries that are based on *cluster ID* or *service descriptors*: the coordinator responds to service discovery queries by returning lists of endpoint addresses matching with the query: the hierarchical implementation is effective because *each router collects information from its associated devices and forwards it to its parents*.

The other mechanism to understand what service a device is providing is called **Device Discovery**: the network is created according to a parent-child relation (with a coordinator), building as a tree (as the addresses tree previously mentioned). To know which service a device offers, a joined device asks to its coordinator that may not have fully all the information and may ask to its parent node, recursively. Each node is responsible for the subtree under its domain: in case of missing information, intermediate routers prepare information reports to answer the queries.

| 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 3.16: undefined undefined

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

Example of APS address map

Figure 3.17: undefined undefined



Figure 3.18: undefined undefined

The **Service Discovery** provides a report that tells for a single device what are the cluster to which it responds: for example, a device can respond telling that it implements a ON/OFF cluster. The service discovery can be direct to the coordinator and is its responsibility to collect information and answer for the whole network. The requests can be directed also to end-device but due to low-power devices, they may not be ready to answer the queries regarding the services they offer. The service discovery does not tell where the device is physically located, only the service offered and their relative identifier (Cluster ID, Device ID, etc): to obtain the location is necessary that a device implements the **Identify Cluster** that forces a device to identify itself by blinking a led.

Binding management The ZDO processes the binding requests received from local or remote EP: both to add entries and delete entries from the APS binding table (*by invoking primitives*). This process requires having an IEEE address.

Managing network and nodes The *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. Differently, the *node management* involves the ZDO to serve incoming requests aimed at performing network discover, retrieving the routing and binding tables of the device and managing **join/leaves** of nodes to the network.

3.0.4 ZigBee Cluster Library (ZCL)

The ZCL is a repository for cluster functionalities: it's a *working library* with regular updates and new functionalities. The developers are expected to use the ZCL to find relevant cluster functionalities to use for their application. The main goal is to avoid re-inventing the wheel, supports **interoperability** and facilitates maintainability: two devices must implement the same application layer to use each other. The ZCL allows to implement the same set of commands and functionalities, standardized by ZCL. Let's consider the example of home automation cluster sketched in 3.18

In a base home automation system we have many applications executing at the same moment: the ZCL allows to specify the behaviours of the involved devices based on a **client-server model**.

A **cluster is a collection of commands and attributes**, which define an interface to a specific functionality. The **device** that stores the attributes, by keeping an internal state, is the **server of the cluster** while the device that manipulates/writes the attributes is the **client of the cluster**. It's not necessary that a server have more computational power than end-devices.

If we think an application that switches the light, it will have an attribute **ON/OFF** and the client will be the switch that turns on/off the light while the server will be the light bulb itself. Clusters are grouped in **functional domains**:

- **General:** allows the access and control of any device, irrespective of their functional domain. Includes general basic functions, implemented by all devices.
- **Closures:** for shade controllers, door locks.
- **HVAC:** for pumps (*like fan, heating, etc*)
- **Lighting:** control lights
- **Measurement and sensing:** illuminance, presence, flow, humidity

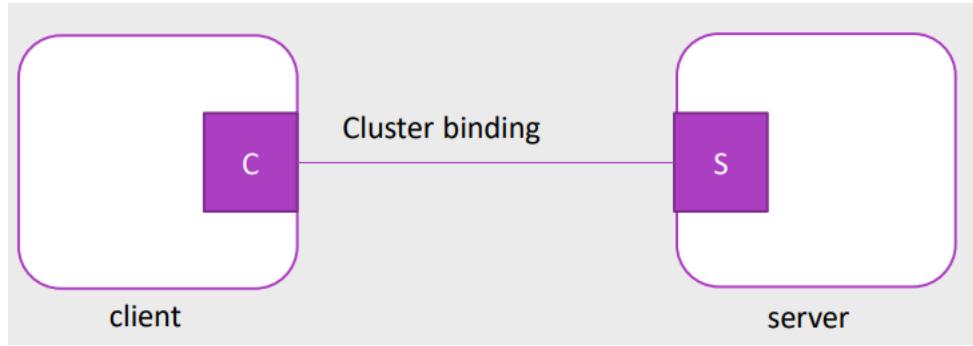


Figure 3.19: undefined undefined

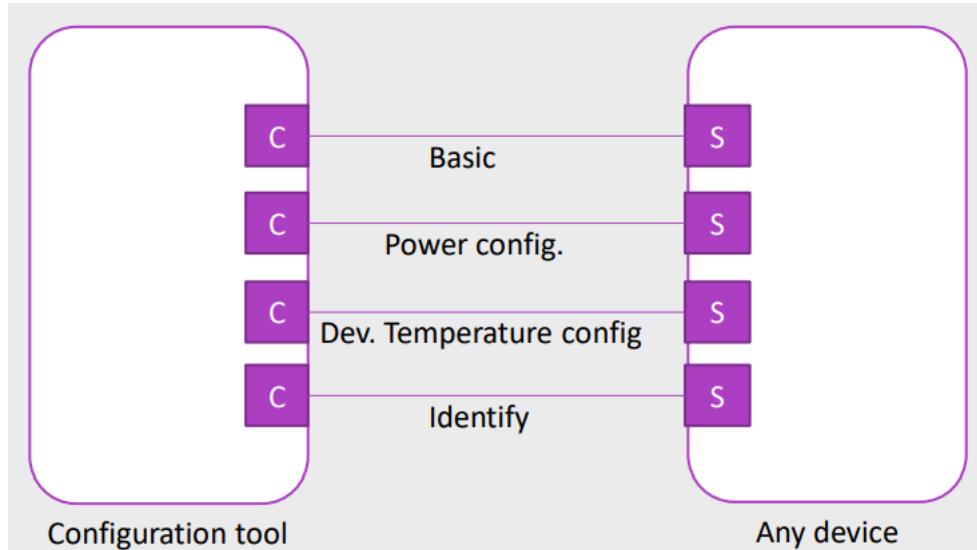


Figure 3.20: undefined undefined

- *Security and Safety*: security zone devices (e.g. *passive infrared*)
- *Protocol interfaces*: interconnect with other protocols. Each functional domain, for each server, defines **commands** and **message structure**. The **commands** are messages (*with their own header and payload*) with a format specified by ZCL: the commands can be read/write attribute or also can be used for dynamic attribute reporting (*useful to periodic reading of the sensors*). The *types of command* are generally tree:
 1. Read/write an attribute
 2. Configure a report and read a reporting response: allows to request periodic attribute/configuration reading. Requests for report whenever an attribute/configuration changes. The client ask the server to report periodically about the state of the server: the server will send periodically a report to the client, without any further request. Also defines parameters of the reporting like *duration*, *period*, *minimum change*, etc.
 3. Discover attributes: to discover the IDs and types of the attributes of the cluster that are supported by the server

The *schemes of use* 3.20 show a typical use of **device configuration and installation cluster**: the configuration phase allows to setting up some parameters by using several clusters. The **Basic** allows to retrieve software version, manufacturer ID, etc. The **PowerConfig** return information about battery and power configuration. The **Temperature Configuration** allows to set threshold, etc. Last, the **Identify** cluster allows to identify physically a device.

Following the schema, usually the installer configure the devices by using specific configuration tools that allows to connect to the devices, apply the specific settings and read their status. As an example, the **Identify** allows to recognize the device by enabling a blinking led.

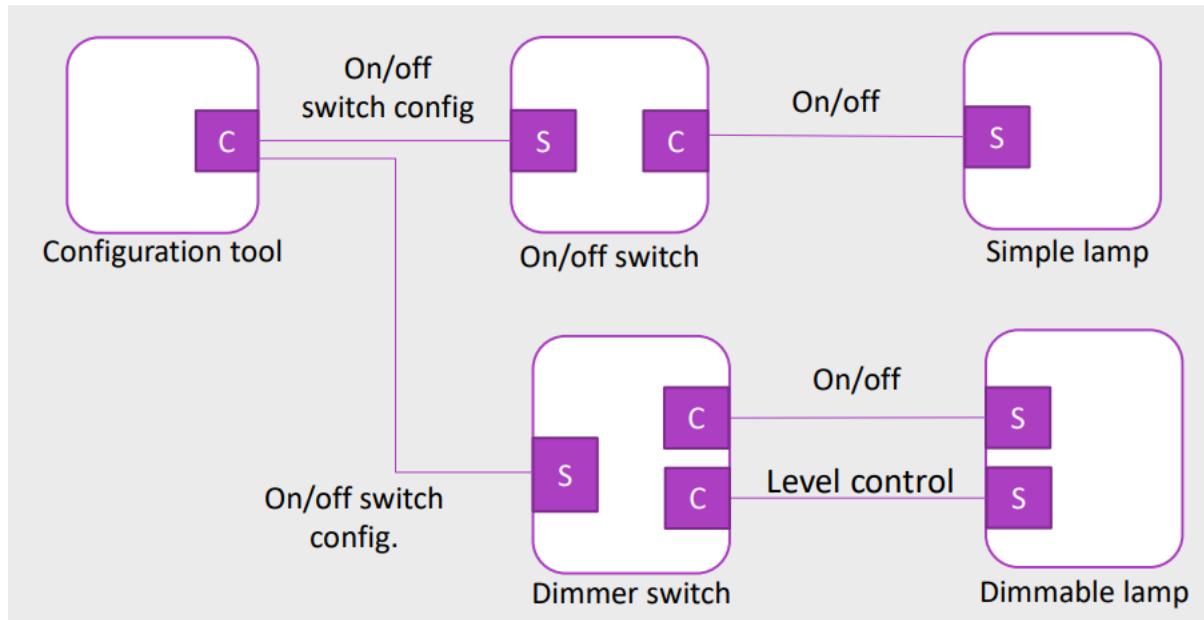


Figure 3.21: undefined undefined

Applied to our ON/OFF previous example, the relative scheme obtained is pictured in 3.21

In this case we want to configure a set of APO, we have one ON/OFF switch which is connected with a "Simple Lamp", we have to create the association between the lamp and the switch, in the same way we must also create the association between the "dimmer switch" and the "dimmable lamp".

This association is created by the **Configuration Tool**, working as a client sets the configuration of the On/Off switch device in such a way that when it wants to turn the lamp on or off it will find the corresponding device and make the request for turning on or off. The same goes for configuring the Dimmer Switch. The configuration tool must also configure the simple lamp. The configuration allows to setup the **binding table** to the **coordinator** by knowing the addresses of the devices and relative APO. This can be done by invoking device and service discovery, alongside physical discovery.

Typically what happens is that the installer has a tablet and it connects to the Zigbee Network, using an application you can access information about the network. When I run this configuration each device knows what it is and what it can do, a lamp for example knows it is a lamp but it is necessary to carry out a **commissioning procedure** so that the lamp is connected to an on/off switch which allows the ignition. It's necessary to execute the procedure of *commissioning* to simplify the deployment of complex smart system, like in a scenario with hundreds of devices to be deployed and configured.

Each devices has many of information assigned to it, contained in the **BASIC** cluster, like the ones listed in 3.22.

The **ZCLVersion** is mandatory to be sure that the ZCL is the right one implemented at application level, specially due to continue updating. Also the **PowerSource** is mandatory because provide information about power sources. Usually the attributes in **BASIC** cluster are in *read-only* access.

Among those information, highly relevant are the **PowerSource**, an 8-bit number that can have the values listed in 3.23.

The value in the last table indicates the **type of battery**, if there is an emergency power supply, etc. Those devices have also the attribute called **temperature measurement cluster** that allows to know the temperature *inside* the device itself. The attribute to know this temperature are specified by **Temperature** cluster as listed in 3.24.

The cluster specified uses only generic commands to *read attributes*, *discover attributes*, *configure and report*. There are no specific commands to program a simple devices as a temperature measurement. For complex devices that also implement part of the **Temperature** cluster there is usually an accessory appendix that specify other commands.

ZCL is designed to enforce a hierarchical approach 3.25 to device functionality by supporting backward compatibility and interoperability: instead of design every possible ZCL cluster for specific *lamp*, it's incremental and allows compatibility by also let the possibility to create custom features not standardized by ZigBee.

| Identifier | Name | Type | Range | Access | Default | Mandatory / Optional |
|-------------------|---------------------------|------------------------|--------------|---------------|----------------|-----------------------------|
| 0x0000 | <i>ZCLVersion</i> | Unsigned 8-bit integer | 0x00 – 0xff | Read only | 0x01 | M |
| 0x0001 | <i>ApplicationVersion</i> | Unsigned 8-bit integer | 0x00 – 0xff | Read only | 0x00 | O |
| 0x0002 | <i>StackVersion</i> | Unsigned 8-bit integer | 0x00 – 0xff | Read only | 0x00 | O |
| 0x0003 | <i>HWVersion</i> | Unsigned 8-bit integer | 0x00 – 0xff | Read only | 0x00 | O |
| 0x0004 | <i>ManufacturerName</i> | Character string | 0 – 32 bytes | Read only | Empty string | O |
| 0x0005 | <i>ModelIdentifier</i> | Character string | 0 – 32 bytes | Read only | Empty string | O |
| 0x0006 | <i>DateCode</i> | Character string | 0 – 16 bytes | Read only | Empty string | O |
| 0x0007 | <i>PowerSource</i> | 8-bit enumeration | 0x00 – 0xff | Read only | 0x00 | M |

Figure 3.22: undefined undefined

3.0.5 ZigBee Security Specification

Security services provided for ZigBee include methods for:

1. key establishment: create the keys without prior information
2. key transport: exchange keys previously setted/stored at configuration
3. frame protection: by using encryption
4. device management Security services are optional and have an overhead, minimum for low power devices, These services form the building blocks for implementing security policies within a ZigBee device. The underlying assumptions are that **level of security** depends on:
 - the safekeeping of the symmetric keys: by avoiding stolen information about keys, also physically
 - the protection mechanisms employed,
 - the proper implementation of the cryptographic mechanisms and associated security policies involved. **Trust** in the security architecture comes from:
 - trust in the **secure initialization** and installation of keying material and
 - trust in the **secure processing and storage** of keying material.

Further assumptions are:

- **correct implementation of all security protocols:** the implementation must follow the standard, according to ZigBee standard and deployment operations
- correct random number generators
- secret keys do not become available outside the device in an unsecured way. The only exception to this is when a device joins the network.

Due to the *low-cost nature of ZigBee devices* we **cannot generally assume the availability of tamper resistant hardware**: it's possible to some extent but it's not provided by the ZigBee standard (*can be possible by anti tamper hardware to a given point*). The level of protection is both at network level of physical level. Hence, physical access to a device may yield access to secret keying material and other privileged information, as well as access to the security software and hardware. Also, **different APO in the same device are not logically separated and lower layers are entirely accessible to the application layer**. Hence different APO in the same device must trust each other.

| Attribute Value | Description |
|-----------------|-------------------------------------|
| 0x00 | Unknown |
| 0x01 | Mains (single phase) |
| 0x02 | Mains (3 phase) |
| 0x03 | Battery |
| 0x04 | DC source |
| 0x05 | Emergency mains constantly powered |
| 0x06 | Emergency mains and transfer switch |
| 0x07 – 0x7f | Reserved |

Figure 3.23: undefined undefined

| Identifier | Name | Type | Range | Access | Default | Mandatory / Optional |
|------------|-------------------------|-------------------------|--|-----------|---------|----------------------|
| 0x0000 | <i>MeasuredValue</i> | Signed 16-bit integer | <i>MinMeasuredValue</i> to <i>MaxMeasuredValue</i> | Read only | 0 | M |
| 0x0001 | <i>MinMeasuredValue</i> | Signed 16-bit integer | 0x954d – 0x7ffe | Read only | - | M |
| 0x0002 | <i>MaxMeasuredValue</i> | Signed 16-bit integer | 0x954e – 0x7ff | Read only | - | M |
| 0x0003 | <i>Tolerance</i> | Unsigned 16-bit integer | 0x0000 – 0x0800 | Read only | - | O |

Figure 3.24: undefined undefined

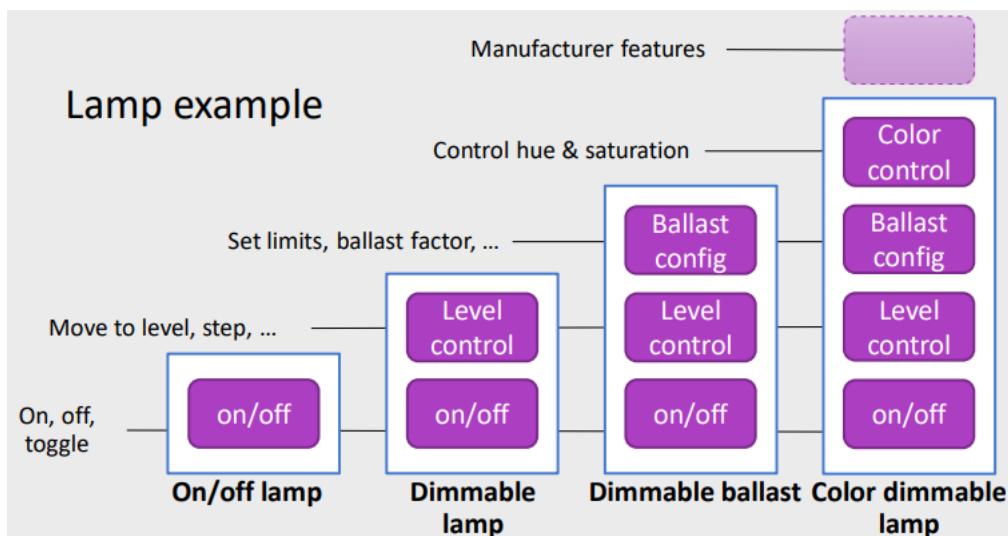


Figure 3.25: undefined undefined

Security Design Choices The security is granted by the **Trust Center** that it's a module in the *Application Layer*, typically allocated in the *ZDO* that distribute the security keys to the devices inside the same network. Two main keys are provided, at different level:

- **Single key per network** (*network level security*)
- **Single key per link** (*device-to-device level security*) The process flows: the devices inside the network uses a **Master key** to connect to the **Trust center**: this master key can be pre-assigned to the device (*write in ROM/Firmware*) or can be injected later in the device. The master key allows to establish a connection to request the **Network keys** or **Link keys**. Those three key allows ZigBee to provide a level of encryption corresponding to *AES – 128* that it's enough for low power devices. The keys are provided by the *APS*. The low power and computing constraints of the devices implies that the encryption is **symmetric** and the decryption is made by the keys provided by the *application layer*. It aims to the protection of individual devices but not individual applications in the same device: this allows the re-use of the same keying material among the different layers of the same device.

The layer that originates a frame is responsible for initially securing it: if a network command need protection this must be ensured at network level security. If protection from *theft of service* is required, network layer security must be used for all frames (*except the one when new device joins*). The reuse of key materials among different layers in a device and link-keys allows to have additional security from source to destination: an application can extends the security by adding other mechanism but it's entirely upon itself.

An *application profiles* should include policies to:

- Handle error conditions arising from securing and unsecuring packets: error conditions may indicate loss of synchronization of security material or may indicate ongoing attacks.
- Detect and handle loss of counter synchronization and counter overflow.
- Detect and handle loss of key synchronization.
- Expire and periodically update keys, if desired.

The keys The keys can be obtained by means of:

- Key transport: a mechanism for communicating a key from one device to another device or other device. It's a sensible phase because at that time the communication is unencrypted: can be encrypted but with more overhead, depending the scenario context.
- Key establishment: a mechanism that involves the execution of a
- Pre-installation: at manufacturing time, install the key into the device or during the deploying phase

The **Network key** are *128-bit* shared by all devices: they are acquired either by key-transport or pre-installation and generally are of two types (**standard vs high security**). The **Link keys** are 128 bit, shared by all devices: they are acquired by key-transport, key-establishment or pre-installation. The key establishment is based on pre-existing master key. Two types are considered (**Global vs Unique**). The **Master key** is a 128 bit key acquired either by key transport or pre-installation. Other keys are used to implement the secure transport of key material: they are derived from the link key with one-way functions.

The **Key Establishment** it's stated by the specification: it describe a variation of Diffie-Hellmann and it's called **SKKE (Symmetric-Key Key Establishment)**. Usually the key establishment involves two entities, an initiator device and a responder device. It evolves as following:

1. *trust provisioning based on trust information (typically the master key)*: the master key can be either pre-installed during manufacturing or it may be installed by a Trust Center (*for example, from the initiator, the responder, or a third-party device acting as a Trust Center*), or it may be based on user-entered data (*for example: PIN, password, or key*)
2. exchange of ephemeral data (a random number)
3. the use of this ephemeral data to derive the link key.

4. confirmation that the link key was computed correctly

The **Trust Center** is the device trusted by devices within a network: it's a functionality implemented in the coordinator or a specified device. In a simple network can be the coordinator and it's usually used to obtain new **network/link key** by connecting to it and requesting new keys. All members of the network shall recognize exactly one Trust Center and there shall be only one in each secure network to provide a trust agreement between all the device in the same network.

The device that joins the network:

- obtain the keys from the trust center according to different protocols, depending on which keys they already have (or no key)
- in low-security applications the Trust Center give it the master key by using unsecured transport
- If the device already has the master key, it can establish a secure communication link with the Trust Center to transport the keys.

Chapter 4

IoT Design Aspects

IoT are special custom devices that need to manage the energy efficiency differently from standard market device. The devices are characterized by:

- Low power
- Low cost
- Small
- Total autonomous

Each device is a full micro-system that embeds:

- Processor
- Memory
- Radio transceiver
- Battery powered or energy harvesting methods: depending on the specific scenario, both allows to avoid wired powered devices.

The energy efficiency based on battery-powered implies that the working life is limited in time: this implies the need to intervene on the field to change the battery. This operation can be costly, respect to the device cost itself. Some other issues are *adaptability to changing conditions* that arises for dynamic network management and programming, adapting its behavior as the environment change. This implies the necessity of dynamic programming to also preserve the interoperability. Another problem is that the devices comes in term of very low complexity and overhead, with reduced complexity of complexity execution and constraints on computation resources. Another issues concerns *multi-hop communication*: standard routing protocols like Distance Vector or similar relies on address table but due to constrained capacity both in term of storage and computational resources, those model does not scale in IoT context multi-hop network.

This also introduce the problem of the *mobility* that need for dynamic routing protocols to scale efficiently, provided the underlying infrastructure.

Moore's Law

"*The number of transistor that can be embedded in a chip grows exponentially (it doubles every two year)*". As a comparison example:

- Intel 4004 in 1971: 2.3k transistors, 740 KHz and 4KB program memory
- Intel core i9 in 2017: 1.8G transistors, 4.4.GHz, 165W and 128 GB

The application of Moore's law to IoT is peculiar and subject to different interpretation,

1. The *performance doubles every two years* at the same cost
2. The *chip's size halves every two year* at the same cost
3. The size and the processing power remain the same but the cost halves every two year.

In IoT all those interpretation are true, based on the specifics scenario: there are application that require small sized sensors and or that have low power consumption, can require higher processing capabilities. There is the need to balance the computational power to the costs, based on the specific application.

The Moore's law does not necessarily solve the problem in IoT design, at least in the near future.

4.0.1 Energy efficiency

It represent one of the critical aspects because devices are usually battery-powered, avoid wired powered devices and avoid maintenance cost. The energy efficiency is one of the main aspects in IoT design. The following diagram shows how the evolution of *processor, HD capacity and memory* grows faster than battery efficiency as pictured in 4.1

The improvements of the battery efficiency is not bound to the Moore's Law: this is also due to the physic limit. The consequences are that in we want to improve the battery efficiency, we need to improve the design aspects of an IoT system, improving the design of the components that heavily rely on battery.

In a laptop, most of the energy is spent on a screen, as shown in 4.2 image.

In a wireless sensor, the energy usage follows a different pattern than in laptop as pictured in 4.3: 20% of battery is used for sensing activities, the 40% is used for wireless and network interfaces activities and the remaining part, about 40%, is used by the processor and the chipset.

The percentage areas can vary based on the specific sensors. There is a trade-off between sensing and transmission: "*a general rule state that transmit 1 byte is equal to compute 1k byte*". Usually the sensing activation frequency it's mandatory based on a given context: reducing it have a direct impact on the quality of sensing data. The optimizable component is surely the processor area but, differently, the sensing area cannot be optimized muchly because it both transmit and receive: the optimizable part is the one that concern the communication timeframe and behavior. A radio for **WiFi Network Interface** can be in three modes, each with different energy consumption:

1. **Sleep Mode:** consume very less and can get the radio operative in short time. The energy consumption is around 10mA.
2. **Listen Mode:** 180mA
3. **Receive Mode:** 200mA
4. **Transmit Mode:** 280 mA

For a sensor (*specifically the moto-clone*) the energy consumption is:

1. Sleep Mode: 0.016mW
2. Listen Mode: 12.35 mW
3. Receive Mode: 12.50mW
4. Transmit Mode: 0.1 power level, 19.2kbps: 12.36 mW
 1. 0.4 power level, 19.2kbps: 15.54 mW
 2. 0.7 power level, 19.2kbps: 17.76 mW

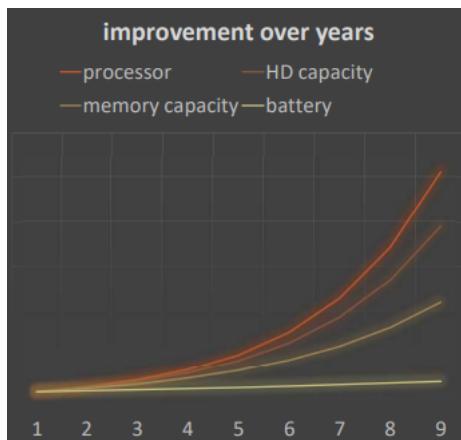


Figure 4.1: undefined undefined

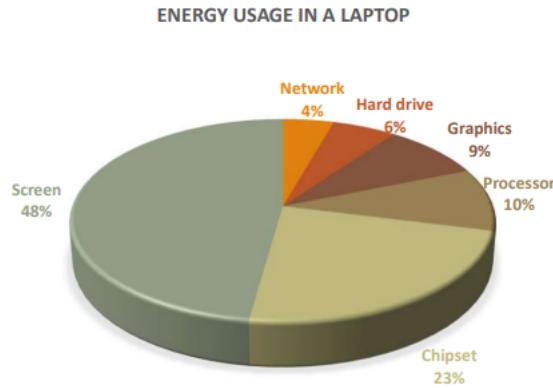


Figure 4.2: undefined undefined

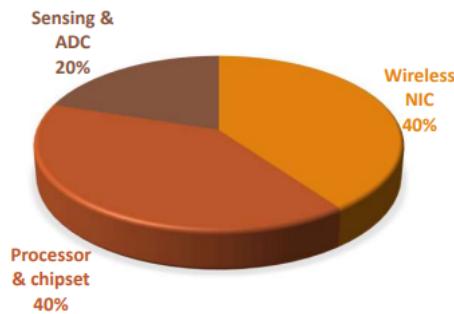


Figure 4.3: undefined undefined

The power level can change based on the distance that are needed to communicate, amplifying the signal. In case of receive mode, it's also necessary to activate a decoder (from a given analogical signal) that require more energy. Those numbers show how it's not useful to put the sleep mode only, but remaining in a listen mode, letting the device communicate. This had an impact on the MAC protocols for IoT which differs from the standard definition. So for sensors, as a rule of thumb, the approach is:

- transmit power is less than receive power
- listen power is more or less equal to receive power
- radio should be turned off as much as possible Switching on and off a component require energy: the decision to switch the status must not be reversed in a short timeframe.

The IoT device are not a general purpose device so it's not needed to be active all the time, providing the service: the key idea is to saving energy by **reducing the period of activity of a sensor**. This is called **duty cycle** and define the repetitivity of the activities of a sensors:

1. Sense: it's more efficient if it's repeated periodically and it's in a constant timeframe
2. Process and store
3. Transmit and receive A sensor alternates a period of activity and a period of inactivity (*defining a duty cycle*): during the inactivity the energy consumption is very low but the process, radio and I/O need to be freezed.

In general, the **duty cycle** of a system is defined as the fraction of one period in which the system is active. The radio activities can represent an exception to this, based on the specific activity that need to be carried out even during an inactivity period. The duty cycle is commonly expressed as a ratio or as a percentage. An example taken form Arduino is the pictured in 4.4: the `delay` instruction does not power off any component. The period of activity of this duty cycle is 400 ms, but the duty cycle itself does not guarantee to save energy consumption.

Instead, consider the following code in which we turn off the components:

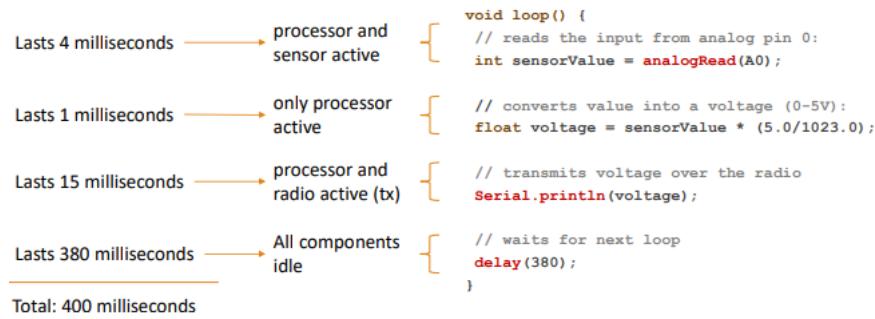


Figure 4.4: undefined undefined

```

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);
}

```

The `turnOn/turnOff` turn on/off a given components and the `idle` instruction puts the processor in idle state with low power consumption for y ms. The `idle` instruction allows to do not power-off the processor but to obtain a duty cycle that by firing a call when the y ms are passed, the processor can return operative. The above code defines 3 different duty cycles, one for each component as is sketched in 4.5.

The duty cycles allows to define or compute the current absorbed by each component based on the general state of each component: the table in 4.6 define the specific value for each state of the considered component. As an example, the processor have two state (*full operation, sleep*) that consume different amount of current (*respectively 8 mA and 15 μ A*).

The battery gives a given amount of power but part of the energy is lost even without plugging it: it estimates to 3% per year on the total provided energy. This also have an impact on the charge of the

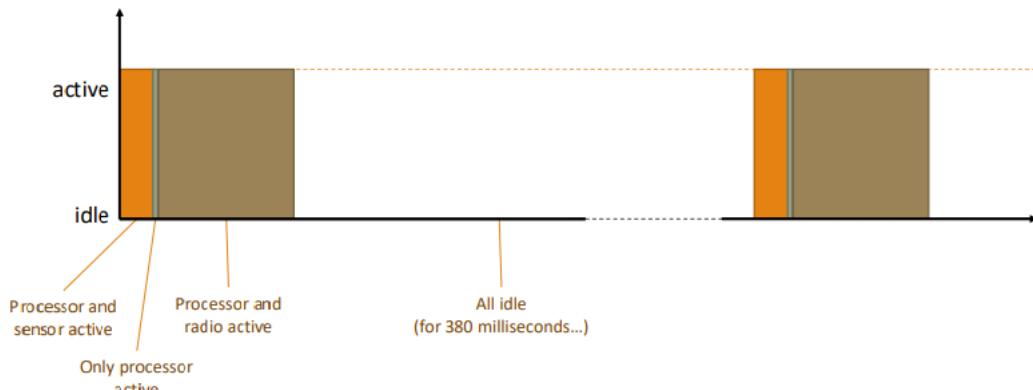


Figure 4.5: undefined undefined

| | Value | units |
|---|-------|---------|
| Micro Processor (Atmega128L) | | |
| current (full operation) | 8 | mA |
| current sleep | 15 | μ A |
| Radio | | |
| current in receive | 19,7 | mA |
| current xmit | 17,4 | mA |
| current sleep | 20 | μ A |
| Logger (storage in the flash memory) | | |
| write | 15 | mA |
| read | 4 | mA |
| sleep | 2 | μ A |
| Sensor Board | | |
| current (full operation) | 5 | mA |
| current sleep | 5 | μ A |
| Battery Specifications | | |
| Capacity Loss/Yr | 3 | % |

Figure 4.6: undefined undefined

battery that decrease overtime.

Example 2 The first model have a 100% DC so it's always fully active while the model 2 have a 5% DC as listed in 4.7, or, in a different visualization as pictured in 4.8

| | model 1: 100%DC | model 2: 5%DC | units |
|--------------------------|--------------------|------------------|-------|
| Micro Processor | | | |
| current (full operation) | 100 | 5 | % |
| current sleep | 0 | 95 | % |
| Radio | | | |
| current in receive | 50 | 4 | % |
| current xmit | 50 | 1 | % |
| current sleep | 0 | 95 | % |
| Logger | | | |
| write | 1 | 1 | % |
| read | 2 | 2 | % |
| sleep | 97 | 97 | % |
| Sensor Board | | | |
| current (full operation) | 100 | 1 | % |
| current sleep | 0 | 99 | % |

Figure 4.7: undefined undefined

The sum of two different activity period form a duty cycle: in the figure 4.8 there is only indicated a single period.

4.0.2 Measuring energy

Energy and power are measured in Joule J and Watt W , respectively $1J = 1W * sec$. In electromagnetism, $1W$ is the work performed when a current of $1A$ (Ampere) flows through an electrical potential difference of $1V$ volt, so: $1W = 1V * 1A$ Since we use direct current and the electrical potential difference is almost

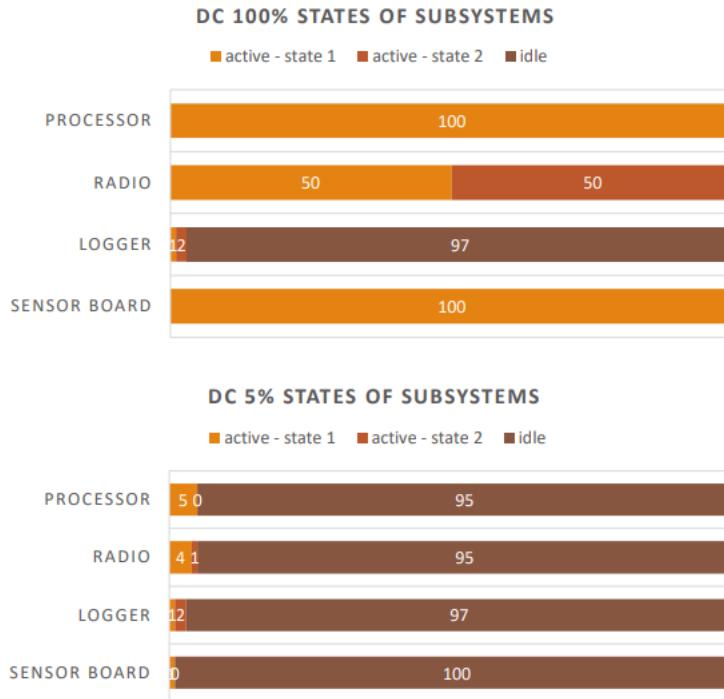


Figure 4.8: undefined undefined

constant, the power and the energy only depend on the current (*Ampere*). Hence we can express both the energy stored in a battery and the energy consumed in *mA h* (*milli-Ampere per hour*).

4.0.3 Example on computing consumption per duty cycle

Consider two different models in which, for each component, the Duty Cycle (*DC*) follows the percentage presented in 4.9:

Note that the first model have a Duty Cycle of 100% so it's an always up system while the second model present a Duty Cycle of 5%.

To compute the energy total cost we must first compute the energy cost of each component, considering its duty cycle period.

The **energy cost of a microprocessor** E_μ *per cycle* can be expressed as:

$$E_\mu = C_\mu^{full} * dc_\mu + C_\mu^{idle} * (1 - dc_\mu)$$

where:

- C_μ^{full} full energy cost microprocessor
- C_μ^{idle} idle energy cost microprocessor
- dc_μ

The C_μ^{idle} cannot be dropped because it's multiplied with a factor that is not neglectable $(1 - dc_\mu)$. The **energy cost radio** E_ρ *per cycle* can be expressed as:

$$E_\rho = C_\rho^T * dc_\rho^T + C_\rho^R * dc_\rho^R + C_\rho^{idle} * (1 - dc_\rho^T - dc_\rho^R)$$

where:

- C_ρ^T radio transmission energy cost
- C_ρ^R radio receival energy cost
- C_ρ^{idle} idle energy cost
- dc_ρ^T percentage transmit duty cycle radio

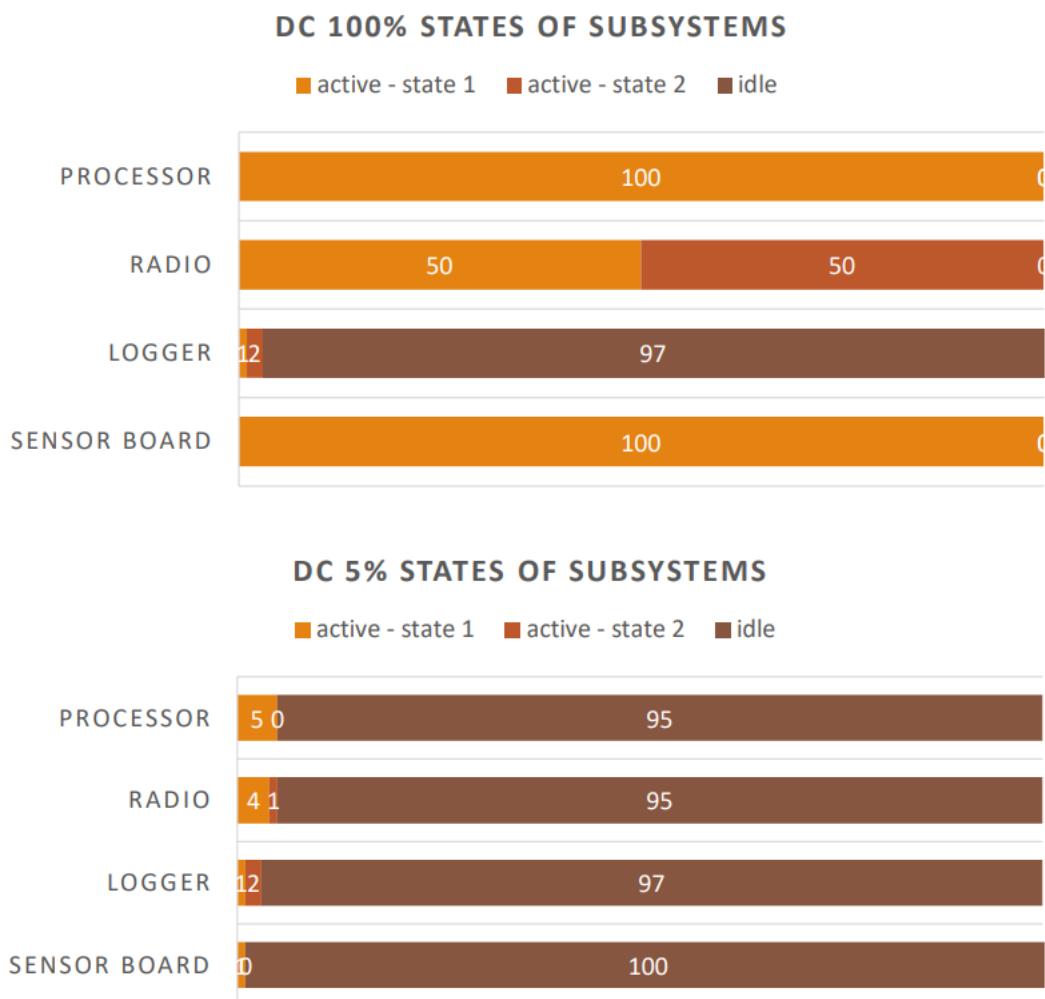


Figure 4.9: undefined undefined

- dc_ρ^R percentage receive duty cycle radio

The **energy cost logger** E_λ and **sensor board** E_σ can be calculated as before, obtaining the **total energy cost per duty cycle** of: $E = E_\mu + E_\rho + E_\lambda + E_\sigma$. The **lifetime**, expressed in number of duty cycles, is:

$$\text{Lifetime} = \frac{B_0 - L}{E}$$

where B_0 is the initial battery charge and L is the battery charge lost during the lifetime due to **battery leaks** and E is the total cost of energy. Because L depends on lifetime and it's based on charge/loss cycle ϵ (*estimated to 3% yearly*), we can obtain a recurrence equation: $B_n = B_{n-1} * (1-\epsilon) - E$ where B_n is the battery charge at cycle n . By solving the recurrence equation we obtain that:

$$B_n = B_0 * (1 - \epsilon)^{n-1} + \frac{E((1-\epsilon)^n) - 1}{\epsilon}$$

The device lifetime is given by n , when $B_n = 0$.

Regarding the two models already cited, we can plot both the battery life (*expressed in months*) and the battery capacity (*expressed in milli-Ampere per hour*) as pictured in 4.10.

The previous graph (4.10) show how the second model that have 5% of DC have a longer battery life than the first-one, thanks to longer duration of idle state of its components. The graph, which in expressed in logarithmic scale, show how enlarging the battery capacity the correspondent battery life for the first model is limited to a couple of days while for the second model the battery life can last up to some months.

The second graph (4.11) show that given two devices, increase the DC corresponds to a decrease of the lifetime battery. To obtain an efficient device, it's necessary to work on the DC to minimize it and obtain a longer battery life.

To gain *energy efficiency* the solution is to reduce the *Duty Cycles (DC)*, however **turning off the processor is a local decision** so the node scheduler knows that are the activires and when the processor should run. Also, turning off the radio is a **global decision** that implies no communication, no reception of incoming messages/commands and the impossibility to act as a router in multihop network.

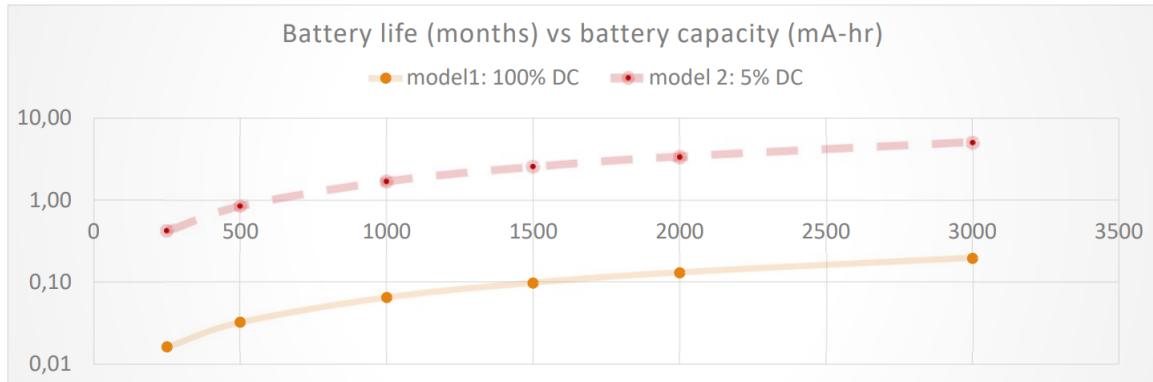


Figure 4.10: undefined undefined

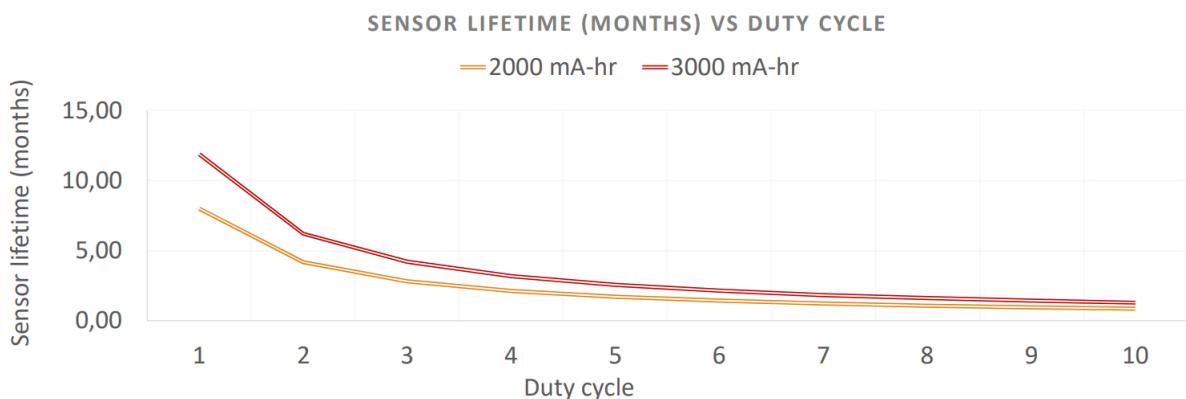


Figure 4.11: undefined undefined

At **MAC Layer**, MAC Protocols arbitrate the access to the shared communication channel: in IoT also implements strategies for energy efficiency like **synchronize the devices** and **turn off the radio when it's not needed** (*so excluding the device from the network*).

4.0.4 Exercise

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

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

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

    turnOn(radioInterface);
    15 milliseconds 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 | 1 | mA |
| current sleep | 20 | µA |
| Sensor Board | | |
| current (full operation) | 5 | mA |
| current sleep | 5 | µA |
| Battery Specifications | | |
| Capacity | 2000 | mAh |

Figure 4.12: undefined undefined

energy consumption per hour:

- The processor has a duty cycle of _____
- The radio has a duty cycle of _____
- The sensor has a duty cycle of _____

Energy consumption in one hour: _____

Lifetime of the device: _____

| | idle | Active |
|------------------|------|--------|
| Processor | | |
| Radio | | |
| Sensor | | |
| Total: | | |

| | value | units |
|-------------------------------------|-------|-------|
| Micro Processor (Atmega128L) | | |
| current (full operation) | 8 | mA |
| current sleep | 15 | µA |
| Radio | | |
| current xmit | 1 | mA |
| current sleep | 20 | µA |
| Sensor Board | | |
| current (full operation) | 5 | mA |
| current sleep | 5 | µA |
| Battery Specifications | | |
| Capacity | 2000 | mAh |

Figure 4.13: undefined undefined

Answer

1. Compute the energy consumption of the device per single hour #todo
2. Compute the expected lifetime of the device #todo

Exercise 2

Consider the sensor specification in the table pictured in 4.14

The device measures the heart-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)

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

Figure 4.14: Exercise 2 - Parameters specification

- 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.

Solution 2

Duty cycle of sampling: DC of processor + sensors: $0.5 \text{ milliseconds (sampling time)} / 0.05 \text{ seconds} = (\text{sampling period}) = 0.01$

Duty cycle of transmitting: DC of radio + processor: $2 \text{ milliseconds (transmit time)} / 0.25 \text{ seconds (transmission period)} = 0.008$

- Sensor power consumption: $E_\mu = 5 \text{ mA} * 0.01 + 5 \text{ uA} * 0.99 = 0.05 + 0.005 \text{ mAh} = 0.055 \text{ mAh}$
- Processor power consumption: $E_\rho = 0.018 * 8 \text{ mA} + 0.982 * 15 \text{ uA} = 0.144 + 0.0147 \text{ mAh} = 0.1587 \text{ mAh}$
- Radio power consumption: $E_\lambda = 0.008 * 20 \text{ mA} + 0.99992 * 20 \text{ uA} = 0.16 \text{ mA} + 0.0198 \text{ mA} = 0.1799 \text{ mA}$

$$E = E_\mu + E_\rho + E_\lambda$$

Battery specification (in table) $B_0 = 2000 \text{ mAh}$
 Power consumption: $2000 \text{ mAh} / 0.3935 \text{ mAh} (\frac{B_0}{E})$
 obtaining **Lifetime:** 5082 h

Exercise 3

Consider the sensor specification in the table pictured in 4.15.

The device measures the heart-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

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

Figure 4.15: Exercise 3 - Parameters specification

- 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.

Solution 3

- Duty cycle of sampling: $0,5ms$ (sampling time) / $0,05s$ (sampling period)= $0,01$
- Duty cycle of processing: 5 milliseconds / 2 seconds = $0,0025$
- Duty cycle of transmitting: 2 milliseconds (transmit time) / 10 seconds (transmission period) = $0,0002$
- Power consumption of sensor (in 1h):
 - $E_\mu = 5mAh * 0,01 + 5uAh * 0,99 = 0,05 + 0,005mAh = 0,055mAh$
- Power consumption of processor (1h):
 - $E_p = 8mAh * 0,0127 + 15uAh * 0,9873 = 0,1016 + 0,0148mAh = 0,1164mAh$
- Power consumption of radio (1h):
 - $E_\theta = 0,0002 * 20mAh + 0,9998 * 20uAh = 0,004 + 0,02mAh = 0,024mAh$

$$E = E_\mu + E_p + E_\theta = 0,1954mAh$$

Battery specification (in table) $B_0 = 2000mAh$
 Power consumption: $2000mAh/0,1954mAh (\frac{B_0}{E})$
 Lifetime: $2000mAh/0,1954mAh = 10.235h$

4.0.5 Exercise 4

Consider a Mote-class sensor with the parameters pictured in table 4.16.

Assume that the device performs a sensing task with the following parameters:

- The sensor board is activated with a rate of $0,1\text{ Hz}$ to perform the sampling; this operation takes $0,5\text{ milliseconds}$. At the end the sensor board is put in sleep mode. During each sensing operation the processor is always active.

| | value | units |
|-------------------------------------|-------|-------|
| Micro Processor (Atmega128L) | | |
| current (full operation) | 8 | mA |
| current sleep | 0,015 | mA |
| Radio | | |
| current xmit | 1 | mA |
| current sleep | 0,02 | mA |
| Sensor Board | | |
| current (full operation) | 5 | mA |
| current sleep | 0,005 | mA |
| Battery Specifications | | |
| Capacity | 2000 | mAh |

Figure 4.16: Exercise 4 - Parameters specification

- After each sampling the processor performs a computation that takes 2 milliseconds.
- Then the processor activates the radio and transmits the data. The transmission takes 1 millisecond and, during it, the processor is active. At the end the radio and the processor are both set in sleep mode. Compute the duty cycle of each component (*sensor board, radio and processor*), and the lifetime of the device (*assuming that the sensor stops working when its battery charge becomes 0*).

Solution 4

- Sampling takes $0.5ms$ with a rate of $0,1Hz$
 - Processing: $2ms$
 - Transmitting: $1 ms$
 - **Duty cycle of sampling (processor and sensors):** $0.5ms/10s = 0,00005$
 - **Duty cycle of processing (only processor):** $2ms/10s (10000ms) = 0.0002$
 - **Duty cycle of transmissions (radio&processor):** $1ms/10s = 0.0001$
 - Power consumption of sensor (in 1h):
 - $E_\mu = 5mA * 0,00005 + 0,005mA * (1 - 0,00005) = 2.5 * 10^{-4}mA + 0.05mA = 0.00525mA$
 - Power consumption of processor (1h):
 - $E_\rho = 8mA * 0.00035 + 0,015mA * (1 - 0.00035) = 0.0028mA + 0,015mA = 0,0178mA$
 - Power consumption of radio (1h):
 - $E_\theta = 0,0001 * 1mA + (1 - 0,0001) * 0,02mA = 100nA + 20\mu A = 0.0201mA$
 - $E = E_\mu + E_\rho + E_\theta = 0.04315mA$
 - Battery specification (*in table*) $B_0 = 2000mAh$
 - Power consumption: $2000mAh / 0.04315mA (\frac{B_0}{E})$
- Lifetime:** $2000mAh / 0,04315mA = 46.349h$

Chapter 5

Case Study: Biologging

The direct observation is an effective way to obtain information about humans and animals activities. The data collection can be performed by using sensors (*e.g. accelerometers, GPS, pressure etc*) so the observation can be continuous and almost in all the aspect of its life.

The direct observation with sensors are actuated based on miniaturized devices attached on free-range animals:

- **Botelemetry:** collected data/signals that are immediately sent to a remote station by means of wireless interface (storage)
- **Bio-logging:** collected data/signals are stored in an internal memory. Researcher need to physically retrieve the device access to data. The **activity recognition** aims at automatically recognizing the actions of an animal from the signal collected during its activity.

5.0.1 Device perspective

It uses a low power logger that produces a huge amount of time-series data. Two alterantive can be followed (*as sketched in 5.1*):

1. **Communicate** the time-series data to a remote station
2. **Retrieve** the logger to download the time-serie data. The memory need to be downloaded when full.

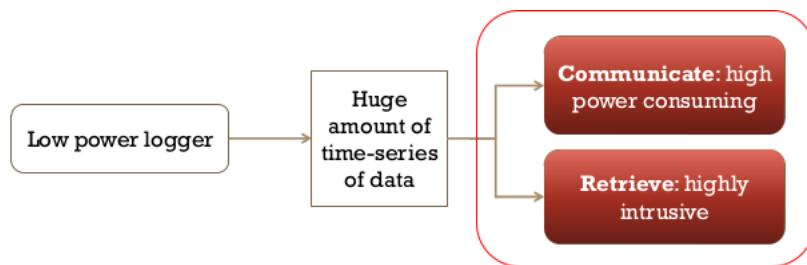


Figure 5.1: First approach

The problem of both approach are the higher energy consumption and *retrieve the stored data* that is an is highly intrusive activity.

A novel approach embed the **AI autoamtic classifier on-board** by using a low power microprocessor. It stores only the result of the classification so being memory efficient and transmit only the results of the classificaton, efficiently affect the communication (*as sketched in 5.2*).

5.0.2 Tortoises case study

Based on paper "Barbuti R., Chessa S., Micheli A., and Pucci R.; "Localizing tortoise nests by neural networks"; PloS One 2016." Protection programs of tortoises aim at retrieving the eggs and bringing them at a protection center, where hatchlings are protected during their most vulnerable period. The identification of **tortoise nests** in wild is usually very challenging, as tortoises are extremely good in

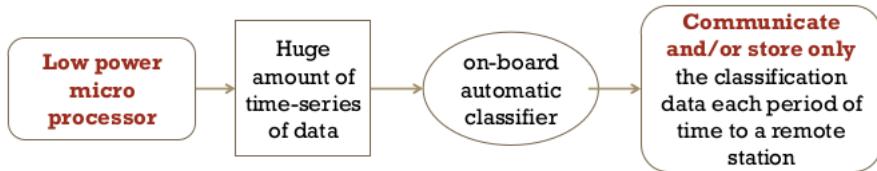


Figure 5.2: Classifier model approach

hiding them. The projects designed a system which automate the identification of the *digging activity* of *female tortoises* in real time and communicates the GPS location to a remote station and retrieve the eggs that need to be carried to a protected location (*the entire process is sketched in 5.3*).

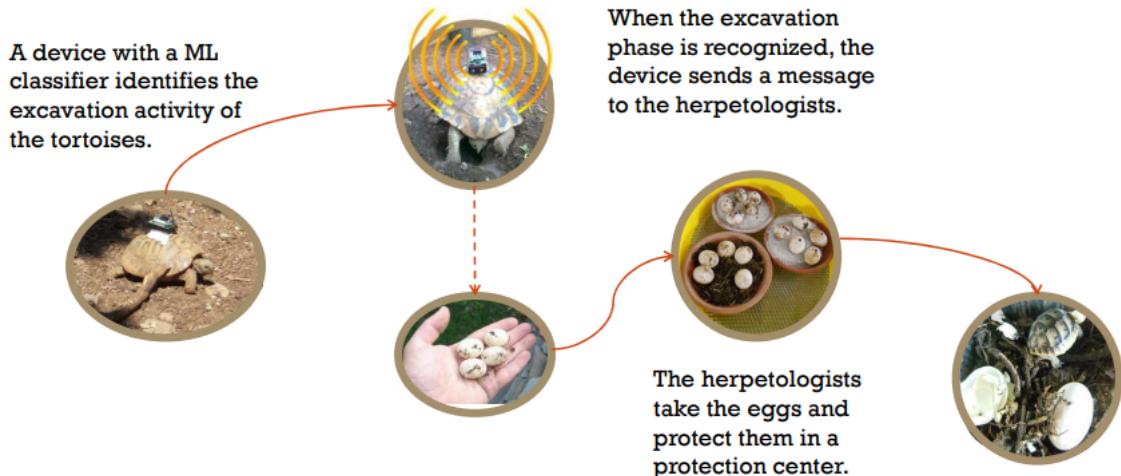


Figure 5.3: Overview process of collection and detection

The oscillatory movement of a tortoise is performed by the two back legs: detecting this specific movement allows to derive the execution of the ability, also because the duration of digging lasts a couple of hours. It's also performed in hot and lit locations, at specific sun hours. Tortoises lay eggs in spring (over 4 months) and a single tortoise may lay eggs more than once (generally up to three/four times). Nesting happens at daytime, in warm and well-lit places. Nesting lasts for more than one hour and the tortoises digs their nests with their hind paws. Those considerations impacted the design of the device as follows:

- The device lifetime must be at least 4 months
- Digging activity indicates a probable nesting: it can be detected with accelerometers
- Use of environmental sensors (*light and temperature*) to limit the use of accelerometers

To detect the motion, an **accelerometer** is used: it's specific for small movements, measuring the tortoise x-axis inclination by measuring the gravity at each movement (*both left and right*). The accelerometer need to sample with a certain frequency, compromising the overall energy consumption: the combination with light sensor and temperature allows to be active only when the environmental conditions are met for the digging, reducing the duty cycle. It's not really important to detect the digging activity from the start but can be a some delay due to its duration (*couple of hours*).

The automata, pictured in 5.4, start from the first step with a short duty cycle. The second step perform relevation with a certain frequency, lessser than the first one. The frequency it's suitable for allows the detection algorithms to work. The step 3 allows to avoid false positives, certifying the actual digging activity: if confirmed the GPS data are transmitted.

The diagram implies having different duty cycles that allows to decrease to a minimum the energy consumption: this allows also to estimate the size battery.

Dataset 1

Initial dataset consists of **raw time-series** from accelerometer (*x axis*) with a MicaZ device that were used for training and test sets. The **sequences dataset** was a sequences of 300 seconds with 1Hz

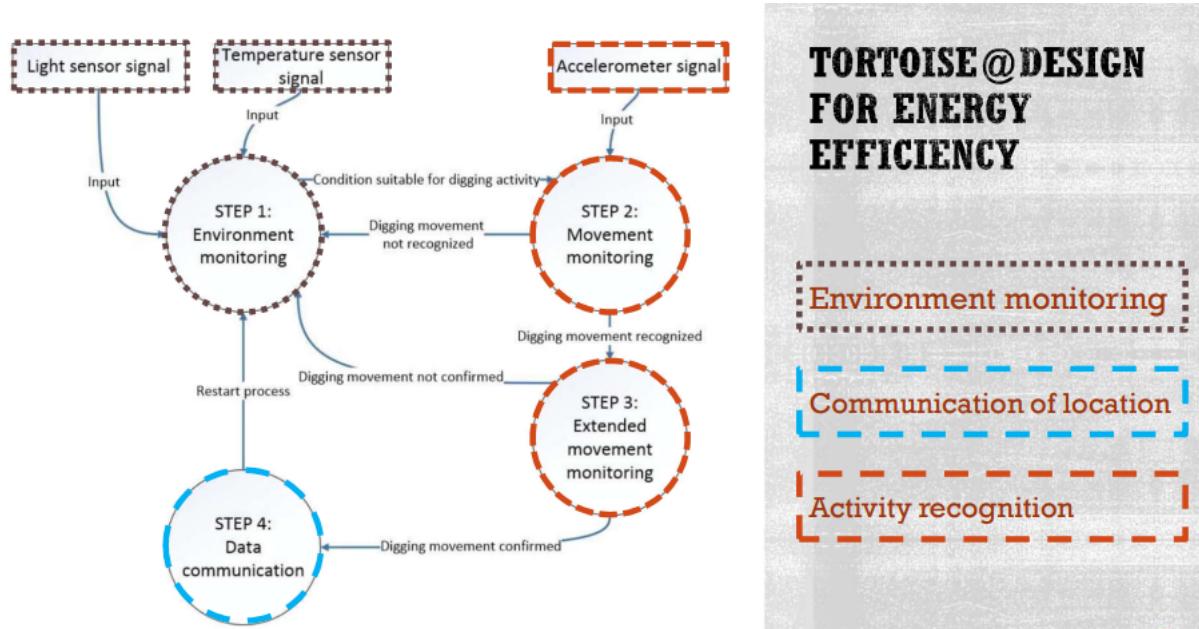


Figure 5.4: Device automata for detection

sampling: the experiment obtained 126 sequences in total with positive and negative classification, with 56 sequences in the test set, the others for training and validation.

The **pattern dataset** (*that identify the repetitive action of a tortoise, presented in 5.5*) was composed of sequences of 90 seconds each, sampled at 1Hz. The experimentation obtained 67 patterns with positive classification and 67 negative for model selection, with 10 patterns with positive classification and 10 negative for model validation.

The size of *window of signals* depends on the shape of the *digging* activity signal, as represented in 5.6.

Different approach were considered for the automatic classifier between *SVM*, *CNN*, *ESN*, *IDNN*, etc. The classification can follow two different approaches:

- **Asynchronous tasks:** classification of single windows via *IDNN*, *CNN*, *SVM*, *ESN*. The output of the neural network depends on an *entire window of signal*.
- **Synchronous tasks:** classification in step by step across a *stream of data* (ESN mainly). The output of the neural network does not need an entire window of samples. It is based on the samples of the *last 90 seconds* (*sufficient to find a pattern*).

The results obtained with **asynchronous tasks** are pictured in 5.7.

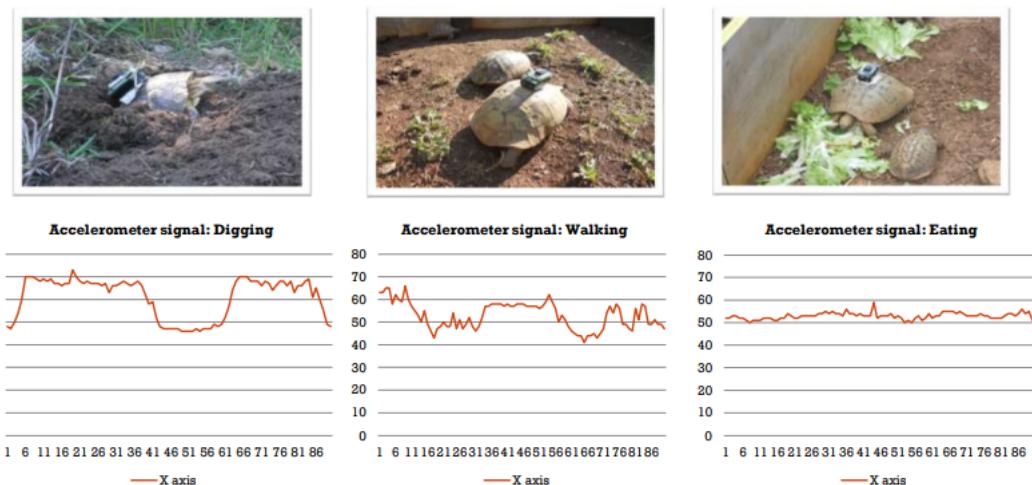


Figure 5.5: Pattern examples of tortoises activity

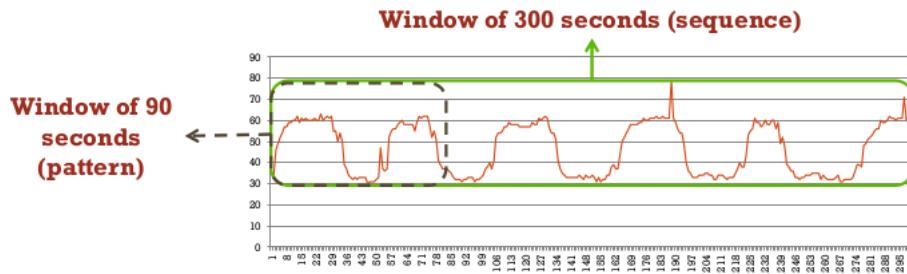
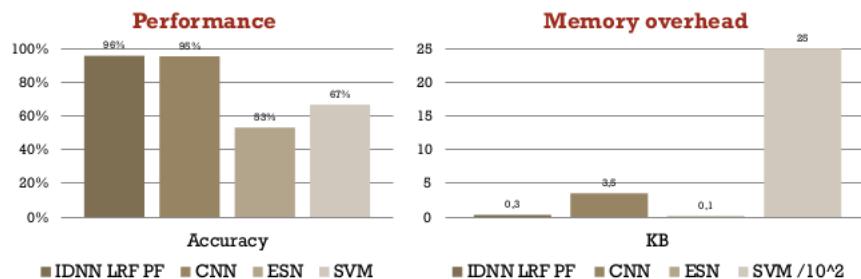
Figure 5.6: Window of signals, identifying **sequence** and **pattern**

Figure 5.7: Classification models result for async tasks

The data in 5.7 shows how SVM have medium performances but have an high memory overhead (*to keep weights and other parameters in memory*): considered a device (*Arduino*) with 32kB of flash memory, the SVM was the worst choice in term of storage.

Differently, for **synchronous tasks** that worked only on the last retrieved sample in the last 90 seconds, the result were optimal on *ESN - Echo State Network* as pictured in 5.8

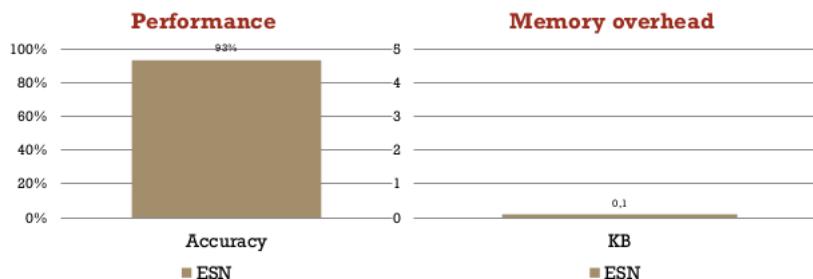


Figure 5.8: ESN results for sync tasks

Energy Efficiency The energy efficiency was gained by embedding other choices in the design phase, involving the specific activity of the device and the purpose of the data collection, like:

1. Avoiding sampling at night hours
2. Environmental condition can be sampled at very low rate (*like 0.01Hz*)
3. Acceleration sample reach higher rate (*5 minutes at 1Hz*) only when environmental condition are suitable
4. If the response is negative can suspend for at least half an hour because digging of a nest lasts at least one hour or more
5. If the response is positive then: repeat 3x the acceleration sampling and analysis three, reduces the impact of false positives
6. If the device is sure the tortoise is excavating then transmit: this allows to limits the number of radio activations and transmission to a few times over several months

In term of memory, two main **data structure** were used:

- One to store the activity recognition machine, either: vectors of the SVM or weights of the neural networks
- One to store the acceleration samples: in the worst case only one window of *300 samples*. One single sample was 2 bytes, so $300 * 2B = 600Bytes$ total.

Even **cloud based processing** was considered, giving this scenario:

- **Store (and transmit) GPS position** every half an hour (*two long, 32 bits each*)
- **Store (and transmit) the acceleration data** sampled at *1Hz* (*10 bits each sample*) For 4 months continuously: $46KBytes (GPS) + 13Mbytes (accelerometer)$

Differently, with **local processing**:

- **Transmit GPS position:** 32 bits latitude, 32 bits longitude only when detected excavation. Occurs only a few times in 4 months (*not all excavations conclude with nesting*)
- **Storage:** the accelerometer data would be at most *3KBytes (a time window)*, even less with ESN and the GPS would be active only when detects excavation.

To conclude the presented use cases, the *raw accelerometer series* were combined with ML Models to guarantee the catching movement executed by tortoises.

For the **asynchronous task**:

- Short sequence of 300 values (five minutes);
- IDNN, CNN, ESN and SVM;
- IDNN LRF PF and CNN obtain the same performance (*95% accuracy*), but with different memory overhead, IDNN 0.3KB and CNN 3.5KB.

For the **synchronous task**:

- First time that the ESN are applied for identifying animal activities;
- The model reached high performance in accuracy (93%);

For both types of tasks, an high accuracy was obtained with a neural network with a few neurons (*5 neurons*).

Exercise 1

Assume this scenario:

- Biologging device for tortoises with *512KB* of storage memory
- Uses one-axis accelerom. sampled at a frequency f
- Each sample is converted by the ADC (*Analogic-Digital Converter*) into a 16 bit integer
- The application stores all accelerom. data in memory. If memory is full the data is lost
- The herpetologist retrieves the device and classifies offline the activities of the tortoise

Estimate the lifetime of the application: for lifetime, in this context, we refer to the **time elapsed from start to the time in which the storage is full**. (*Note: disregard energy consumption and battery capacity*).

Solution 1

Lifetime = $256K/f$ seconds, so if $f = 1Hz$, the lifetime is 73 hours

| Content of the log | Meaning |
|--------------------|--------------------------|
| 00 | sleep – time t |
| 01 | walk – time t+5 seconds |
| 01 | walk – time t+10 seconds |
| 01 | walk – time t+15 seconds |
| 10 | eat – time t+20 seconds |
| 01 | walk – time t+25 seconds |
| 01 | walk – time t+30 seconds |
| 11 | nest – time t+35 seconds |

Figure 5.9: Example of log and relative activities

Exercise 2

Same as the previous exercise, but the application processes the data:

- analyses a sequence of **5 seconds** of accelerometer data
- for each sequence, it produces a classification of the activity of the tortoise encoded into **2 bits**:
 - 00 (sleep);
 - 01 (walk);
 - 10 (eat);
 - 11 (nest)

See example in the table 5.9. Compute the lifetime of the device (*defined as in exercise 1*).

Solution 2

Every *5 seconds*, the device stores 2 bits in the storage: this means storing 1 byte every 20s. Since the storage can contain up to $512KB$, the lifetime is $512kb * 20s = 121days$.

Exercise 3 Same as Exercise 2, but the application **stores the activity classification only when it changes**:

- if was "walk" and the new one is "walk" then no storage
- If was "walk" and the new one is "eat" then store "eat" (2 bits) and **current time** (30 bits).

An example is pictured in the table pictured in 5.10

Compute the lifetime of the device (*defined as in exercise 1*). Consider, as before, that the memory full implies data lost.

Hint: assume that, on average, the activity of the tortoise changes every half an hour.

Solution 3 Solution without computations is $\frac{512kB}{4*20} = 7.5$ years.

| Logfile fragment | Corresponds to |
|------------------|----------------|
| < 00, t > | <sleep,t> |
| < 01, t+5 > | <walk,t+5> |
| < 10, t+20 > | <eat t+20> |
| < 11, t+35 > | <nest,t+35> |

Figure 5.10: Exercise 3 - logfile example

Exercise 4

Consider the device of the Exercise 3:

- it samples the accelerometer with frequency f
- at each sample it computes a new classification and, if changed, it stores it

Assume that:

- sampling takes m seconds
- computing the classification and storing it takes n seconds

Compute the duty cycle of the device.

Solution 4

The devices execute the sampling every $1/f$ seconds. Hence the period of activity is: $p = \frac{1}{f}$ seconds.
In each period it spends $n + m$ seconds to sample, compute and store so:

- $\frac{1}{f} - m - n$ seconds, in **idle state**.
- so the **Duty Cycle (DC)** is: $\frac{(n+m)}{p}$

Those result are valid unde the condition: $\frac{1}{f} \geq n + m$

Chapter 6

MAC Protocols

In order to efficient the power consumption, is necessary to reduce/optimize the DC: this does not apply to **radio interface** directly so careful observation must be taken to address the activity of the radio interface at MAC layer. By operating at MAC layer we can reduce the radio duty cycle while mantaining network connectivity. The optimal solution involves a trade-off between *energy*, *latency* and *bandwidth*. In this scenario, MAC protocols change their objectives, taking the role of implementing DC by developing:

1. **Synchronization of nodes** (*as in S-MAC or IEEE 802.15*): implement a distributed protocol so the nodes agree on the activity period of the network. It's based on explicit synchronization.
2. **Preamble sampling** (*as B-MAC*): another way to obtain synchronization despite it's not a fully standardized mechanism.
3. **Polling** (*IEEE 802.15.4*): there is an asymmetry between the roles of the nodes in synchronizing process, with an ubalanced workload between the sender node and the receiver node.

Those approaches are implemented as **distributed coordination protocol**: the synchronization of the nodes is performed by agreeing **on when can turn on/off the radio**. To build large multi-hop network those protocol can have an high impact on latency: the latency adopted by the synchronization protocols can be problematic for hundreds of devices (*e.g. multi-hop ZigBee network with high number of devices*) because each hop introduce additional delay due to the processing and transmission time of each node. This behavior can determine packet loss because of the sending is performed during inactive period of the neighbors's node. The syncrhonization of nodes allows the node to turn on the radio simultaneosly by coordinating between all nodes and when the radios are active the network is connected while when the radio is inactive there is no network activity available. The goal is to have radio low duty cycle, minimizing the overall energy consumption by remaining inactive for most of the time.

6.0.1 Syncrhonization: S-MAC

It's a *medium access control protocol* for wireless multi-hop network. The key idea is that it uses only **local synchronization**: the nodes implement synchronization locally by exchaging synchronization packets only with around neighbors. The farest node can be totally un-synchronized respect to a given node.

The syncronization mechanism of exchanging SYNC messages allows to synchronize the clock to a common timeframe of radio activation: to communicate they just to wait the activity period of the communication timeframe. A SYNC frame contains the **schedule** of the node: if a node detects adjacent nodes with a pre-defined listen period will use the same period, otherwise it chooses its own period. The choosen period is advertised to the neighbors by SYNC frames. So nodes alternate *listen* and *sleep* periods in which, during sleep time, the sensor cannot detect incoming messages. Two different nodes can decide different schedule of activity for the radio but the "*most popular schedule*" among the neighbors it's the most suitable to communicate with the highest range of devices. A node may revert to someone else schedule if its own schedule it's not shared by any other device.

A node **receives** frames from the neighbors during its own **listen period**: node A can send a frame to node B only during the listen period of B (*as pictured in 6.1*):

- node A may need to turn on its radio also outside its listen period

- node A should know all the listen periods of its neighbors
- At startup a node preliminary listens the SYNC frame of its neighbors

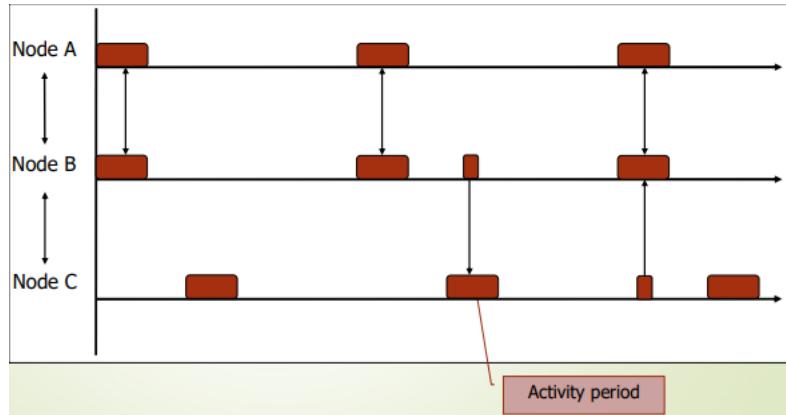


Figure 6.1: undefined undefined

In the previous exchange 6.1, A and B have the same listen period so they're able to communicate without problem: the communication between B and C require that the node B activate its radio in the listen period of C, despite it's outside of its own active period.

So the frame are sent during the listen period of the receiver: the problem of **collision** arises if two nodes have the same listen period, they will send packets on the same time. To avoid collisions, the adaptive duty cycle use a **Carrier Sense** check it's executed before the transmission and if the channel is busy and a node fails to get the medium, the frame is delayed to the next period. So if an RTS or CTS is received, the radio is kepted up until the end of the transmission just incase it's the next hop of commmunication. This simple optimization allows avoiding collisions on the communiciation channel.

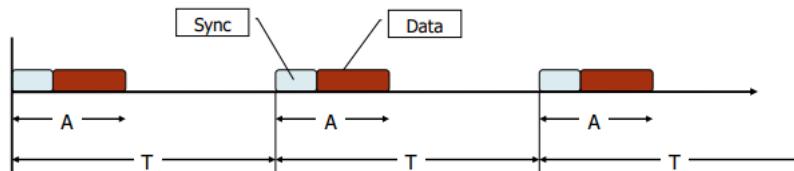


Figure 6.2: undefined undefined

The **S-MAC Energy Consumption** follows the diagram pictured in 6.3. The diagram shows the *aggregate energy consumption over a 10-hops path*: as the data shows, the adaptive duty cycle is a little optimization used by S-MAC so if a node overhears a RTS or a CTS it keeps its radio on until the end of the transmission just in case it's the next hop of communication. As the diagram shows, the **larger is inter-arrival period, the smaller is the load of the network**.

Latency

While traveling across a multihop path, a frame may have to wait (*in the worst case*) for the listen period of each intermediate node. This is mitigated by the fact that (*hopefully*) a number of nodes will converge towards the same schedule (*not guaranteed anyway*).

Latency must be well addressed, as shown by the exchange pictured in 6.4: from A to C the communication can happen within one activty perio but between C and D there is a *waiting time*, the same happen with E and F: this *waiting periods* increase the overall latency. A trade-off must be achieved because a larger duty cycle ca surely lower the latency but increasing the energy consumption.

Another problems that affects the IoT devices is the **quality of clock component** that usually it's not suitable for exact syncrhonzization: they are cheap and are affected by environmental conditions. There are conditions that make clocks of different devices diverge (*e.g. a device with a shield vs no shield respect to temperature impact*), impacting the synchronziation between the devices.

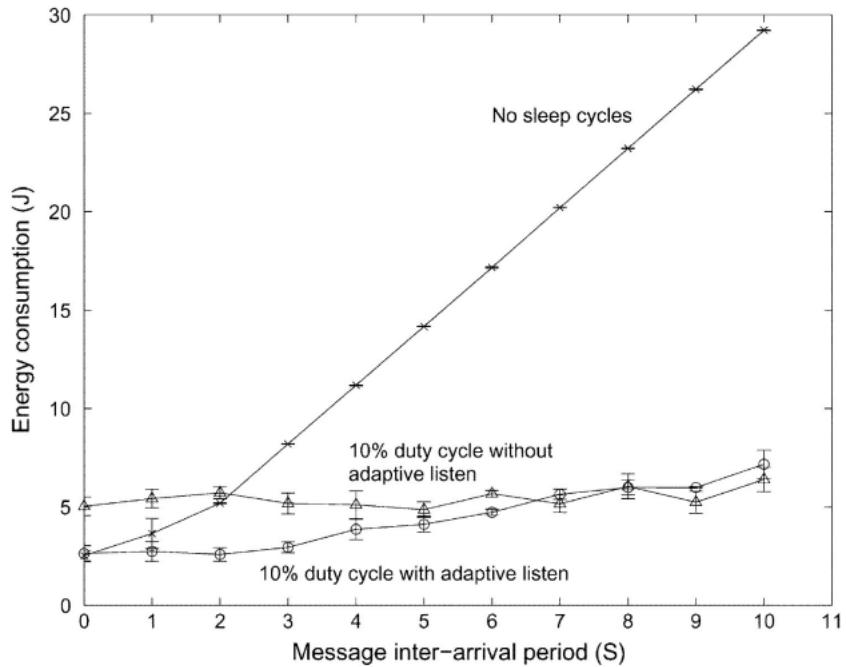


Figure 6.3: S-MAC Energy consumption

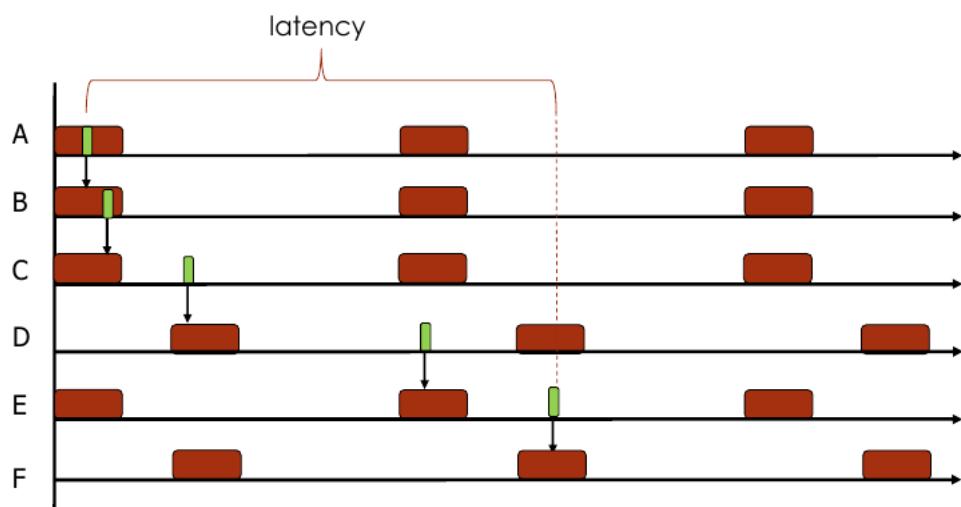


Figure 6.4: Cumulative latency in multihop transmission

6.0.2 Preamble Sampling: B-MAC

The key idea is to reduce the complexity of the protocol, obtaining synchronization by differentiating the behavior of the receiver and the transmitter. A **sender** sends whenever it wants that contains a very long preamble in its header while the **receiver** activates its radio periodically to check if there is a preamble on the air. This last activity is called **preamble sampling** and it's based on **Low-Power Listening (LPL) mode**.

The general schema is shown in 6.5: if the receiver during the *preamble sampling* detects a preamble **keeps the radio on to receive the frame**, otherwise turns off the radio. The idea is to spend more in transmission but save energy in reception because the preamble sampling should be very short and cheap. The costs of radio activation/deactivation at the receiver side are balanced by a *low rate sampling*. Surely to be effective, this implies that the **preamble should be longer than the sleep period**.

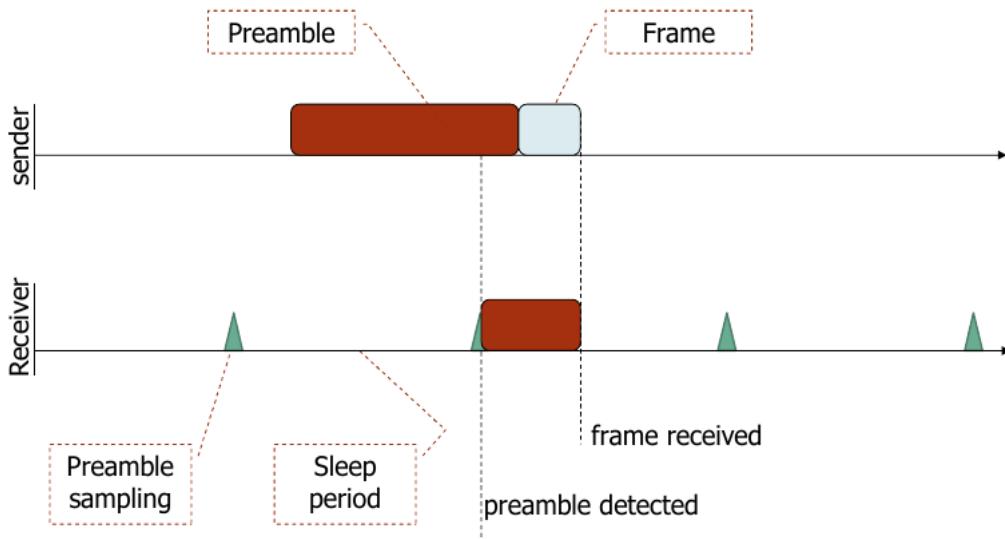


Figure 6.5: undefined undefined

The green peaks in 6.5 indicates the **preamble sampling** for small fraction of time. The interval between two *peaks (sleep period)* it's a fixed parameter given by the B-MAC protocol. The sampling duration, differently, cannot be enforced by the protocol but depends on the specific device/hardware performances. To avoid partially communication by receiver side, the **long preamble** it's used: it does not contain anything useful but the only purpose it's to signal that meaningful packets will be sent at the end of the preamble packets. The protocol works because the length of the preamble is longer than the interval between two periods.

The idea is to give *more work to the transmitter, lesser to the receiver*: in multi-hop devices network this allows to save the overall energy if a scenario with multiple receivers.

As mentioned, the preamble sampling it's based on **Low-Power Listening (LPL)** that also have its own overhead: the diagram in 6.6 shows the Current consumption over time for the *Mica-Mote* radio during its initialization/startup/transmission/sleep phases.

The radio keeps an internal clock to be synchronized to the bit flowing on the radio channel: this requires an initial setup by the clock (**init radio**). The diagram also indicates that the *init* phase must be avoided over time to reduce the current consumption. Another result is that the transmission represents the activity with the most current expenditure, alongside the ADC (Analog-Digital Converter) activity period.

This simple model allows us to define a **model**, both for transmitter and receiver sketched in 6.7.

Based on the general model in 6.7, to **model the lifetime** we need make some assumption like that there is only *one receiver and one transmitter*. Their parameters are:

1. f_{data} : frequency of **transmitted data** (in hertz $\frac{1}{sec}$)
2. f_{check} : frequency of **preamble sampling**

Hence, at the **transmitter** (*considering only the radio activity*), we have:

- **Duty cycle data:** $DC_{tx} = f_{data} * (t_{preamble} + t_{data})$

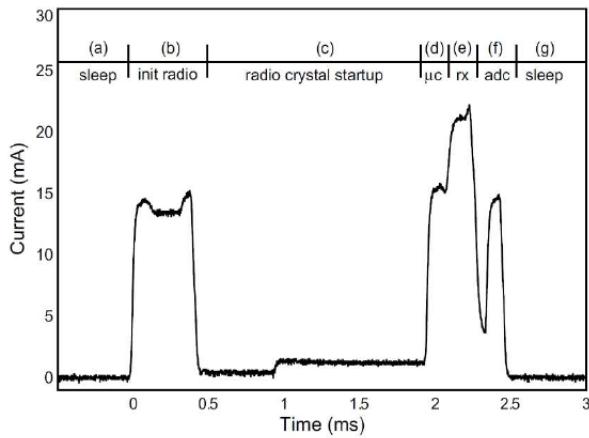


Figure 6.6: undefined undefined

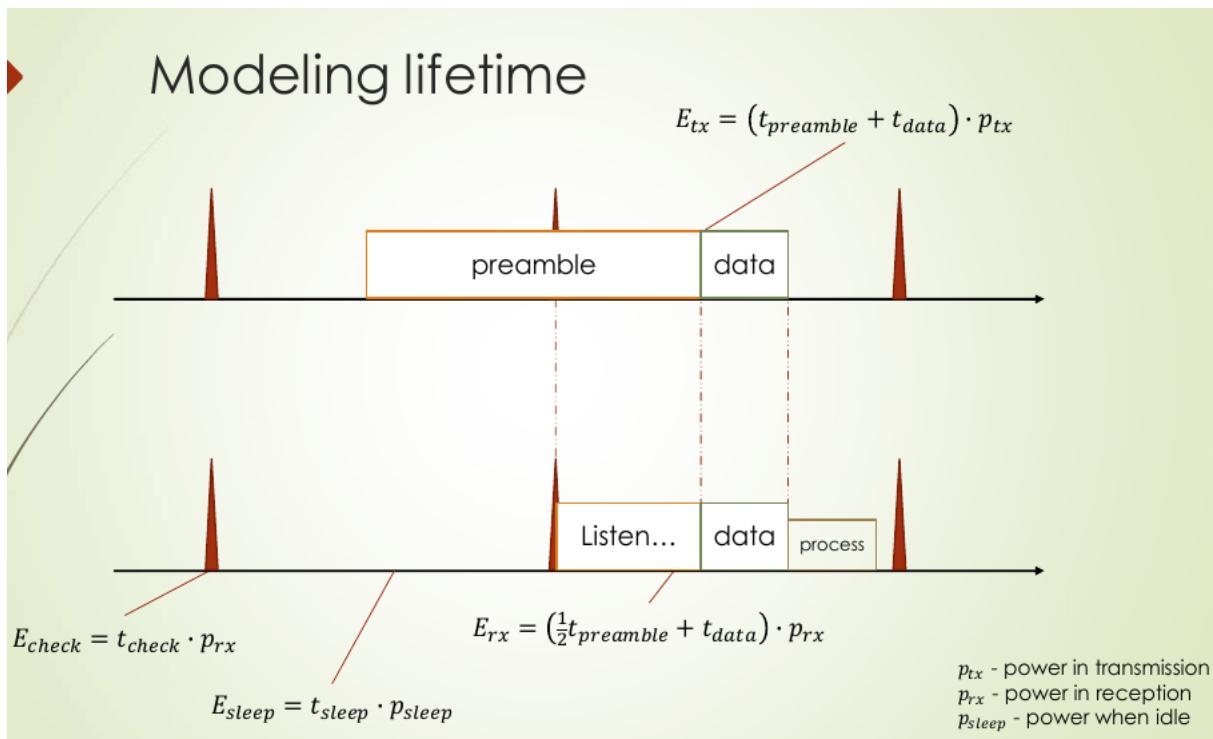


Figure 6.7: Transmitter and receiver lifetime model

- **Duty cycle check:** $DC_{check} = f_{check} * t_{check}$
- **Energy (in joule) spent in t seconds at the transmitter side:**

$$ET(t) = t * (p_{tx} * DC_{tx} + p_{rx} * DC_{check} + p_{sleep} * (1 - DC_{tx} - DC_{check}))$$

While, at the **receiver side** we have:

- **Duty cycle data:** $DC_{rec} = f_{data} * (\frac{1}{2}t_{preamble} + t_{data})$
- **Duty cycle check:** $DC_{check} = f_{check} * t_{check}$
- **Energy (in joule) spent in t seconds at the receiver side:**

$$ER(t) = t * (p_{rx} * DC_{rec} + p_{rx} * DC_{check} + p_{sleep} * (1 - DC_{rec} - DC_{check}))$$

Thus, the overall **lifetime** are:

- **Transmitter:** $lifetime = battery_{charge}/ET(1)$
- **Receiver:** $lifetime = battery_{charge}/ER(1)$

In the table 6.8 are sketched some value of the specified parameter from the original BMAC paper for the *CC1000 radio*:

| Parameter | value |
|-----------------|-------------|
| p_{tx} | 60 mW |
| p_{rx} | 45 mW |
| p_{sleep} | 0,09 mW |
| preamble | 271 bytes |
| data frame | 36 bytes |
| byte length | 4,16 E-04 s |
| check length | 3,5 E-04s |
| preamble length | 1,13 E-01 s |
| frame length | 1,5 E-02 s |

Figure 6.8: BMAC Parameters

Lifetimes

The following results assume a battery of $3000mAh$ and disregard the processing, sensing and battery leaks in the computation. The data in 6.9 shows the lifetime at *transmitter side*, showing that by decreasing the sample frequency interval (t_{check}) (from *1sample every min* to *1 sample every 20 min*) we can increase te overall lifetime. Analogues results are obtained for the receiver 6.10.

The previous model consider only two nodes (*one receiver and one transmitter*): even considering several transmitters, the lifetime trend does not change and still result in the same shown in 6.9. The node *lifetime* depends on the **check interval** (*of preamble sampling*) and the total amount of traffic in the network cell. Each line in the picture 6.11 diagrams shows the lifetime of a node at that sampe rate and LPL (*Low-Power-Listening*) check interval: the circles occur at the maximum lifetime (*indicating optimal check intervals*) for each sample rate.

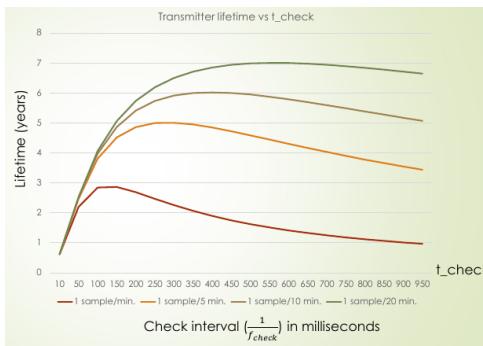


Figure 6.9: Transmitter lifetime vs t_{check}

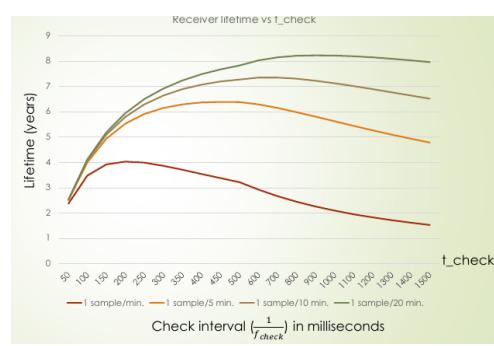


Figure 6.10: Receiver lifetime vs t_{check}

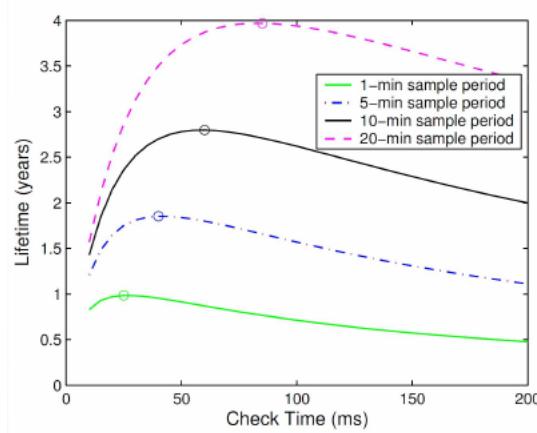


Figure 6.11: Lifetime with several transmitter nodes

Strengths and drawbacks

As mentioned previously, the clock must be not necessarily synchronized but by measuring the same way the time: 1 second must correspond to 1s in every device, despite, as previously mentioned, the decreasing quality of measuring of the clocks used in IoT device. The **strengths** of the B-MAC Protocol are:

1. It's not a network organization protocol
2. It's simple to use and configure (*having only one parameter*)
3. It's transparent at the higher layers

While the **drawbacks** are:

1. Long check intervals have an impact on the throughput of the network but in IoT this is acceptable. B-MAC is suitable for low transmission rate.
2. Long check interval imply long, expensive preambles
3. In some cases it may result more expensive than using other form of synchronization

6.0.3 X-MAC

X-MAC is an evolution of B-MAC aimed at **reducing the impact of long preambles**. It allows a *receiver* to stop the preamble transmission: the preamble this time contain also information of the **ID of target node** so a receiver can check if it's the recipient of the frame and interrupts the preamble transmission to request the data frame. In figure 6.12 comparison schema between *LPL (B-MAC)* and *X-MAC*.

During the *transmission phase*, the transmitter (*S*) send *short preambles* containing the target address information: when the receiver (*R*) wakes up, catch the short preamble and reply with an **early ACK** that allows *S* to stop the sending of short preamble and start sending the **data frame**.

After receive a frame, the receiver *R* does not turn off the radio immediately to allows other nodes that wanted to transmit during the preamble transmission but were not allowed (*as they sensed the channel was occupied*), so the receiver remain active to catch eventually other communications: this is indicated by the gray area after *R*'s reception phase (*low part diagram X-MAC*).

X-MAC vs B-MAC The comparison pictured in 6.13 is made by simulation on **total duty cycle of transmitters**: the scenario was a *star connected network* with 1 receiver and several transmitter that varies over time. Each station transmits every 9 seconds with randomized jitter, using also different LPL intervals (*different check intervals of B-MAC*).

Another following development of X-MAC is known as **BoX-MAX**: it still try to reduce the impact of long preamble by attaching inside the preamble message also the data itself, so the receiver send an ACK after having received the packets containing both the preamble and the data frame. This is suitable for **small data packets**. The general schema of BoX-MAX is pictured in 6.14

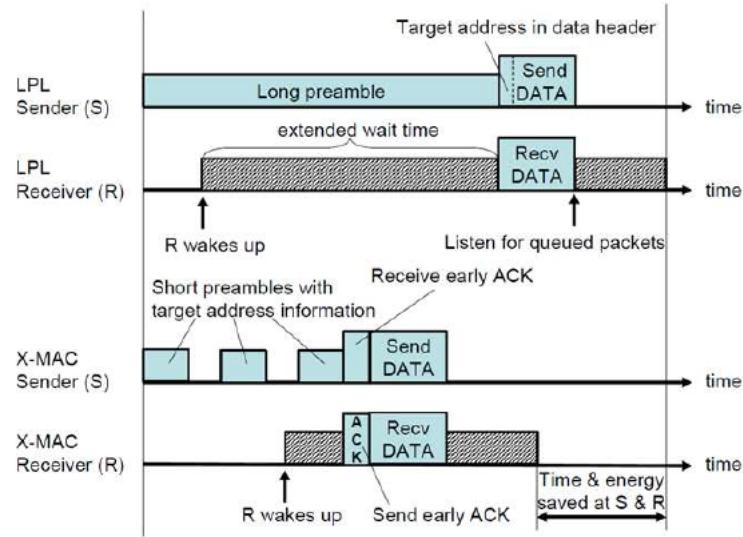


Figure 6.12: B-MAC (LPL) vs X-MAC periods

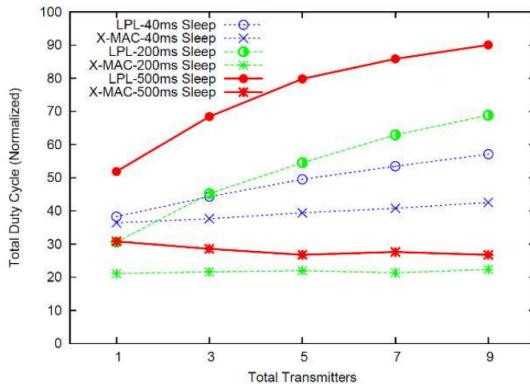


Figure 6.13: X-MAC vs B-MAC duty cycles

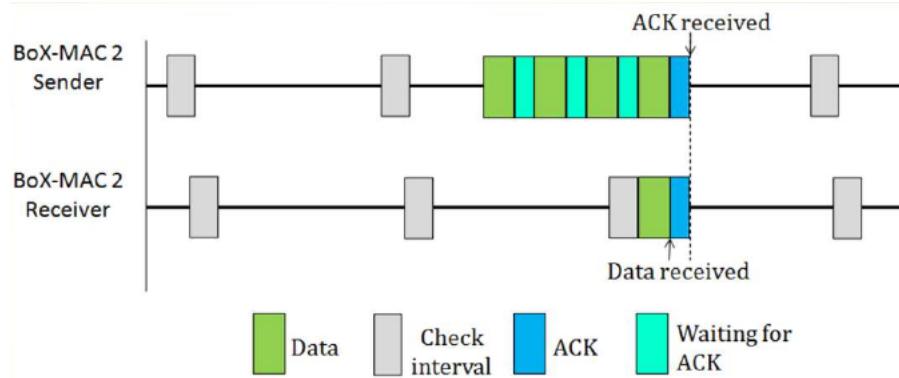


Figure 6.14: BoX-MAC single hop transmission

For a **multi-hop routing** in BoX-MAC, we refer the schema in 6.15 : the transmission involves three different nodes. The first node i_1 try the transmission multiple time before having success: the node i_2 first need to sample the channel and then receive the communication so it's allowed to send a *ACK-TX* to i_1 and the same process is repeated between i_2 and i_3 .

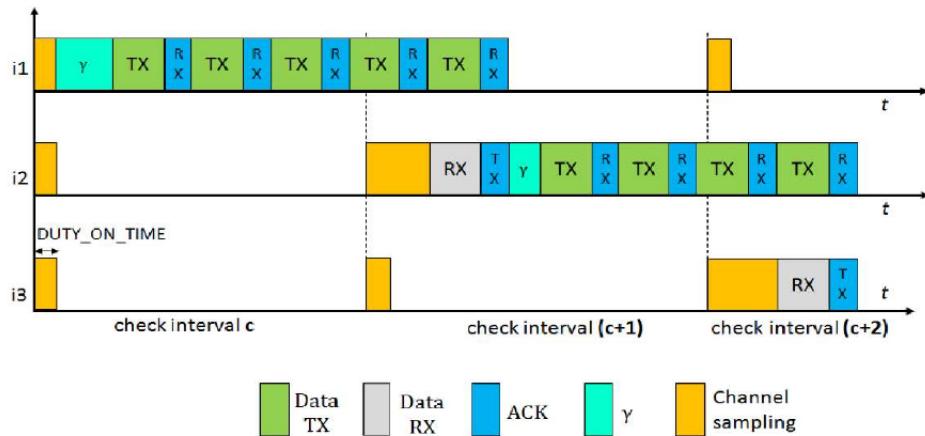


Figure 6.15: BoX-MAX multihop transmission

Polling This method is widely used in IEEE 802.15.4: can be combined with other synchronization methods and usually allows an **asymmetric organization** of the nodes by having *one master* that issues periodic beacons and *several slave nodes* that can keep the radio off whenever they want. (See section 6.1 on IEEE 802.15.4 for more details).

6.1 IEEE 802.15.4 Standard

The following chapter is entirely based on "J. Zheng and A. Jamalipour, Wireless Sensor Networks: A Networking Perspective, Wiley-IEEE Press".

The **IEEE 802.15.4 standard** specifies the **physical** and **MAC layers** for low-rate wireless *Personal Area Networks (PAN)*. Its protocol stack is simple and flexible, it does not require any infrastructure and it is suitable for short-range communications (*typically within a range of 10 meters*). For these reasons it features ease of installation, low cost, and a reasonable battery life of the devices. The physical layer of the IEEE 802.15.4 has been designed to coexist with other IEEE standards for wireless networks such as *IEEE 802.11* and *IEEE 802.15.1 (Bluetooth)*. It features activation and deactivation of the radio transceiver and transmission of packets on the physical medium. It operates in one of the following three license-free bands:

- 868–868.6MHz (e.g., Europe) with a data rate of 20 kbps;
- 902–928MHz (e.g., North America) with a data rate of 40 kbps; or
- 2400–2483.5MHz (worldwide) with a data rate of 250 kbps.

The MAC layer provides **data and management services** to the upper layers. The **data service** enables transmission and reception of MAC packets (*Protocol Data Unit (PPDU)*) across the physical layer. The **management services** include synchronization of the communications, management of guaranteed time slots, and association and disassociation of devices to the network. This is performed by a set of features like **Energy Detection (ED)**, **Link Quality Indicator (LQI)** (*that allows to choose the best channel for a given communication*), **Channel Selection**, **Clear Channel Assessment (CCA)** (*more information later*). In addition the MAC layer implements basic security mechanisms.

Physical layer

There are several channels operating at different frequencies (*Mhz*) as pictured in 6.16: the lower channels are used for short range devices (*baby monitor, automatic gate remote controller, etc*) while the upper channels (11–26) are for large range of communications.

It's designed to operate well even in highly noisy environment: the physical channel is designed to be more robust respect to Bluetooth as shown in 6.17.

As mentioned in the previous chapters (9.0.3), the **Signal-to-noise ratio (SNR)** is a measure of the strength of a signal relative to the background noise present in a given environment or system. It is expressed as a ratio of the *signal power* to the *noise power*, typically measured in decibels (*dB*).

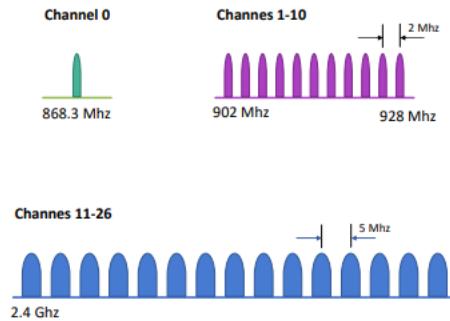
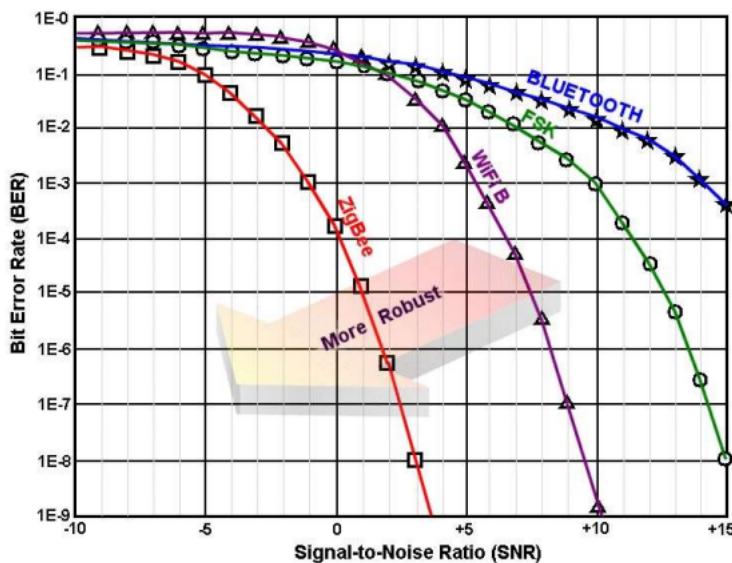
Figure 6.16: Physical channels with relative *Mhz*

Figure 6.17: undefined undefined

In communication systems, the signal refers to the information or data that is being transmitted, while noise refers to any unwanted or random fluctuations in the signal. **The higher the SNR, the better the quality of the signal and the more accurate the transmission of information.** Conversely, a low SNR indicates a weaker signal that is more susceptible to errors and interference from noise.

The **Energy Detection (ED)** is used to find a free channel and for carrier sense: the estimation time for ED equals the average over 8 symbols interval. The **detection threshold** is at $10dB$ above the sensitivity level. The **Link Quality Indicator (LQI)** indicates the quality of data packets that are received by a node: it's based on ED or on the *signal/noise ratio*. It's assessed each time a packet is received and must contemplate 8 different levels of quality. The estimated value for *LQI* is forwarded to the network and application layers.

For the **Channel Assessment**, the main objective is to detect if the channel is *busy* and operates in 3 modes:

- **Mode 1:** uses ED; if the energy level exceeds the detection threshold, then the channel is marked as *busy*.
- **Mode 2:** perform *Carrier Sense*, the channel is *busy* if the detected signal has the same characteristics as the sender.
- **Mode 3:** Combination of modes 1 et 2 (*AND/OR*).

Data services At the *physical layer*, the *PPDU (Physical Protocol Data Unit)* reports the result of the transmission to the upper layer (*if successfull or failed*). The main reasons for a transmission to fail are:

1. radio transceiver *out of order*
2. radio transceiver is in the *reception mode*

3. radio transceiver is *busy*

The **frame** have the structure pictured in 6.18:

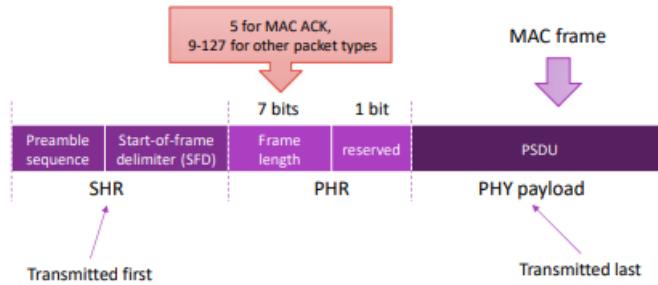


Figure 6.18: Frame structure

It's composed by:

- **SHR (Synchronization Header)**: synchronisation with the receiver
- **PHR (PHY Header)**: information about the frame length
- **PHY Payload**: the MAC frame
- **SFD (Start-of-frame delimiter)** : tell the receiver that the real data is beginning
- **PSDU (Physical Service Data Unit)**: it's the actual payload, up to 127 bytes. It's not a good idea to use all of them all despite are only few bytes: with long frames there are problem of carrier sense and multiple access.

MAC Layer

Also at the MAC Layer, we can differentiate three different types of services:

1. **Data services**: transmission and reception of **MAC frames (MPDU)** across the physical layer.
2. **Management services**: perform *synchronization of the communications, channel access, management of guaranteed time slots, association and disassociation of devices.
3. **Security services**: allows *data encryption, access control, frame integrity and sequential freshness*.

The MAC layer defines two types of nodes: **Reduced Function Devices (RFDs)** and **Full Function Devices (FFDs)**.

RFD are meant to implement end-devices with reduced processing, memory, and communication capabilities which implement a subset of the MAC layer functions. In particular the RFD can only associate to an existing network and they depend on **FFDs** for communication. One **RFD** can be associated to only one **FFD** at a time. Example of RFD devices are simple sensors or actuators like light switches, lamps and similar devices.

The **FFDs** implement the full MAC layer and they can act either as the *Personal Area Network (PAN)* coordinator or as a generic coordinator of a set of RFDs. The PAN coordinator sets up and manages the network, in particular it selects the PAN identifier and manages associations or disassociation of devices. In the association phase the PAN coordinator assigns to the new device a 16 bit address. This address can be used in alternative to the standard 64 bit extended IEEE address which is statically assigned to each device.

The FFDs cooperate to implement the **network topology** as pictured in 6.19. The actual network formation is performed at the network layer, but the MAC layer provides support to two types of network topologies: **star** and **peer-to-peer** (*as shown in 6.19*). In the **star topology** one FFD is the PAN coordinator and it is located in the star centre. All the other FFD and RFD behave as generic devices and they can only communicate with the coordinator which synchronizes all the communications in the network. Different stars operating in the same area have different PAN identifier and operate independently of each other.

In the **peer to peer topology** each FFD is capable of communicating with any other device within its radio range. One **FFD** (*normally the FFD which initiated the network*) act as PAN coordinator, and the other **FFDs** act as routers or end devices to form a multihop network as shown in the previous figure. The **RFDs** act as end devices and each RFD is connected only with one **FFD**.

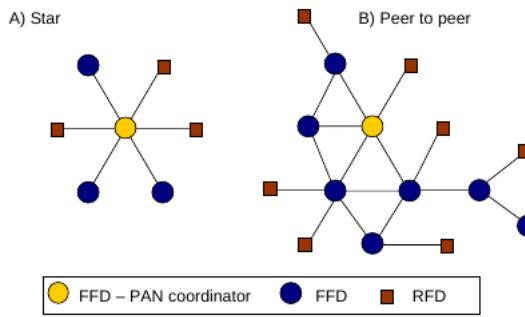


Figure 6.19: Star topology vs Peer to peer topology

6.1.1 Channel access

The MAC protocol have two channel access:

1. **superframe structure**: used in **star topologies** (*it can also be used in peer to peer topologies organized in trees*) and provides synchronization between nodes to enable energy savings of the devices.
2. **no superframe structure**: is more general and can be used to support communications in arbitrary **peer to peer topologies**.

1. Access with superframe

A superframe is composed by an **active** and an **inactive** portion as shown in 6.20. All the communications happen during the active portion, hence the *PAN coordinator (and the connected devices)* may enter a *low power (sleep)* mode during the inactive portion. The active portion comprises up to **16 equally sized time slots**. The first time slots is the **beacon frame** and is sent by the PAN coordinator to begin the superframe. The beacon frames are used to synchronize the attached devices, to identify the PAN, and to describe the structure of the superframes.

The actual communications between the end devices and the coordinator take place in the *remaining time slots*. The time slots in the active portion are divided into a **Contention Access Period (CAP)** and a (*optional*) **Contention Free Period (CFP)** as shown in 6.21.

In the **CAP period** the devices compete for channel access using a standard slotted *CSMA-CA protocol* (*Carries Sense Multiple Access with Collision Avoidance*). This means that a device wishing to transmit data frames first waits for the beacon frame and then it *randomly selects a time slot for its transmission*: if the selected time slot is busy because another communication is already ongoing (*this is detected using carrier sense*) then the device selects randomly another time slot. If the channel is *idle*, the device can begin transmitting on the next slot.

The **CFP period** is optional and it is used for low-latency applications or applications requiring specific data bandwidth. To this purpose the PAN coordinator may assign portions of the active superframe (*called **Guaranteed Time Slots** or GTS*) to specific applications. The GTSs form the **contention-free period (CFP)**, which always begins at the end of the active superframe starting at a slot boundary immediately following the CAP. Each GTS may comprise more than one time slots and it is assigned to an individual application which access it without contention.

In any case the PAN coordinator *always leave a sufficient number of frames for the CAP period for the other devices and to manage the ssociation/disassociation protocols*. Note also that all contention-based

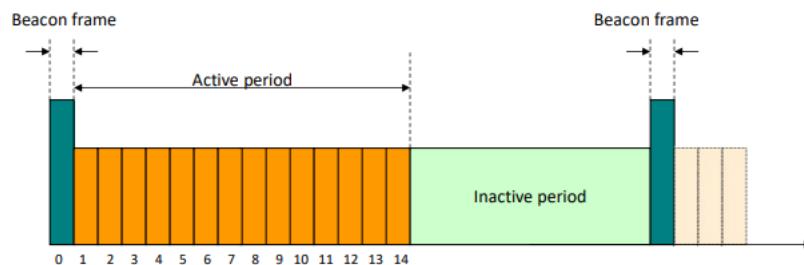


Figure 6.20: Superframe division between beacon, active period and inactive period

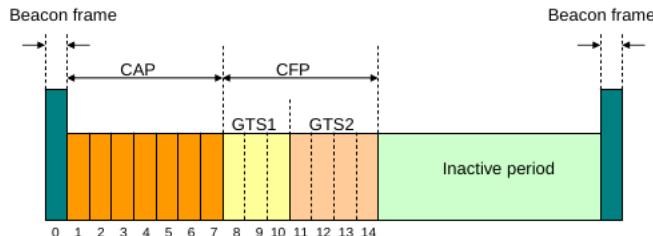


Figure 6.21: Division between CAP, CFP and GTS over active period

transactions shall be complete before the beginning of the CFP, and each device transmitting in a GTS shall complete its transmission within its GTS.

The PAN coordinator may optionally avoid the the use of the **superframe structure** (*thus the PAN is called **non beacon-enabled***). In this case the PAN coordinator never sends beacons and communication happens on the basis of the **unslotted CSMA-CA protocol**. The coordinator is always on and ready to receive data from an end-device while data transfer in the opposite direction is **poll-based**: the end device periodically wakes up and polls the coordinator for pending messages. The coordinator responds to this request by sending the pending messages or by signalling that no messages are available

Data transfer models

The standard supports three models of data transfer:

1. end device to the coordinator (*or router*),
2. coordinator (*or router*) to an end device
3. Peer to peer

The **star topology** use only the first two models because the data transfers can happen only between the PAN coordinator and the other devices. In the peer to **peer topology** all the three models are possible since data can be exchanged between any pair of devices. The actual implementation of the three data transfer models depends on whether the network supports the transmission of beacons, thus obtaining two network models: *beacon-enabled vs non-beacon enabled*.

Data transfers in beacon-enabled networks

Data transfer from an end-device to a coordinator: The end device first waits for the network beacon to synchronize with the superframe. When the beacon is received, if it owns a GTS it directly use it, otherwise it transmits the data frame to the coordinator using the slotted CSMA-CA protocol in one of the frames in the CAP period. The coordinator may optionally acknowledge the successful reception of the data by transmitting an acknowledgment frame in a successive time slot. (*Figure A of 6.22*).

Data transfer from and to a coordinator to an end device: The coordinator stores the message (*a data frame*) and it indicates in the network beacon that the data message is pending. The end-device usually sleeps most of the time and it *periodically listens to the network beacon to check for pending messages*. When it notice that a message is pending it explicitly requests the message to the coordinator using the **slotted CSMA-CA in the CAP period**. In turn, the coordinator sends the pending message in the **CAP period** using the slotted CSMA-CA. The device thus acknowledges the reception of the data by transmitting an acknowledgment frame in a **successive time slot** so that the coordinator can remove the pending message from its list (*Figure B of 6.22*).

Peer-to-peer data transfers: If the sender or the receiver is a end device then **one of the above schemes is used**. Otherwise both the source and the destination are coordinators and they issue their own beacons because two end-devices *cannot communicate directly*. In this case the sender must **first synchronize with the beacon of the destination** and act as an end device. The measures to be taken in order to synchronize coordinators are beyond the scope of the IEEE 802.15.4 standard and are thus left to the upper layers. The syncronization procedure is sketched in 6.23.

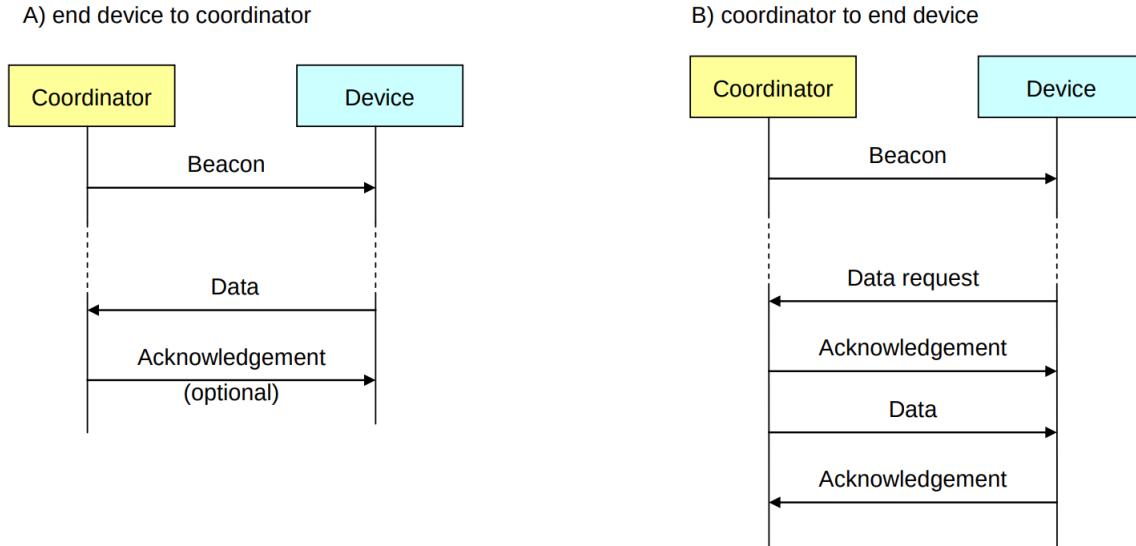


Figure 6.22: Data transfer models in beacon-based networks



Figure 6.23: P2P Data Transfer in Beacon-based network

Data transfers in non beacon-enabled networks

Data transfer from an end device to a coordinator: In this case the end device transmits directly its data frame to the coordinator using the **unslotted CSMA-CA protocol**. The coordinator acknowledges the successful reception of the data by transmitting an optional acknowledgment frame. (*Figure A of 6.24*).

Data transfer from a coordinator to an end-device: The coordinator stores the message (*a data frame*) and **waits for the appropriate device to request for the data**. A device can inquiry the coordinator for pending messages by transmitting a request using the *unslotted CSMA-CA protocol* (*this request happens at an application-defined rate*). The coordinator acknowledges the successful reception of the request by transmitting an **acknowledgment frame**. If there are pending messages, the coordinator transmits the messages to the device using the *unslotted CSMA-CA protocol*. Otherwise, if no messages are pending, the coordinator transmits a message with a **zero-length payload** (*which indicates that no messages are pending*). The device acknowledges the successful reception of the messages by transmitting an acknowledgment frame so that the coordinator can discard the pending messages (*Figure B of 6.24*).

Peer to peer data transfer: : In peer-to-peer PANs each device can communicate with each other device in its *radio range*. In order to do this effectively, the devices wishing to communicate need either to:

1. keep the **radio constantly active** in order to be ready to receive incoming messages or
2. to synchronize with each other.

In the former case the device can directly transmit the data using *unslotted CSMA-CA* while in the second case the device has to wait until the destination device is ready to receive. Note however that the devices synchronization is beyond the scope of the IEEE 802.15.4 standard and it is left to the upper layers.

MAC Layer Service primitives

The MAC layer provide data and management services to the upper layer (*normally the ZigBee network layer*). Each service is specified by a **set of primitives** which can be of four generic types (*as pictured*

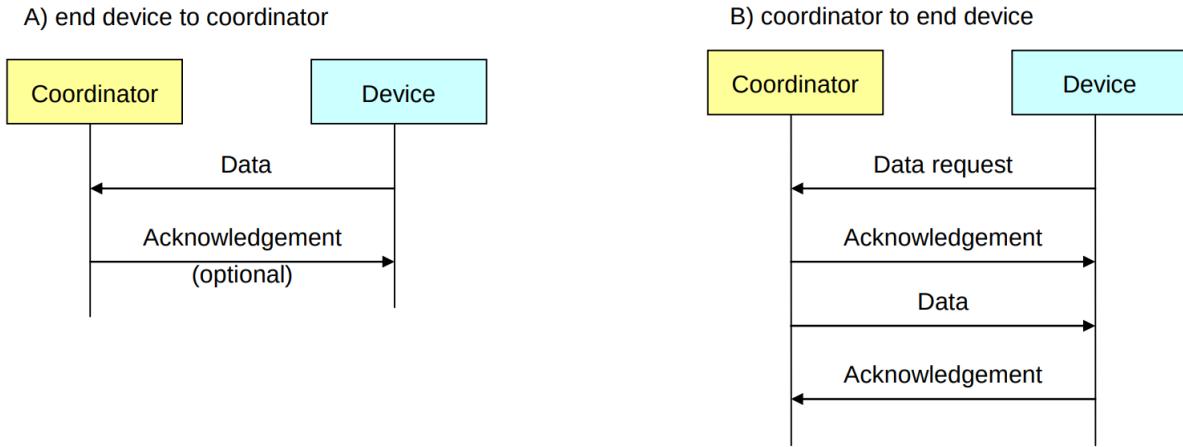


Figure 6.24: Non beacon-based data transfer model

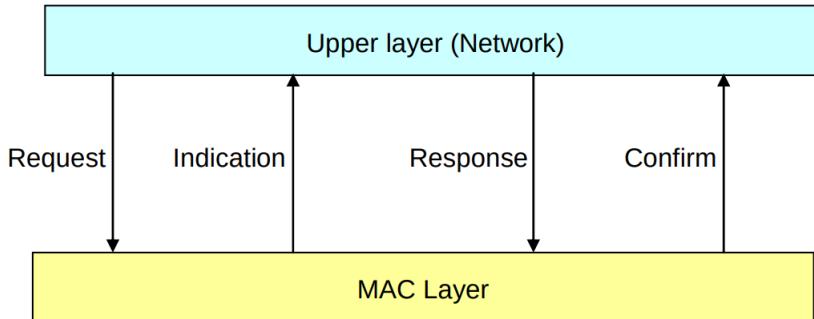


Figure 6.25: MAC Layer services primitive

in 6.25):

- **Request:** It is invoked by the upper layer to request for a specific service;
- **Indication:** It is generated by the MAC layer and it is directed to the upper layer to notify the occurrence of an event related to a specific service;
- **Response:** It is invoked by the upper layer to complete a procedure previously initiated by an indication primitive;
- **Confirm:** It is generated by the MAC layer and is directed to the upper layer to convey the results of one or more service requests previously issued.

Data service The data service comprises one main service which exploits only the **request**, **confirm** and **indication** primitives. The **DATA.request** primitive is invoked by the upper layer to send a message to another device. The result of a transmission requested with a previous **DATA.request** primitive is reported by the MAC layer to the upper layer by the **DATA.confirm** primitive, which returns the status of transmission (*either success or an error code*). The **DATA.indication** primitive corresponds to a "**receive**" primitive: it is generated by the MAC layer on receipt of a message from the physical layer to pass the received message to the upper layer. The overall exchange is sketched in 6.26

Management service The management services of the MAC layer include functionalities for *PAN initialization*, *devices association/disassociation*, *detection of existing PANs* and other services exploiting some of the features of the MAC layer. The main management services are summarized in **Table 6.27**: in the table symbol *X* in a cell corresponding to **service S** and **primitive P** denotes that *S* uses the primitive *P*, while symbol *O* means that primitive *P* is optional for the RFDs.

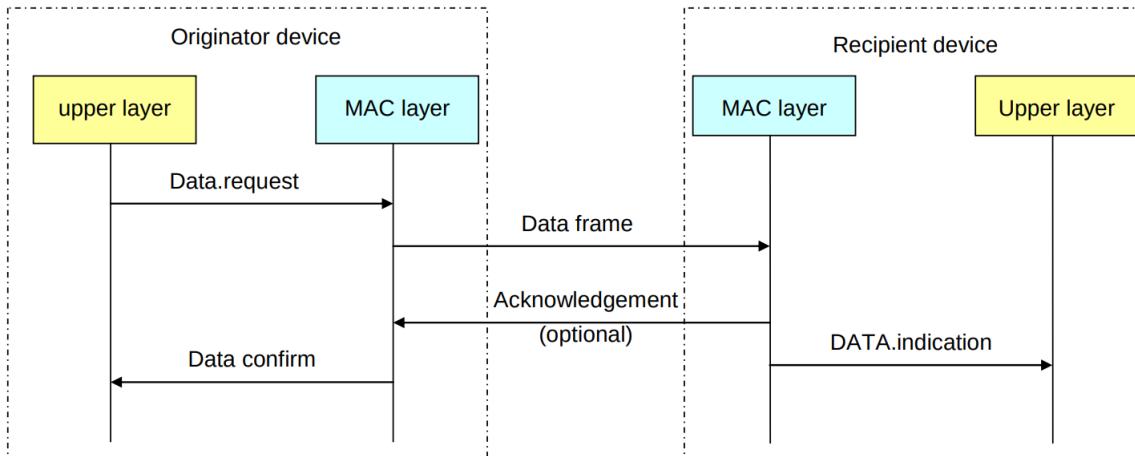


Figure 6.26: Data service exchange using MAC layer primitives

| Name | Request | Indication | Response | Confirm | Functionality |
|---------------|---------|------------|----------|---------|---|
| ASSOCIATE | X | O | O | X | Request of association of a new device to an existing PAN. |
| DISASSOCIATE | X | X | | X | Leave a PAN. |
| BEACON-NOTIFY | | X | | | Provides to the upper layer the received beacon. |
| GET | X | | | X | Reads the parameters of the MAC. |
| GTS | O | O | | O | Request of GTS to the coordinator. |
| SCAN | X | | | X | Look for active PANs. |
| COMM-STATUS | | X | | | Notify the upper layer about the status of a transaction begun with a response primitive. |
| SET | X | | | X | Set parameters of the MAC layer. |
| START | O | | | O | Starts a PAN and begins sending beacons. Can also be used for device discovery. |
| POLL | X | | | X | Request for pending messages to the coordinator. |

Figure 6.27: Management service functionalities

ASSOCIATE service flow example

Let's describe the **ASSOCIATE** service (*as sketched in 6.28*): this service is invoked by a device wishing to associate with a PAN which it have already identified by preliminary invoking the **SCAN** service. The **ASSOCIATE.request** primitive takes as parameters (*among others*) the **PAN Identifier**, the **coordinator address**, the **64-bit extended IEEE address** of the device. The primitive sends an association request message to a coordinator (*either PAN coordinator or a router*): since the association procedure is meant for **beacon-enabled networks**, the association request message is sent during the **CAP period** using **slotted CSMA-CA Protocol**.

The coordinator **acknowledges immediately** the reception of the association messages, however this *acknowledgement does not mean that the request has been accepted*.

On the **coordinator side** the association request message is passed to the upper layers of the coordinator protocol stack (*using the ASSOCIATE.indication primitive*) where the decision about the association request is actually taken. If the request is accepted the coordinator selects a **short 16 bit address** that the device may use later in place of the **64-bit extended IEEE address**. The **upper layers** of the coordinator thus invoke the **ASSOCIATE.response** primitive of the coordinator MAC layer: this primitive takes as parameters the 64 bit address of the device, the new 16 bit short address and the status of the request (*which can be association successful or an error code*). The primitive thus generates an association response command message which is sent to the device requesting association using **indirect transmission**, i.e., the command message is added to the list of pending messages stored on the coordinator.

The **MAC layer** of the device automatically issues a *data request message* to the coordinator after a pre-defined period following the acknowledgement of the association request command. The coordinator

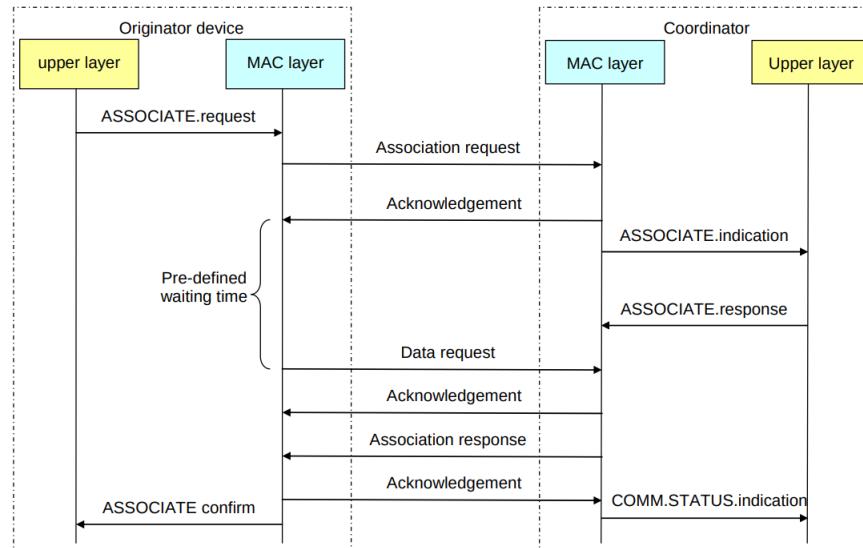


Figure 6.28: ASSOCIATE primitives invocation

then sends the association response command message to the device. Upon receiving the command message, the devices' MAC layer issues a **ASSOCIATE.confirm** primitive, while the MAC layer of the coordinator issues the **COMM-STATUS.Indication** primitive to inform the upper layer that the association protocol is concluded either with success or with an error code.

MAC layer security

The IEEE 802.15.4 MAC layers provides a basic support for security, and it leaves advanced security features (*such as keys management and device authentication*) to the upper layers. All the security services are based on symmetric-keys and use keys provided by the higher layers. The MAC layer security services also assume that the keys are *generated, transmitted, and stored by the upper layers* in a secure manner. Note also that the security features of the MAC layer are optional and the applications can decide when and which functionality they use. The security services provided by the MAC layer are the following:

- **Access control:** allows a device to keep a list of devices (called the Access Control List, or ACL) with which it is enabled to communicate. If this service is activated, each device in the PAN maintains its own ACL and it discards all the incoming packets received from devices not included in the ACL.
- **Data encryption:** uses symmetric cryptography to protect data from being read by parties without the cryptographic key. The key can be shared by a group of devices (typically stored as the default key) or it can be shared between two peers (stored in an individual ACL entry). Data encryption may be provided on data, command, and beacon payloads.
- **Frame integrity:** uses an integrity code to protect data from being modified by parties without the cryptographic key and to assure that the data comes from a device with the cryptographic key. As in the data encryption service the key can be shared by a group or by pairs of devices. Integrity may be provided on data, beacon and command frames.
- **Sequential freshness:** orders the sequence of input frames to ensure that an input frame is more recent than the last received frame.

Chapter 7

Embedded Programming

We can define *embedded systems* as a combination of hardware, software and mechanical component. Mainly they're based on a microcontroller: it's a chip that embeds a microprocessor, memory, IO interfaces and optimized mechanism over IO components. The microcontroller interacts with an electro-mechanical devices to which it provides control. Given this controlling aim, it often has *real-time* constraints.

On the market exists different types of microcontrollers, having different processors, memory and guaranteed performance: they can be specific, also known as *ASICs - Application-Specific Integrated Circuits* or be general purpose, thus adaptive based on the specific application scenario. In terms of capacity, those devices are highly limited with a very small memory footprint of about 16kB of program memory based on flash memory technology and 8kB of SRAM for data. Usually there isn't any type of *file system* thus this features must be provided (*and implemented by libraries*) by the developer itself, detailing the controlling steps of the features.

On these devices usually there aren't any **conventional operating system** but they contain only a set of libraries to be able to execute specific functions. During the compilation, these libraries are static linked to our injected code. Different systems, like *RaspberryPi*, have the features of having a full OS. In this chapter we'll consider of having only devices without an OS.

This implies also that it is not possible to write and compile the code directly on the microcontroller but it's necessary to write the code on a full-fledged computer/OS and compile the given code using a *cross-compiler*, specifying at compilation time the type of system on which the code will run and then upload it on device firmware. The executable file includes the user's code, a set of libraries that implement the interconnection with the hardware and mimic the OS functions.

Usually the code is written in C both for performance reasons (*mainly being able to manipulate low-level registers*): as explained later, the `main` is provided by the *OS* itself. This methodology is known as *co-design*, in which both hardware and software are designed and bundled together, without a proper user interface to interact with them.

Based on the specific purpose, when uploading the binary files into the devices can be necessary to add some more information to be able to carry out peculiar function like the *device identifier* to implement *routing functions*. This scenario shifts the *programming paradigm* usually used on a classical computer: in classic programming we provide a `main` function but in embedding systems the `main` function is provided by the device itself that executes the setup operation, initializing the device and then activates the task that implements the functionalities specific for the device. Two things are embedded in user's code: the *initial device configuration* and the *code to run at runtime*. The first is executed by the `main` function that initializes the specific data structure, then the function calls the user's specific code. This approach allows to simplify the initialization, without repeating the procedure everytime.

Usually the software execution on an embedded system is structured as a **loop cycle** (*as a form of duty cycle*) that includes:

- Reading from transducers
- Taking a decision
- Controlling actuators
- Optionally communicating with other devices

Sampling sensors needs regular intervals to work properly (*as we'll see later*). All these steps are executed in a **control loop** that is a function invoked by the `main` after device initialization: the user only provides

the function to be repeated, the *loop* itself it's embedded in the device control behavior.

Due to its simplicity, the interaction with hardware at low level happen by the code interacting with the components by means of **commands** and **interrupts**: a *command* activates the hardware component (*e.g.* *read from a transducer*) while an *interrupt* signals that the command has been executed.

In parallel with a classical OS, the commands are available in terms of *system calls* invoked by the user's code: if there is a waiting time, the invoking thread is suspended. The interrupts are managed by the OS kernel and re-activates the suspended threads, allowing *async event management* due to the thread/process abstraction and the interfaces exposed by the kernel. So in conventional OS, the programmer's code just sees a library stub function that executes the commands and returns a value: the suspension mechanism of a thread is transparent to the use but requires also a *stack* (*e.g.* *TCB*) for each thread to store its context. This approach guarantees asynchronicity, abstracting the passing time between the requested execution and the final result. For the type of **constrained devices** considered, usually the RAM memory is very small (*e.g.* *Arduino 1 had 4kB RAM*) that serves for communication buffers, variables and all the basic setup functions of the devices. In case of insufficient memory, this device usually adopts mainly two different strategies:

1. **Event loop**: single thread that can be suspended but without including thread scheduling. Mainly used in Arduino 1.
2. **Event based programming and task**: manage directly interrupts, implementing **event handlers** for the actions to be carried out in response to those events. This model is present in TinyOS but also supported by Arduino.

7.0.1 Arduino model

The flow process of Arduino is defined in a *single loop function* that may also invoke other functions: the loop is executed by a **single thread**, without suspension thus the I/O makes the thread in waiting until the IO is complete, but without contemplating any thread scheduling. If you want to *delay* the execution explicitly it's necessary to use *delay* function in the code itself: this mainly happens to impose a strict time in sampling. The waiting periods do not save energy, as already seen.

In figure 7.1 is sketched the event loop model adopted in Arduino.

The ordered steps are:

1. The first **init** call is executed by the device itself and it's used to initialize the device to be able to communicate with the hardware components.
2. At the end of the **init** function, the **main** loop is invoked. This phase contemplates the send of commands to the hardware. When the command has been executed, the Arduino RTS (*Run-Time Support*) signals the end of command communication and return.
3. After the command execution is terminated, the main loop is re-activated by the main thread. If the *active workload* is already done, we can explicitly invoke a **delay** function that sends a command to a timer, suspending the CPU until the timer reactivates the main loop by firing a signal.

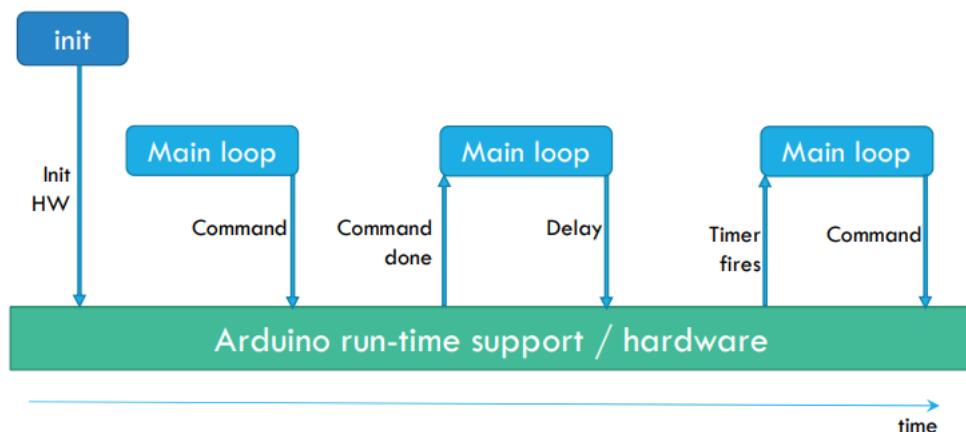


Figure 7.1: Arduino event loop model

The Arduino simple model fits well with simple sensing and controlling activities, including natively also libraries for actuators. Despite it's not born for long, stable and asynchronous communications, recent version includes libraries and HW to support **asynchronous event management** (*requiring to manage communications through serial line*) that is as the foundation of communication between devices. Mainly, sensing activities are synchronous, while communication and specific sensing are usually asynchronous.

7.0.2 Case Study: TinyOS

TinyOS hasn't the concept of event loop but was designed to support **synchronous management of event** by the means of:

- **Commands:** offers functions to program and activate the hardware
- **Events:** it abstract the *interrupts* in form of *upcall*, the programmer has to define handler function for each event or use handler function provided by the RTS.
- **Tasks:** defines **non-preemptive tasks** that are execute sequentially, allowing to manage different independent activities. When the task execution is terminated and there aren't anymore to execute, the CPU goes in *idle mode* so avoiding to store the context of a given task. Still, interrupts should be handled as soon as they arrive by means of an event handler: those events can start a task to perform complex/long computation and can be *pre-empted only by events*. This is done with little overhead using the stack. This is the only exception to task management and it's mainly due to the fact that:
 1. During handler execution it's not possible to receive another interrupt so the second interrupt reception would be delayed
 2. The event handler it's not suitable to implement complex task but only to update data structure, thus complex work must be posted as a **task**. The event handler should be *as short as possible*, allowing to update data structure and give commands to the HW but if the event management require more work, this work must be post as a **task**, as already said.

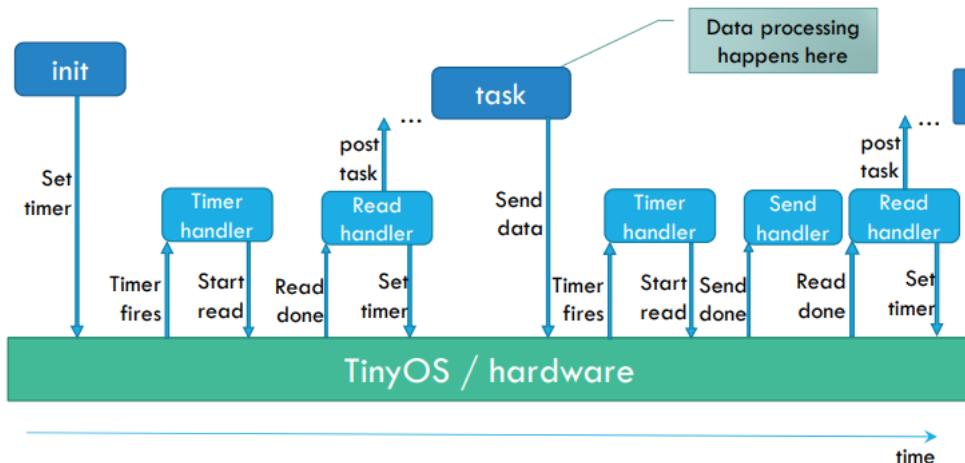


Figure 7.2: TinyOS asynchronous model

The control loop is not provided in the underlying RTS: in the example pictured in 7.2, the timer handler is invoked when the interrupt *timer* is fired. The handler will stop shortly after sending the *reading* command to the RTS: the result is not immediate but will arrive later after the RTS will notify that the operation is complete (*Read done*). Upon reception of the readed values, the reader handler is executed and the process is delegated to a task. In the read handler, alongside posting a task, it's necessary to provide what to do after the task execution and this is done by setting another timer. After the task is completed, it sends data (*transmitting the data to other device*, which takes time and it's not immediately performed; when complete will be signaled by the RTS with "Send done") and then the RTS will signal that the timer will fire the end signal. After a task is performed, the operations are repeated thanks to the event-handler chain association. The general abstraction is sketched in figure 7.3.

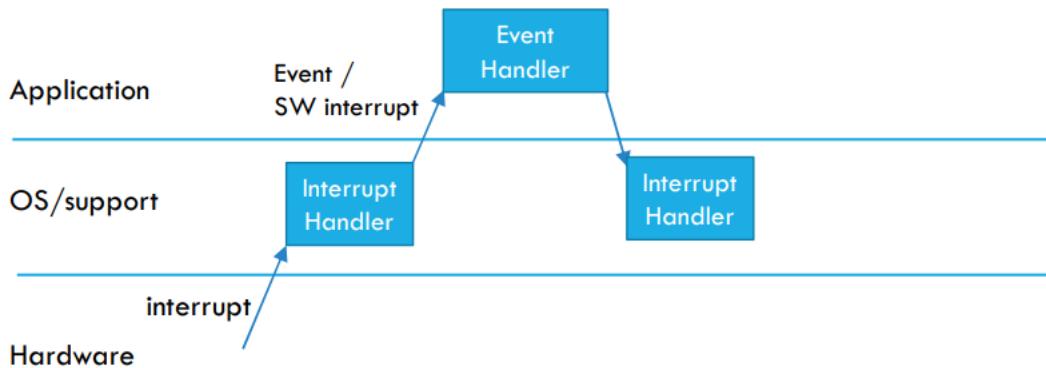


Figure 7.3: Simple abstraction: interrupt handler invoke event handler function

The *interrupt handler* it's only an invokation of the event handler and *must be the simplest one*: it's still possible to invoke a command in the event handler but **that command must relate to a different hardware component from which the interrupt was received**. Manipulate the same data structure of components from which the interrupt was received can lead to an **incosistent state**. This mostly

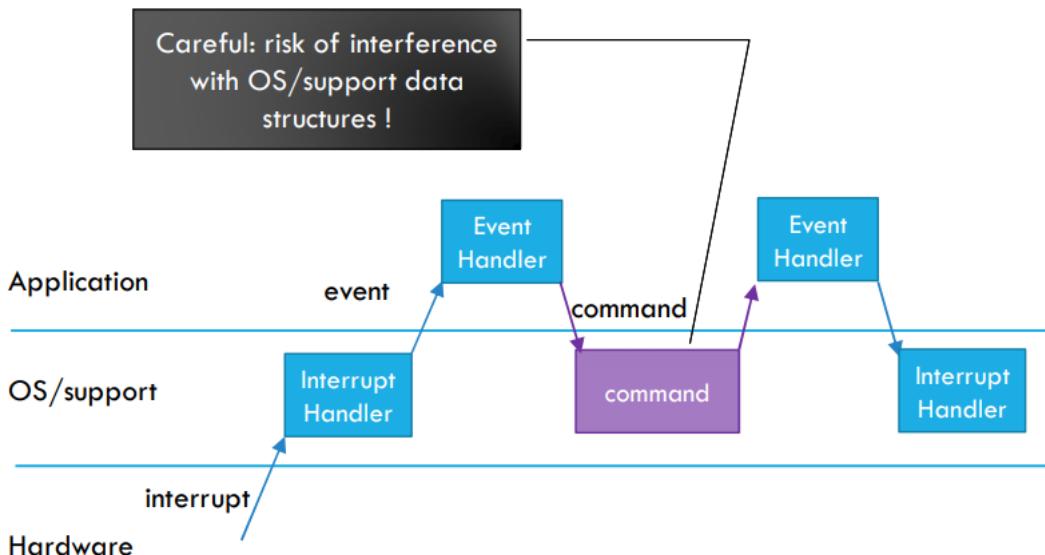


Figure 7.4: Risk of concurrent modification of RTS DS

justify the introduction of task event management: this allows to strictly decouple the interrupt handler from the event handler, adding another layer of abstraction, as sketched in 7.5.

To support asynchronous communication, Arduino provides an **interrupt** mechanism to be able also to go in *low-power* mode: this allows to avoid to save state of current process. The key idea, explained in detail later, it's that *interrupts* should be handled as soon as they arrive by using event handlers. The event handlers should be as short as possible, allowing to *update data structure, send commands to hardware components (not all components)*, obtaining a model similar to TinyOS's behavior.

7.0.3 Case Study: Arduino

Arduino is an **open-source electronics prototyping platform** based on flexible, easy-to-use hardware and software. It comprises three elements: a board, the IDE and the reference forum.

The following board 7.6 is *Arduino Uno* based on *AVR Arduino microcontroller Atmega328* with:

- SRAM 2KB (data)
- EEPROM 1KB

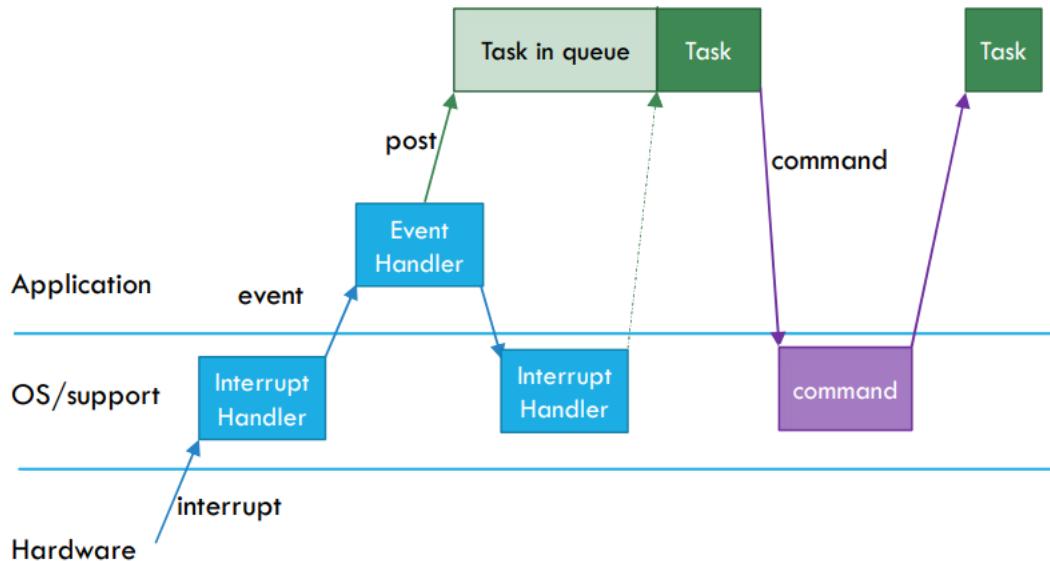


Figure 7.5: TinyOS task abstraction solution to concurrent modification of RTS data structure

- Flash memory 32 KB (program)
- 14 digital pins (both input and output)
- 6 analog pins (only input)
- other pins for power

The circuit is powered with 6V, so the value 1 correspond to 6V/1024. The ADC converts the voltage in 10 bits.

Some terminology:

- *"sketch"*: a program you write to run on an Arduino board
- *"pin"*: an input or output connected to something. (*e.g. output to an LED, input from a knob*).
- *"digital"*: value is either **HIGH** or **LOW**. (*aka on/off, one/zero*) (*e.g. switch state*)
- *"analog"*: value ranges, usually from 0 – 1023. (*e.g. LED brightness, motor speed, etc.*)

The **variables** already defined:

- *Constants*:
 - level of energy (**HIGH**, **LOW**)
 - mode of pin (**INPUT**, **OUTPUT**, **INPUT_PULLUP**)
 - `led13(LED_BUILTIN)`
- *Types*: word, strings, etc;
- *Variable scope and qualifiers*: **volatile**;
- *Usefulness*: `sizeof()`

The overall *structure* it's based on two functions:

- `void setup()`...: called when a sketch start. Will run only once.
- `void loop()`...: user defined code.

The **builtin function** that can be used in `loop()` are:

- **Digital functions**: `pinMode()`; `digitalRead()`; `digitalWrite()`;

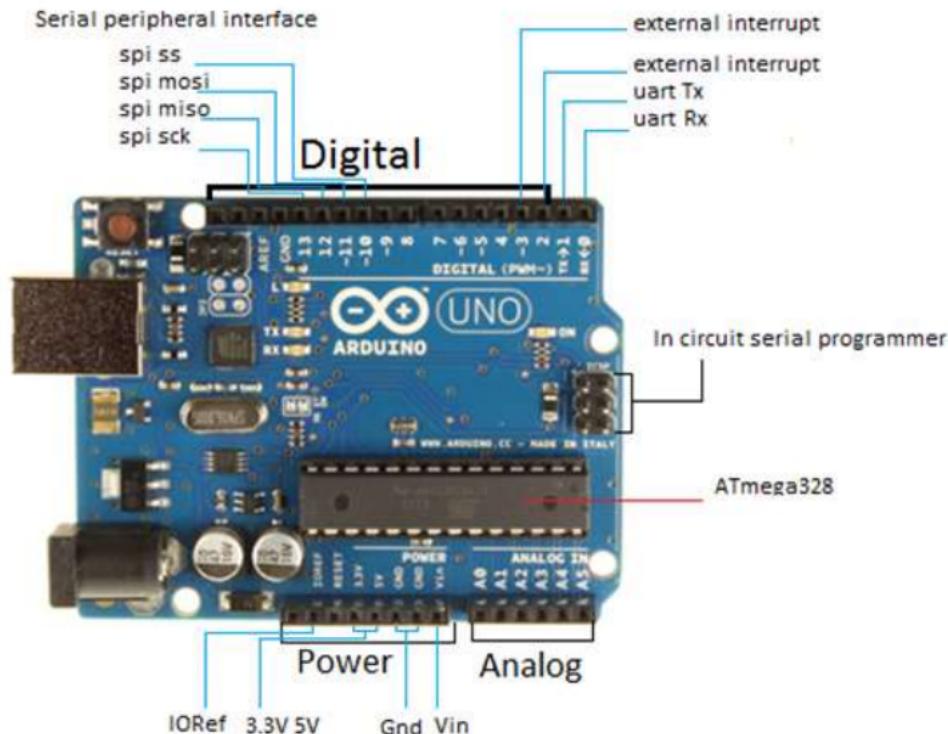


Figure 7.6: Arduino Uno analog/digital pins and power pins

- **Analog functions:** `analogReference()`; `analogRead()`; `analogWrite()`;
- **Advanced I/O:** `tone()`; `noTone()`; `shiftOut()`; `shiftIn()`; `pulseIn()`;
- **Time:** `millis()`; `micros()`; `delay()`; `delayMicroseconds()`;
- **Math/trigonometry:** `min()`; `max()`; `abs()`; `sin()`; `cos()`;
- **Random Numbers:** `randomSeed()`; `random()`;
- **Bits and Bytes:** `lowByte()`; `highByte()`; `bitRead()`; `bitWrite()`; `bitSet()`; `bitClear()`; `bit()`;
- **External Interrupts:** `attachInterrupt()` `detachInterrupt()`;
- **Interrupts:** `interrupts()`; `noInterrupts()`;
- **Communication:** `Serial`; `Stream`;

Here an example of *analog and digital read*:

```
// Reads an analog input on pin 0 and converts it to voltage;
// Reads a digital input on pin 2;
// When input on pin 2 is high prints voltage in the serial and switches the led.
const int buttonPin = 2; // the number of the pushbutton pin
const int ledPin = 13; // the number of the LED pin
int buttonState = 0; // variable to read the pushbutton status
void setup() { // runs once when you press reset
    Serial.begin(9600); // init serial line at 9600 bps
    pinMode(ledPin, OUTPUT); // init. the LED pin as an output
    pinMode(buttonPin, INPUT); // init. pushbutton pin as an input
}

void loop() {
    // reads the state of the pushbutton value:
    buttonState = digitalRead(buttonPin);
    if (buttonState == HIGH) { // if the pushbutton is pressed
        digitalWrite(ledPin, HIGH); // turns LED on... // ... and reads the input (in
        [0,1023] on analog pin 0:
    }
}
```

```

        int sensorValue = analogRead(A0); // Convert analog reading to a voltage (0-5V)
        :
        float voltage = sensorValue * (5.0 / 1023.0);
        Serial.println(voltage); // print out the voltage
    }
    else digitalWrite(ledPin, LOW); // turns LED off
}

```

Exercise Consider the following fragment of Arduino code:

```

void loop() {
int sensorValue = analogRead(A0);
Serial.println(sensorValue);
delay(100);
}

```

Compute its duty cycle assuming that:

- Reading an analog value takes 2 milliseconds
- Transmitting along the serial line takes 5 milliseconds

7.0.4 Arduino interrupts

As in TinyOS, allows management of **asynchronous events**: this is possible by providing an interface to manage *interrupts*, allowing async access to sensor data and actuators. There are three types of interrupts:

- **External**: a signal outside, connected to a pin
- **Timer**: internal to Arduino (*e.g. timer feature, managed by RTS*)
- **Device**: an internal signal coming from a device (*ADC, serial line, etc*). Interrupts are managed by RTS of Arduino. For **external interrupts**, the support is provided by Arduino at run-time by declaring `attachInterrupt(interrupt#, func-name, mode)`; in the `setup()` function (*Shown later*).

Arduino provides only two *external interrupts pins*, respectively *INT0* and *INT1* which are mapped to **pins 2 and 3**: they can be set to trigger on **RISING** or **FALLING** signal edges, on **CHANGE** or on **LOW** level. The triggers are interpreted by hardware, and the interrupt is very fast. The following are the possible values of `mode` parameter:

- **RISING**: the interrupt occurs when the pin passes from **LOW** to **HIGH** state. (*Shifting from 0V to 5V*).
- **FALLING**: the interrupt occurs when the pin passes from **HIGH** to **LOW** state
- **CHANGE**: the interrupt occurs when the pin switches state
- **LOW**: the interrupt occurs whenever the pin has **LOW** state. Not necessary a change of state. If it remains **LOW** the interrupt occurs again
- **HIGH**: the interrupt occurs whenever the pin has **HIGH** state. Not necessary a change of state. If it remains **HIGH** the interrupt occurs again.

The connection pictured in the *breadboard* sketched in 7.7 implement:

- A **button** to digital input 2: with $10\text{k}\Omega$ resistor
- A **led** to digital output 7: with 220Ω resistor

The code of the two function `setup` and `loop` is the following:

```
/** * test interrupt */
volatile int greenLed=7;
volatile int count=0;
void setup() {
    Serial.begin(9600);
    pinMode(greenLed, OUTPUT); //set green light as output
    digitalWrite(greenLed, LOW); //write LOW to digital pin 7
    attachInterrupt(0, interruptSwitchGreen, RISING); // 0 because it is pin 2
}
```

The `Serial.begin(speed)` specify the data rate in bits per second for serial data transmission: the rate must be the same setted in the Serial Monitor so be sure to be able to receive the data at the same rate of emission.

```
void loop() {
    count++;
    delay(1000);
    // interrupts are received
    // also within delay!
    Serial.print("Count: ");
    Serial.println(count);
    if (count == 10) {
        count = 0;
        digitalWrite(greenLed, LOW); //turn off the green light, resetting the counter
        Serial.println("Counter reset");
    }
}

void interruptSwitchGreen(){
    digitalWrite(greenLed, HIGH); //turn on the green light
    count=0; //reset the counter
    Serial.print("Count: ");
}
```

The first thing we can notice is that the two variables we define (`greenLed` and `count`) above the `setup` function are declared as *volatile*. If you don't declare them as volatile the processor would allocate them in a register but this computer would mean that when one of these variables is updated, the update would have no effect in the loop where it is used. For the `count` variable there is the risk of concurrent modification both by the `loop()` function and the interrupt handler function `interruptSwitchGreen()`: if `count` is set to 0 and was not declared as *volatile*, the modification would be noticed by the two different function that manipulate the variable's value. In this way the compiler is forced to store the variable in memory, there is also another variable which is `greenLed` which is volatile even if it has never been written, it is in practice a *constant* and therefore in this case they could also avoid call it volatile. The code turns on a led which is initially off. In the `setup` code we manage an interruption that when arrive turn on the led, in the `loop` function then this led is only turned off and to turn it off we go to reset a counter.

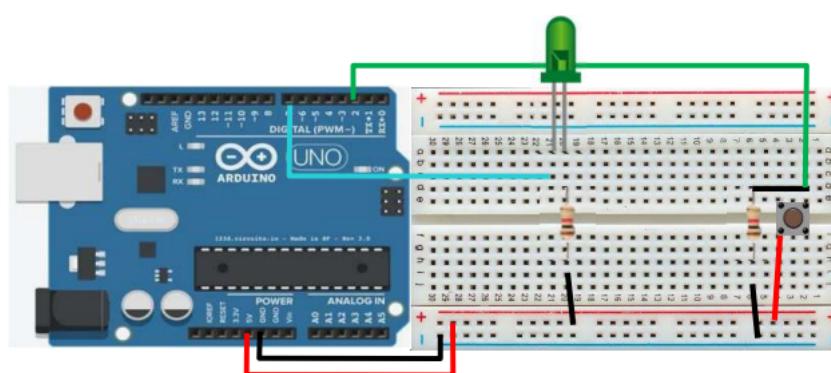


Figure 7.7: Example breadboard with button, led and two resistors

Chapter 8

Energy Harvesting

Energy harvesting comes to a wide range of topics like *energy harvesting IoT architecture, properties of the energy source, battery and load and energy neutrality*.

The IoT device that we consider are battery-powered (*either rechargeable or changeable*). The battery life can be increased, for example by enlarging batteries despite it is come with major costs. Another point of view is to extends device lifetime but reducing the computational ability and limited communications. Those two are the main pathways to prolong the battery life: both can be applied. The decisions regarding the battery are done at the beginign while the duty cycle structure can be *modified*, by making it *with a dynamic behavior*: adapting the DC can prolong the lifetime, by respecting the device functional requirements.

The alternative is give by **energy harvesting** which consists in converting energy from one from to another. The source of energy can have different properties (*periodic, non-predictable, etc*): after identifying the source, the tradeoff between how acquiring it physically and the effective utilization in the device must be designed.

The energy harvesting implies also a complex design of the device, allowing to parametrize more features of the device.

8.1 Harvesting architectures

The **energy source** is the source to be harvested while the **harvestng source** is the technology used to extact energy from the environment. In most of the cases this sources have a not controllable behavior so the device's harvesting source must take the behavior into account. The **load** is the consumption of energy in a device due to its activities: it varies over time based on the specific activities the device is executing at a time. Overall, an **Harvesting system** is a system that supports a variable load from a variable energy harvesting source. It allows to power the device even in a period when the energy source does not provide energy by storing it. To match energy supply and load, two main approaches are used:

1. **Energy buffer:** as a rechargeable battery or a supercapacitor
2. **Adapting load:** align the workload to the actual energy supply, implying also reducing functions

Neither of these approaches may be sufficient because the *load* cannot be reduced arbitrarily (*having a dynamic DC it's a complex task to perform*) and the *buffer* one it's not the ideal solution because there is no *infinite storage* and must be also considered *energy leaks*.

In a simplified scenario 8.1, we have two components:

There are problems to be addressed: the device can be **abruptly turned off** and the state management of internal state of the device must be addressed, exploiting the energy to mantain consistency and resume operation later. Another issue is that the energy supply can be the bare minimum, oscillating between the threshold to work properly.

8.1.1 Direct harvesting model

In the simplest scenario **no energy buffer is provided** to store energy thus the excess supply is *wasted*: the power produced immediately is consumed so, referring the diagram 8.2, the device can operate anytime at time t when: $P_s(t) \geq P_c(t)$ where:

- $P_s(t)$ is the **power harvested** at time t

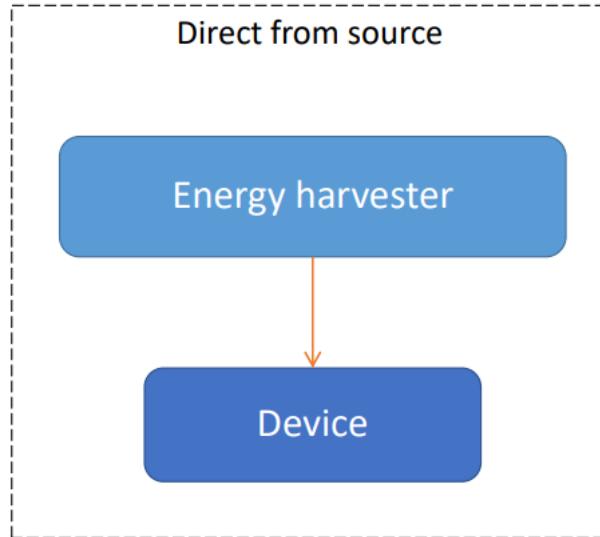


Figure 8.1: Scenario overview

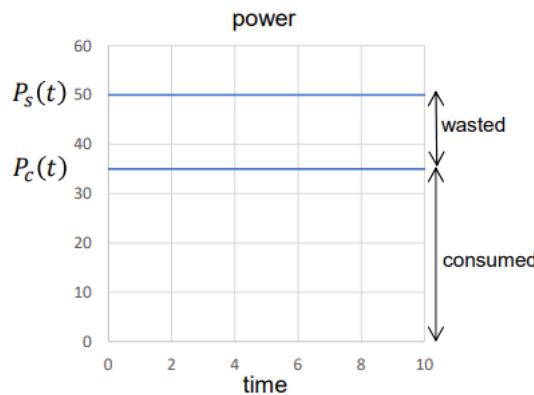


Figure 8.2: Energy base model

- $P_c(t)$ is the **power consumption on the load** at time t

The *waste of energy* is given by the following conditions:

- whenever $P_s(t) < P_c(t)$: the device is turned *off* due to insufficient energy
- whenever $P_s(t) > P_c(t)$: $P_s(t) - P_c(t)$ is in excess

8.1.2 Energy buffer model

Another model is **with energy buffer** 8.3: with this model, in principle, the device can work anytime but the reality is different.

In this model the energy is harvested whenever possible and stored for future use. The *residual energy* is stored and it is used later when either there are no harvesting opportunities or the device task require more energy.

The problem is that no exists an **ideal energy buffer** that can *store any amount of energy, does not leak energy over time, has a decreasing charging efficiency* $\mu = 1$ that in the real world is below 1. The device can operate any time if, for every time interval $(0, T]$:

$$\int_0^T P_c(t) dt \leq \int_0^T P_s(t) dt + B_0 dx$$

where B_0 is the initial charge of the *ideal supply*. The integral express the **amount of energy the device has consumed** (*consume power multiplied by time*), the same is for the energy supply, as pictured in ??.

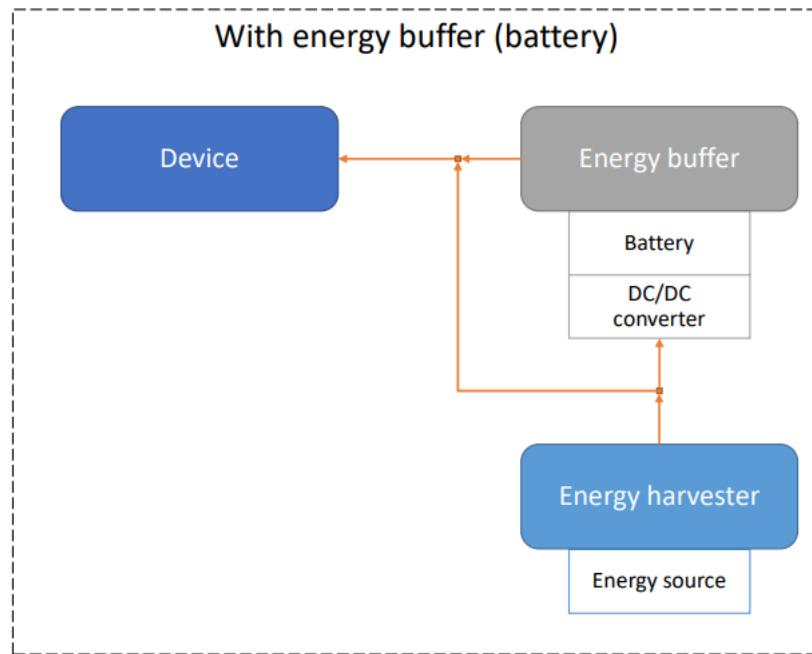


Figure 8.3: Energy buffer model

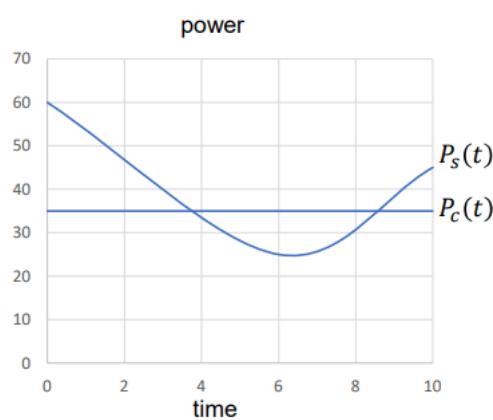


Figure 8.4: Power diagram with buffer

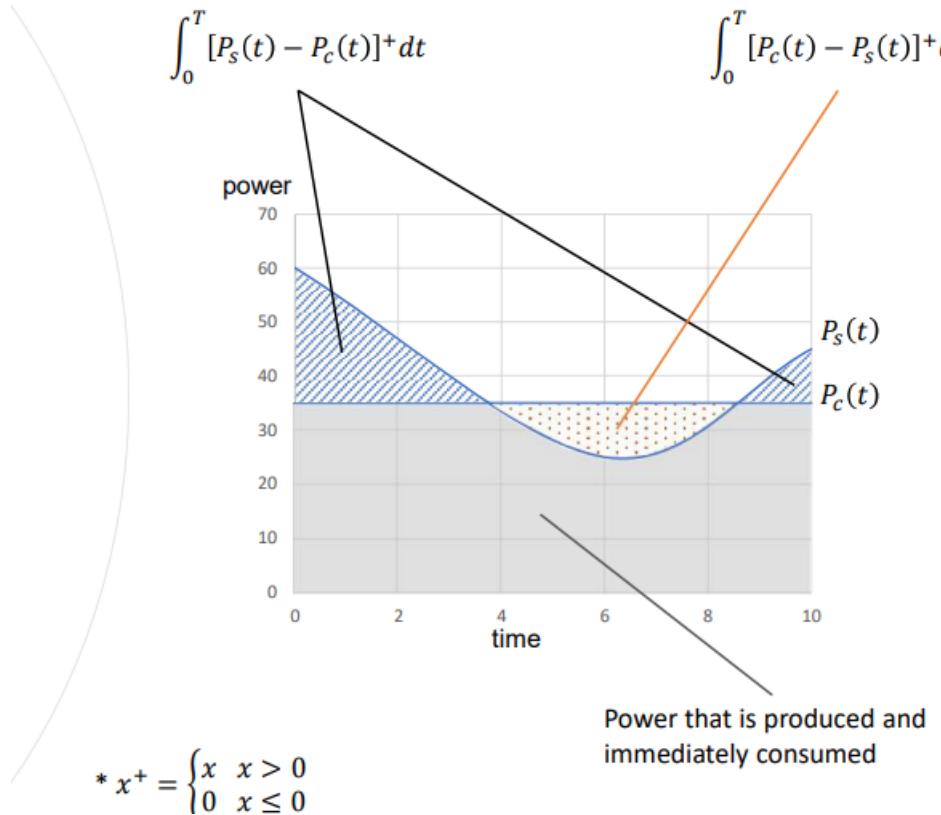


Figure 8.5: Buffer model expanded

This model does not consider the point previously cited about the ideal energy buffer like *energy leaks and charging efficiency*. The diagram in ?? picture the *energy storing* using the previous model:

As shown, we can compute how much power we are using from the buffer: this is done only for values of x (or the difference in the integral) over 0.

8.1.3 Non-ideal energy buffer model

This model still refer to **ideal buffers** for some of the parameters that define the behavior. Differently, *real-world* buffers are defined by others adjunctive parameters:

- B_{max} : maximum battery capacity (*energy buffer size*)
- B_t : battery charge at time t
- $P_{leak}(t)$: be the leakage power of the battery at a time t
- $\mu < 1$: the charging efficiency of the battery
- $P_s(t)$: power harvested at time t
- $P_c(t)$: load at time t
- B_0 : initial charge of the buffer
- **Rectifier function:**

$$x^+ = \begin{cases} x & x > 0 \\ 0 & x \leq 0 \end{cases} \quad (8.1)$$

The energy conservation leads to the following equation $\forall T \in (0, \infty]$:

$$B_t = B_0 + \mu \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{leak}(t) dt \geq 0$$

where:

- The first integral accounts for the **energy produced in excess** (*thus not consumed*) that goes to buffer
- The second accounts for the *energy consumed from the buffer* (*when the production was insufficient*)
- The last integral accounts for **buffer energy leak**

In the previous model, what is still missing is the *buffer limit*: is necessary to guarantee that the buffer capacity is not exceeded or, better, to guarantee that there is no *wasted energy*. This can be formalized as by imposing that $\forall T \in (0, \infty]$, the value of B_{max} is:

$$B_{max} \geq B_0 + \mu \int_0^T [P_s(t) - P_c(t)]^+ dt - \int_0^T [P_c(t) - P_s(t)]^+ dt - \int_0^T P_{leak}(t) dt$$

8.1.4 Exercise

Consider an *harvest-store-use* device with a **non-ideal energy buffer**:

- In the interval $[0, 10\text{sec}]$ the energy production is constant and produces $P_s(t) = 80mA$
- In the interval $[0, 4\text{sec}]$ the load is $P_c(t) = 150mA$
- In the interval $[4\text{sec}, 10\text{sec}]$ the load is $P_c(t) = 20mA$
- The charging efficiency is $\mu = 95\%$
- The battery charge at time 0 is $400mAh$
- The energy leak of the battery is negligible Compute the battery charge at times 4sec and 10sec .

Chapter 9

Wireless Networks

9.0.1 Wireless networks

Wireless allows to replace cables in communications in cyber-physical systems that can embed computers in physical objects. Wireless networks are networks of **hosts** connected by **wireless links**: we refer to host as end-system devices that run application (battery-powered, small or mobile). There are two modes of operations:

- **Infrastructure**: e.g. by providing an Access Point that can provide a link to a cabled infrastructure and offer various services
- **Ad hoc networking**: there is no central coordination so they must somehow coordinate themselves and manage properly shared resources

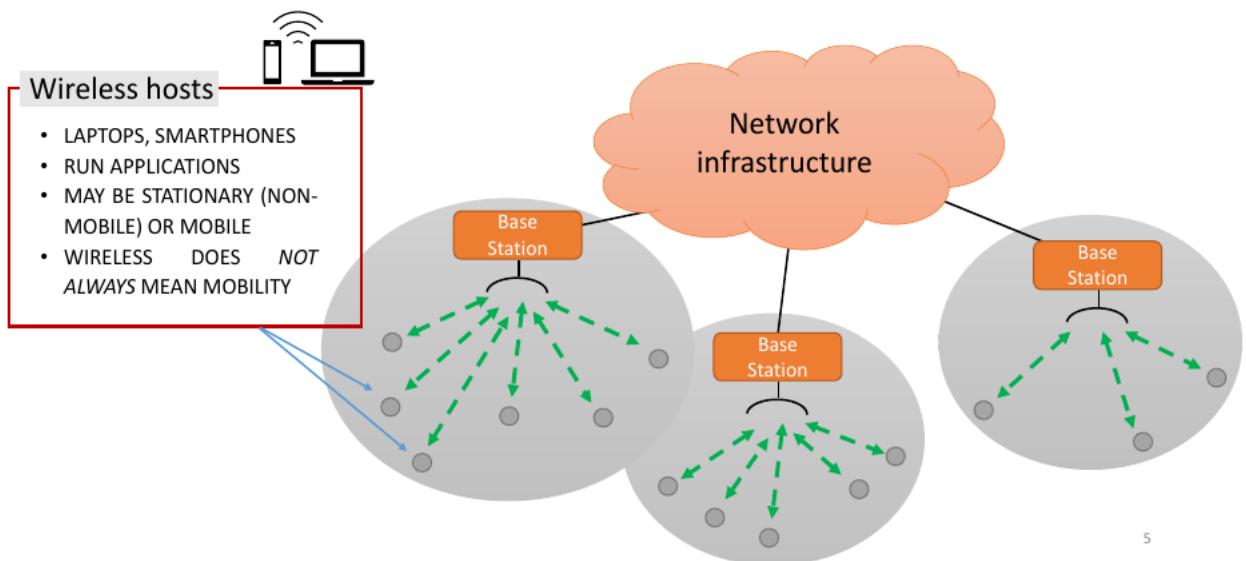


Figure 9.1: undefined undefined

The network infrastructure can be a mix of cabled and wireless infrastructure. The devices connected to the base station can be both mobile or not; the same can happen with the type of links that can be cabled or wireless, depending on the scenario. The **base station** have a relevant role in structured network: it's responsible to manage the resources of the *physical medium*. They usually are represented by cell towers or Access Point. The **wireless links** allows to connect mobile to base station and can be used as backbone links. In **infrastructure mode** base station connects mobiles into wired networks. Mobile can change base station providing connection into wired network.

Characteristic of wireless links The category 802.11 refers to the Wifi family of protocols.

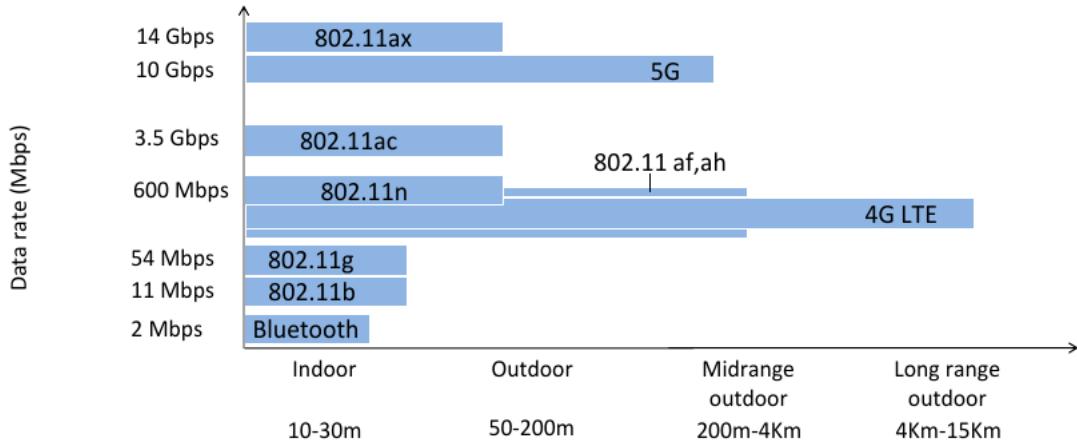


Figure 9.2: General wireless schema

9.0.2 Wireless Network taxonomy

We distinguish the network type based on two category, as shown in the table 9.3.

An example of *infrastructure, single hop* is the mobile connection or through the WiFi. The schema being *no infrastructure, multiple hosts* is used when different devices needs to exchange information and makes routing decisions among them, without relying on a fixed infrastructure.

9.0.3 Charateristics of wireless communications

There are foundamental differences between wired and wireless links:

- **Decreased signal length:** radio signals attenuates as it propagates trought matter causing **path loss**
- **Interference:** wireless frequency can be shared by other wireless devices by specification but engines or appliances may interfere as well.
- **Multipath propagation:** the reflection of the wave on context object can be distorted and change the origianl signal that it's necessary to rebuild

Communication Environment metrics

Some important metrics in **communication environment** are:

- **SNR - Signal to Noise Ratio:** measured at the received. The SNR *bit error rate (BER)* is the probability that a transmitted bit is received in error at the receiver. Based on different modulation technique we can achieve a lower or higher data rates, with different BER. Refer the results in 9.4.

| | Single hop | Multiple hops |
|-------------------------------|--|--|
| infrastructure (e.g., APs) | host connects to base station (WiFi, WiMAX, cellular 3G,4G,5G) which connects to larger Internet | host may have to relay through several wireless nodes to connect to larger Internet: MESH networks |
| no infrastructure | no base station, not necessarily connection to larger Internet (e.g. Bluetooth) | no base station, no connection to larger Internet. May have to relay on other nodes to reach a given wireless node (ZigBee, ad hoc, VANET) |

Figure 9.3: undefined undefined

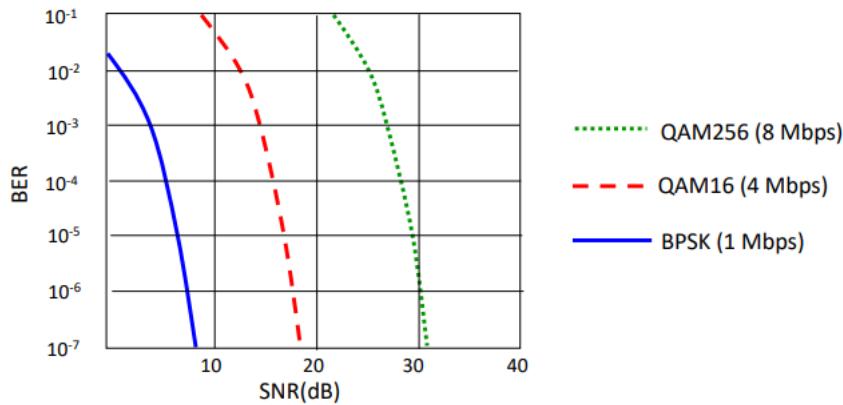


Figure 9.4: BER/SNR comparison between BPSK, QAM16 and QAM256

BPSK have a lower data rate and if we increase the SNR by increasing the *energy of the signal*, we lower the BER. For QAM16: you need more energy to get the same BER than BPSK at a certain level, as you send more information.

Obstacles

Signal attenuation or obstacles limit transmission ranges: the situation sensed by a node, given that there may be a wall, which prevents two devices to detect each other, while they can talk with a central host. According to how those host are positioned in distance:

- A has large signal strength to B, but when we arrive at B the energy of the signal decrease and B is able to detect it.
- With higher distance A is not able to detect C signal. Also since B may receive two different signals at the same time, it may be difficult for it to reconstruct a signal. With the distance the amplitude of the signal decrease but despite that, the signal from C to B is received, the same from A to C but the intersection of receiving two signals from two different sources to B can be problematic.

The intended scenario is pictured in 9.5

Some of wireless network challenges are that nodes have **limited knowledge** regarding a terminal that cannot hear all the others or **hidden/exposed terminal** problems (*see later*). Another main problem is **Mobility or Failure of terminals** in which they move in the range of different base station. **Limited terminals** regards the battery life, memory and processing. In 9.6 is pictured the protocol stack that we'll describe.

Let's describe the **MAC layer** for wired network. We start from simple assumption like:

1. a **single channel** for all communications
2. all stations can transmit on it and receive,
3. if frames are sent simultaneously on the channel the resulting signal is *garbled* and a **collision** is generated, generally all stations can detect collisions. Different protocol are at this level, like: *ALOHA*, *slotted ALOHA*, *CSMA*, etc.

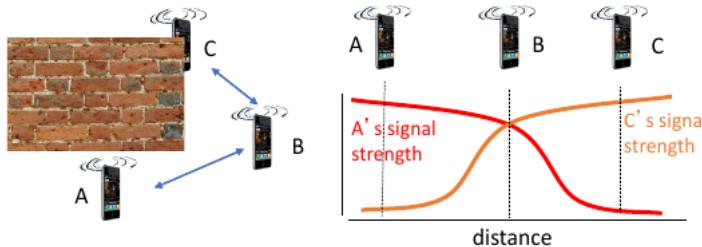


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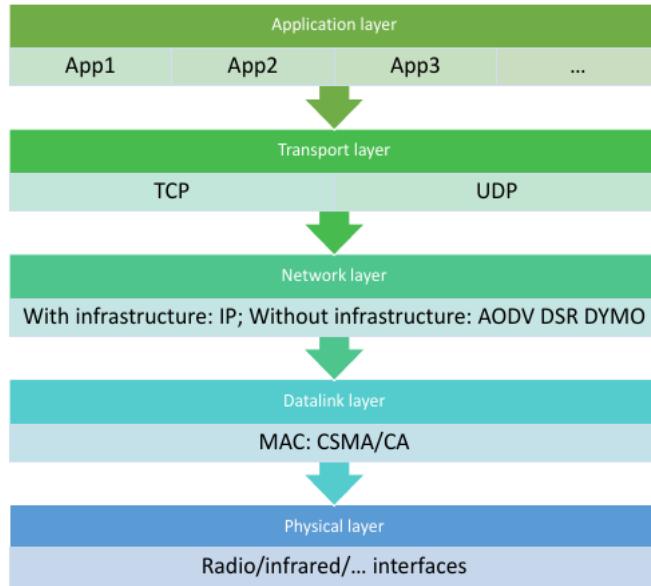


Figure 9.6: undefined undefined

CMSA/CD - Carrier Sense Multiple Accesses with Collision Detection

The basic idea is that when a station has a frame to send, it first listens to the channel to see if anyone else is transmitting; if the channel is **busy**, the station waits until it becomes **idle**. When a channel is **idle**, the station transmits the frame: if a *collision* occurs the station waits a random amount of time and retransmits.

In the scenario shown in 9.7, the signal is transmitted at time t_0 because the channel was *idle* but at time t_1 another signal (*the red one*) is transmitted by generating a collision on the channel. So in CSMA/CD a station **abort its transmission as soon it detects a collision**: if two stations sense the channel idle simultaneously and start transmitting, they quickly abort the frame as soon as a collision is detected. It's widely used on LAN In MAC sub-layer like *IEEE 802.3 Ethernet*.

The CSMA/CD behaviour can be described by defining:

- T is the *time required to reach the farthest station*
- It takes a minimum of RTT time ($2*T$) to detect a collision

So we can consider a **slotted system** 9.9 with *mini-slots* of duration 2τ , so if a node starts transmission at the beginning of a mini-slot, by the end of the slot either two things can happen:

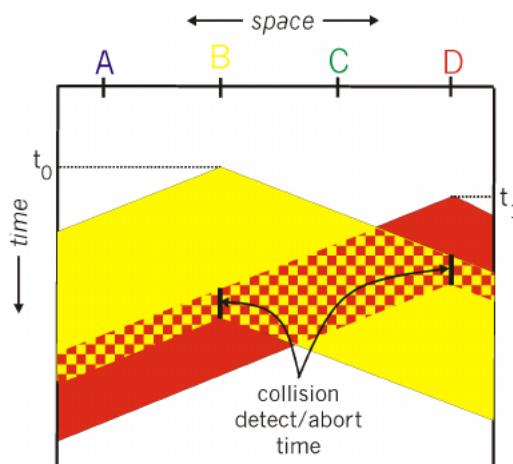


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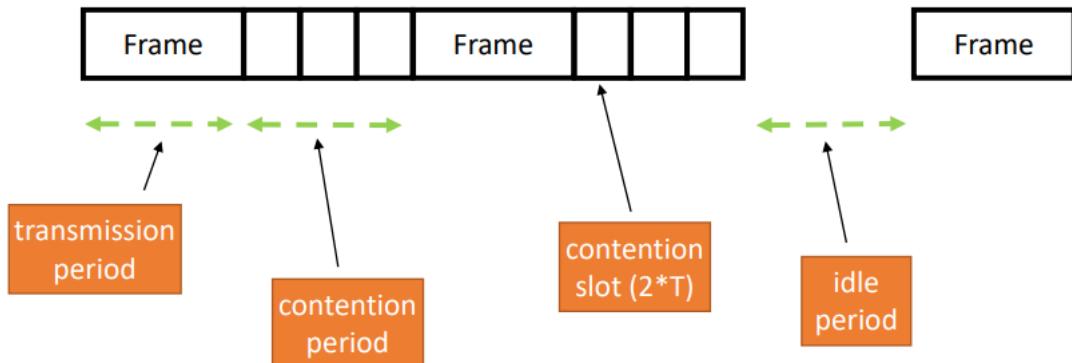


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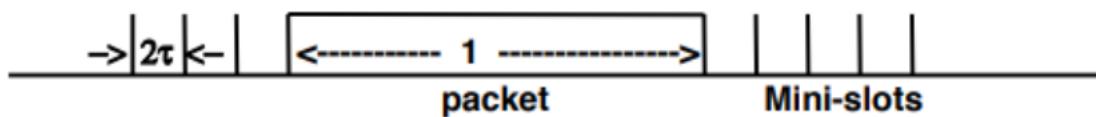


Figure 9.9: undefined undefined

1. No collision occurred and the rest of the transmission will be uninterrupted (because now the channel is occupied and this condition is detectable by other nodes)
2. A collision occurred but by the end of the mini-slot the channel would be idle again
So a collision at most affect *one* mini-slot.

Binary Exponential Backoff The algorithm used by CSMA/CD to retry retransmission is called **Binary Exponential Backoff** and defines how much time the station must wait before trying transmitting again.

The time after a collision is divided in **contention slots**: the length of a slot is equal to the *worst case round propagation time* (*so if T is the time to reach the most distant station, the length will be $2T$*). After the first collision each station waits 0 or 1 slot before trying again: so after collision i the nodes chooses x at random in the interval $[0, 2^i - 1]$ so that it skips x slots of time before retrying the transmission. Number at hands, after:

- 10 collisions, interval is frozen at $[0, 1023]$
- 16 collisions, failure is reported to upper levels (*retransmission is aborted*).

Why does this approach not work with wireless network? The algorithm described is suitable in **wired networks** but not in **wireless scenarios**. The main problems are:

1. The transmitted sides is sensing if there is another sending a signal in the channel. In wireless is not possible to both transmit and receive (*at least with 1 antenna*), the problem is that you transmit your signal with high energy, the one you receive has low energy, so it happens that you do not recognize the other. With wireless transceiver you cannot detect collision.
2. If a node is out of range, it may not note a collision, this problem is called **hidden terminal problem**
3. Exposed terminal problem:

9.0.4 Hidden terminal problem

The problem is sketched in 9.10.

The node A can receive and transmit to B because B is in his radio range. The same happens to C: can transmit and receive to/from B and D because they are in C's radio range. The problem arises when A is sending to B and C senses the medium: *it will not hear A because it's out of C's range* so if C starts to transmit to anybody (*either B or D*) this generates a collision at B.

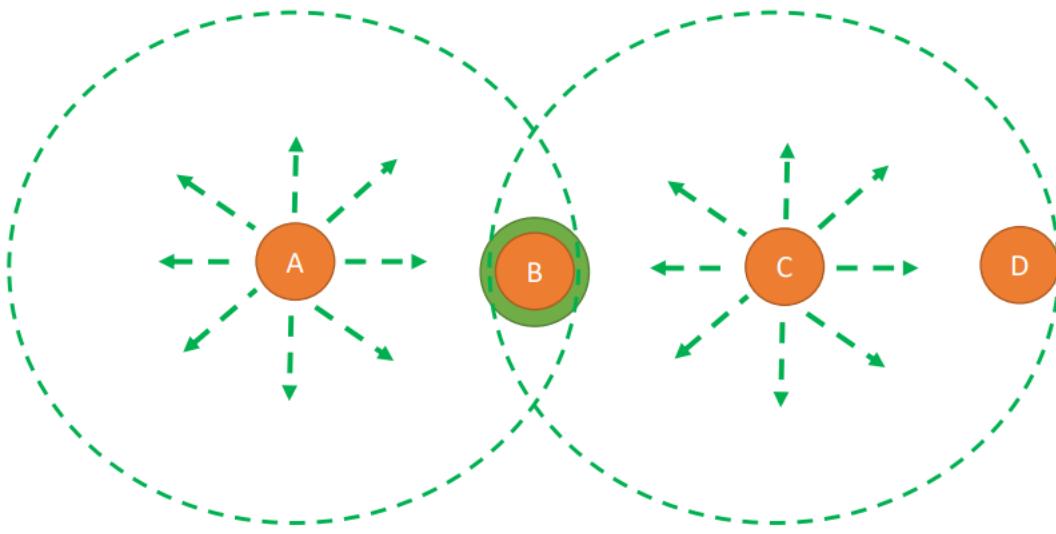


Figure 9.10: undefined undefined

- **Hidden terminal problem:** C is not able to detect a potential competitor because it is out of range: a collision happens at B (*the receiver*). For the same reason A does not detect the collision so **C is hidden** with respect to the communication from A to B. Usually this problem arises when *two or more stations which are out of range of each other transmit simultaneously to a common recipient*.

9.0.5 Exposed terminal problem

The **Exposed terminal problem** is sketched in figure 9.11.

The node B is transmitting to A: the node C wants to transmit to D so C senses the medium and because detect the B → A transmission it concludes that cannot trasmit to D. But, **the two transmission can actually happen in parallel**.

- **Exposed terminal problem:** C hears a transmission. C does not send to D despite its transmission would be Ok. So **C is exposed** with respect to the communication from B to A. Usually this problem arises when *a transmitting station is prevented from sending frames due to interference with another transmitting station*.

The solution on wireless network is represented by **MACA Protocol**.

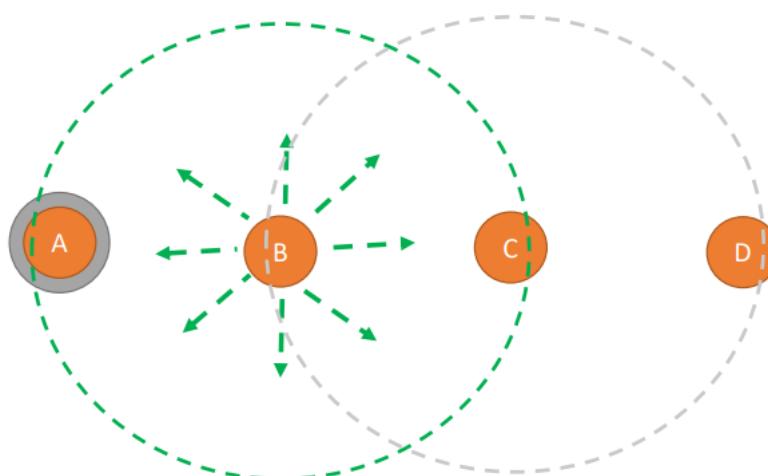


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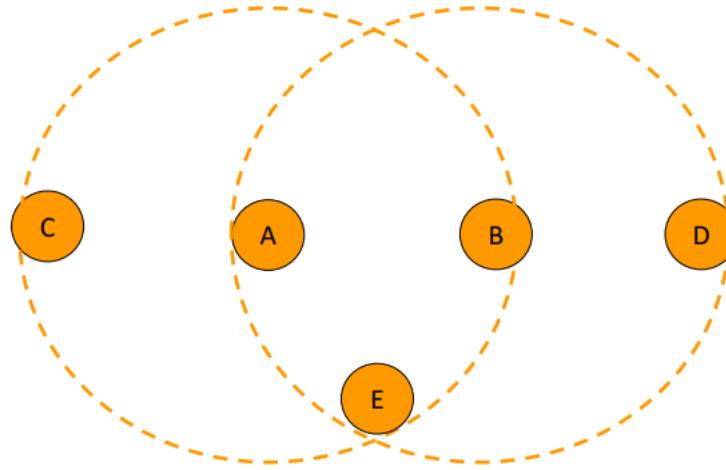
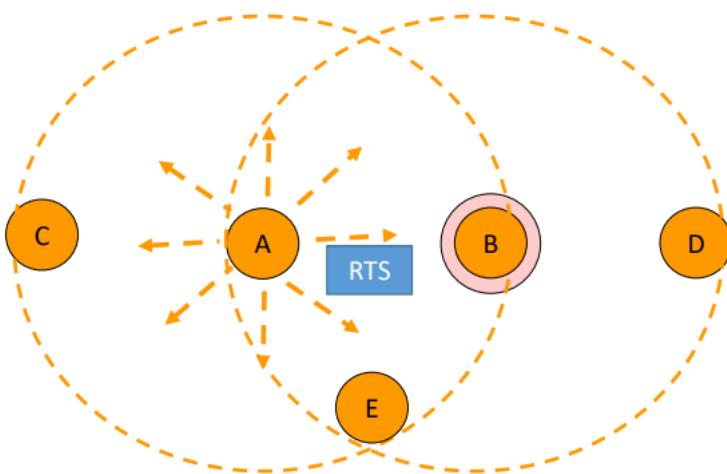


Figure 9.12: undefined undefined

Figure 9.13: **Step 1:** A wants to transmit to B so send a **RTS - Request To Send** packet to B: *the short frame sended include also the length of the data frame that will eventually follow.*

9.0.6 MACA - Multiple Access with Collision Avoidance

The basic idea is to stimulate the receiver into transmitting a short frame first and then transmit a long data frame. So stations hearing the short frame **refrain from transmitting** during the transmission of the subsequent data frame.

The scenario is pictured in 9.12 and it's here described:

- C is **within** range of A and **out** of range of B and D
- D is **within** range of B and **out** of range of A and C
- E is **within** range of both A and B

The protocol flows:

- **Step 1:** A wants to transmit to B so send a **RTS - Request To Send** packet to B: *the short frame sended include also the length of the data frame that will eventually follow.*
-
- **Step 2:** B, C and E receive the **RTS** from A (*because they're in A's radio range*). If B wants to receive the message, it replies with a **Clear To Send - CTS** that is a short frame with data length copied from RTS sended by A.

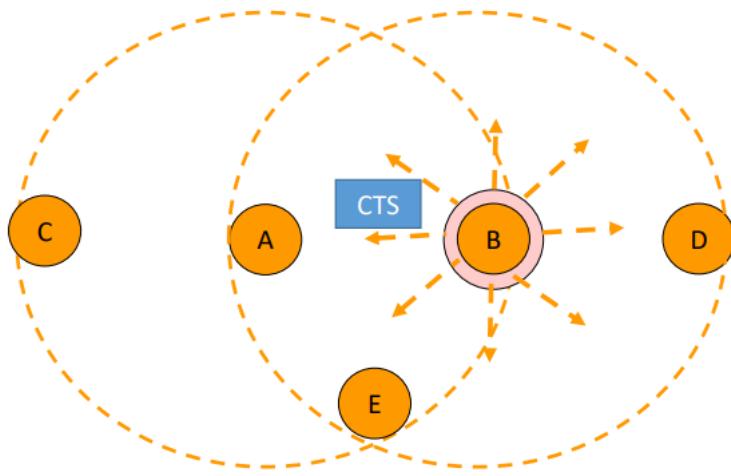


Figure 9.14: **Step 2:** B, C and E receive the **RTS** from A (*because they're in A's radio range*). If B wants to receive the message, it replies with a **Clear To Send - CTS** that is a short frame with data length copied from RTS sended by A.

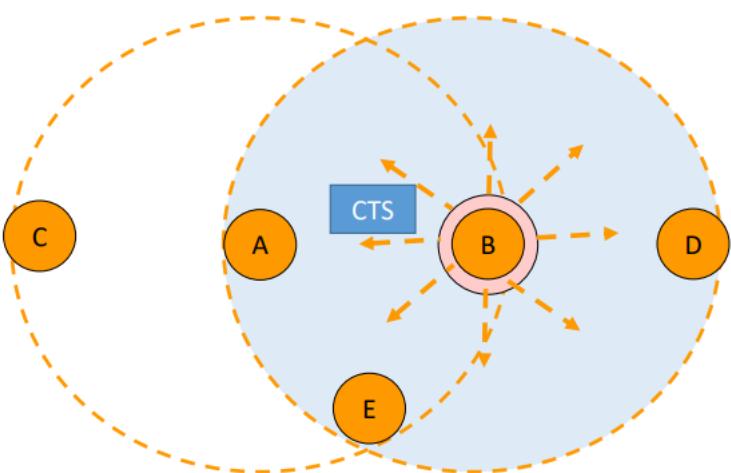


Figure 9.15: **Step 3:** the **CTS** sended by B is received by A, D, E

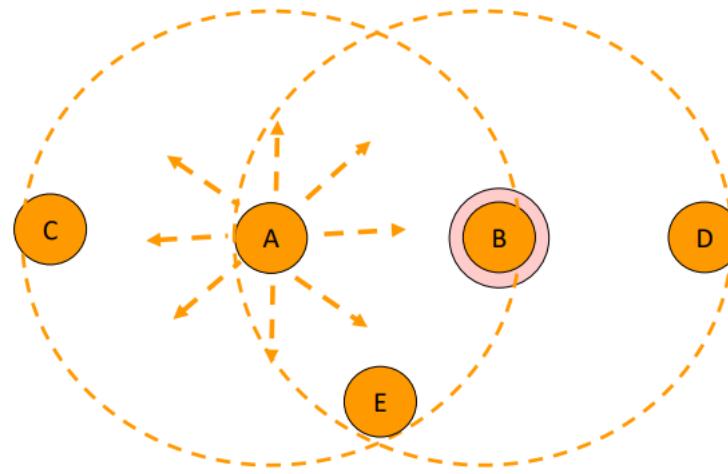


Figure 9.16: **Step 4:** upon reception of the **CTS** frame by B, A (*whose the only interested in receiving*) start to transmit the data frame

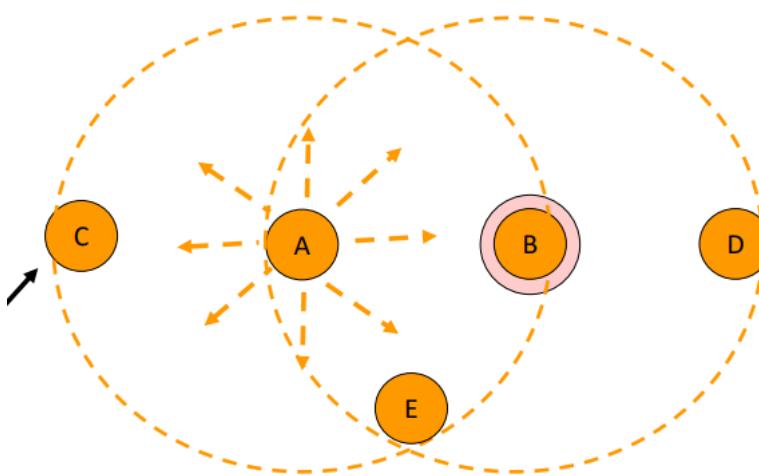


Figure 9.17: **C hears the RTS from A but not the CTS from B** so it is free to transmit (*may be interested in transmitting*). So **C is exposed**

- **Step 3:** the **CTS** sended by B is received by A, D, E
- **Step 4:** upon reception of the **CTS** frame by B, A (*whose the only interested in receiving*) start to transmit the data frame

Problems:

1. **C hears the RTS from A but not the CTS from B** so it is free to transmit (*may be interested in transmitting*). So **C is exposed**. Refer the figure 9.17.
2. **D hears CTS from B but not RTS from A** so should stay silent until data framr transmission completes. So **D is hidden**. Refer the figure 9.18.

MACA collisions Given the previous scenario, *what happen if another node out of the range of A and B wish to trasmit a message to node E?*

- C and B sends **RTS** simultaneosly to A: **the two RTS messages collide so no CTS message is generated.**
- C and B use *Binary Exponential Backoff* to retry send the RTS.

MACAW: MACA for Wireless Network

Fine tunes MACA to improve performance:

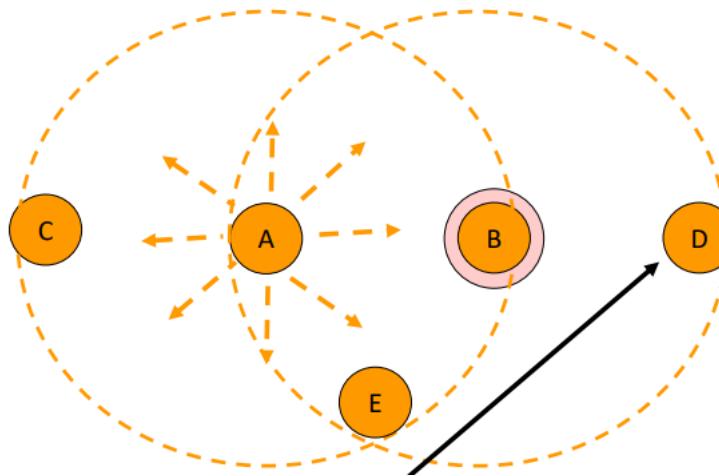


Figure 9.18: **D hears CTS from B but not RTS from A** so should stay silent until data frame transmission completes. So **D is hidden**

- introduces an **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
- exponential backoff is run for each separate pair source/destination and not for the single station
- mechanisms to exchange information among stations and recognize temporary congestion problems
- CSMA/CA used in IEEE 802.11 is based on MACAW

Questions (2)

- Exposed
- Hidden
- Collision

9.1 IEEE 802.11

The IEEE 802.11 identify a protocol family: each release is identified by a subsequent letter. The first one was the legacy mode and rarely used: was at 1-2 Mbps data rate implemented via Infrared signals with a radio frequencies in the 2.4 GHz band (*as frequency range*). Subsequent releases were:

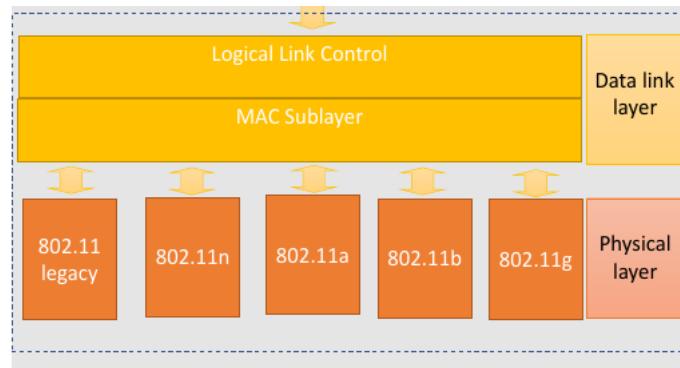
- 802.11a : operate at 5GHz band with a throughput of 23 Mbps and data rate of 54 Mbps.
- 802.11b : operate at 2.4GHz but poses a problem of interference with other appliances (*cordless telephones, microwave, etc*). Had a throughput of 4.3 Mbps and data rate maximum of 11 Mbps.
- 802.11g :
- 802.11n : operate at 2.4GHz band and 5GHz It support **MIMO** technologies for using multiple antennas at the transmitter and receiver
- 802.11ac - WiFi 5
- 802.11ax - WiFi 6 The table in 9.19 provide a short summary.

All of those use **CSMA/CS** for Multiple Access and have base-station (*infrastructure*) and ad-hoc network versions (*implementing function to access the medium, see previous*). With lower frequencies we have longer wave length: it suitable for IoT sensors. Despite the max data rate is not huge remains suitable for transmitting data.

We can have also different implementation at **data link layer** of both **MAC sublayer** and **Logical Link control** as shown in ??.

| 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 9.19: undefined undefined

Figure 9.20: undefined undefined
??

Architecture A group of stations operating under a coordination function may or may not use a *base station* or *Access Point (AP)*. If using AP a station communicates with another by channeling all the traffic through a centralized AP: so AP provide connectivity with other APs and other groups of stations via fixed infrastructure. It can also support *ad hoc networks* by introducing a *group of stations that are under the direct control of a single coordination function without the aid of an infrastructure network*.

Channel association

The spectrum of a mean is divided into channel at different frequencies: the AP admin chooses the frequency for AP. At this level the interference is possible because channels can be same as that chosen by neighboring AP.

A new host must be associated with an **AP**: first it scan the channel frequencies and listen for *beacon frames* (like a sort of hello frame, advertise device on the device on the same frequency and sended by the AP). The beacon frame contains the name of the network (SSID) and MAC address of AP (BSSID). The node select one AP to associate and perform authentication (if needed) and then run the DHCP protocol to get IP address in the AP's subnet.

Active/Passive scanning AP periodically sends beacons frames on their frequency: the node when arrived detect beacons frame and select AP. Nodes select the AP and send the association request. The choose of the AP made by nodes is not mandatory described in the specific: usually is selected the AP with the best **signal strength** that also is indicative of the number of communication opened by AP with other nodes so is a measure of quality/disponibility of resources. The **passive scanning** flows as following:

1. Beacon frames sent from APs
2. association request frame sent so *H1* to selected AP
3. Association Response frame sent: selected AP to H1

The **Active scanning** flows:

1. Probe Request frame broadcast from H1
2. Probe Response frames sent from APs
3. Association request frame sent: H1 to selected AP
4. Association Response frame sent from selected AP to H1

MAC Sublayer A sketched version of the MAC sublayer is presented in 9.21.

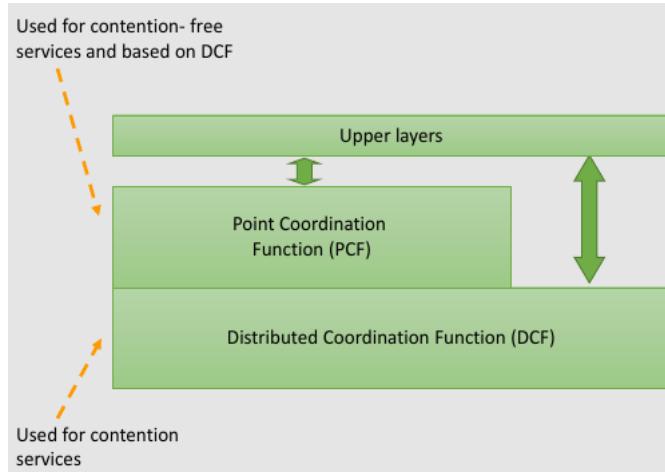


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- **Point Coordination Function (PCF)** : uses base station to control all activity in its cell. AP pools stations for transmission. It's based on DCF.
- **Distributed Coordination Function (DCF)**: used for contention services, is based on MACA.

DCF must be implemented by all stations: it's completely decentralized and uses a best effort asynchronous traffic. Stations must contend for the channel at each frame using CSMA/CA. *Carrier sensing* is performed at two levels:

- *Physical*: by checking the frequency to determine whether the medium is in use or not. It detects an incoming signal and any activity in the channels due to other sources.
- *Virtual*: is performed by setting a duration information in the header of an RTS, CTS and data frame. So keeps the channel *virtually busy* up to the end of data frame transmission. A channel is marked **busy** if either the physical or the virtual carrier sensing indicate busyness.

Priority access to the medium is controlled through the use of **interframe space (IFS)** time intervals. The IFS is mandatory periods of idle time on the transmission medium.

Three IFS specified by the standard:

- *Short (SIFS)*:
- *Point Coordination Function (PIFS)*:
- *Distributed Coordination Function IFS (DIFS)*: The hierarchical order based on priority is given by: SIFS < PIFS < DIFS

The exchange of RTS and CTS between sender and receiver allows the other nodes to calculate the *NAV (Network Access Vector)* that is an **estimation of duration** of communication between sender and receiver (*a sort of period of silence to avoid illegal accesses to the mean*), as shown in 9.22.

9.1.1 Mobile Networks

Nowadays there are more mobile-broadband-connected devices than fixed-broadband. The 4G-5G cellular network now embrace internet protocol stack, including SDN. There are two important different challenges:

- *Wireless:*
- *Mobility:* handling the mobile user who changes point of attachment to network or by the provider that wants advertise a service. It also poses authentication and authorization problems towards user requested services.

Components of cellular network architecture The *MSC* intermediate the connection between different cells sets of networks, it also manage the billing information by tracking times and call setup. MSC can manage more than 4 cells or *base station*: some MSC can be also used as gateway to the *wired-telephone network*.

From 4G to 5G we have a change in the architecture, integrating software engineering choices in new components like supporting orchestration and function virtualization (*More at <https://doi.org/10.3390/en12112140>*).

With the evolution of mobile network technology both evolves with the *access techniques*, as the time diagram show in 9.24.

FDMA/TDMA

Frequency Division Multiplexing Access/Time Division Multiplexing Access are two techniques used for **sharing mobile-to-BS (base station) radio spectrum**. They can be combined in one by *dividing the spectrum in frequency channels and divide each channel into time slots* as pictured in 9.25

Another methods is *CDMA - Code Division Multiple Access*: is a digital cellular technology that allows multiple users to share the same frequency band simultaneously. It works by **assigning a unique code to each user, which is used to modulate the user's signal**.

CDMA uses spread spectrum technology, which spreads the user's signal across a wide bandwidth. This makes it possible for multiple users to transmit their signals at the same time and on the same frequency band without interfering with each other.

The **unique code assigned to each user acts as a key to unlock the signal at the receiving end**. The receiver is able to identify and separate the different users' signals based on their unique codes, allowing each user to receive their own signal without interference from other users, as pictured in 9.26

Even in case of different generated signal, if the receiver is able to known the code used by the sender, even if the received signal is the overlap of different codes of different sender the receiver will be able to reconstruct the data. The specific code used by the sender is negotiated beforehand with the receiver.

2G Network Architecture (voice)

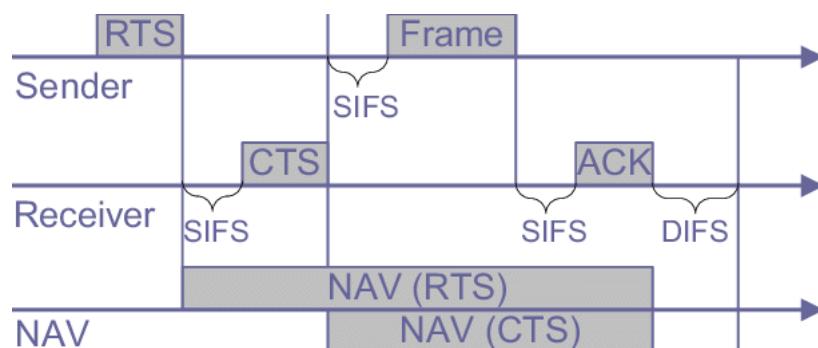


Figure 9.22: Exchange flow to determine the NAV

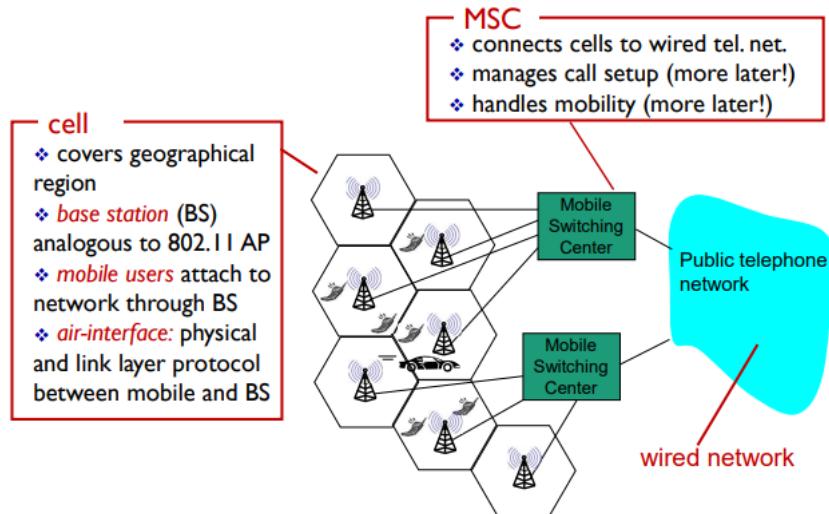


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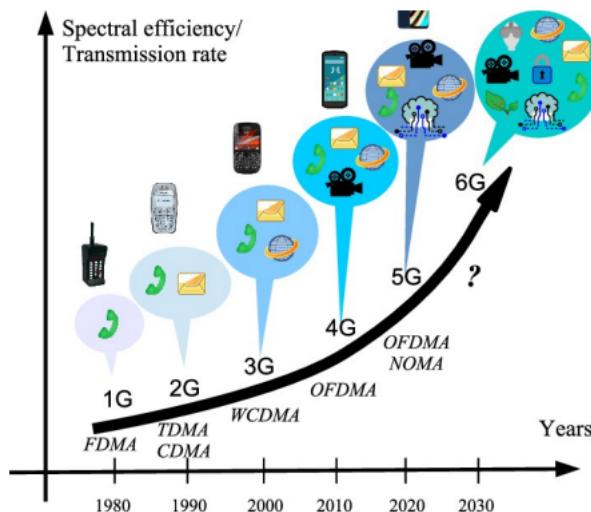


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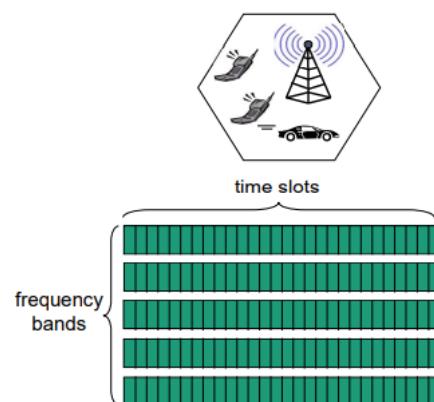


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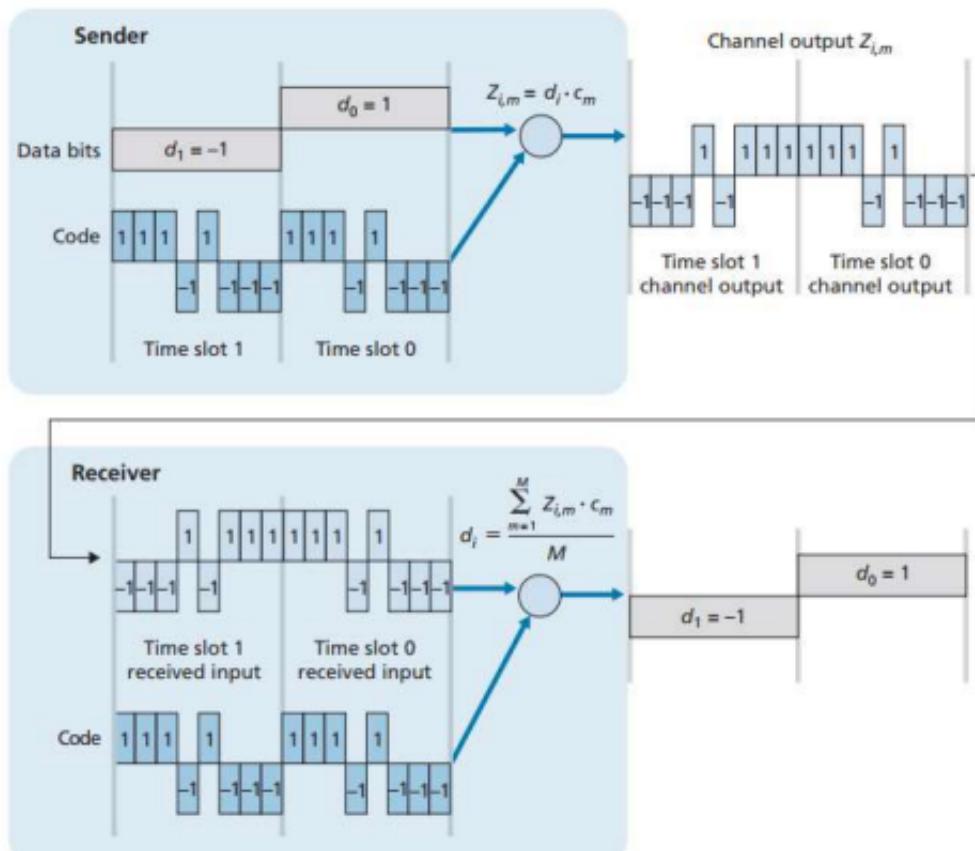


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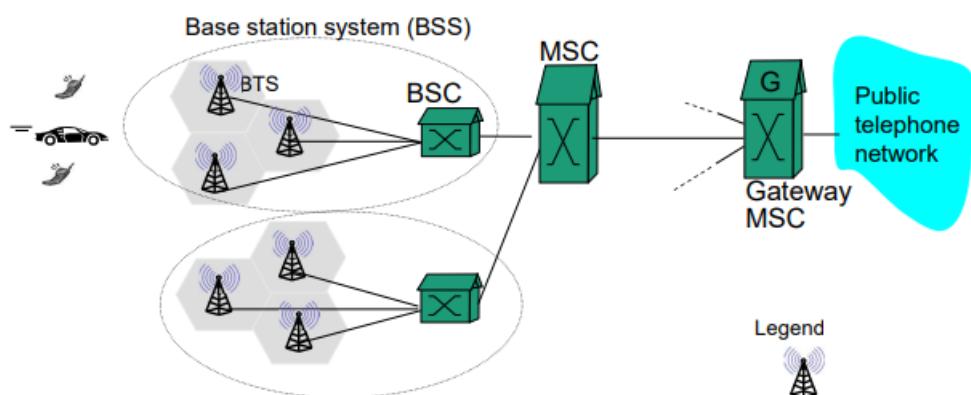


Figure 9.27: 2G network architecture for voice communication

Chapter 10

Mobile Networks

3G Network Architecture (voice+data) New cellular data network operate in parallel (*except at the edge*) with existing cellular voice network. The voice network is unchanged in core and operates *circuit switching* while *data network * 2G Network Architecture (voice)ates in parallel by operating **packet switching**. The general schema is pictured in 10.2



Figure 10.1: Symbol reference

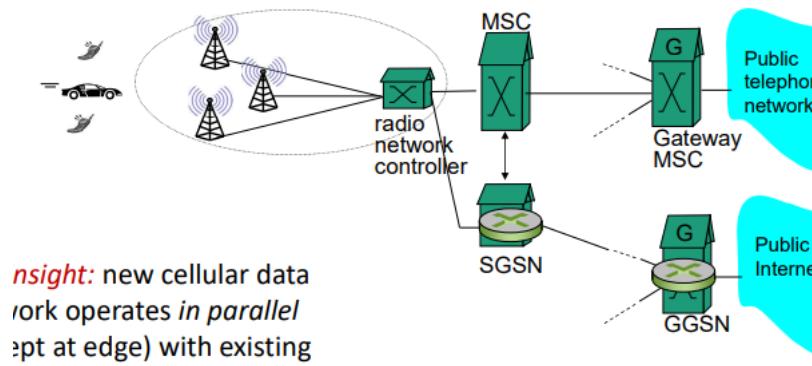


Figure 10.2: 3G Network Architecture

10.0.1 3G vs. 4G LTE (Long Term Evolution) network architecture

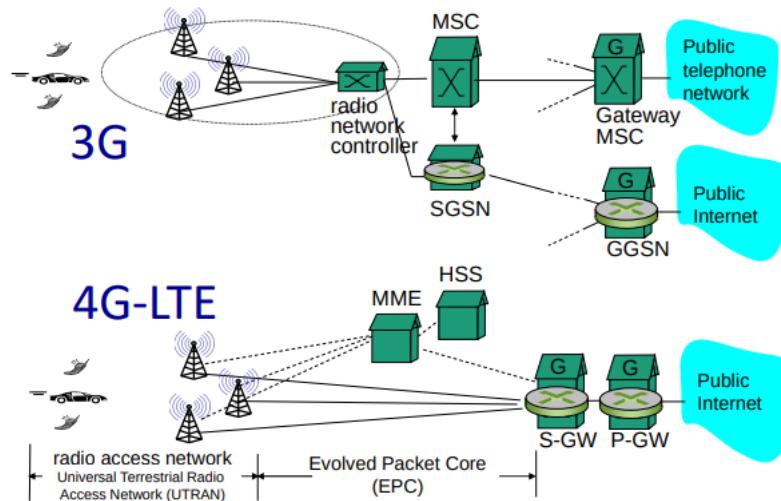


Figure 10.3: 3G vs 4G LTE Network Architecture

The changes between the 3G and 4G netowkr architecture are in the core network, like:

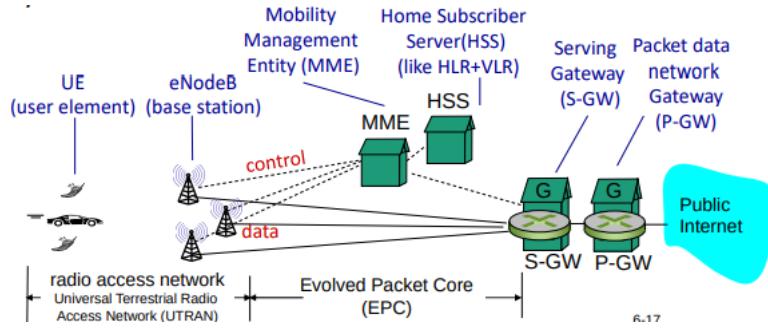


Figure 10.4: 4G-LTE Network Architecture

- **All-IP core:** IP packets are tunneled from base station to gateway and there is no separation between voice and data so all traffic is carried over IP core to gateway. The architecture is pictured in 10.4

10.0.2 4G/5G cellular networks

There are some similarities to *wired internet* like:

- edge/core distinction where we have application services (edge) and core (e.g. services to authenticate devices)
- Global cellular network: operators agree on a network of networks among all geographical countries
- Use of protocols like HTTP, DNS, TCP, UDP, DHCP
- Mobile networks are interconnected to internet to be able to use services

Between differences from wired internet there are:

- Mobility as a first class service
- User *identity* via SIM card
- Business models: user subscribe to a cellular provider called "home network" that works differently when roaming on visited nets. The global access is granted thanks to authentication infrastructure and inter-carrier settlements

Architecture

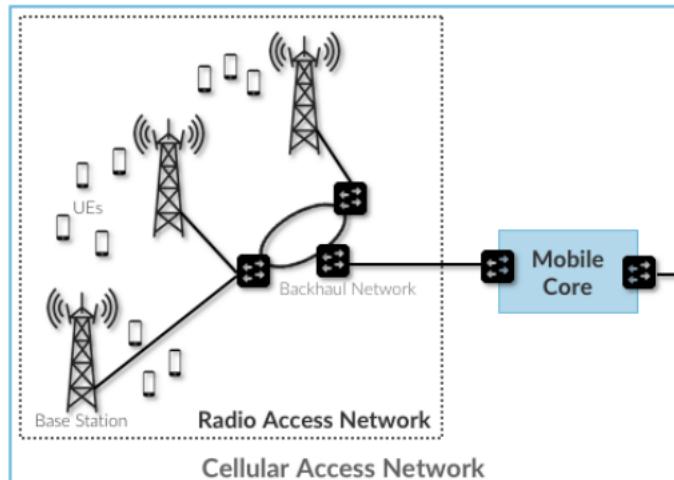


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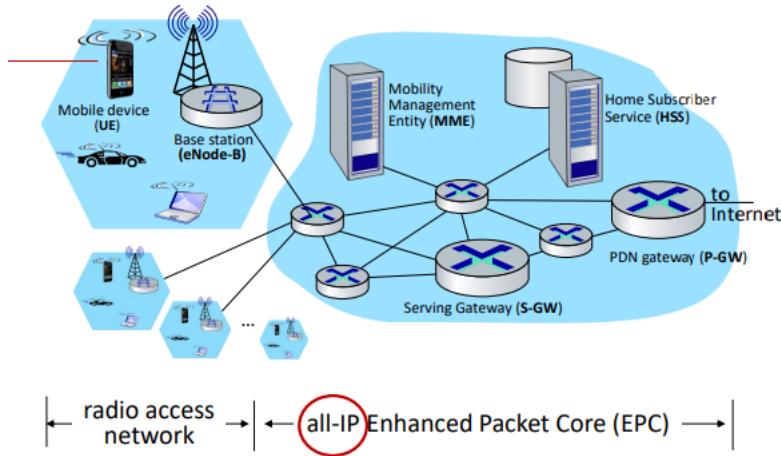


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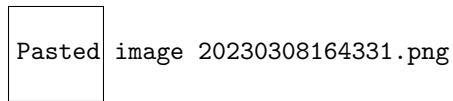


Figure 10.7: Mobile core architecture

- **Mobile Core:** provides IP (*internet*) connectivity for both data and voice services. Also ensure QoS requirements and allows to track user mobility to ensure uninterrupted service, providing *billing* and *charging*.
- **Backhaul Network:** allows to connect base station to mobile core (*interconnecting the RAN*) by using optics or wireless solution (*IAB - Integrated Access Backhaul*).
- **Radio Access Network (RAN):** it's a distributed connection of Base Stations (BSs) and allows to manage the radio spectrum.

Elements of 4G architecture

In the **radio access network** the mobile device can be a large series of devices like *laptop*, *IoT* devices with 4G LTE radio: they are identified by 64 bit *International Mobile Subscriber Identity (IMSI)* stored on the **SIM - Subscriber Identity Module**.

The **core network** is composed by **Home Subscriber Service - HSS** that contains information about subscribers with their identifiers and allows to manage the authentication phase. It maintains the information about the device's "*home network*". To be able to authenticate, it works with **Mobile Management Entity - MME**.

The **Mobile Management Entity** performs the device authentication, coordinated with mobile home network HSS. The MME is also involved when changing the base station and allows to track the device and page the device location (*ask the base station for the presence of this device*). For data packets transfer we need to establish a *data path* from the mobile device to the **Serving Gateway (S-GW)** (the *tunneling* and the data path is explained later). Both the **Serving Gateway (S-GW)** and **PDN Gateway (P-GW)** are on the path from mobile to/from internet network: the S-GW forwards IP packets to and from the RAN, the P-GW is a gateway to mobile cellular network that looks like any other internet gateway router. It provides *NAT services* and supports access-related functions like *policy enforcement*, *traffic shaping and charging*. When devices move to one base station to another, also the S-GW gateway is involved in this process.

A simplified view of the *mobile core* architecture is pictured in 10.7

For example, a single **MME/PGW** pair might serve a metropolitan area, with SGWs deployed across 10 edge sites spread throughout the city, each of which serves 100 base stations.

In 4G there is a strong separation between **data plane** and **control plane** that allows the mobility management and the bootstrapping of the data path:

The **base station** forwards both control and user plane packets between the mobile core and the user. The separations concerns:

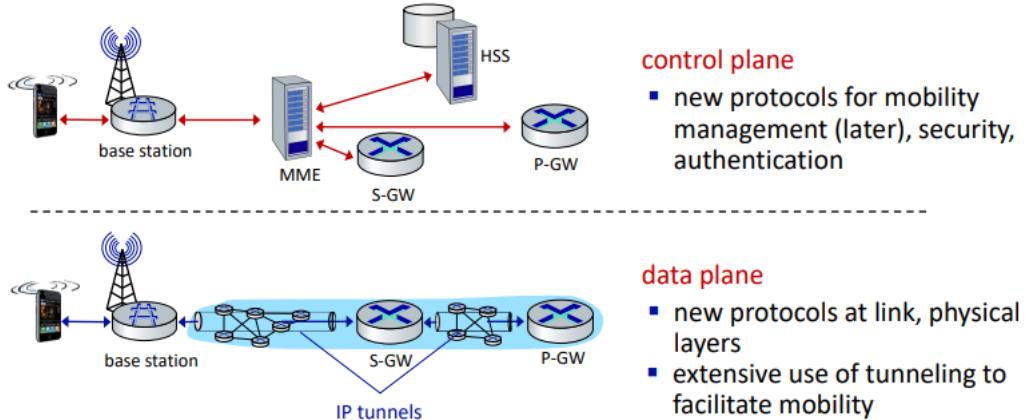


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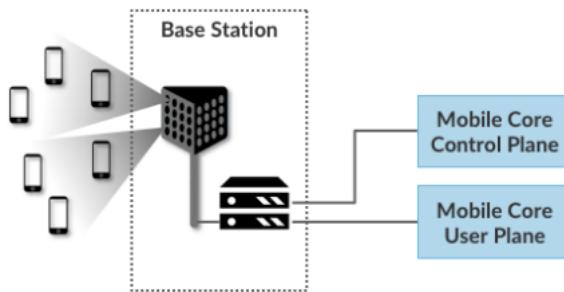


Figure 10.9: undefined undefined

- **Control plane:** the packets are tunneled over SCTP/IP (Stream Control Transport Protocol) that is an alternative reliable transport to TCP, tailored to *carry signaling (control)*. It allows to provide user's device authentication, registration and mobility tracking.
- **User plane:** packets are tunneled over **GTP (General Packet Radio Service) Tunneling Protocol.

The Long Term Evolution (LTE) **data plane protocol stack** in the *core network* adopt, as already mentioned, the **tunneling mechanism** (*as pictured in 10.10*): mobile datagrams are encapsulated using GPT and sent inside a UDP packet to the Serving Gateway (S-GW). The S-GW re-tunnels the UDP datagrams to P-GW, allowing reaching internet networks. The tunneling mechanism described allow supporting *mobility*: only tunneling endpoints change when mobile user moves. In this context the S-GW represent a it's a fixed point both from the device to internet and viceversa so if the device change base station, the S-GW is able to *retrieve* the new base station of the device and change the IP address to deliver the packet to the correct base station in which the device is connected. This mechanism allows to implement mobility across base stations.

LTE: Link Layer Protocol The first hop **LTE Link Layer protocols** (10.11) in the IP range defines:

- **Packet Data Convergence:** contains header for compression, decompression, encryption and decryption.
- **Radio Link Control (RLC):** implement fragmentation/re assembly by ensuring reliable data trasnfer.
- **Medium Access:** requesting and use of radio *transmission slots*

Between the *LTE radio access network* we have several mechanism like:

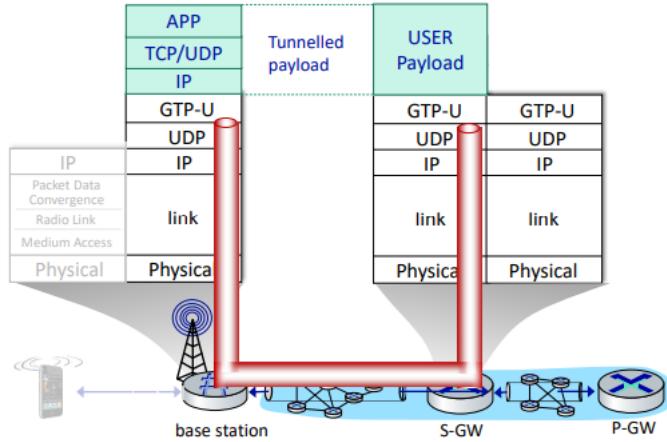


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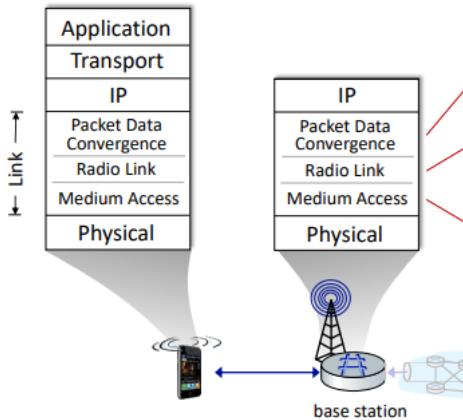


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- **Downstream channel:** combination of FDM and TDM within frequency channel (*OFDM - Orthogonal Frequency Division Multiplexing: orthogonal refer to minimal interference between channels.*)
- **Upstream:** FDM, TDM similar to OFDM. Each **active mobile device allocated two or more 0.5 ms timeslots in or more channel frequencies**. The scheduling algorithms is not standardized so it's up to the operator and allows up to 100's Mbps per device.

Associating with a base station

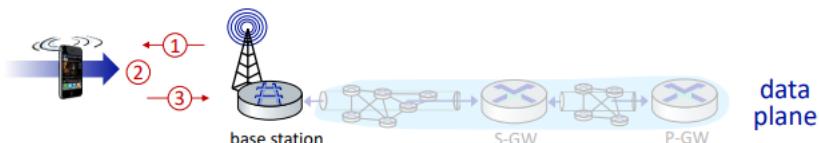


Figure 10.12: Process of association with a base station

1. BS broadcast primary synchronization signal every 5 ms on all frequency
2. Mobile finds a primary synch signal and locate the second synch signal on this frequency: mobile then finds info broadcast by BS like channel bandwidth and configuration. Mobile may get informations from multiple base stations, multiple cellular networks.
3. Mobile selects which BS to associated with (*e.g. preference for home carrier*)

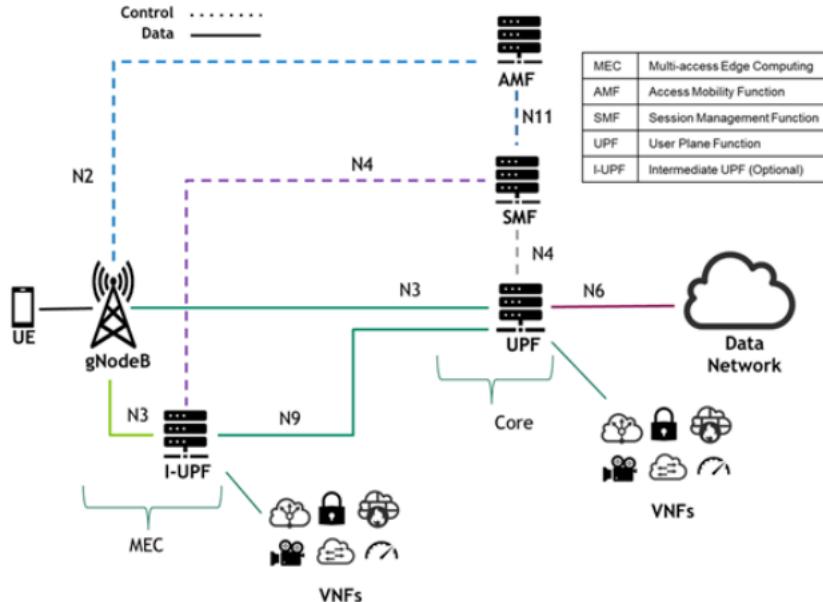


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- More steps till needed to authenticated, establish state and set up control plane.

The **sleep modes** of LTE allows to put radio to *sleep* to conserve battery:

- Light Sleep*: after 100 millisecond of inactivity: need to wake up periodically to check downstream transmissions.
- Deep Sleep*: after 5-10 seconds of inactivity then the mobile may change cells while deep sleeping so need to re-establish association

10.0.3 5G architecture

The main goal of 5G is to increase in peak bitrate, 10x decrease in latency and 100x increase in traffic capacity over 4G. The **5G New Radio Frequencies** have two frequency bands:

- FR1: 450MHz - 6 GHz
- FR2: 24GHz - 52 GHz The 5G is not backwards-compatible with 4G: the *millimeter wave frequencies* have much higher data rates but over shorter distances because uses **pico-cells** that have a diameter of 10 to 100m. This implies a dense deployment of *new base station*.

The underlying idea is to realize the functions of authentication, tracing and so on by means of **microservices** implemented through **Network Function Virtualization**: this allows the deployment of those functions both close to the core network and base stations so the path between the mobile device and the function/service is really close, reducing the latency and load balancing the traffic. This also avoids traffic directly flowing into the core network and managing the traffic at the edge.

5G User Plane

The 5G user plane is sketched in 10.13.

The **UPF - User Plane Function** allows to forward traffic between RAN and internet, corresponding to the S-GW/P-GW combination into the **EPC**. It's also responsible for:

- Packet inspection and application detection
- QoS management
- Traffic usage reporting This component allows flexibility to deliver user plane functionality at the edge as well as the network core because UPF can be co-located with edge and central data centers at both locations, implementing also **MEC - Multi Access Edge Computing** (see next lecture).

5G Control Plane

The basic 5G architecture schema is sketched in 10.16.

- **AMF (Core Access and Mobility Management Function)**: connection and reachability management, mobility management, access authentication and authorization, and location services
- **SMF (Session Management Function)**: manages each UE session, including IP address allocation, selection of associated UP function, control aspects of QoS, and control aspects of UP routing.
- **PCF (Policy Control Function)**: manages the policy rules that other CP functions then enforce.
- **UDM (Unified Data Management)**: Manages user identity, including the generation of authentication credentials.
- **AUSF (Authentication Server Function)**: Essentially an authentication server.
- **SDSF (Structured Data Storage Network Function)**: a "helper" service used to store structured data.
- **UDSF (Unstructured Data Storage Network Function)**: A "helper" service used to store unstructured data.
- **NEF (Network Exposure Function)**: A means to expose select capabilities to third-party services
- **NRF (NF Repository Function)**: A means to discover available services.
- **NSSF (Network Slicing Selector Function)**: A means to select a Network Slice to serve a given UE. Network slices are essentially a way to partition network resources in order to differentiate service given to different users

Deployment options

Two main deployment options are considered (*as shown in 10.15*):

1. **Non standalone (4G+5G) over 4G's EPC**: first schema in which 5G base stations are deployed alongside existing 4G base stations in a given geography to provide a data-rate and capacity boost. In NSA, the control plane traffic between user equipment and the 4G Mobile Core utilizes 4G base stations and the 5G base stations are used only to carry user traffic.
2. **Non standalone (4G+5G) over 5G's NG-Core**: second schema

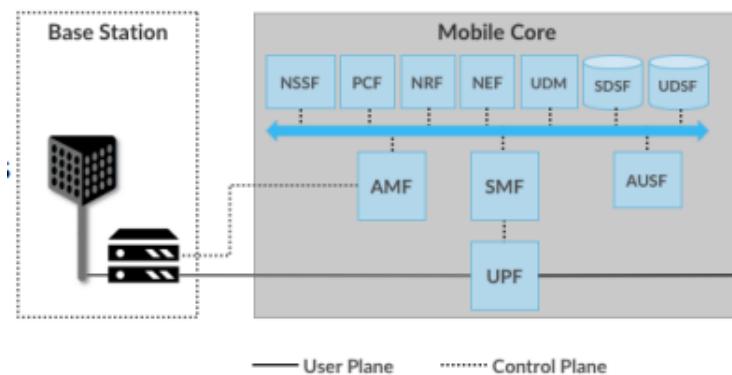


Figure 10.14: 5G Control Plane

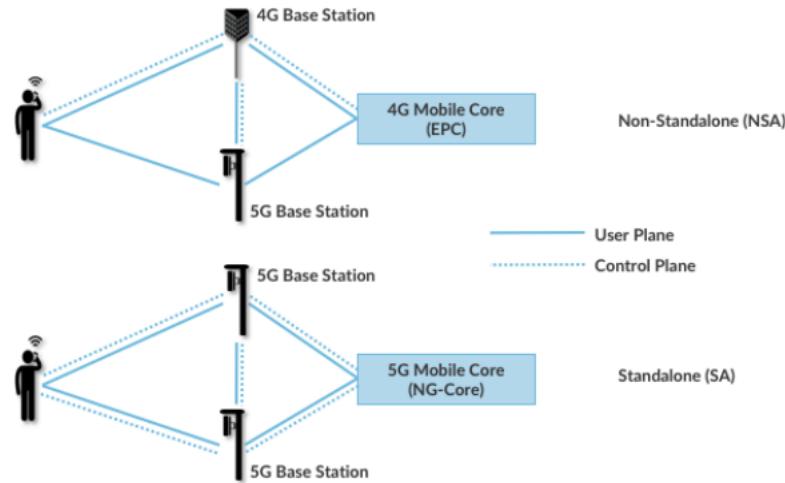


Figure 10.15: Non standalone (4G+5G) over 5G's EPC vs over 5Gs NG-Core

10.0.4 Mobility

From the network perspective, the spectrum of mobility have a wide area of scenarios and application, as shown in 10.17.

The **home networks** allows to have a service plan with a cellular provider (*Verizon, Orange*) where

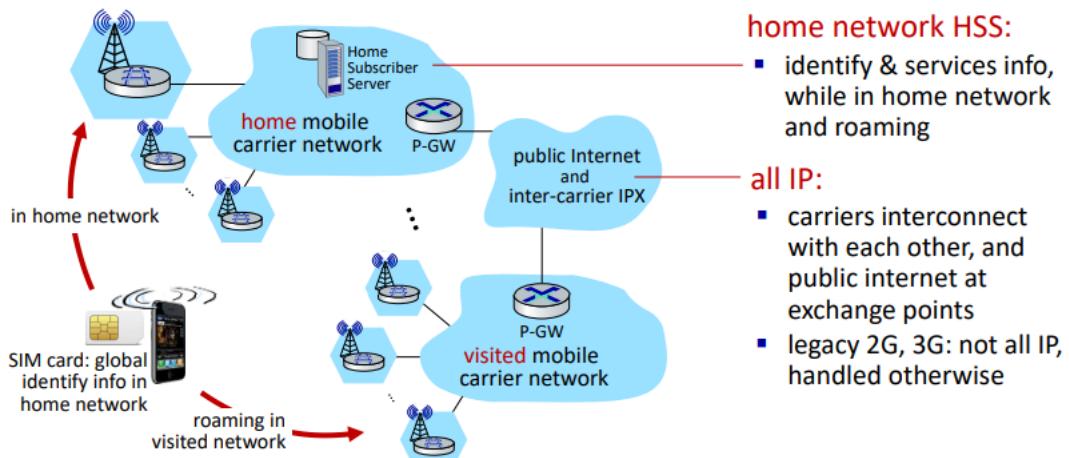


Figure 10.16: Mobility scenario

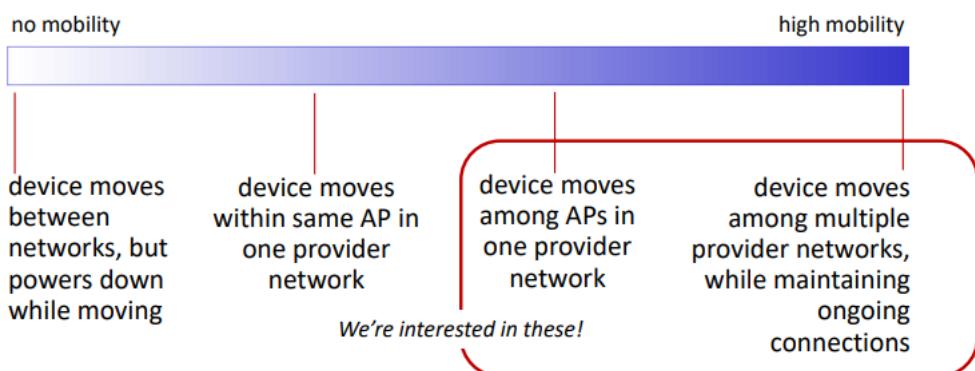


Figure 10.17: Mobility spectrum

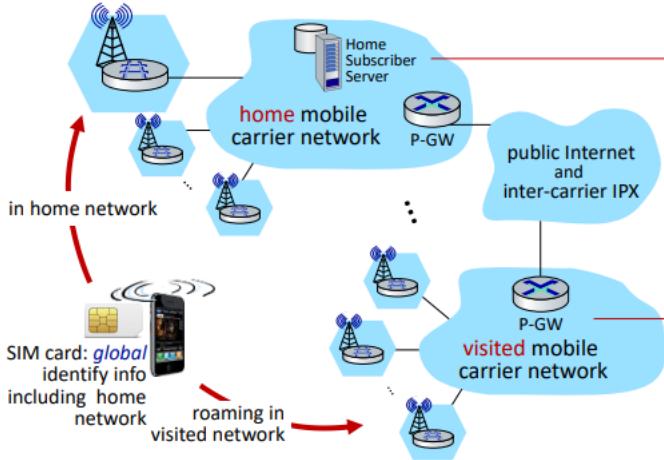


Figure 10.18: Flow between home network and host network for mobility purposes

the home network HSS stores identity and service informations of the device. The **visited network** is any network other than your home network and by service agreement with other networks allows to provide access to *visiting mobile*, implementing mobility. The described scenario is pictured in 10.18.

Wifi/ISP does not have a concept of Home network where the user informations are stored but they are stored on the device or with the user (eg. username, password), different networks different credentials (*Think of eduroam*).

To implement mobility and have a correspondence between the mobile device and the home network/visited network we have two different approaches:

1. **Network router handle it:** the network router handle the management of the mobility. The routers advertise well-known name, addresses (e.g. permanent 32-bit IP address) or number (phone cell) of visiting mobile node via usual *routing table exchange*. Internet routing could do this already without changes: routing tables indicate where each mobile is located by using **Longest Prefix Match**. This approach is not scalable to a billions of mobiles: we could have routing tables too large to expand and retrieve data (*coconsidering 32 bit IP addresses*).
2. **End-system handle it:** the functionality is provided at the *edge*. There are two types of routing:
 - (a) **Indirect routing:** communication from correspondent to mobile goes through home network and then forwarded to remote mobile (*connected to a third-party visited network*). The correspondent, known the home network gateway send the request and thanks to the HSS - Home Subscriber Server that contains the updated address of the device, is able to forward the request to the Serving Gateway of the *visited network*. Refer the schema in 10.19.
 - (b) **Direct routing:** correspondents get foreign address of mobile, sending directly to mobile device. The *IMSI* is used as a sort of *MAC address* of the device. Refer the schema in 10.20.

In the *indirect routing* a mobile-device-to-visited network association protocol is needed: the mobile device will need to associate with the visited network and will similarly need to disassociate when leaving the visited network. There is also the need of a *visited-network-to-home-network-HSS registration* to allow the visited network to register mobile device's location with the HSS in the home network. A datagram tunneling protocol between the home network gateway and the visited network gateway router is needed to allow the home gateway performs encapsulation and forwarding of the correspondents original datagram and, on the receiving side, the gateway router performs decapsulation, NAT translation and forwarding of the original datagram to the mobile device.

In the *direct routing* the process is less transparent to the correspondent because it must get care of the address from home agent. In case the mobile changes visited network the request sending can be handled but with additional complexity by allowing the HSS to be queried by the correspondent only at the beginning of the session.

This last approach requires a **registration** procedure to be sure that the home network knows where the device is, as pictured in 10.21.

The mobile device needs an IP address in the visited network:

1. permanent address associated with the mobile device's home network

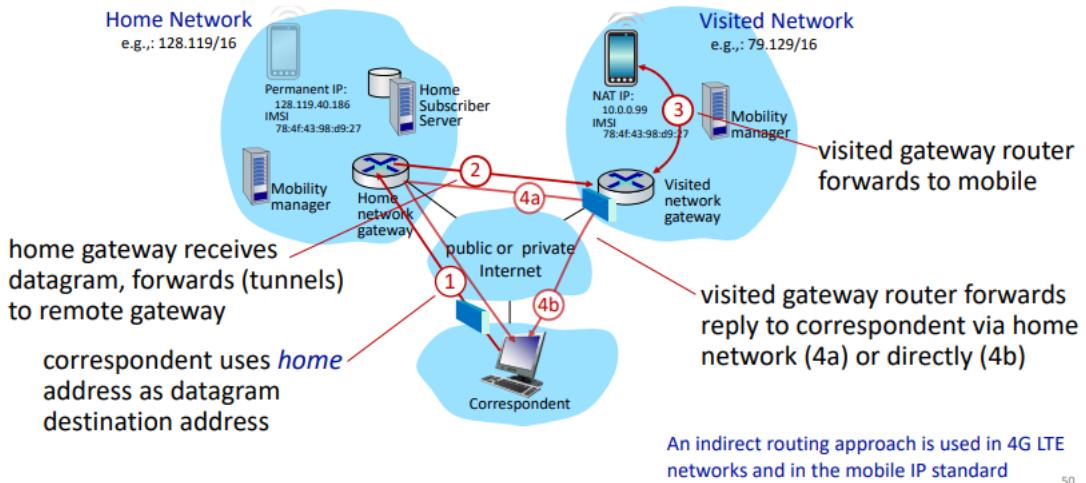


Figure 10.19: Indirect routing schema

2. New address in the address range of the visited network
3. IP address via NAT The end result is that the visited mobility manager known about the mobile and the home HSS knowns the location of mobile.

In case on **indirect routing**, the scenario is different:

1. The correspondent use **home** address as datagram destination address
2. The home gateway receives datagrams and forwards (*by tunneling*) to remote gateway
3. Visited gateway router forwards to mobile
4. The visited gateway ryter forwards reply to correspondent via home network (a) or directly (b). The main requiremenets for mobility in *indirect routing* are:
 5. *Mobile-device-to-visited-network association protocol*: the mobile device will need to associate with the visited network and will similarly need to dissociate when leaving the visited network.
 6. *Visited-network-to-home-network HSS registration*: The visited network will need to registrer the mobile device's locatio with the HSS in the home network
 7. *A datagram tunneling protocol between home network gateway and visisted network gateway router*: the home gateway perform encapslation and forwarding of the correspondent's original datagram.

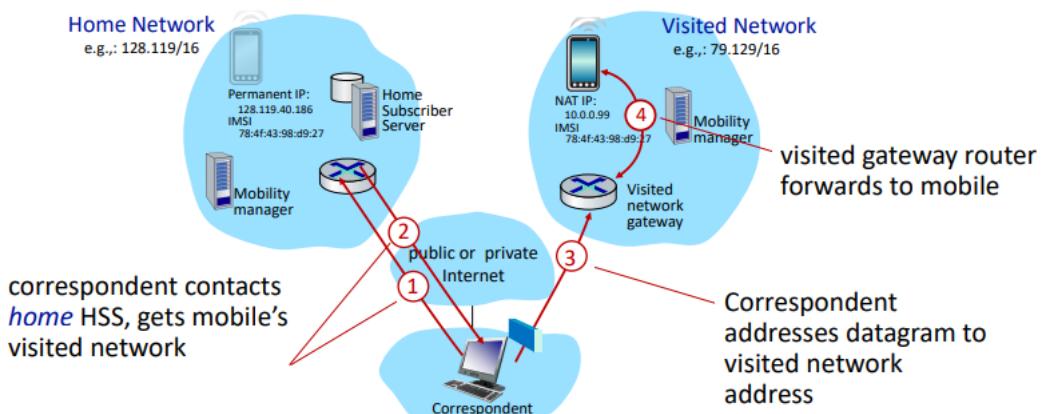


Figure 10.20: Direct routing schema

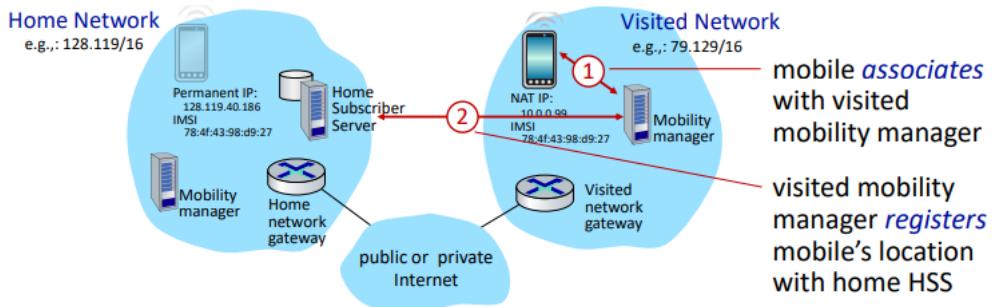


Figure 10.21: undefined undefined

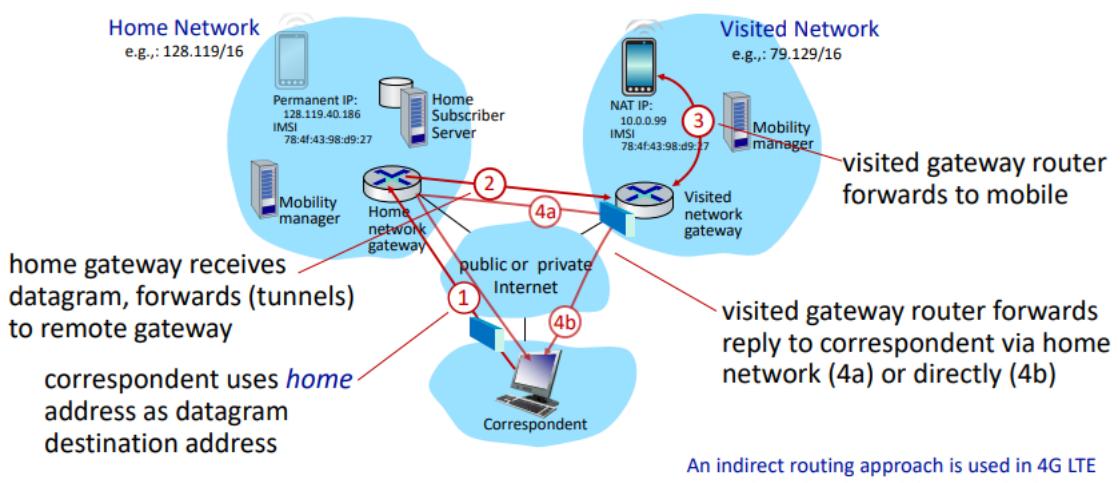


Figure 10.22: undefined undefined

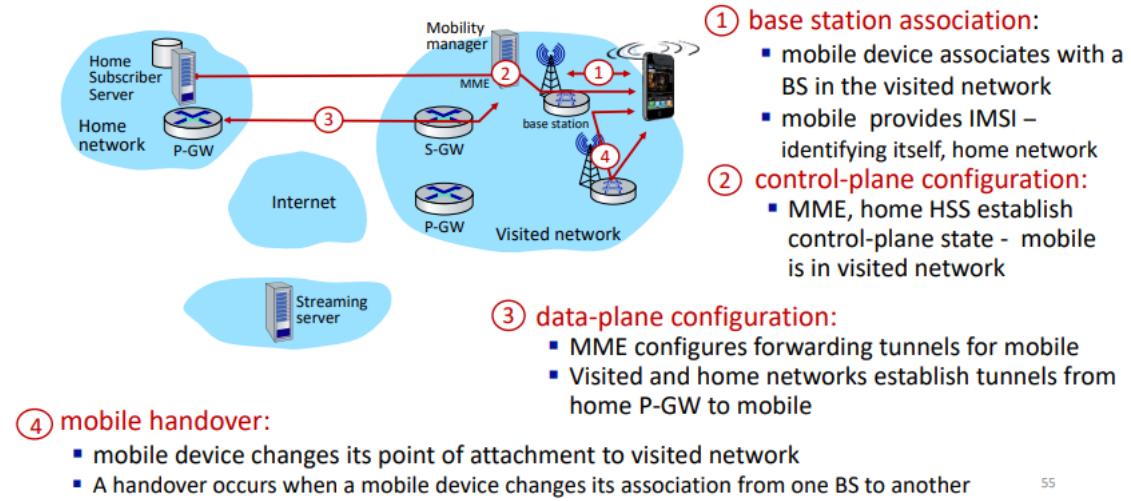


Figure 10.23: undefined undefined

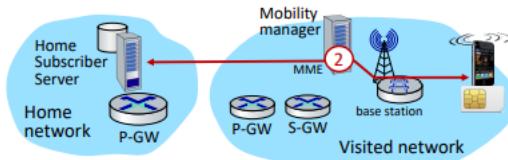


Figure 10.24: undefined undefined

On the receiving side, the gateway router performs **decapsulation, NAT translation and forwarding** of the original datagram to the mobile device. Some considerations about **indirect routing** evaluate the problem of **triangle routing** that results in an inefficient model when correspondent and mobile are in the same network (*due to the problem of forwarding the messages to the home network and re-routing them to the correspondent's original network which correspond to the visited network of the destination device*). The mobile device can see an interrupted flow of datagrams as it moves between network, losing some datagrams but the on-going TCP connection between correspondent and mobile can be maintained. The following schema describe the steps. So if the mobile changes visited network it's necessary to update the HSS in the home netowkr, changing the tunnel endpoint to terminate at the gateway router of the new visited network.

Regarding the mobility with **direct routing**, it overcomes triangle routing inefficiencies at cost of being *non-transparent to correspondent* because he need to get care of the address from home agent. For this type of routing, if the mobile changes visited network, the HSS is queried by the correspondent only at the beginning of the session, requiring additional complexity.

Mobility in 4G

allows the mobile to communicate with the local MME via a BS control-plane channel. The MME uses mobile's IMSI information to contact mobile's home HSS to retrieve authentication, encryption and network service information and, in return, the home HSS knows the mobile now reside in the visited network. The BS and mobile select parameters for BS-mobile and data-plane radio channels.

The MME configures the data plane for the mobile device so all traffic to/from the mobile device will be *tunneled* through the device's home network. Two different tunnels are established: 1. **S-GW to BS tunnel:** when the mobile changes base station, simply change the endpoint IP address of tunnel 2. **S-GW to home P-GW tunnel:** to support the indirect routing.

The **tunneling via GTP (GPRS tunneling protocol)*** allows the mobile's datagram directed to the streaming server to be encapsulated using GTP.

The **handover (also known as handoff)** is the process of transferring an ongoing call or data session from one base station (BS) to another base station while maintaining the continuity of the communication. Handovers are necessary when the mobile device moves from one cell to another, and the signal strength of the current base station becomes too weak to maintain the connection.

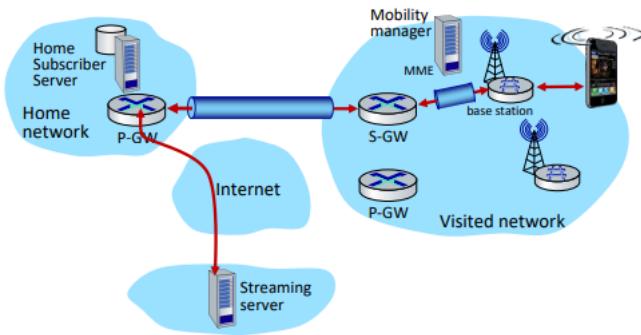


Figure 10.25: undefined undefined

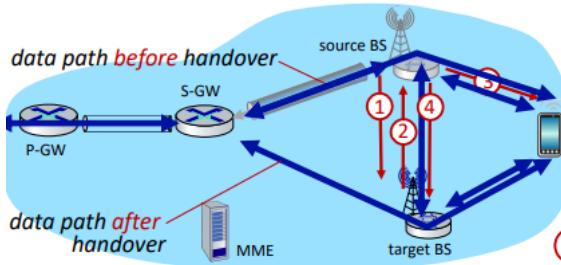


Figure 10.26: undefined undefined

The steps are:

1. Current source BS chooses to select a handover: selects target BS, sends **Handover Request message** to target BS
2. Target BS pre-allocates radio time slots, responds with **HR ACK** with information for mobile
3. Source BS informs mobile of new BS: mobile can now send via new BS. The handover looks complete to the mobile
4. Source BS stops sending datagrams to mobile, instead forwards to new BS (*who forwards to mobile over radio channel*).
5. Target BS informs MME that it is new BS for mobile: MME instructs the S-GW to change tunnel endpoint to be new target BS
6. target BS ACKs back to source BS: handover complete, source BS can release resources
7. Mobile's datagram now flow through new tunnel from target BS to S-GW

Mobile IP

The mobile IP architecture uses *indirect routing* to route traffic via home networks and using tunnels. Operates by two agents:

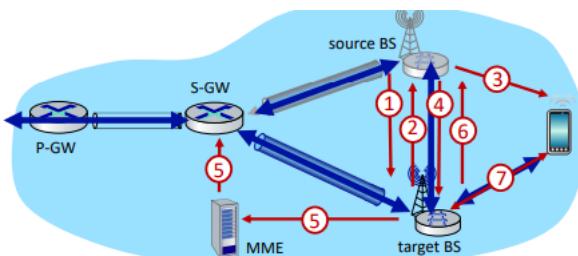


Figure 10.27: undefined undefined

1. *Mobile IP Home Agent*: combined roles of 4G HSS and home P-GW
2. *Mobile IP Foreign Agent*: combined roles of 4G MME and S-GW The protocols for agent discovery in visited network, registration of visited location in home network via ICMP extensions.

Chapter 11

SDN - Software Defined Networking

The **network layer** have two main functions to be carried out:

- **Forwarding:** move packets from router's input to the appropriate router output
- **Routing:** determine route taken by packet from source to destination

The forwarding activity is implemented by the ***data plane***, the routing is implemented by the ***control plane***. Respectively, both planes operates on fast timescale (*per-packet in case of forwarding*) and slow time scale (*per control event in case of routing*).

Two main approaches exists to structuring the network control plane:

- **Per-router:** is the traditional one
- **Logically centralized control:** also known as **Software Defined Networking**.

Per-router control plane

In this approach, there is an *individual routing algorithms* component in each router and every router interact with the control plane to compute the forwarding tables as pictured in 11.1. In traditional IP networks, the control and data plane are **tightly coupled**, embedded in the same networking devices and the whole structure is highly *decentralized*. The *network resilience* was a crucial design goal in the early days of Internet.

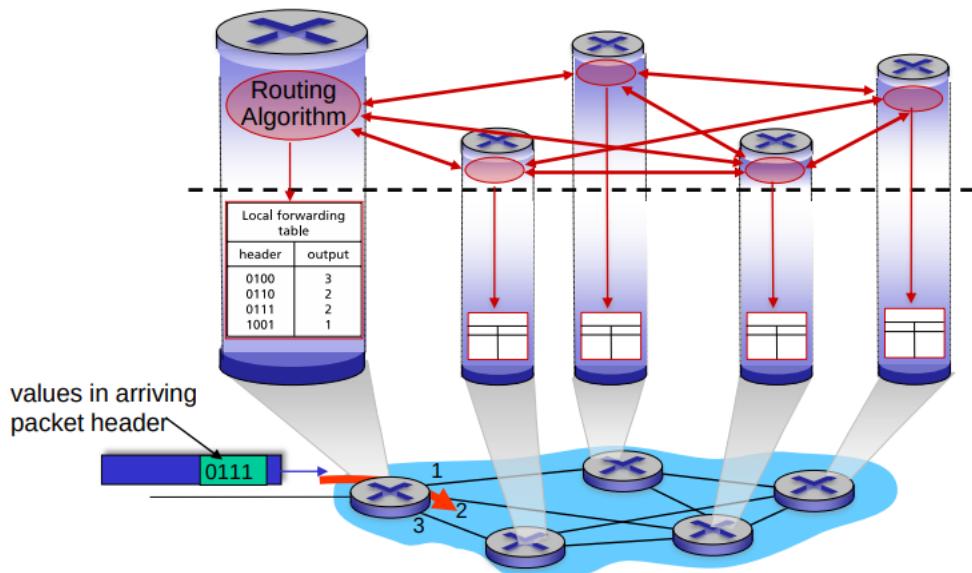


Figure 11.1: undefined undefined

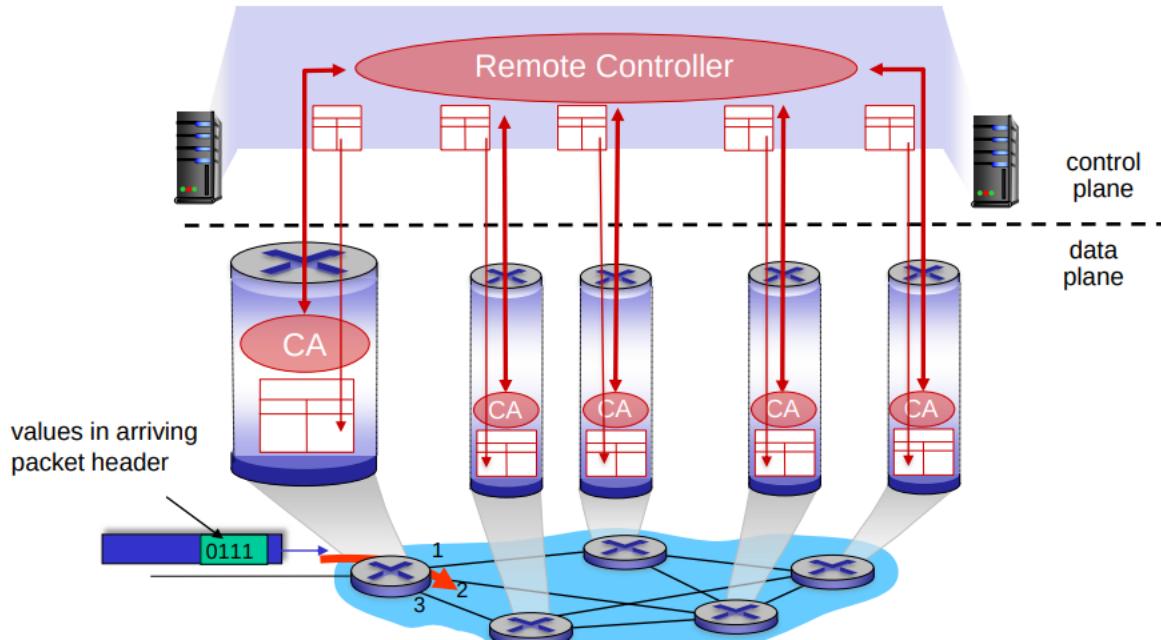


Figure 11.2: undefined undefined

Software-Defined Networking control plane

In this approach, the **remote controller** computes and installs the forwarding tables in each router, as pictured in 11.2.

The rationale behind a **logically centralized** control plane reside in the fact that is easier to carry out management network functions by *avoiding router misconfiguration* and gaining greater flexibility of traffic flows. The so called *table-based forwarding* (*e.g OpenFlow API*) allows programming routers in different ways:

1. *Centralized programming easier*: compute tables centrally and distribute
2. *Distributed programming more difficult*: compute tables as a result of distributed algorithm implemented in each and every router

There are some difficult regarding the **traffic engineering** with a traditional router. For example, let's consider those scenarios and relatives implications:

- *What if the network operator want $u \rightarrow z$ traffic to flow along $uvwz$ rather than $uxyz$?* There is the need to re-define link weights so traffic routing algorithm computes routes accordingly: the tuning of the weight does not provide enough control on the routing itself. Refer the diagram in 11.3
- *what if network operator wants to split $u \rightarrow z$ traffic along $uvwz$ and $uxyz$ (load balancing)?* It's not possible or at least require a new routing algorithm. Refer the diagram in 11.4.
- *what if w wants to route blue and red traffic differently from w to z ?* Not possible. Refer the diagram in 11.5.

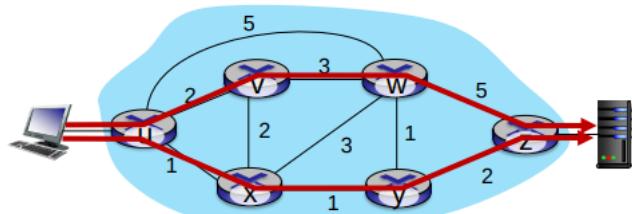


Figure 11.3: undefined undefined

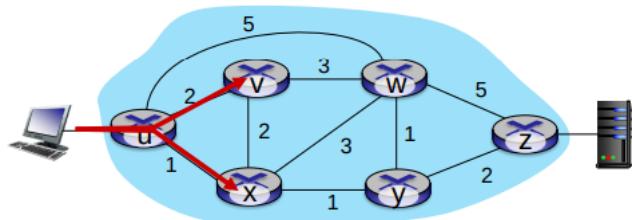


Figure 11.4: undefined undefined

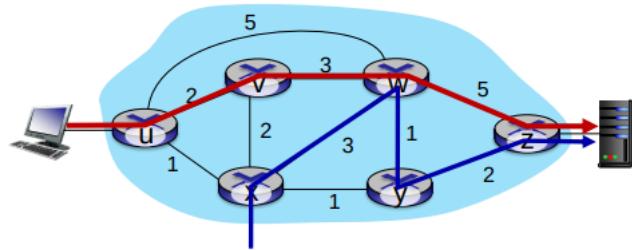


Figure 11.5: undefined undefined

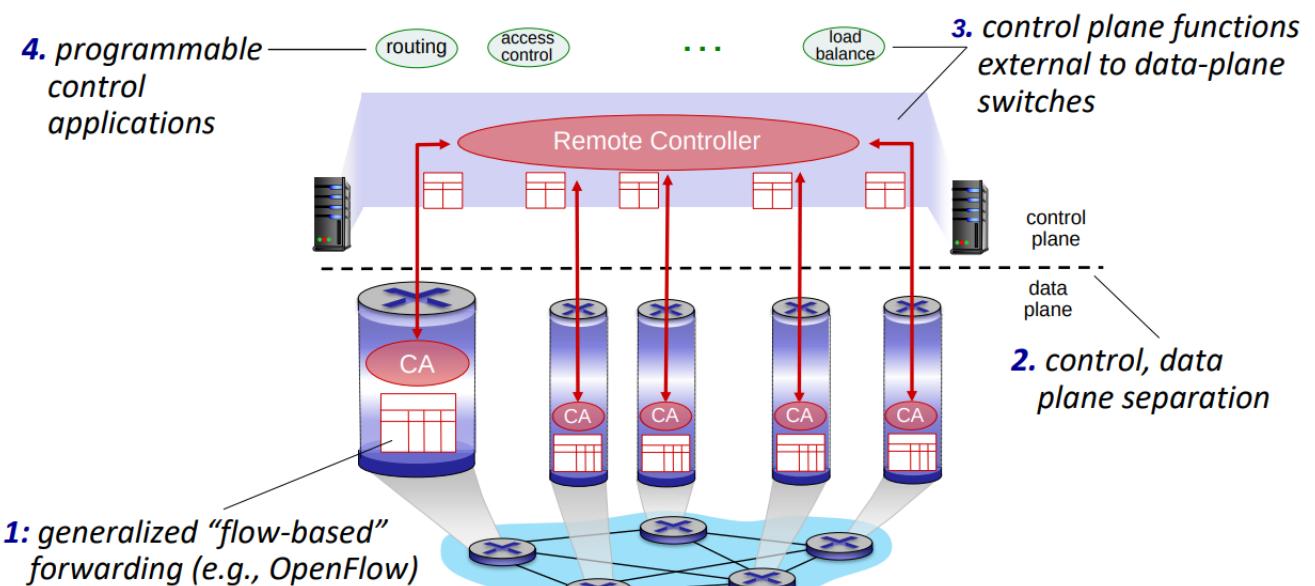


Figure 11.6: Overview of logically centralized control plane features

11.0.1 SDN Architecture

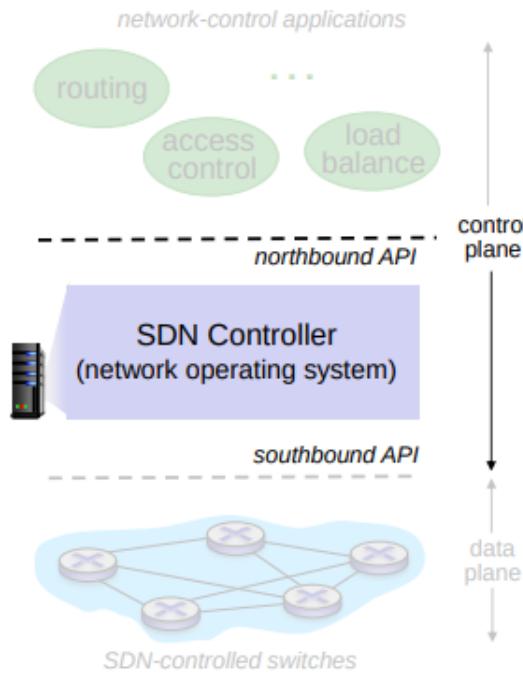


Figure 11.7: undefined undefined

The main three components are:

1. **Data plane switches**: they implement generalized data-plane forwarding in hardware. The forwarding table is already computed, installed under the supervision of the controller. They provide also API for table-based switch control (*like OpenFlow*) and provide a protocol for communicating with the controller. They are *dummy* devices, without added complex and routing mechanisms to be computed.
2. **SDN Controller**: maintain the network state information and interact with the network control application above via the *northbound API* and the network switches via the *southbound API*. It's implemented as distributed system to guarantee scalability, performance and fault-tolerance. It separates the control and the data plane (*as opposed to classical routing*): it represents the *Network Operating System* because it performs routing decisions based on different customizable criteria.
3. **Network control apps**: they implement the control function (*like routing, access control and load balancing*) using lower-level services, using the APIs provided by the SDN Controller. This layer can also be *unbundled* so provided by third-party supplier. Can have different routing vendor or SDN controller, customizable thanks to the northbound/southbound API exposure. Specifically, the northbound API provides a deeper abstraction respect to southbound API (*mainly OpenFlow*).

11.1 SDN Data Plane

The SDN data plane represents the resource or infrastructure layer made by forwarding devices: it allows to perform the transport and processing of data according to decisions made by the SDN control plane. It performs those functions without embedding software, implementing an autonomous decision mechanism. The data plane can have virtual switches or physical switches, as sketched in 11.8.

The main function of the SDN data plane is to forward packets between network devices based on instructions provided by the SDN controller. The controller communicates with the data plane switches using a standardized protocol called OpenFlow, which allows the controller to program the switches to perform specific actions based on network conditions.

Some of the key functions of the SDN data plane include:

1. **Packet forwarding**: The data plane switches are responsible for forwarding packets between network devices based on the instructions provided by the controller. They also need to be able

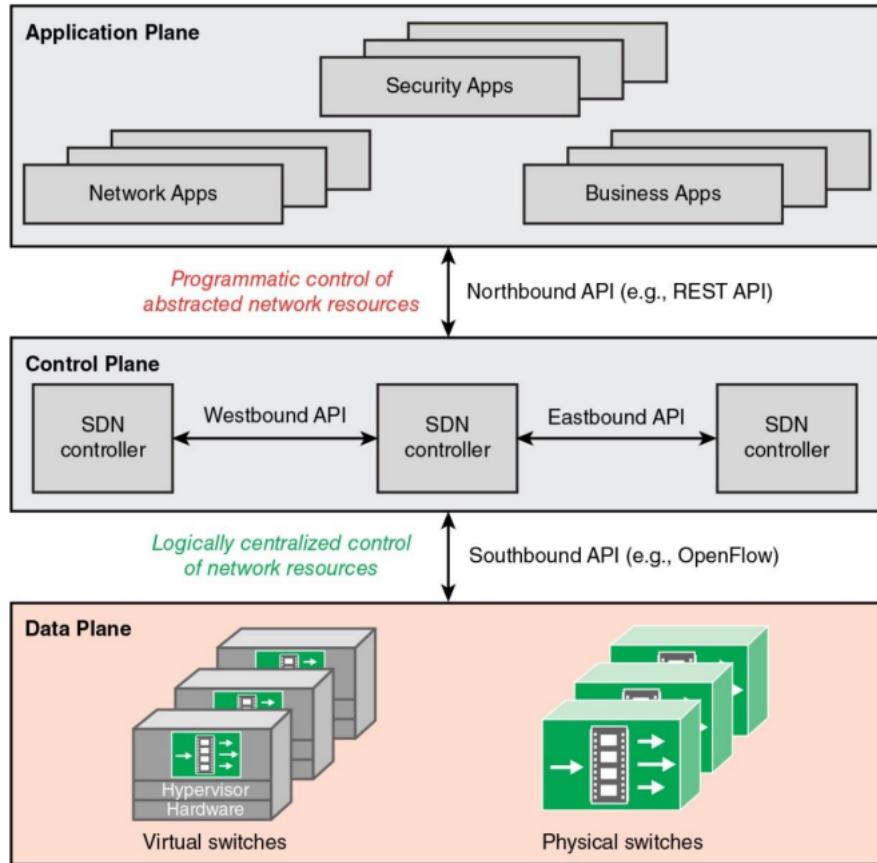


Figure 11.8: undefined undefined

to forward packets at high speeds, without causing bottlenecks or delays. It accepts incoming data flows from other network devices and end-systems: forwards them along the data forwarding paths computed and established according to the rules defined by the SDN applications. The *control support function* include the interaction with the SDN controller for management of forwarding rules (*the reference standard specification is mainly OpenFlow Switch Protocol*).

2. **Traffic shaping:** The data plane can implement traffic shaping policies to manage the flow of traffic through the network. For example, it can prioritize certain types of traffic, such as voice or video, over other types of traffic to ensure that they are delivered without delay.
3. **Security:** The data plane can implement security policies to prevent unauthorized access to the network. For example, it can filter out packets that do not meet certain criteria, such as those coming from a known malicious source.
4. **Quality of Service (QoS):** The data plane can implement QoS policies to ensure that certain types of traffic are given priority over others. For example, it can ensure that real-time applications like voice and video are given higher priority over other types of traffic.
5. **Load balancing:** The data plane can implement load balancing policies to distribute traffic across multiple network paths. This helps to prevent congestion and ensure that traffic is delivered efficiently.

The **Generalized forwarding** operated by the data plane consists in providing each router a **forwarding table (flow table)** that use the "*match plus abstraction*": match bits in arriving packets and take the corresponding action. Two main forwarding techniques are used:

1. **Destination-based forwarding:** forward based mostly on destination IP address
2. **Generalized forwarding (followed by OpenFlow):** many header fields (e.g. MAC Address, destination port, etc) can determine the action and many actions are possible on a given flow/packet like drop/copy/log packet/modify. It generalize both matching information and action to be taken.

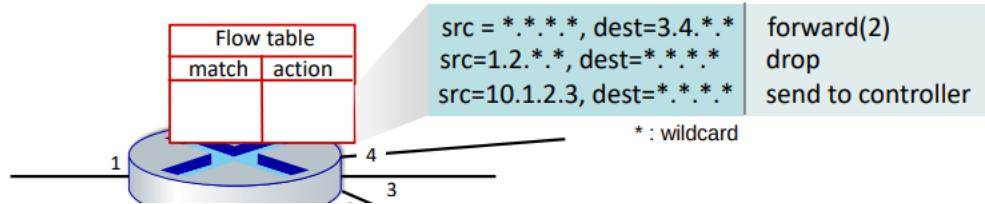


Figure 11.9: undefined undefined

The **flow** is defined by the header fields values (*respectively in link-, network-, transport-layer fields*). The generalized forwarding define simple packet handling rules (11.9):

- **match:** pattern values in packet header fields
- **actions:** for matched packet can **drop**, **forward**, **modify** or send matched packets to controller to decide the action to be performed.
- **priority:** disambiguate overlapping patterns (*flows can match more than one entry so needs disambiguation*)
- **counters:** allows to count the number of bytes and packets, mainly for statistics. Those are helpful to identify patterns and derive rules based on traffic volumes and parameters, updating the controller knowledge on the network.

The packet can be sent to the controller only once: the first time a packet is send back to the switches with informations for future patterns (*e.g. as in the last picture*).

OpenFlow: Flow table entries

The following figure in 11.10 present the information that can be used at different layer to set the matching rules in the flow tables.

Examples As pictured in 11.11 and, as an example of switch implementation in 11.12.

OpenFlow abstraction The *match plus action* abstraction allows to unifies different kinds of devices, based on their behavior:

- **Router:** the **match** is the longest IP prefix, the **action** forward out a link
- **Switch:** the **match** is the destination MAC address, the **action** forward or flood
- **Firewall:** the **match** is the IP address and the TCP/UDP port numbers, the **action** is permit or deny

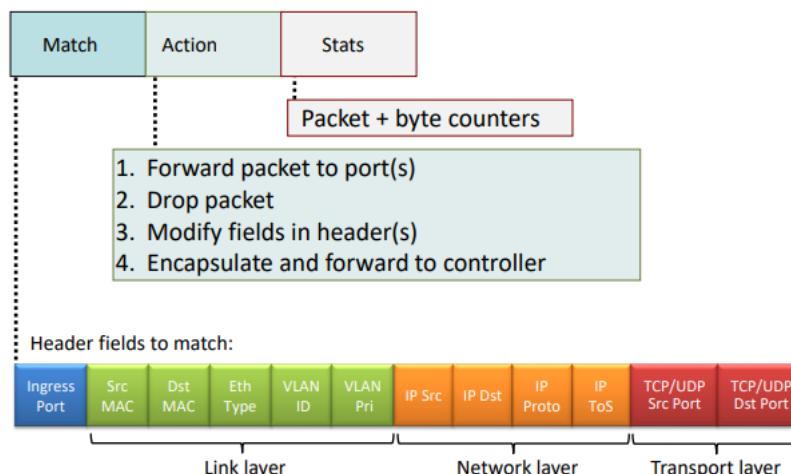


Figure 11.10: undefined undefined

Destination-based forwarding:

| Switch Port | MAC src | MAC dst | Eth type | VLAN ID | VLAN Pri | IP Src | IP Dst | IP Prot | IP ToS | TCP s-port | TCP d-port | Action |
|-------------|---------|---------|----------|---------|----------|--------|----------|---------|--------|------------|------------|--------|
| * | * | * | * | * | * | * | 51.6.0.8 | * | * | * | * | port6 |

IP datagrams destined to IP address 51.6.0.8 should be forwarded to router output port 6

Firewall:

| Switch Port | MAC src | MAC dst | Eth type | VLAN ID | VLAN Pri | 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 Pri | IP Src | IP Dst | IP Prot | IP ToS | TCP s-port | TCP d-port | Action |
|-------------|---------|---------|----------|---------|----------|--------|-------------|---------|--------|------------|------------|--------|
| * | * | * | * | * | * | * | 128.119.1.1 | * | * | * | * | drop |

Block (do not forward) all datagrams sent by host 128.119.1.1

Figure 11.11: undefined undefined

Layer 2 destination-based forwarding:

| Switch Port | MAC src | MAC dst | Eth type | VLAN ID | VLAN Pri | IP Src | IP Dst | IP Prot | IP ToS | TCP s-port | TCP d-port | Action |
|-------------|---------|-----------------------|----------|---------|----------|--------|--------|---------|--------|------------|------------|--------|
| * | * | 22:A7:23: 11:E1:02 | * | * | * | * | * | * | * | * | * | port3 |

layer 2 frames with destination MAC address 22:A7:23:11:E1:02 should be forwarded to output port 3

Figure 11.12: undefined undefined

- **NAT:** the **match** is IP address and port, the **action** is to substitute a private IP address with a public IP address. So the boundaries between switches and router's behaviour is blurring.

Example 2 The idea is that the OpenFlow controller have a complete overview of the network, providing the forwarding tables to the switches without them implementing and re-compute the algorithms itself. In the example picture in 11.13, the datagram from host h5 and h6 are destined to h3 or h4 and should be forwarded via s1 and from there to s2. The routing tables are configured to forward the traffic by passing from s1.

OpenFlow Switch

In a OpenFlow switch there is more than a one flow tables, usually organized in pipeline as showed in 11.14. The group table specify a more complex behavior that refer to a group of flows, specifying rules for group of flows based on their attribute. Both those two type of table specify the data plane. The control channel allows to communicate to the control plane: typically can have a connection with multiple controllers as they are implemented in a distributed way. The simplest configuration is the **master-slave** with only one controller while the complex one can include active-passive controller for redundancy.

Flow table pipeline The packet entering the switch are analyzed according to those mentioned tables as sketched in 11.15

The passage through different table accumulate the actions associated with a given **match** forming a **pipeline of actions** that will be executed only as final step before the packet is sent out as stated in 11.16.

If there is a match on one or more entry in the table, the match is defined to be with the highest priority matching entry. If there is a match only on a table-miss entry, the table entry may contain instructions as with any other entry. In practice, te table-miss entry specifies one of three actions:

1. **Send packet to controller:** this will enable the controller to define a new flow for this and similar packet or decide to drop the packet
2. **Direct packet to another flow table** further down the pipeline

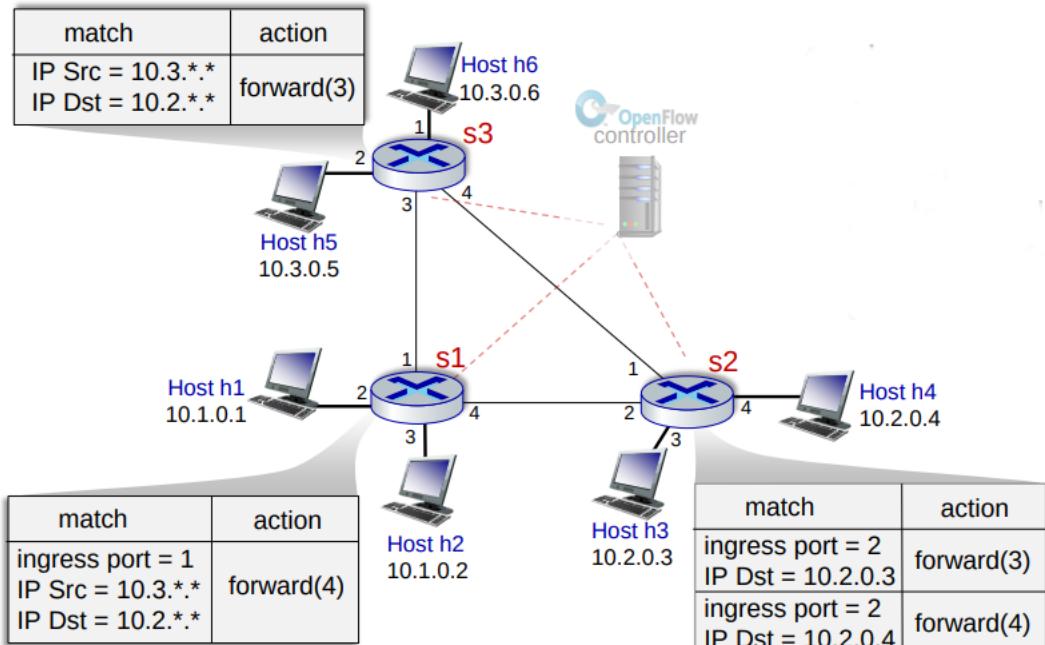


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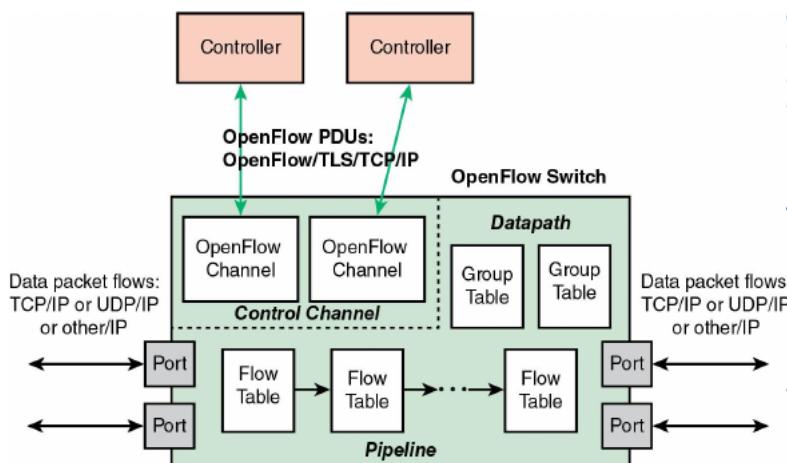


Figure 11.14: undefined undefined

3. **Drop the packet:** If there is no match on any entry and there is no table-miss entry, the packet is dropped.

11.2 SDN Control plane

The general structure of the SDN Control plane is sketched in 11.17.

We may distinguish three layers:

1. **Communication layer:** in the bottom one there is the OpenFlow implementation and the SNMP protocol.
2. **Network-wide state management:** the central part is the core of the controller. It collects and manages the information about the underlying infrastructure (*host information, how many switches, how many active ports are active, etc*) and according to those information build the general network overview and extract statistics and manage dynamically flow tables.
3. **Interface layer to network control apps:** In the upper layer there are components that handle the interaction with application like *network graph, RESTful API* to expose the network topology

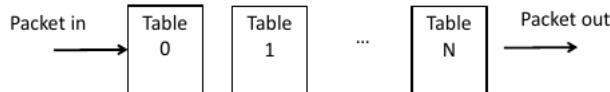


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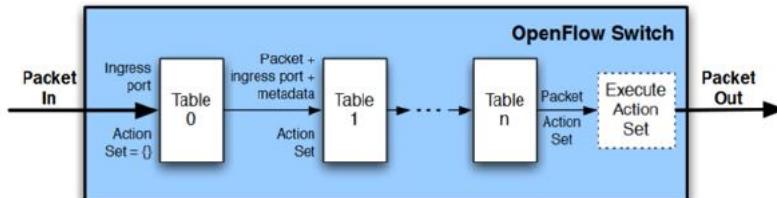


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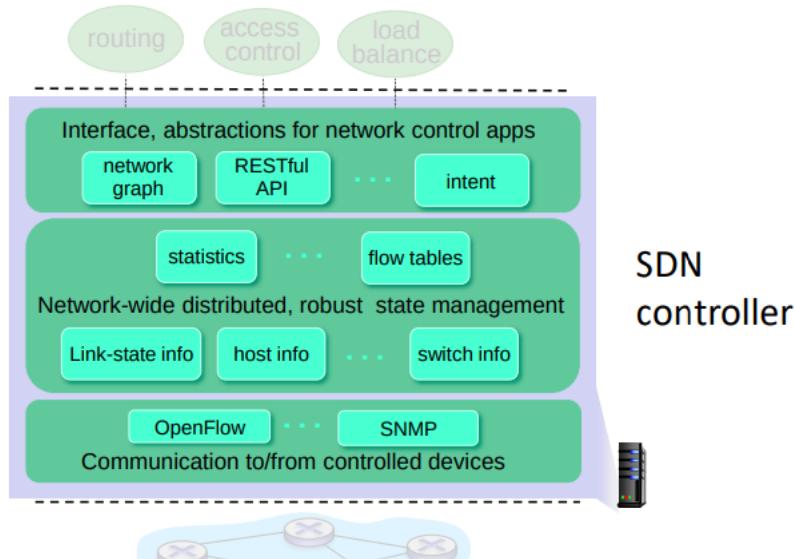


Figure 11.17: undefined undefined

to the application or *intent* that, for example, state at high level "*drop the malicious traffic pattern*" without specifying how: the SDN controller elaborates this intent and traduce this intent in a set of rules to be installed based on the current network topology.

11.2.1 OpenFlow

The **OpenFlow protocol** operates between a *controller* and *switches*: use TCP to exchange messages (*suggested with TLS*). There are three classes of messages:

1. **Controller to switch:** These OpenFlow messages are initiated by the controller and sent to the switch to manage its behavior. Examples of **controller to switch** messages include **packet-out** messages to send packets to a specific port or set of ports, **flow-mod** messages to add, modify or delete flow entries in the switch's flow table, and **barrier-request** messages to synchronize the switch's processing with the controller.
2. **Asynchronous (Switch to controller):** These OpenFlow messages are initiated by the switch and sent to the controller to notify it of events that occur on the switch. Examples of asynchronous messages include **packet-in** messages that inform the controller of packets that match a flow entry with the "*send to controller*" action, **port-status** messages that notify the controller of changes in the state of switch ports, and **error** messages that report errors encountered by the switch.
3. **Symmetric (both directions):** These OpenFlow messages can be initiated by either the controller or the switch and are sent in both directions to maintain the state of the OpenFlow channel. Examples of symmetric messages include **echo-request** and **echo-reply** messages to test the

OpenFlow Controller

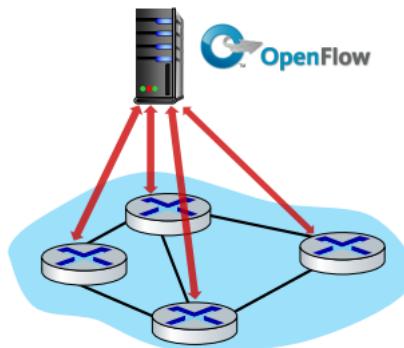


Figure 11.18: OpenFlow controller schema

connectivity and responsiveness of the channel, and features-request and features-reply messages to exchange information about the switch's capabilities and configuration.

The main **controller-to-switch** messages can be of the following type:

- **features**: controller queries switch features, switch replies
- **configure**: controller queries/sets switch configuration parameters
- **modify-state (FlowMod)**: the controller ask the switch to add, modify, delete an entry in the routing rule table
- **packet-out**: controller can send this packet out of specific switch port. The controller instruct the switch to implement a specific action for a specific pattern.

The main **switch-to-controller** messages can be:

- **packet-in**: transfer packet to controller. For this packet the switch delegate the control to the controller.
- **flow-removed**: the switch inform the controller that has deleted an entry in its flow table
- **port-status**: inform the controller of a change on a port

Usually network operators don't *program* switches by creating/sending OpenFlow message directly but use higher-level abstraction at controller.

SDN: Control/data plane interaction example The interaction between the SDN control plane and data plane consists of 6 steps, as pictured in 11.19.

1. S1 is experiencing link failure so uses OpenFlow **port-status** message to notify the controller
2. SDN Controller receive the message and updates link status info
3. Dijkstra's routing algorithm application has previously registered to be called whenever link status change so it's called
4. Dijkstra's routing algorithm access the network graph information, link state information in the controller and computes new routes
5. Link state routing app interacts with flow-table-computation component in the SDN controller, which computes new flow tables needed
6. Controller uses Openflow to install new tables in switches that need updating

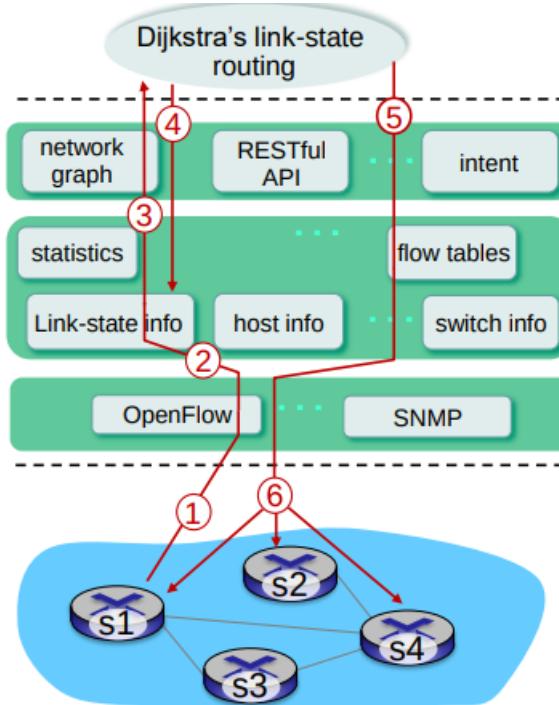


Figure 11.19: undefined undefined

11.3 Topology discovery and forwarding

Traditionally the **routing** function is distributed among the routers in a network: in an **SDN controlled network** it make sense to centralize the routing action within the SDN controller. The controller can develop a *consistent view* of the network state for calculating shortest paths and can implement application-aware routing policies. **Data plane switches** are relieved of the processing and storage burden associated with routing, leading to improved performances because **centralized routing** application performs two different functions:

1. **Link/Topology discovery:** routing function needs to be aware of the links between data plane switches. The topology discovery in OpenFlow is not fully standardized.
2. **Topology manager:** maintains the topology information for the network, computing routes in the network like the shortest path between two data plane nodes or between a data plane node and a host.

The **Topology Discovery** is implemented by exploiting two major *initial configuration* features of Openflow (*OF*) switches:

1. every OF switch has initially set the IP address and TCP port of a controller to establish a connection as soon the device is turned on
2. switches have pre-defined behavior which support by implementation the support of the topology discover. It's supported by preinstalled flow rules to route directly to the controller via a **Packet-in** message any message of the **Link Layer Discovery Protocol (LLDP)**.

11.3.1 LLDP - Link Layer Discovery Protocol

It's a **neighbor discovery protocol** of a single jump: it advertises its identity and capabilities and receive the same information from the adjacent switches. It's a vendor neutral protocol (*defined by IEEE*) ad operates at **layer 2** of OSI Model. It can be used also in traditional network and it's used by switches that support active configuration. In OpenFlow network, switches send the LLDP messages to discover the underlying topology as a direct request of the controller.

LLDP uses *Ethernet* as its transport protocol, thus the Ethernet type for LLDP Is 0x88cc. An LLDP frame contains the following fields (11.20):

- **Chassis ID (Type 1):** contains the identifier of the switch that sends the LLDP packet.

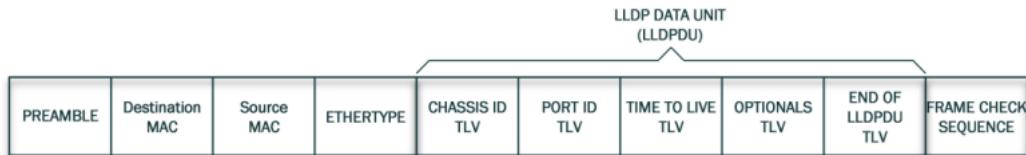


Figure 11.20: LLDP Fields

- **Port ID (Type 2):** contains the identifier of the port through which the LLDP packet is sent.
- **Time to Live (Type 3):** time in seconds during which the information received in the LLDP packet is going to be valid.
- **End of LLDPDU (Type 4):** indicates the end of the payload in the LLDP frame

Switch initialization

The initialization under the *LLDP* protocol, for the pictured scenario in 11.21, implies the need of the controller to understand the **circular topology** of the switches.

When the switch is initialized:

- Establish a connection with the controller
- The controller send a message *FEATURE REQUEST MESSAGE* to the switch
- The switch responds with a message *FEATURE REPLY MESSAGE*
- It informs the controller of relevant parameter for the discovery of the links like the **Switch ID** and a list of **active ports** with their respective MAC associate, among other. At the end of the initial handshake, the controller knows the exact number of active ports on the OF switches **but** it doesn't know the physical connections between switches so it needs to build it by performing *Topology Discovery*

The **topology discovery** it's based on the information obtained from the initial handshake so the controller known the exact number of active ports:

1. The controller generates a **Packet-Out** message per active port on each switch discovered on the network and encapsulates a **LLDP packet** inside each generated message.
2. When an OF switch receives a LLDP message sent by the controller, it **forwards the message by the appropriate Port ID** included in the message to adjacent switches
3. Upon receiving the messages by a port that are not the controller port, **the adjacent switches encapsulate the packet within a Packet-In message addressed to the controller**. Meta-data is included in the message such as **Switch ID, Port ID** where the LLDP packet is received, among others
4. When the packet comes back to the controller from an adjacent switch, the controller extracts this information, and then it knows a link exists between those switches

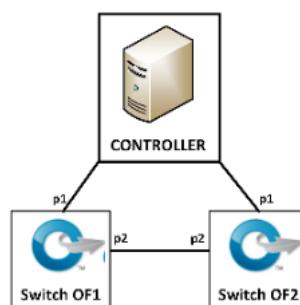


Figure 11.21: undefined undefined

The controller at the end known the **Switch ID** and **Port ID** in the LLDP message and **Switch ID** and **Port ID** in metadata (*from which the switch received the LLDP message*). This process is repeated for every OF switch on the network: the entire process of discovery is performed periodically. In a network of S switches interconnected by a set of links L , the total of packet-out message that the controller sends out to the network to discover all existing link between OF switches with P active port is:

$$Total_{packet-out} = \sum_{i=1}^S P_i$$

Let's clarify with an example pictured in 11.22:

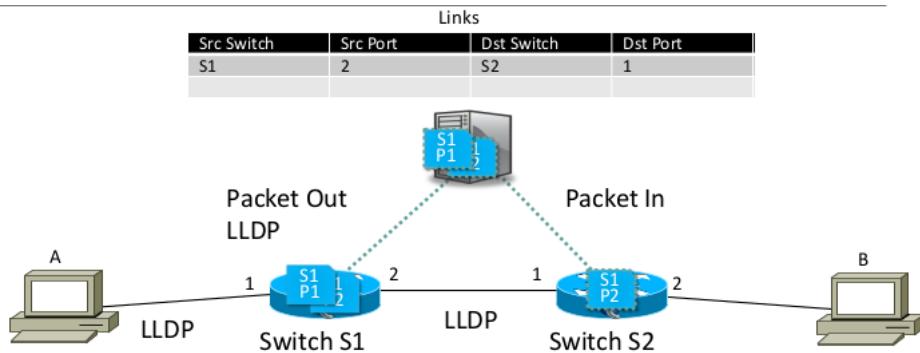


Figure 11.22: Topology Discovery Scenario

The controller send a **Packet-Out** to $S1$: the switch send the packet $S1 - P1$ to host A which it's not an LLDP device so did not answer, while send the LLDP packet $S1 - P2$ to switch $S2$. The switch $S2$ add its metadata information like **Switch ID**, **Port ID** and send the **Packet-In** message to the controller that now knows that $S1$ and $S2$ are adjacent because the packet sended by $S2$ contains the information that the initial LLDP packet was received from $S1$ via port 1_{S2} .

The topology discovery itself does not able both the controller and the switches to identify which hosts are reachable. The controller can learn that there is a **reachable host** in the network (*that is not an OF switch, so do not reply to OF packets*): the discovery is triggered by **unknown traffic entering** the controller's network domain either from an *attached host* or from a *neighboring router*. (*For unknown we mainly refer to not LLDP packets*).

For the **path computation**, initially flow tables on all switches are *empty*, but assume that **Host table** and **Topology** at the controller level are fully populated with the necessary knowledge of the network and host. Refer the scenario in picture 11.23: when the switch receive a packet from the host A send the packet to the controller so it can compute the path and send the **Flow Mod** to update the flow table of the switches along the path from A to B . Based on the assumption that the controller already have all the knowledge about the host table and topology, the $S1$ and $S2$ flow table are updated as in figure.

These Flow Mod packets (*both from the controller to $S2$ and $S1$*) will be sent to each switch in **reverse order**, from the switch closest to the destination and so on until the source switch: the rationale behind this order is to **avoid the scenario in which multiple switches trigger the path computation to the controller** while there is the flow table updating operation ongoing by the controller.

All future packets from this flow will match directly at each switch and no longer need to take a trip up to the controller.

Exercise Describe the source, destination and semantics of the following OF messages:

- packet-in
- packet-out
- FlowMod:

11.3.2 Application of SDN

The SDNs's early adopters were companies that manages datacenter, for several use cases:

- Switching fabrics - SDN within data center: from black box to white box switches, server interconnected by software

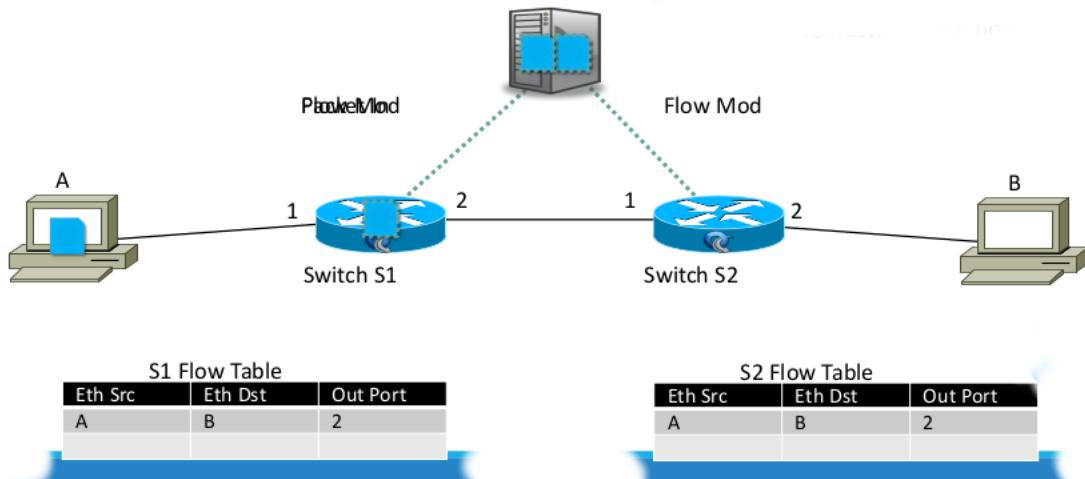


Figure 11.23: LLDP Path Computation

- Virtual networks - SDN to setup, manage and shutdown
- Wide area networks - as a traffic engineering methods, optimizing the traffic between different datacenters (*e.g. Google WAN for inter-datacenter traffic*).

Here we analyze the **B4 - Google Use case** of SDN inside Google Datacenters.

Google WAN

There are two separate backbones:

- **B2**: carries internet facing traffic. It have a growing traffic than the internet.
- **B4 11.24**: carries inter-datacenter traffic (*sort of horizontal traffic*). It have more traffic than B2 that also grows faster than B2

Google have its own globally deployed WAN, private and connected to all its datacenter. Data center are deployed across the world (as shown in 11.25) and need to ensure **multi-tenancy availability zone and redundancy** to guarantee availability and reliability of its service. The content are served based on geographic locality and replicated for fault tolerance among few dozens of datacenter around the world.

This network it's not on the public internet and must be cost-effective for high volume of traffic, performing load balancing among the DC.

Three main *type of flow types* are consired:

1. **User data copies** to remote data center for availability/reliability (*lowest volume, most latency intensive, highest priority*)

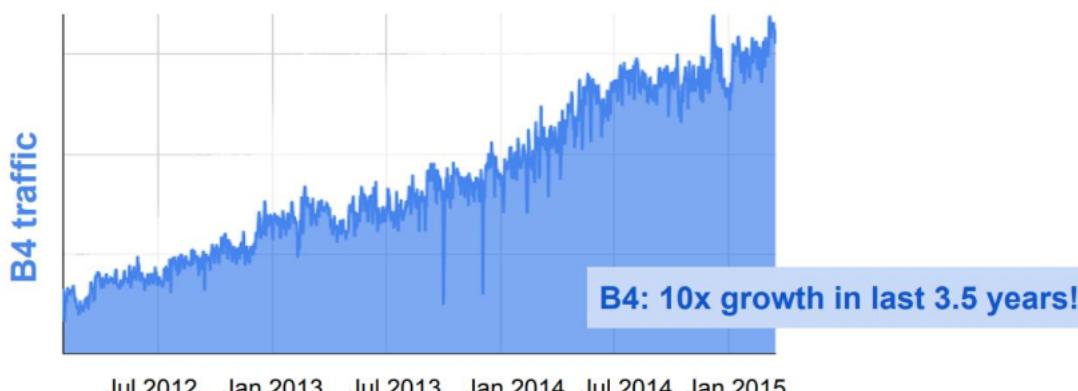


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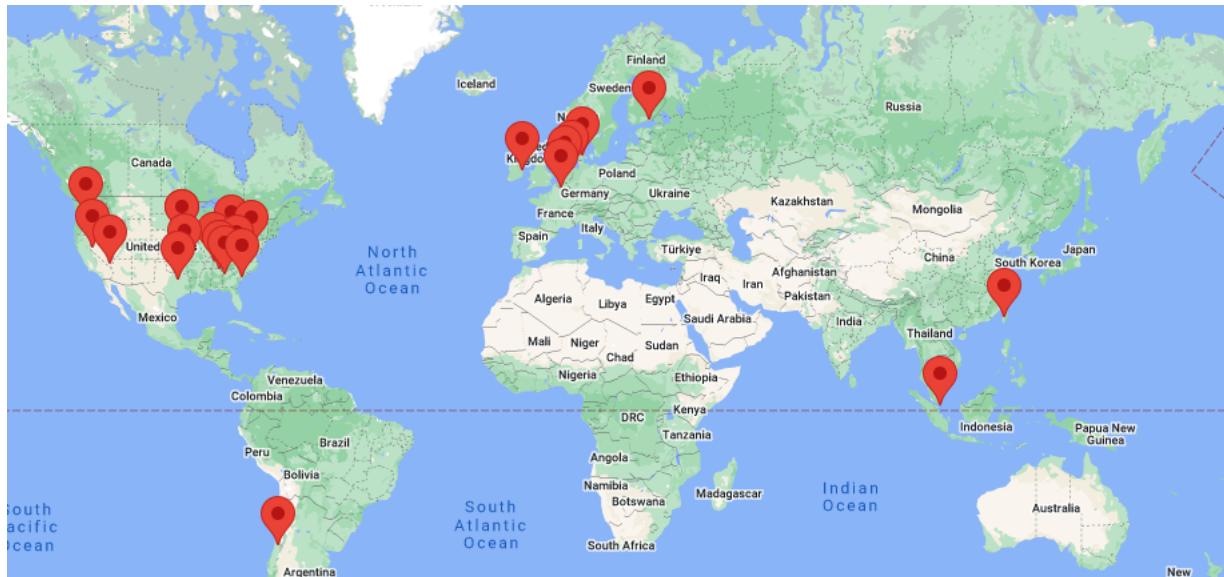


Figure 11.25: Google Datacenter Locations

2. Remote storage access for computation over distributed data sources
3. Large-Scale data push **synchronizing state across multiple data center** (*highest volume, least latency intensive, lower priority*)

The main problem in traditional WAN routing is that all the flows are treated with the same behavior (*so there is no QoS*), all the links are used on average with 30% to 40% with some peaks, downgrading overall performance in a small timeframe.

The **backbone B4** has been built considering some requirements:

- *Elastic bandwidth demand*: applications can tolerate periodic failures or temporary bandwidth reductions
- *Moderate number of sites*: few dozens of sites, no need for large routing tables
- *End application protocol*: Google has the control of the application so can optimize the schedule of the data transfer, using a fine-grained application protocol. This avoid the need for link provisioning.
- *Cost sensivity*: private intercontinental links cost, so it needs to be used at its full capacity

The main *design decisions* applied on B4 backbone are related to:

1. **Customize HW and SW**: customize routing and monitoring protocols to requirements with a rapid custom protocol development
2. **Low cost switching hardware**: edge application control limits need for large buffers but the limited number of sites avoid the need to manage large forwarding tables
3. **Centralize traffic engineering (TE)** : allows more optimal and transfer traffic engineering than distributed control routing. It allows also to share bandwidth among competing applications. Usually the **TE server** is an application that works on top on the SDN controller.
4. **Increase link utilization**: allows an efficient use of expensive long haul transport. With **Traffic Engineering** usually we refer as a set of techniques to optimize and control traffic flows in a telecommunication network in order to ensure a maximum throughput and a sufficient QoS level.

B4 Architecture Overview

The **B4 architecture overview** is pictured in 11.26.

Each site have an *OFA - OpenFlow Agent* while the *site controller* it's based on a distributed *NCS - Network Controller System* to avoid a single point of failure. The *switch hardware* forwards traffic without using any complex control software and builded by using Google custom design with commodity

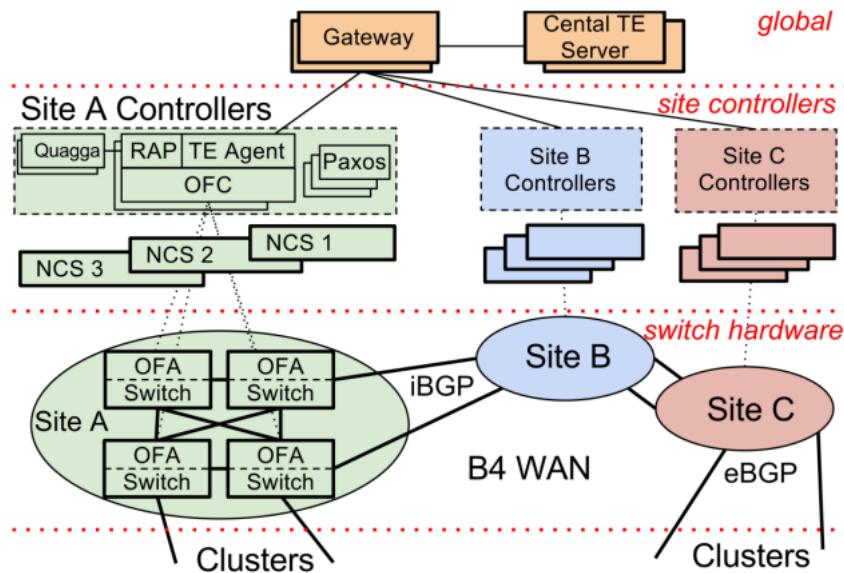


Figure 11.26: B4 Backbone General Architecture

silicon.

The **control layer** is composed by *NCS* hosting both OpenFlow controllers (*OFC*) and Network Control Application (*NCAs*): the *OFCs* maintain network state based on *NCA* directives and switches events but also instruct the switches to set forwarding table entries based on this changing network state.

The **global layer** is composed by a logically centralized applications like the *SDN Gateway* and a *Central TE Server*: the *SDN Gateway* abstracts details of OpenFlow and switches hardware from the central *TE server*. Each *B4* site consists of multiple switches with potentially hundreds of individual ports.

Each cluster contains a set of BGP router that peer with *B4* switches at each WAN site: the rationale behind this choice was made due to the familiarity of the operator with the BGP protocol and maintain protocols retro-compatibility, enabling also a gradual rollout.

The **traffic engineering** components in the *global layer* are pictured in 11.27:

The figure shows an overview of the **TE architecture**. The *TE Server* operates over the following state:

- The **Network Topology** graph represents sites as vertices and site to site connectivity as edges. The *SDN Gateway* consolidates topology events from multiple sites and individual switches to *TE*. *TE* aggregates trunks to compute site-site edges. This abstraction significantly reduces the size of the graph input to the *TE Optimization Algorithm*.
- The **Flow Group (FG)**: For scalability, *TE* cannot operate at the granularity of individual applications. Therefore, we aggregate applications to a Flow Group defined as `{source site, dest site, QoS}` tuple.
- A **Tunnel (T)** represents a site-level path in the network, e.g., a sequence of sites (A → B → C in 11.26). *B4* implements tunnels using IP in IP encapsulation.
- A **Tunnel Group (TG)** maps FGs to a set of tunnels and corresponding weights. The weight specifies the fraction of FG traffic to be forwarded along each tunnel.

TE Server outputs the Tunnel Groups and, by reference, Tunnels and Flow Groups to the *SDN Gateway*. The *Gateway* forwards these Tunnels and Flow Groups to *OFCs* that in turn install them in switches using OpenFlow.

Another main component is the **Bandwidth Enforcer**: to capture relative priority, we associate a *bandwidth function* with every application, effectively a contract between an application and *B4*. This function specifies the bandwidth allocation to an application given the flow's *relative priority* on an arbitrary, dimensionless scale, which we call its **fair share**. We derive these functions from administrator-specified *static weights* (the slope of the function) specifying relative application priority. In the example pictured in 11.28, *App1*, *App2*, and *App3* have weights 10, 1, and 0.5, respectively. Bandwidth functions are configured, measured and provided to *TE* via Bandwidth Enforcer.

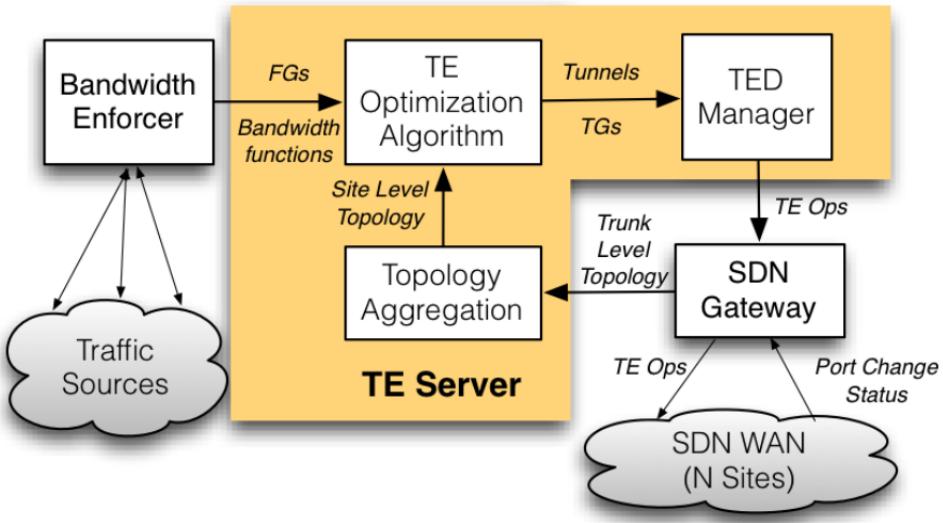


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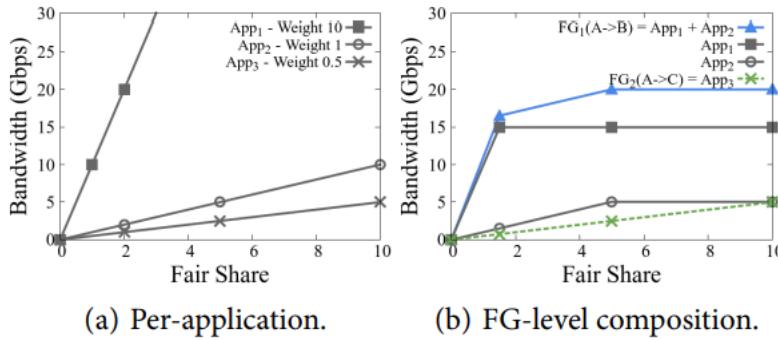


Figure 6: Example bandwidth functions.

Figure 11.28: Bandwidth functions

Improvements results OpenFlow has helped Google improving B4 backbone (*as shown in 11.29*) ⁽¹⁾:

- Utilization near 100% for elastic loads
- Mirror production events for testing on virtualized switches
- Reduced complexity
- Reduced costs

With follow-up improvements ⁽²⁾:

- hierarchical topology
- decentralized TE algorithms

⁽¹⁾ Sushant Jain et al. "B4: experience with a globally-deployed software defined wan". In Proc. of the ACM SIGCOMM 2013 ACM, New York, NY, USA, 3-14

⁽²⁾ Hong CYY et al.,. B4 and after: managing hierarchy, partitioning, and asymmetry for availability and scale in google's software-defined WAN. In Proc. Proc. of the ACM SIGCOMM 2018 Aug 7 (pp. 74-87)

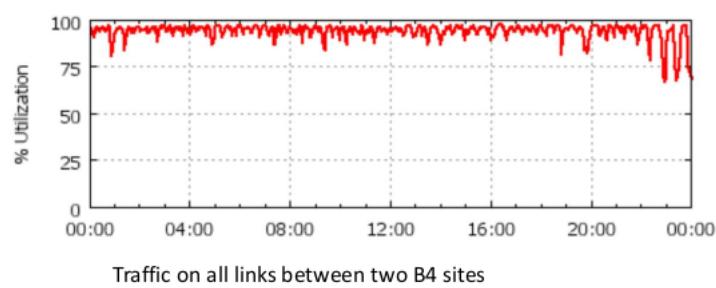


Figure 11.29: undefined undefined

Chapter 12

Network Function Virtualization

Within SDN, **Network Function Virtualization (NFV)** allows *programmable networking*: it's mainly used in 5G and datacenter, allowing managing traffic with different requirements by performing load balancing, security, etc. The global traffic trend have increased within the user requirements: more data and rapidly changing services involves also an increase in *CapEx*. To give a context, in traditional telco industry this increase was based on deploying physical equipment for each function that is part of a given service: this has led to *long product cycles, very low service agility and dependencies on specialized hardware (invest money and time to configuire that must last years to not sustain useless costs)*.

A typical enterprise network is pictured in 12.1.

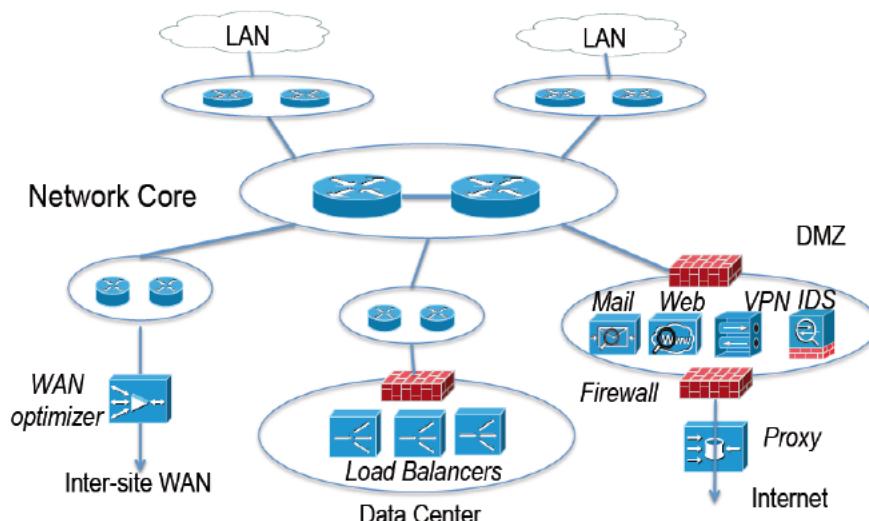


Figure 12.1: undefined undefined

This network contains beside all the routing gear, the *load balancer* connected to the data center or the *DMZ* that provide computing for third services inside the enterprise network: those function manage flows for internal purpose (*IDS, VPN, Mail, etc*). Those last functions are good candidates to be virtualized by NFV. Virtualize this function represent an advantage because they're usually in high number inside an enterprise network (*taken from https://doi.org/10.1145/2070562.2070583*) as shown in table 12.2.

The complexity of internet arises, shifting from end to end device to a multiple type of device as an intermediary between two end nodes. So we can state the problem as *increasing demand* from users and short-lived service with high data rates: this implies the need to purchase and operate physical equipment, obtaining a dense deployment of network equipment. The telco operator so shifted from hardware pure based solution to software-based solution: they grouped in ETSI - European Telco Standards Institute.

12.0.1 Key idea

NFV address the previous problem by leveraging virtualization technologies: allows to **decouple hardware from software, allowing to migrate and execute network function where needed**. A

| Type of appliance | Number |
|--------------------------|-------------|
| Firewalls | 166 |
| NIDS | 127 |
| Media gateways | 110 |
| Load balancers | 67 |
| Proxies | 66 |
| VPN gateways | 45 |
| WAN Optimizers | 44 |
| Voice gateways | 11 |
| Total Middleboxes | 636 |
| Total routers | ~900 |

Figure 12.2: undefined undefined

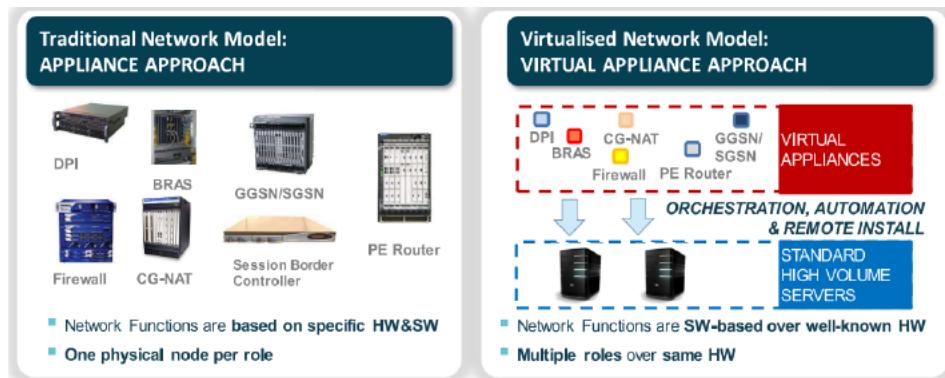


Figure 12.3: undefined undefined

Network Service can be decomposed into a set of **Virtual Network Functions (VNFs)**. The picture 12.3 shows the shift that the virtualization achieve.

The main **use cases** for NFV are the one where data plane packet processing and control plane in mobile and fixed network, like:

- **Switching elements:** BNG, CG-NAT, routers
- **Mobile network nodes:** HLR/HSS, MME, SGSN, GGSN/PDN-GW, RNC, Node B, eNodeB
- Functions contained in home routers and set top boxes to create virtualized home environments
- **Tunneling gateway elements:** IPsec/SSL VPN gateways
- **Traffic analysis:** DPI, QoE measurement
- **Service Assurance, SLA monitoring, Test and Diagnostics**
- **NGN signaling:** IMS
- **Converged and network-wide functions:** AAA servers, policy control and charging platforms
- **Application-level optimization:** CDNs, Cache Servers, Load Balancers, Application Accelerators
- **Security functions:** Firewalls, virus scanners, intrusion detection systems, spam protection

Use case: vEPS

Both the **core (EPC)** and the **RAN (Radio Access Network)** can be virtualized, this allows to improve the network usage efficiency and guarantee higher service resiliency thanks to the flexibility allocation of different NFs on the hardware pool and by providing dynamic network configuration.

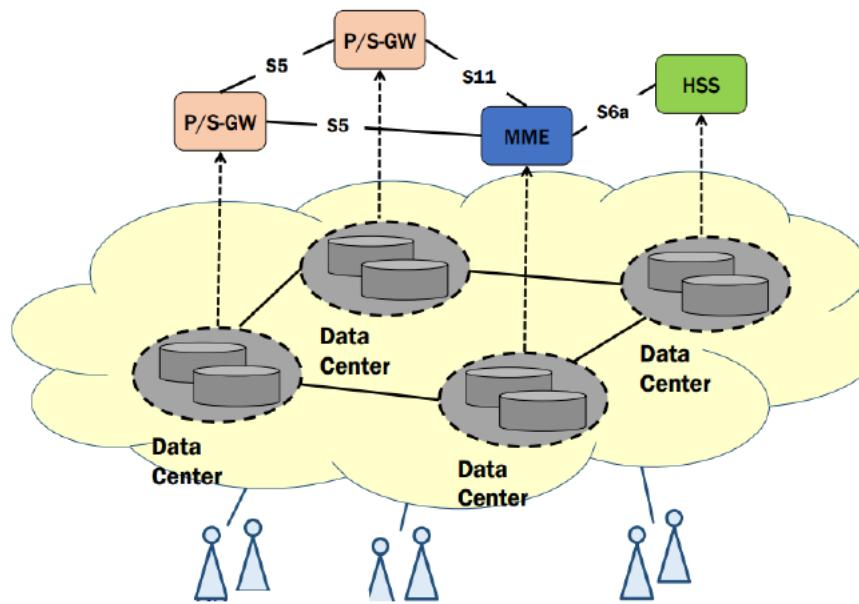


Figure 12.4: undefined undefined

The following image shows how the shift from the hardware-based functions is performed by virtualizing and splitting the function across different locations that can be connected by IP network, even if they're located in different datacenters, allowing a **virtualized RAN**.

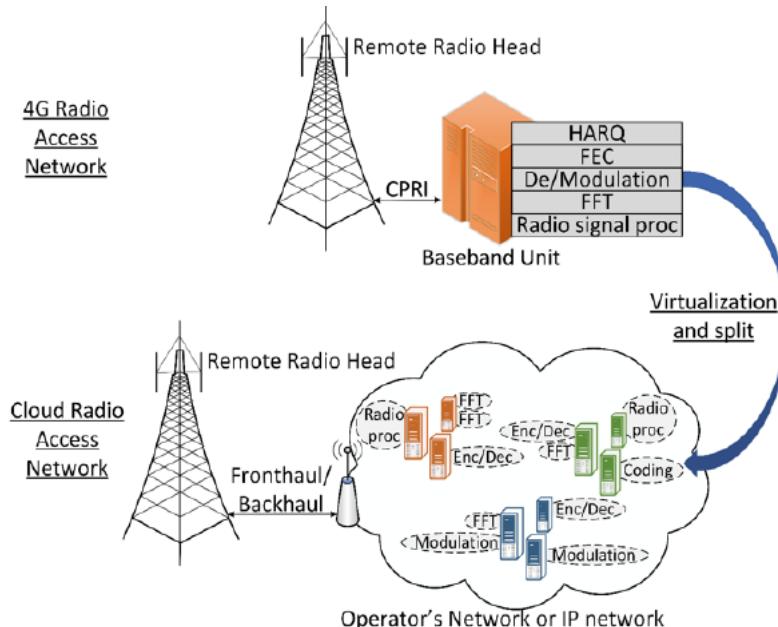


Figure 12.5: undefined undefined

The benefits are that in traditional networks, all devices are deployed on proprietary/closed platforms. All network elements are enclosed boxes, and hardware cannot be shared. Each device requires additional hardware for increased capacity, but this hardware is idle when the system is running below capacity.

With NFV, however, network elements are independent applications that are flexibly deployed on a unified platform comprising standard servers, storage devices, and switches. In this way, software and hardware are decoupled, and capacity for each application is increased or decreased by adding or reducing virtual resources.

The cons consists in having **overhead** respect to the specialized hardware that can have **optimized performance** respect to a general device server.

12.0.2 Network service

Usually a telco operator need a chain of the Network function, being able to differentiate the treatment between each flow, as described in 12.6

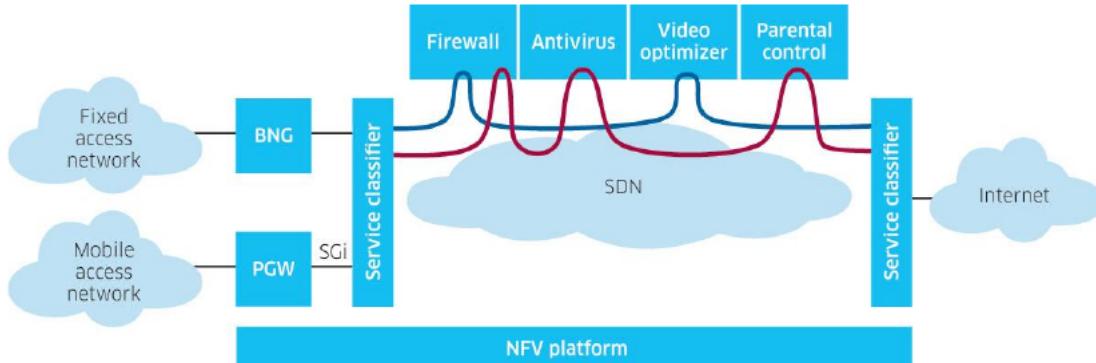


Figure 12.6: undefined undefined

The pictured feature is called **Network service chaining**, also known as **Service Function Chaining (SFC)** (see IEEE RFC7665) and uses SDNs capabilities to create a chain of connected network services, such as L4-7 services like firewall, NAT and intrusion protection.

Network operators can use network service chaining to set up suites or catalogs of pathways for traffic travel through the network. Any one path can consist of any combination of connected services depending on the traffic's requirements. Different traffic requirements might be more *security, lower latency, or an overall high quality of service (QoS)**.

The primary advantage of network service chaining is to automate the way virtual network connections can be set up to *handle traffic flow* for connected services.

For example, an SDN controller could take a chain of services and apply them to different traffic flows depending on the source, destination, or type of traffic. The chaining capability automates what traditional network administrators do when they connect up a series of physical L4-7 devices to process incoming and outgoing network traffic, which traditionally may require a number of manual steps.

A network service in NFV is an **end-to-end network service** that can be defined as **forwarding graph of network functions and endpoints/terminals**, basically what an operator provides to customers. A network service can be viewed architecturally as a *forwarding graph* of *Network Functions (NFs)* interconnected by supporting network infrastructure: these network functions can be implemented in a single operator network or interwork between different operator networks. The underlying network function behaviour contributes to the behaviour of the higher-level service. An example is pictured in 12.7.

In the previous picture (12.7) there is a chain of network functions. The interconnections among the *NFs* and endpoints are depicted by *dashed lines*, representing logical links. These logical links are supported by physical paths through infrastructure networks (*wired or wireless*). Endpoints can be a network enterprise (A) or a datacenter (B), depending on the specific scenario.

In figure 12.8 a topological view of the previous picture:

VNF can also be decomposed in different functions: the VNFs run as VMs on physical machine (called **Points of Presence - PoPs**) so the placement it's generally located where it's function it's optimal. As an example, consider VFN-1 as a cache service that is placed at the edge of the network. Consider also the pictured schema where the nested function VNF-FG-2 is composed by three different *Virtualized Network Functions* (respectively VNF-2A, VNF-2B, VNF-2C). The virtualization allows to migrate and instantiate those functions among different PoPs, also automating those operations by **orchestrating** the setup, installation and execution of VFN autonomously.

12.0.3 NFV Architectural Framework

The **architectural framework** addresses the following:

- **NFVI (Network Function Virtualization Infrastructure):** The resources required to setup a Network service

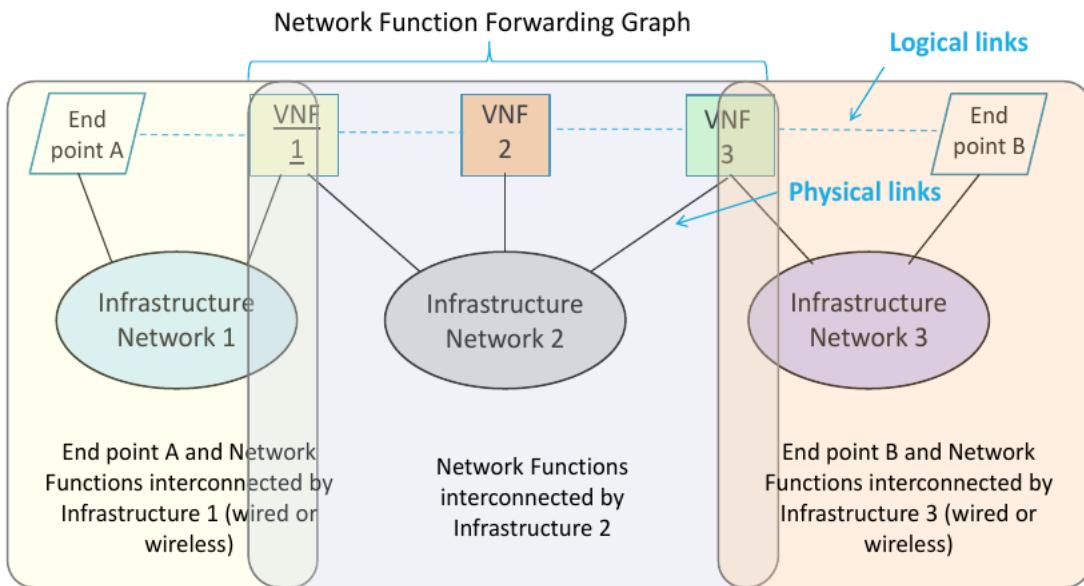


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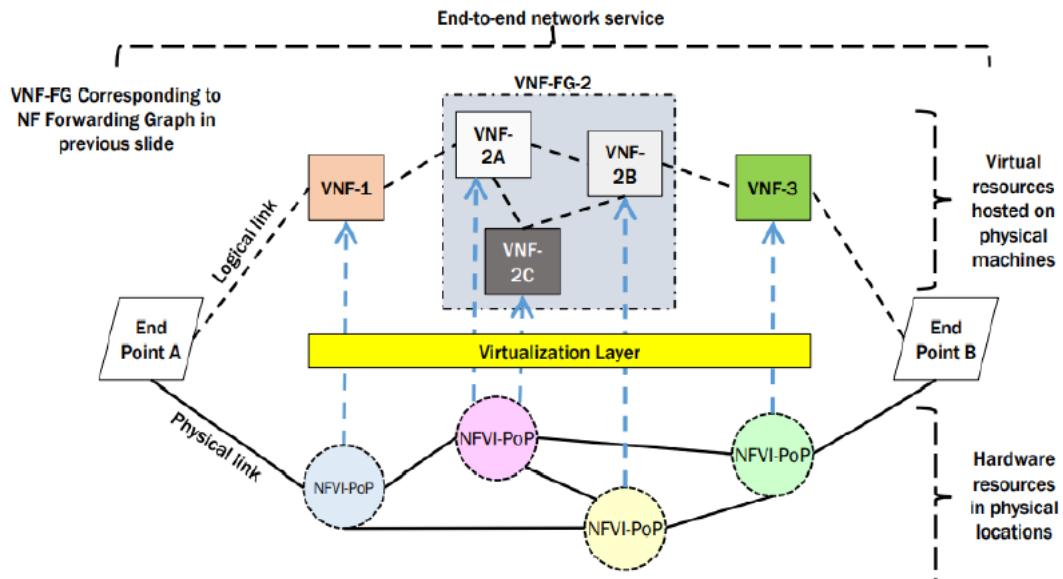


Figure 12.8: Topological view of 12.7

- **VNF (Virtualized Network Function):** The functionality that is required due to the decoupling network functions into software and hardware
- **MANO (Management and Orchestration) :** allocate a set of virtual resources and support the management of orchestration of the functions

The general infrastructure schema is pictured in 12.9.

The **NFV infrastructure (NFVI)** comprises the hardware and software resources that create the environment in which VNFs are deployed. Each **VNF** is implemented in software to run on virtual computing, storage, and networking resources. Finally, the **NFV management and orchestration (NFV-MANO)** is the component responsible for the management and orchestration of all resources in the NFV environment, ensuring the quality of service and the SLAs.

NFV Infrastructure It comprehends the totality of all **hardware and software components** which build up the environment in which VNFs are deployed, managed and executed by virtualizing physical computing, storage, and networking and places them into resource pools. The **physical hardware resources** include computing, storage and network that provide processing, storage and connectivity to

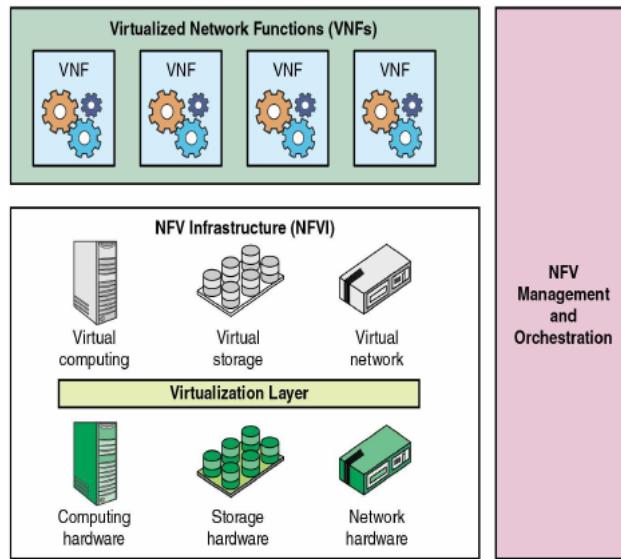


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VNFs through the virtualisation layer (*e.g. hypervisor*). The computing hardware, in this context, is assumed to be general-purpose and the storage resources can be differentiated between shared network attached storage (*NAS*) and storage that resides on the server itself.

Overall, inside the *NFV Infrastructure* we can identify 3 different domains (*as shown in 12.10*):

- **Compute domain:** provides commercial off-the-shelf (*COTS*) high-volume servers and storage.
- **Hypervisor domain:** mediates the resources of the compute domain to the VMs of the software appliances, providing an abstraction of the hardware. (*e.g. VMs but now VNFs are also executed in containers, implementing Cloud Native Functions (CNF)*)
- **Infrastructure network domain:** comprises all the generic high volume switches interconnected into a network that can be configured to supply network services.

The NFVI can span across *several location*, so there are only **two main types of networks**:

- **NFVI-PoP network:** interconnects the computing and storage resources contained in an *NFVI-PoP*. It also includes specific switching and routing devices to allow external connectivity.
- **Transport network:** interconnects *NFVI-PoPs*, *NFVI-PoPs* to other networks owned by the same or different network operator, and *NFVI-PoPs* to other network appliances or terminals not contained within the *NFVI-PoPs*.

We focus on **Infrastructure network domain** by providing an example of **OpenStack Networking deployment** (12.11):

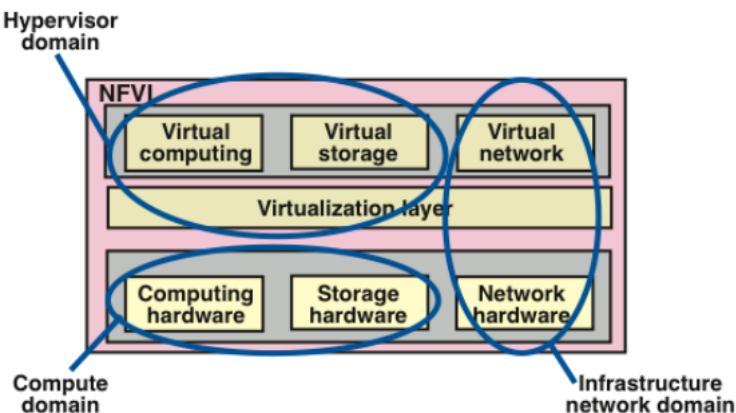


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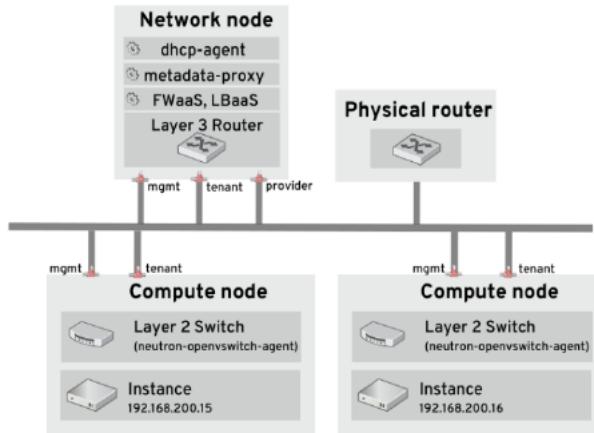


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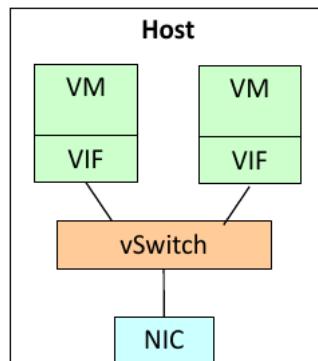


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In the previous picture (12.11), we have a dedicated *OpenStack Networking node* performing L3 routing and DHCP, and running advanced services like *FWaaS (Forwarding as a Service)* and *LBaaS (Load Balancing as a Service)*. There are also two *Compute nodes* run the **Open vSwitch (openvswitch-agent)** and have two physical network cards each, one for tenant traffic, and another for management connectivity. The OpenStack Networking node has a third network card specifically for provider traffic. The **vSwitch** provide connectivity between VIFs (*Virtual Interfaces*) and PIFs (*Physical Interfaces*) that allows to connects different Virtual Machines (12.12). It also handle the traffic between VIFs colocated on the same physical host. The virtual switch usually reside in the host and are typically entirely software (*as an example, see Open vSwitch*).

12.0.4 Management and Orchestration (MANO)

The schema pictured in 12.13 illustrates the NFV Reference Architectural Framework: the *MANO* component is sketched on the right (*gray area*).

Overall, the *Management and Orchestration* component provides the functionality required for the **provisioning of the VNFs** by detailing the VNFs configuration and the configuration of the infrastructure on which the VNFs run. It also includes **orchestration and lifetime management of physical and/or software resources** supporting the infrastructure virtualization and the lifecycle management of VNFs. Includes *databases* used to store information and data models defining deployment and lifecycle properties of functions, services and resources. Defines **interfaces used for communications between components of the MANO**, as well as coordination with traditional network management, such as *OSS/BS*.

Going bottom-up, the first component is **VIM - Virtualized Infrastructure Management**: it comprises the functions that are used to control and manage the interaction of a VNF with computing, storage and network resources under its authority. A single instance of a VIM is responsible for controlling and managing the NFVI compute, storage, and network resources, usually within one operator's infrastructure domain. To deal with the overall networking environment, multiple VIMs within a single

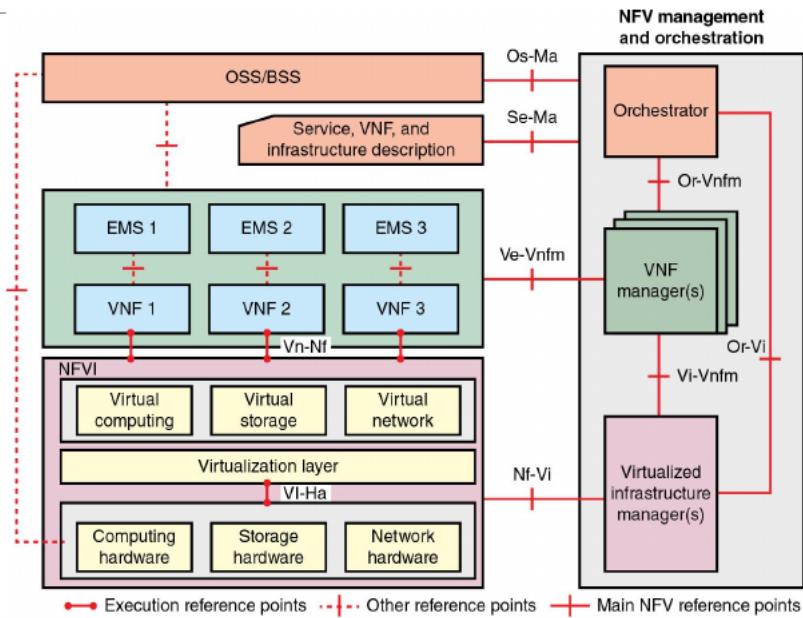


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MANO may be needed.

The second component is the **Virtual Network Function Manager - VNFM**: It oversees the *lifecycle management* by instantiation, update, query, scaling up/down, terminate of VNF instance. It's also under its responsibility the *collection of NFVI performance measurement results* and faults/events information, and correlation to VNF instance -related events/faaults.

Finally, the **NFV Orchestrator - NFVO** is responsible for installing and configuring new network services (*NS*) and virtual network functions (*VNF*) packages alongside the management of the lifecycle of network service and global resources. The **Network services orchestration** it's responsible of manage/coordinate the creation of an end-to-end service that involves VNFs: it creates end-to-end service between different VNFs and can instantiate VNFM, where applicable. Differently, the **Resource orchestration** manages and coordinates the resources under the management of different VIMs.

Overall, the *NFV MANO* internal schema is pictured in 12.14.

The **Network Services Catalog** act as a repositories of network services and have four main purposes:

1. **List of the usable network services:** a deployment template for a network service in terms of

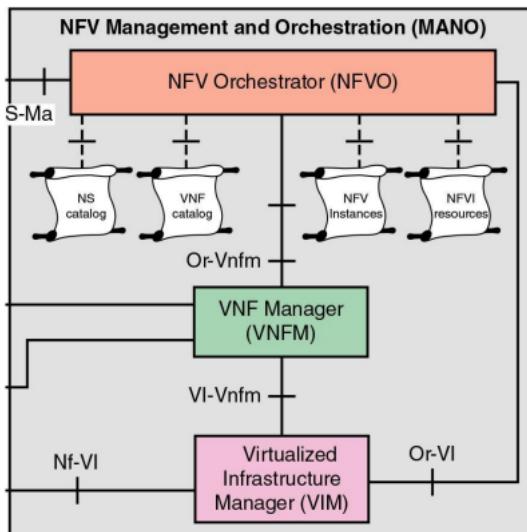


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VNFs and description of their connectivity through virtual links is stored in NS catalog for future use.

2. **Database of all VNF descriptors (VNFD)**: a VNFD describes a VNF in terms of its deployment and operational behavior requirements.
3. List of **NFVI resources** utilized for the purpose of establishing NFV services.
4. List containing details about network services instances and related **VNF instances**.

12.1 Network Slicing

The 5G network are intended to provide three types of services:

- *mMTC - massive Machine Type Communications*: massive number of devices communicating with each other and requires low cost along with long battery backup time
- *URLLC - Ultra-Reliable Low Latency Communications*: needs simultaneous low-latency and increased reliability mechanisms
- *eMBB - Enhanced Mobile Broadband*: higher data rates along with large coverage area

Those services are not uniquely determined, but are correlated to the specific use case. The metrics can vary as the specific technical requirements. The table 12.15 report the guaranteed services with a relative example and the ensured requirements.

Network slicing idea is to create different logical network on top of the physical one. The resources are pooled together, on the physical resources: this allows to shape and address the requirements of the previous use cases. Each subnetwork will perform slicing of the physical network resources to yield an *independent network* for its applications.

Basically network slices allow to create *customized networks* realized by creating multiple virtual and end-to-end networks. This can be done by exploiting the two technical elements already presented:

- NFV: implements the NFs in a *network slice*. The virtualization allows the isolation of each network slice from all other slices: this assures QoS and security requirements for that slice, independently from other network slices.
- SDN: once a network slice is defined, SDN operates to monitor and enforce QoS requirements by controlling and enforcing the behavior of the traffic flow for each slice.

There are several ways to combine NFV with SDN: the SDN controller can be used with the *VIM (Virtual Infrastructure Manager)* to program and route the traffic flows, providing traffic isolations and balancing the resources to some flows respect to others.

5G Use case

The general scenario is sketched in 12.17, without great detail.

Two locations are considered in 12.17: the edge it's closer to antennas and the core cloud is the remote one. The underlying hypothesis is that the first have few resources compared with the core cloud DC: if you need to support low-latency requirements, balancing resources respect to the total utilization and flow heavy computation to the core cloud.

Some terminology:

| 5G use cases | Example | Requirements |
|-------------------------------------|---|---|
| Mobile Broadband (eMBB) | 4K/8K UHD, hologram, AR/VR | High capacity, video cache |
| Massive IoT (mMTC) | Sensor network (metering, agriculture, building, logistics, home, etc.) | Massive connection (200000/km ²), mostly immobile devices, high energy efficiency |
| Mission-critical IoT (URLLC) | Motion control, autonomous driving, automated factory, smart-grid | Low latency (ITS 5 ms, motion control 1 ms), high reliability |

Figure 12.15: 5G Use cases table

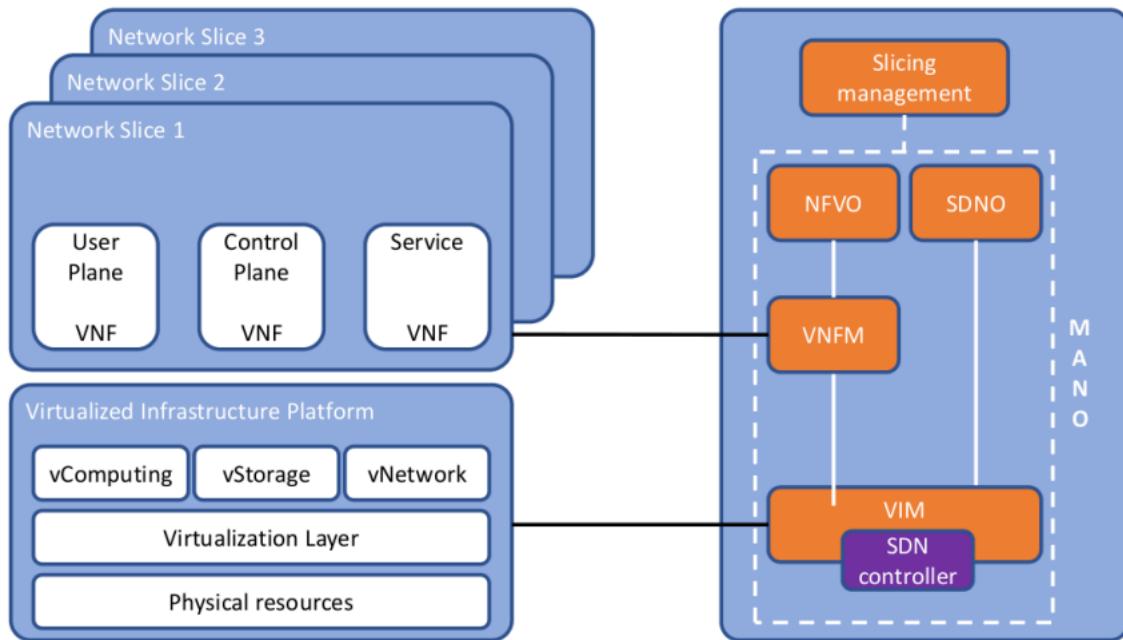


Figure 12.16: Network Slicing: component interaction flow

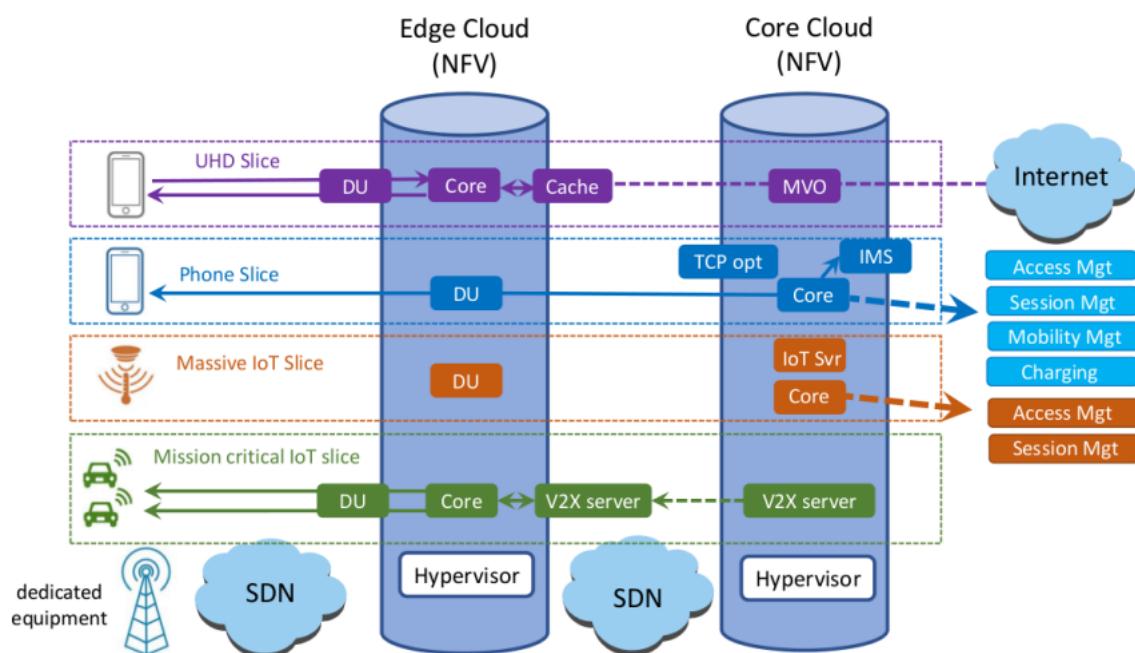


Figure 12.17: Example scenarios: distribution of services among different data center locations

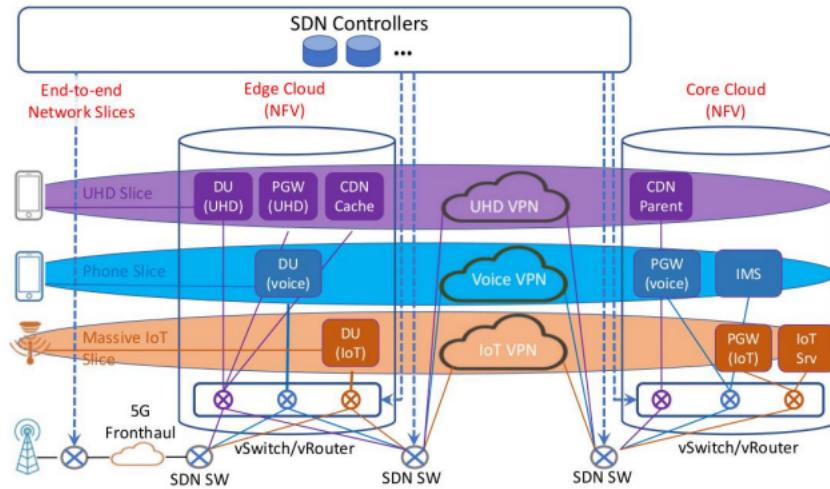


Figure 12.18: Flow filtering, different view of 12.17

- *v2x*: for application services
- *Radio Unit (RU)*: radio hw unit
- *Distributed Unit (DU)*: typically deployed close to the RU
- *Centralized Unit (CU)*: can be placed in the cloud (*radio resource control, packet data converge protocol*)

NFV allows to move those functions where needed, based on specific requirements and provided resources. For the phone slice, the core is distributed in the core cloud, moving the workload to the more resource-powered location. The distinguish scenario between IoT (*pictured in 12.17*) consists in having the possibility, in the second case, to move the function from the core to the edge.

The isolation of different flow, as pictured in 12.18, is usually performed by the *vSwitch* or *vRouter* within a node. The **SDN SW (ingress)** classifies the traffic incoming from the fronthaul: flow filtering enforces isolation and implement the forwarding rules based on the classification provided. The traffic flows through the *egress* router and flows in the specific VPN. SDN Controllers allows to define how to handle the traffic, defining the flow rules to be applied by the router/switches along the path chain.