COST Action CA15104

Collaborative White Paper on Future Architecture and Protocols for IoT

COST Action CA15104 (IRACON) aims to achieve scientific networking and cooperation in novel design and analysis methods for 5G, and beyond-5G, radio communication networks.

The scientific activities of the action are organized according to two types of Working Groups: disciplinary and experimental Working Groups. In total, IRACON consists of 6 working groups: Radio Channels (DWG1), PHY layer (DWG2), NET Layer (DWG3), OTA Testing (EWG-OTA), Internet-of-Things (EWG-IoT), Localization and Tracing (EWG-LT) and Radio Access (EWG-RA). A sub-working group of EWG-IoT was also recently created: IoT for Health.

This white paper focuses on the Internet of Things (IoT). First, it introduces the IoT field with a general definition and the main applications, with the related requirements. Then, a description of the technologies available nowadays is provided; for each technology the main key parameters are given, and some quantitative and/or qualitative key performance indicators are reported. The white paper concludes with a brief overview of IoT architectures and a mapping between the identified applications and the most appropriate technology.

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List of acronyms

ACK Acknowledgement

AI Artificial Intelligence

AP Access Point

BLE Bluetooth Low Energy

BPSK Binary Phase Shift Keying

BW Bandwidth

CE Coverage Enhancement

CoAP Constrained Application Protocol

CR Code Rate

CSMA Carrier-Sense Multiple Access

CSMA/CA Carrier-Sense Multiple Access with Collision Avoidance

CSS Chirp Spread Spectrum

C-V2X Cellular Vehicle-to-Everything

DCC Decentralized Congestion Control

DCF Distributed Coordinating Function

D2D Device-to-Device

DL Downlink

DSME Deterministic and Synchronous Multichannel Extension

DSRC Dedicated Short Range Communications

DSSS Direct Sequence Spread Spectrum

EDCA Enhanced Distributed Channel Access

eDRX extended Discontinuous Reception

eNB enhanced Node-B

FEC Forward Error Correction

FDD Frequency Division Duplexing

FDMA Frequency Division Multiple Access

FFD Fully Function Device

GSM Global System for Mobile communication

GSMA GSM Association

3GPP 3rd Generation Partnership Project

5G 5th Generation

HARQ Hybrid Automatic Repeat Request

IEEE Institute of Electrical and Electronics Engineers

IETF Internet Engineering Task Force

IoT Internet of Things

IIoT Industrial IoT
IP Internet Protocol
IPS Indoor Positioning System
ISM Industrial Scientific Medical
KPI Key Performance Indicator
LDPC Low Density Parity Check
LLDN Low Latency Deterministic Network
6LoWPAN IPv6 over Low-Power Wireless Personal Area Networks
LPWA Low Power Wide Area
LPWAN Low Power Wide Area Network
LR-WPAN Low-Rate Wireless Personal Area Network
LTE Long Term Evolution
LTE-M Long Term Evolution for Machines
MAC Medium Access Control
MBMS Multimedia Broadcast/Multicast Service
MEC Mobile Edge Computing
MCL Maximum Coupling Loss
MCS Modulation and Coding Scheme
MIMO Multiple Input Multiple Output
MNO Mobile Network Operator
MTC Machine Type Communications
NB-IoT Narrow Band IoT
NFV Network Function Virtualisation
NOMA Non Orthogonal Multiple Access
NR New Radio
OCB Outside the Context of BSS
OFDM Orthogonal Frequency Division Multiplexing
OFDMA Orthogonal Frequency-Division Multiple Access
OS Operating System
PDR Packet Delivery Ratio
PHY Physical
PRB Physical Resource Block
PSM Power Saving Mode
QAM Quadrature Amplitude Modulation
QoS Quality of Service
QPSK Quadrature Phase Shift Keying

RAT Radio Access Technology
RAW Restricted Access Window
ReSF Recurrent Low-Latency Scheduling Function
RFD Reduced Function Device
RPL Routing Protocol for Low-Power and Lossy Networks
RSSI Received Signal Strength Indication
RSVP Resource Reservation Protocol
RX Receiver
SC-FDMA Single Carrier FDMA
SDN Software-Defined Networking
SF Spreading Factor
TDD Time Division Duplex
TDMA Time Division Multiple Access
TSCH Time-Slotted Channel Hopping
TWT Target Wake Time
TX Transmitter
6TiSCH IPv6 over the TSCH
UE User Equipment
UL Uplink
V2P Vehicle-to-Pedestrian
V2R Vehicle-to-Roadside
V2V Vehicle-to-Vehicle
V2X Vehicle-to-everything
WSN Wireless Sensor Network

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1. Introduction

The proliferation of embedded systems, wireless technologies, and Internet protocols have enabled the Internet of Things (IoT), to bridge the gap between the virtual and physical world by enabling the monitoring and control of the physical world by data processing systems. IoT refers to the interworking of everyday objects that are equipped with sensing, computation, and communication capabilities. These networks can collaboratively interact and perform a variety of tasks autonomously [IoT01].

A formal definition of the IoT can be found in a White Paper of the IEEE Internet Initiative published in 2005 [IoT02]: "*Internet of Things envisions a self-configuring, adaptive, complex network that interconnects Things to the Internet through the use of standard communication protocols. The interconnected Things have physical or virtual representation in the digital world, sensing/actuation capability, a programmability feature and are uniquely identifiable. The Things offer services, with or without human intervention. The service is made available anywhere, anytime, and for anything taking security into consideration*.".

A large variety of communication technologies has gradually emerged, reflecting a large diversity of application domains and of requirements. Some of these technologies are prevalent in a specific application domain, such as Bluetooth Low Energy in Personal Area Networks [IoT03], and Zigbee in Home Automation systems [IoT04]. Others, like Wi-Fi Low Power, Low Power Wide Area Networks (LPWAN) [IoT05], and cellular communications, such as the 3GPP Long Term Evolution for Machines (LTE-M) and Narrowband IoT (NB-IoT), have a much broader scope. In addition, this landscape is constantly and rapidly evolving, with new technologies being regularly proposed, and with existing ones moving into new application domains.

In this document, we first overview the above-mentioned solutions, providing their main features and characteristics, such as some key performance indicators and possible future developments. We also discuss the suitability of these technologies in terms of satisfying the requirements of the identified applications.

The rest of this section shortly introduces the most promising application scenarios in terms of raising interest of major industry stakeholders. Besides, we discuss the integration of IoT into the Fifth Generation (5G) of Mobile Radio Networks ecosystem.

1.1 IoT Applications

Smart Cities

One of the most paradigmatic applications for IoT networks, addresses the problem of enhancing the automation of cities and improving citizens' wellbeing.

The most common example is the *metering of utilities consumption*, such as electricity, water or gas. In many countries, the electricity metering is already controlled remotely through power line technology, but operators are planning to

upgrade the meters with a secondary radio interface to increase the redundancy of these devices. On the contrary, gas and water meters are still disconnected from the Internet.

Smart parking applications make it possible to monitor parking slots in a city and on that basis, guide car drivers to the closest free one via an app installed on their smartphones. This allows to optimise vehicular traffic flows in a city. The density of devices and parking slots depends largely on the size of the city considered.

Another interesting application is *waste management*; the idea is to equip trash bins around the city with sensors to detect how full they are in order to plan for waste collection and minimise the effort needed for this task. In this case, the devices are battery powered but the lifetime required could be quite short since the collection of wastes is scheduled almost daily and, thus, the operators may replace the batteries very often.

In a smart city also the operation of the public lighting system can be controlled and optimised via IoT. Light poles can be equipped with sensors able to detect the presence of people or cars in order to turn on the light only when needed, saving a considerable amount of energy. A recent Gartner's report estimated that *smart lighting* systems could reduce energy costs by 90%, and its market will grow from 46 million units in 2015 to 2.54 billion units in 2020 [IoT06]. In this case, sensors can be plugged to a power source. The devices are mostly autonomous but they could receive commands from the network or report about their status in a very sporadic way. In order to perform efficient wireless controlling for the smart lighting system, scalability and the possibility to implement multi-hopping is required.

Smart Buildings

The basic goal of a smart buildings is make our life more comfortable, safer and pleasant and, also, to increase energy efficiency. It is reported that we spend more than 87% of our time in indoor environments, including home and commercial buildings. In 2016, the global market for smart homes was valued at $39.93 billion and predicted to reach up to $79.57 billion by 2022 with a Compound Annual Growth Rate of 11.3% [IoT09]. According to Gartner, a typical family home will have 500 smart devices by 2022 [IoT10].

In *home automation* applications, energy constraints can be relaxed as many devices can be plugged to a power source. For monitoring purposes, latency is not a tight requirement yet, in some cases, a command to an actuator (e.g., turning on/off a light) should be transmitted with no perceivable latency.

Another interesting application belonging to the category of smart buildings is *microgeneration*. A microgeneration plant has the target of locally generating and providing heat and power to the building with small scale equipment. Typically, this use case involves photovoltaic cells, solar panels, wind turbines and other devices, deployed on the building roof. The precise monitoring of the energy produced by this equipment can help optimise the energy distribution on a larger

scale. The devices will be deployed mostly outdoor on roof tops, and they could be plugged to a power source.

Smart Agriculture

Tens or hundreds of sensors per hectare will be deployed in agriculture to monitor the health of vineyards, olive trees or other types of cultivations. The precise monitoring of plants status, referred as *crops monitoring*, can lead to a more efficient use of the natural resources such as water, and let the operators act faster in case of a spreading disease. Due to the slow variations of the health status of the plants, it is still possible to transmit a report with a very low rate. The devices will be most likely battery powered and deployed outdoor.

Another field of application is related to *soil and air monitoring*. Most applications under this category do not pose stringent requirements on latency. Traffic density is very low despite the potentially large number of sensors to be deployed.

Industry 4.0

Industry 4.0 is a term coined in Germany in 2011 to represent the 4-th industrial revolution It includes many different application domains and, most often, it is used to denote Smart Manufacturing approaches where wireless communications and cyber-physical technologies are applied to industry plant automation.

The innovation that Industry 4.0 brings about stems from the idea of *controlling* machines at a very low level, this including the hundreds of analog signals that are sampled and used in control loops to activate the actuators, via radio technologies. The shift from wired to wireless networks results into huge reductions of capital expenditure associated to the deployment and maintenance of wires. Moreover, wired networks are rigid by nature. This makes it difficult to adapt to changes in industrial environments. On the other hand, transmitting control signals through a radio transceiver requires a reasonably wide bandwidth and very low latency (lower than ten milliseconds). The most important challenges include: extremely high reliability, low latency, robustness, fault tolerance, massive scalability, interoperability, and energy efficiency. Reliability against interference is highly indispensable because industries encompass several wireless networks, heavy machinery, and co-located communication systems that can interfere.
As far as *monitoring* is concerned, requirements are more relaxed, in terms of both, latency and reliability.

Automotive Applications

This application scenario comprises a number of use cases that are described next. First, *cooperative awareness* foresees the broadcasting from each vehicle of messages informing about vehicles' status (type, size, etc.) and movements (position, direction, speed). Cooperative awareness is generally defined as a service to be used by other applications; indeed, it allows each vehicle to gather knowledge about the presence and movements of neighboring cars and trucks.

Second, *platooning* allows a small number of trucks to drive together as if they were virtually linked (e.g., accelerating and decelerating at almost the same time). The group is called platoon and is formed by a leading vehicle and one or more following vehicles.

Also, *lane merging* is a use case allowing a smooth merge of vehicles coming from different lanes into a single lane.

See through is an application typically involving two vehicles in the same lane in the same direction, where the following vehicle is able to have the same perception of the environment of the leading vehicle. This might imply, for example, the transmission of videos from the leading to the following vehicles and could be used to check road availability before an overtaking.

Next, the *extended sensing* application refers to the exchange of data gathered through local sensors or live-video images among vehicles, pedestrians and the V2X server.

Finally, *remote driving* enables a remote driver or a V2X application to operate a remote vehicle.

For all the above application scenarios, some typical application requirements can be found in Table 1 ahead [IoT13, IoT14].

Table 1: Application requirements.

Application	Offered Traffic	Devices Number / Density	Deployment	Energy Efficiency	Latency	Reliability
Smart City						
Metering of utilities consumption	From 1 to 50 packets of few bytes per day	Up to 10.000 devices per km^2	Indoor / Deep indoor	Not an issue	Typically < 1 minute	Typically 90-95%
Smart Parking	Up to 60 packets of tens of bytes per day	3.000 per km2	Outdoor/ Indoor / Deep indoor	Not an issue	Typically < 1 minute	Typically 90-95%
Waste Management	Few bytes every hour	One per waste in a city	Outdoor	Yes	Typically < 1 minute	Typically 90-95%
Smart Lighting	One packet of 100 bytes per day	One per lamp post	Outdoor	Not an issue	Typically < 1 minute	Typically 90-95%
Smart Buildings						
Home automation	Five/ten packets of 50 bytes per day	Up to 50 devices per unit	Indoor / Deep indoor	Some devices may by battery charged	Typically < 100 ms for actuators	Typically 90-95%

Application	Offered Traffic	Devices Number / Density	Deployment	Energy Efficiency	Latency	Reliability
					< 1 minute for monitoring	
Microgeneration (photovoltaic cells, solar panels, etc.)	100 bytes twice per day	Few per building	Outdoor	Yes	Typically < 1 minute	Typically 90-95%
Smart Agriculture						
Crops Monitoring	One packet of 100 bytes every 6 hours	Tens / hundreds of devices	Outdoor	Yes (energy harvesting)	Typically < 1 minute	90%
Environmental (soil, air) monitoring	One packet of few bytes per day	Tens of devices	Outdoor	Yes (energy harvesting)	Typically < 1 minute	90%
Industry 4.0						
Monitoring	One packet of 50 bytes per hour	Up to 1000 devices per machine	Indoor / Deep indoor / Outdoor	Yes (energy harvesting)	Typically < 10 s	Typically 90-95%
Controlling	Update frequency can be in the order of 10 – 500 ms	Up to 1000 devices per machine	Indoor / Deep indoor / Outdoor	Yes (energy harvesting)	Typically < 10 ms	99.999%
Automotive						
Cooperative awareness	1-10 packets/s of 300-500 bytes per each vehicle	From few neighbours up to hundreds	Outdoor	Yes, not an issue	Typically < 100 ms	90%
Platooning	At least 30 packets/s of 50-1200 bytes	Up to 5-10	Outdoor	Yes, not an issue	25 ms	90%
Lane merging	Kilo to megabits /s for a short time	Few nodes	Outdoor	Yes, not an issue	< 30 ms	99.9 %
See through	15-30 Mbit/s	2 nodes	Outdoor	Yes, not an issue	50 ms	99%
Extended sensing	10-1000 Mbit/s	Few neighbours	Outdoor	Yes, not an issue	3-100 ms	90-99.999%
Remote Driving	UL: 25 Mbit/s DL: 1 Mbit/s	One vehicle	Outdoor	Yes, not an issue	20 ms	99.999%

1.2 IoT and the 5G Ecosystem

The 5G mobile radio network is an ecosystem, made of many interdependent elements: RATs (Radio Access Technologies), core, cloud, end users, their User Equipment (UE), Mobile Network Operators (MNOs), equipment manufacturers, service providers, and other. All these elements are currently evolving while 5G is being specified, so that, as in the past, the Fifth Generation of Mobile Radio Networks is a step forward in an evolutionary scenario stemming from that of 4G networks. However, one of the key aspects of 5G that comes as a profound change with respect to the past, is that the 5G ecosystem is specifically designed to support (also) the IoT evolution.

The IoT has been conceived and deployed in the past years using communication technologies defined outside the domain of 3GPP. At the same time, the evolution of 2G, 3G and 4G air interfaces was more oriented towards human-centric applications (with the exception of the recent developments of LTE-M and NB-IoT). This paved the way to the success of many non-3GPP communications standards (like 802.15.4/Zigbee for instance) or proprietary solutions (like LoRaWAN for instance) for the IoT.

The scenario has now changed. The attention that 3GPP and the main stakeholders of the 5G ecosystem are offering to the IoT has notably increased in recent years. Further, a number of players have started presenting 5G as the interface between the physical and the digital world, thus emphasizing even more its role as enabler of the IoT. One of the documents delivered by 3GPP within Release 16 in June 2018 starts with a clear mention to the IoT [IoT11]: "*5G: the need to support different kinds of UEs (e.g., for the Internet of Things (IoT)), services, and technologies is driving the technology revolution to a high-performance and highly efficient 3GPP system.".*

Clearly, 5G will comprise a number of communication technologies, starting from the 5G New Radio (NR), under development at 3GPP, including 3GPP standards like LTE-M and NB-IoT, and the successful non-3GPP solutions that have grown in terms of market shares in the past few years (like, e.g., LoRaWAN); according to [IoT14], "... *the 5G system shall enable the UE to select, manage, and efficiently provision services over the 3GPP or non-3GPP access.".*

2. Low Power Wide Area Networks Solutions

Low Power Wide Area (LPWA) systems enable network deployments with both longer coverage ranges and lower energy consumption. These conditions are highly effective for sensors and actuators networks in IoT, where one often needs to reach far distances, possibly avoiding multi-hopping to reduce complexity and energy consumption. Maintenance and deployment costs can also be reduced. LoRa, NB-IoT and LTE-M, can be classified as LPWA technologies.

2.1 LoRa Air Interface

2.1.1 LoRa Technology

LoRa is a Physical Layer developed by Cycleo (a French company) later acquired by Semtech. It is used in LoRaWAN. Its first objective is to allow very low power operations to ensure with a single battery a long lifetime to the devices, more than 10 years. It also allows long communication ranges (2-5 km in urban areas and up to 15 km in suburban areas). The downside is low data rates, some tens of bit per second in the most robust options. However, LoRa can offer a certain flexibility and can reach rate up to 50 kbit/s [LoRa01, LoRa02].

LoRa physical layer is based on Chirp Spread Spectrum (CSS) modulation. Using a bandwidth larger than the necessary one to transmit the data flow, LoRa performs spectrum spreading which brings robustness against some characteristics of the channel (interference, frequency selectivity, Doppler effect). One original characteristic of LoRa is that information is carried by a cyclic shift in the chirp, see Figure 1 (position modulation).

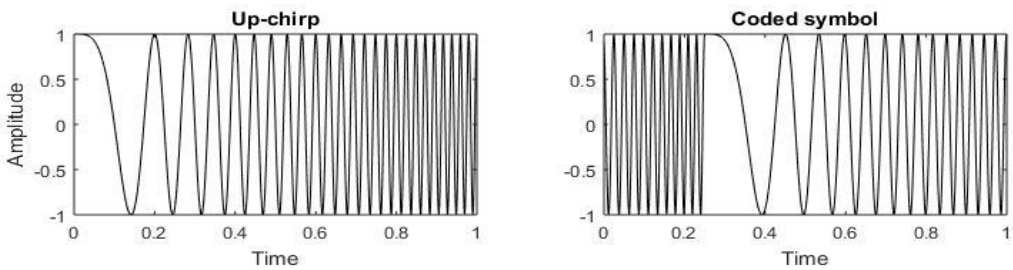

Figure 1: Up-chirp and a code symbol. SF bits are coded per symbol, so 2^{SF} possible shifts.

The transmitter generates chirp signals by varying their frequency over time and keeping phase between adjacent symbols constant. The signal frequency band is usually 125, 250 or 500 kHz in the Industrial Scientific Medical (ISM) bands of 868 or 915 MHz. However, there also exist some narrower bands (7.8 to 62.5 kHz) in the 166 and 433 MHz bands. The main characteristics LoRa's modulation depends on a number of parameters:

- The Spreading Factor (SF): it is related to the duration of a symbol. The longer the symbol is, the larger the spreading factor, the more robust the transmission (so the longer the range) but the lower the data rate. LoRa employs six orthogonal spreading factors (7 to 12). A SF=6 also exists but the modulation is different (Frequency Shift Keying). Signals generated at different SF are quasi-orthogonal. Consequently, multiple frames can be exchanged in the network at the same time and frequency, as long as each one is sent with one

of the six different SFs and that the gateway can perform simultaneous decoding of the different channels.

- Forward error correction (FEC) techniques are also used to increase the receiver sensitivity. LoRa uses Hamming codes. The Code Rate (CR) index defines the amount of FEC in LoRa frame. LoRa offers CR = 0, 1, 2, 3 and 4, where CR = 0 means no encoding and the effective coding rate is 4/(4+CR), ranging from 1 (no coding) to ½.
- The output of the encoder passes through the Whitening block (optional). Whitening induces randomness, in order to make sure that there are no long chains of 0's and 1's in the payload. An interleaving block is then implemented to avoid bursts of errors. The interleaver uses a diagonal placing method to scramble each code word.

A packet contains a preamble (for the detection and synchronization purpose), possibly a header, mandatory in some modes and the payload, with a maximum size between 51 bytes and 222 bytes, depending on the SF.

The raw data rate varies according to the SF and the bandwidth, and it ranges between 22 bit/s (BW = 7.8 kHz and SF = 12) to 27 kbit/s (BW = 500 kHz and SF = 7). The SF 6 offers another option with a rate of 50 kbit/s. Frequency hopping is exploited at each transmission in order to mitigate external interference.

The choice of the bandwidth, the SF and the CR impact on the Time-on-Air. An increase in this time will consequently increase the *off* period duration due to the duty cycle regulation for LPWAN. Although few information bits are transmitted per packet, the packet duration can be long, more than one second for large SF and small bandwidth.

To decode a packet, first it is necessary to detect the preamble consisting of successive up-chirps (typically 4 or 6) and two down-chirps (the up-chirp reversed in time). This allows the synchronization and the detection of the beginning of the frame. The decoding consists in multiplying each symbol by a down-chirp. The resulting signal is a sine wave with a fixed frequency, given by the shift. The Fourier transform then exhibits a peak, easy to detect, that allows to recover the information. Besides, if an interfering user corrupts the signal, it will not prevent the good packet detection as long as its power is less and the peaks it generates are not *stronger* than the desired ones (capture effect).

LoRaWAN networks are based on single hop transmissions, leading to a star-of-stars topology. Devices transmit directly their packets to gateway nodes that relay messages to a central network server through another network (Cellular, Wi-Fi or Ethernet for instance). Bi-directional communications is allowed too.
LoRaWAN defines three classes of devices (A, B and C):

- Class A devices, aiming low cost and long life devices, use pure ALOHA to access the channel in the uplink. A Class-A device is always in sleep mode, unless it has something to transmit. After transmission, the device listens during two window periods, defined by a duration, an offset time and a data rate. Feedback can only occur after a successful uplink transmission. The

second window can increase robustness in the downlink and it is disabled when downlink traffic is received by the end-device in the first window.

- Class B devices are designed to support additional downlink traffic, at the price of higher energy consumption. A Class-B device synchronizes its internal clock using beacons emitted by the gateway. This process is called a "beacon lock". After synchronization, the device negotiates its ping-interval. The LoRa server is then able to schedule downlink transmissions on each ping-interval. By doing so, additional downlink traffic can be supported and without relying on prior successful uplink transmissions.
- Finally, Class C devices are always listening to the channel except when they are transmitting.

Class A is intended for end-devices. The other classes must remain compatible with Class A. The three classes can coexist in the same network and devices can switch from one class to another. However, there is no specific message defined by LoRaWAN to inform the gateway about the class of a device and, hence, this must be handled by the application.

Communication between end-devices and gateways start with a Join procedure. Each frame is transmitted with a specific SF. An important parameter in LPWANs and networks operating in unlicensed bands is the maximum allowed duty-cycle. It corresponds to the percentage of time during which an end-device can occupy a channel and equals 1% in EU 868 for end-devices. If necessary in order to increase information rate, channel selection can be pseudo-random at each transmission and compliant with the maximum duty-cycle. Frequency hopping is also exploited at each transmission in order to mitigate external interference.

A summary of the key parameters of LoRa is given in Table 2.

Table 2: Summary of the LoRa key parameters.

Key Parameters	***Values***	***Comments***
Bit Rate	*~22 bit/s – 50 kbit/s*	*Depending on the spreading factor*
Frequency Bands	*69 MHz, 433 MHz, 868 MHz (Europe) and 915 MHz (North America)*	*A 2.4 GHz version has recently emerged*
Bandwidth	*125, 250, 500 MHz*	*Some smaller bandwidths are also available (7.8 to 62.5 kHz) in the 433 MHz band*
Topology	*Stars of stars*	
Transmission Range	*Up to 15 km*	*A few km in Urban area.* *Link budget: 155 dB – 170 dB best case*
Current consumptions (TX)	*18 mA at 10 dBm* *84 mA at 20 dBm*	*Very low cost batteries and possible 10 years lifetime*

2.1.2 LoRa Key Performance Indicators

A non-exhaustive list of KPIs suitable for LoRa networks includes the following:

- Range: Studies about the performance of LoRa are still rare and outputs are unclear. Ranging performance has been performed showing the possibility in open fields to reach distances of more than 10 km. If the long range is then ensured, the coverage in non-line of sight areas remains to be studied in more details. The low frequency should however ensure a good coverage. Besides, if non-line of sights is due to buildings in cities, it is easy possible to deploy more base stations to avoid uncovered areas.
- Power consumption: Data sheets ensure a low consumption and measurements and experiments do confirm that lifetime of several years, if not a decade, can be expected. This however requires longer studies to confirm these figures.
- Reliability: Feedback can guarantee a certain level of reliability but it is to be mentioned that the downlink is also subject to the duty cycle limitation so that the number of acknowledged packets has to be carefully designed. Reliability will be mainly linked to the ALOHA protocol used for Class A devices. It is well known that the performance of ALOHA is poor in terms of success rate and, further, it does not support a network load increase, due to the interference increase. Hence, as long as the network load is low enough (taking into account the number of SF, frequencies, devices and the duty cycle), reliability should be enforced. LoRa in its actual form will not support the scale change, most of the studies showing that a gateway cannot handle more than 500 or 1000 nodes.
- Latency: In addition to the restrictions on Duty Cycle, the long packet duration makes LoRa not adapted to low latency applications.

2.1.3 LoRa Future Development

LoRa is intended for smart monitoring applications, either in rural areas where gateways cannot be densely deployed, or in cities where the reduction in range can be compensated by denser gateway deployment. However, latency is an issue, due to the packets time on air or duty cycle. Definitely, LoRa should not be used for critical communications requiring ultra-reliable communications and low latency.

However, for the already envisioned applications and especially in smart cities, the main challenge is scalability. Scalability is limited due to interference and ALOHA seems not adapted in this case. However, long life of devices can only be ensured thanks to a minimal scheduling in the network, reducing the needed channel state information for transmission (grant free access). Besides, a listen before talk protocol is available for LoRa but its relevance for long range communications is limited: what the transmitter hears is not necessarily what the receiver hears. As a consequence, the way to significantly increase the number of transmitting devices is in the gateway (class C devices). Gateways are always on and have to be connected to an energy source. Consequently, efficient signal processing schemes can be implemented. Indeed, multiuser detection has been

widely used for spread spectrum schemes and LoRa can benefit from this aspect. It can be a rather efficient physical (PHY) layer for Non Orthogonal Multiple Access (NOMA) as illustrated in Figure 2 but additional research work is needed, both at the theoretical and experimental levels.

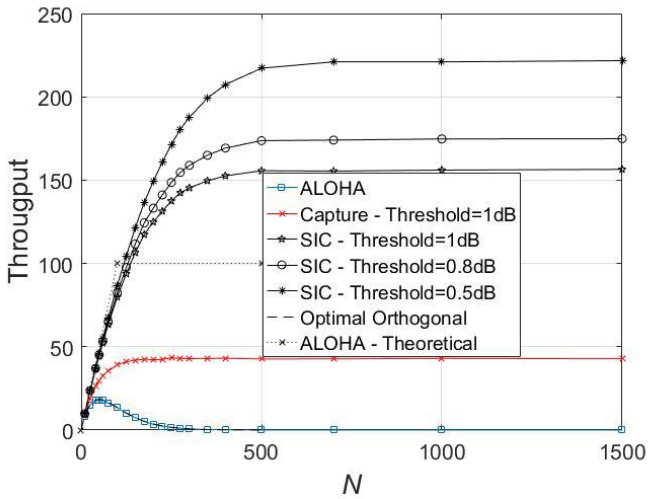

Figure 2: Performance improvement with Serial Interference Cancellation in LoRa networks [LoRa04].

If uncoordinated and grant free access can be achieved in large scale network, this will however drastically impact the level of interference. Especially for networks evolving in ISM bands, it will be essential to cope with interfering sources coming from other types of communications. The heterogeneity in all dimensions (bandwidth, time on air, etc.) will create interference with a stochastic behavior (in amplitude, in time, in space) that is not well modeled by the traditional approaches (Gaussian, correlation). It is crucial to gain additional insights into these aspects to devise appropriate channel access strategies.

Robust and efficient channel access is certainly one key challenge towards a large scale IoT, and the LoRa waveform exhibits nice properties to find its place in this evolution. Beyond the Gateways we come back to the traditional "Internet world" which has its own challenges – including big data, edge computing for instance – that are not addressed here. Besides, improvements can also be made at the device level. Micro-batteries with more energy stored can be realized and energy harvesting or low consumption wake-up radios could certainly play a role to relax the energy constraint on the end devices and make the downlink easier to use. Besides superposition coding or the power-domain NOMA idea could allow simultaneous transmission of several packets and reduce the duty cycle limitation. This last approach however has a high complexity and energy cost and cannot be envisioned without improvements in the energy that can be made available in the devices.

2.2 NB-IoT and LTE-M

The increasing interest in the IoT and massive machine Type Communication (MTC) foreseen in 5G networks has led standardization bodies like 3GPP and GSM (Global System for Mobile communication) Association (GSMA) to define cellular technologies thought for IoT. The main examples are NB-IoT and LTE-M, which follow rules and numerology compliant with LTE.

2.2.1 NB-IoT Technology

NB-IoT is designed to achieve an efficient communication in the cellular IoT framework and reach a longer battery life for a massive distribution of nodes. It is characterised by three key elements: low cost, large number of connections per cell and a robust coverage, with very good penetration in underground and indoor environments [NBIoT01].

NB-IoT is standardized in Release 13 of 3GPP, emerging as an alternative LPWA solution. NB-IoT leverages on the LTE standard and numerology, but it is designed for ultra-low-cost MTC, supporting a massive number of devices per cell. From LTE it takes the synchronization, radio access, resources definition and assignment. The standard allows modifications to regular LTE by enhancing the link budget and reducing the energy consumption, complexity and costs to a minimum.

While the other cellular systems for MTC are based on existing radio access technologies, NB-IoT can either operate in a stand-alone mode or within the guard bands of LTE carriers or within an LTE carrier. It supports a nominal system bandwidth of 180 kHz (equal to the one of an LTE Physical Resource Block (PRB)) in both uplink and downlink. The (narrowband) channel spacing is 15 kHz as in LTE, but it can be decreased to 3.75 kHz in uplink communications [NBIoT02].

As in LTE, NB-IoT eNBs (enhanced Node-B) employ Orthogonal Frequency Division Multiple Access (OFDMA) in downlink and UEs use Single Carrier Frequency Division Multiple Access (SC-FDMA) in uplink. However, the modulation schemes are limited to Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK) to reduce complexity and ensure a better link budget. A single process Hybrid Automatic Repeat Request (HARQ) is expected in both uplink and downlink and only half-duplex operation is allowed. NB-IoT UEs (cat NB1/NB2) implement power control in uplink, in order to keep a low power and consumption where possible and minimize inter-device interference.

The expected Coverage Enhancement (CE) is mainly achieved by allowing repetitions (i.e., temporal diversity [NBIoT03]). The signaling for control information and data are repeated a number of times in different uplink and downlink channels. Each replica has a different coding and more replicas can be combined at the receiver to increase the reception probability.

NB-IoT introduces also a UE categorization in three classes of devices, based on measured power levels. It allows an energy efficient operation, though keeping an

ultra-low device complexity. To further reduce costs, the device searches for only one synchronization sequence and can use a low sampling rate (e.g., 240 kHz) to establish basic time and frequency synchronization to the network. Also, the maximum transport block size is 680 bits and a single transmit-receive antenna can guarantee the performance objectives of NB-IoT.

Techniques like Power Saving Mode (PSM) and extended Discontinuous Reception (eDRX) are used to increase the battery lifetime for cellular IoT devices. Energy consumption critically depends on the device behavior when it is not on an active session: these idle time intervals for cellular networks are used to monitor paging and perform mobility measurements. For this reason, PSM and eDRX support a reduced energy consumption by extending the periodicity of paging occasions or requiring no monitoring at all.

2.2.2 LTE-M Technology

Along with NB-IoT, LTE-M was introduced in Releases 12/13, where compliant UE devices are classified as LTE Cat-M (Cat-M1 and Cat-M2). LTE-M is an extension of LTE with features for improved support for machine-type communications and IoT [NBIoT01].

In what concerns the physical layer, LTE-M can be regarded as an extension of LTE's In fact, the access scheme of LTE-M is OFDMA in the downlink and SC-FDMA in the uplink, following the LTE numerology and allowing coexistence between LTE-M and LTE users. However, LTE-M devices allow relevant modifications that include i) low device complexity and cost, ii) long device battery lifetime, iii) coverage enhancement, iv) support of massive number of devices and v) flexible deployment in an LTE network.

Compared to other LTE UEs and to address the specific IoT use case, a Cat-M1 UE has a reduced peak rate for user data to 1 Mbit/s in Uplink (UL) and Downlink (DL) (instead of 10 Mbit/s) and a reduced radio frequency bandwidth to 1.4 MHz (instead of 20 MHz). Furthermore, to achieve lower complexity and costs, an LTE-M device has one receiver antenna chain, a maximum transmit power of 20 dBm instead of 23 dBm, a maximum transport block size of 1000 bits, and it allows a half-duplex operation (i.e., no transmission and reception at the same time).

As in other LPWAN technologies, LTE-M exceeds by 20 dB the coverage of existing LTE networks. This is achieved through retransmission or repetition techniques. The initial CE target of 20 dB seems to be reachable with CE mode B, supporting up to 2048 repetitions [NBIoT01].

As in NB-IoT, both PSM and eDRX techniques are supported to extend the battery lifetime of LTE-M devices to years or potentially decades. Reduced peak rates and bandwidth also help reduce the power consumption when the device is active.

One relevant advantage of LTE-M included in the standard, is the possibility of operating in either i) full-duplex Frequency Division Duplexing (FDD), ii) half-duplex FDD or iii) Time Division Duplex (TDD). Furthermore, the legacy system is divided into narrowbands, where each one comprises 6 PRBs and spans 1.08 MHz.

UEs can retune from one narrowband to another upon decision of the enhance Node B (eNB).

2.2.3 NB-IoT and LTE-M Key Performance Indicators

Both NB-IoT and LTE-M have to ensure a UE battery lifetime above 10 years: energy consumption has to be maintained to minimum levels. To this aim, they implement PSM and eDRX to allow larger intervals for the device to stay in "idle" mode. PSM defines a time period in which the device is unreachable by the eNB and has all the circuitry off. Instead, cycles of eDRX determines with which periodicity paging requests will occur, thus leaving the device ON but in idle mode. Intervals of eDRX can last from 9.22 s to 3 hours for NB-IoT, and from 10.24 to 44 min for LTE-M (Rel. 13).

For technical details and comparison between the two cellular technologies, Table 3 defines the main parameters. The coverage is evaluated at Maximum Coupling Loss (MCL), when considering a transmit power of 23 dBm.

Table 3: Summary of NB-IoT and LTE-M key parameters.

Key Parameters	***NB-IoT***	***LTE-M***
Peak Data Rate	*UL: 250 kbit/s (max)* *DL: 250 kbit/s*	*1 Mbit/s in UL and DL*
Duplexing	*HD, FDD*	*FD & HD* *FDD & TDD*
Bandwidth	*180 kHz*	*1.08 MHz*
Deployment	*Standalone, In-band LTE, Guard-band LTE*	*In-band LTE*
Coverage at MCL	*164 dB*	*155.7 dB*
Averaged current value (Data TX/RX)	*Max 140 mA*	*Max 190 mA*

Measurements and recent studies analyze the system performance of NB-IoT and LTE-M in terms of latency, energy consumption and reception success probability. In what concerns latency and energy consumption, we can compare results obtained by [NBIoT04] and [NBIoT05]. Simulations of a NB-IoT system in [NBIoT05] show a latency in transmitting a packet for the cases of stand-alone and in-band deployments. In both cases, the requirement of less than 10 s latency is satisfied, with better latency in the stand-alone case (6.6 s against 9.9 s). Evaluations in [NBIoT04] for a LTE-M system result in less than 9 s latency, satisfying again the 10 s requirement.

Analysis in [NBIoT04] estimates a battery life which is equal to 7.6 years, which is less than the requirements, by assuming a battery of 5 Wh and a maximum consumption in transmission of 500 mW. For this reason, Rel. 15 includes new techniques to improve Cat M1 energy saving. Instead, [NBIoT05] estimates the lifetime in the stand-alone and in-band cases of NB-IoT, finding that the battery life target can be met or even exceeded, depending on the application.

The work in [NBIoT06] shows simulation results of the success probability, P_s, in uplink transmission while changing the parameter configuration of the network,

as shown in Figure 3. The simulated UEs can be in one of the three coverage classes based on predefined thresholds.
The paper starts analysing a configuration with low performance (legend red star, with 29.8 kbit/s of throughput and P_s = 39.5%). If the number of repetitions increases, the success probability may increase at the expense of lower throughput, due to the less efficient use of radio resources. The opposite is also true (black line). Another varying parameter is Z_c which denotes the capacity of possible accesses per second. For suitable values, it is possible to improve both throughput and success probability. For achieving a success probability above 90%, it is necessary to change the distribution of the devices among the different coverage classes by tuning category thresholds. In this way, the system can find an improved balance between devices and better reach the present UEs.

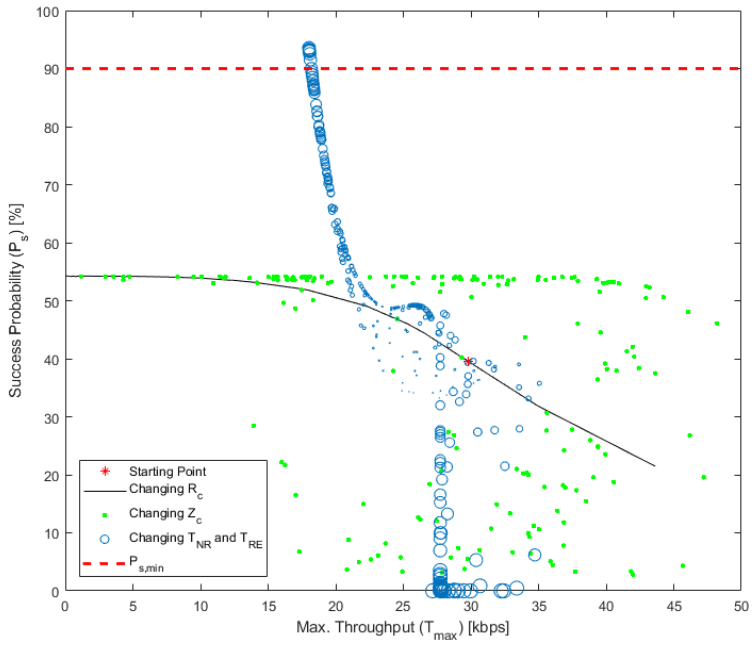

Figure 3. Impact of Design Parameters on NB-IoT [NBIoT06].

2.2.4 NB-IoT and LTE-M Future Development

The interest in deployment of cellular technologies for MTC is increasing. NB-IoT and LTE-M are developed by companies like u-blox in small chipsets. For large manufacturing series (purchasing more than 100 pieces), one module of Cat NB1 has a unit price of less than 12 EUR, while one module of Cat M1 has a unit price of less than 20 EUR. Both prices are below that of UEs thought for regular (data and voice) LTE communications.

Given the low cost and remarkable performance of both technologies, they are called to play a key (yet different) role in the future of the LPWAN market.

In comparison with other non-cellular solutions, both NB-IoT and LTE-M take the advantages of being a sub-set of the existing network of a mobile operator, who has to take care of the maintenance of eNBs, its complexity, and the transport of

UE data to the network core. Moreover, they operate in licensed band, where the network and interference management is supervised by the mobile operator.

However, NB-IoT and LTE-M are probably not going to be competing technologies. They have different performance results in terms of mainly throughput and coverage. Throughput achieved is higher in LTE-M, but the coverage of NB-IoT LTE-M supports also voice over LTE at the expense of larger cost and energy comsumption than Cat NB1 UEs.

Therefore, NB-IoT and LTE-M can be used differently depending on the specific application requirements: nodes requiring a robust coverage but with the possibility of throughput at 50 kbit/s will implement NB-IoT, otherwise they will implement LTE-M.

3. Low Power Short-Range Solution

3.1 IEEE 802.15.4-Based Solutions

IEEE 802.15.4 standard is designed particularly for low power and Low Rate Wireless Personal Area Networks (LR-WPANs). This standard provides the specifications of the PHY layer and Medium Access Control (MAC) sub-layer for networking architectures consisting of low-cost wireless embedded devices with consumption and bandwidth limitations [LP01].

There are many solutions that could be implemented on top of the IEEE 802.15.4, as illustrated in Figure 4 [LP02]. ZigBee [LP03] is one of the most widely used, as along with its extension, Zigbee Internet Protocol (IP) [LP04], released in 2013 to support a scalable architecture with end-to-end IPv6 networking to better accommodate the IoT-specific design requirements. Other relevant standards, which provide LR-WPANs with mesh capability, are: WirelessHART [LP05], ISA SP100.11a [LP06], ZWave [LP07], WIA-PA [LP08], ANT [LP09], IP500 [LP10], etc.

In order to create an open and standardized protocol stack for constrained networks and devices, the IETF group has developed a number of IP-based protocols on top of IEEE 802.15.4: IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN) [LP11], Routing Protocol for Low Power and Lossy Network (RPL) [LP12], Constrained Application Protocol (CoAP) [LP13], etc.

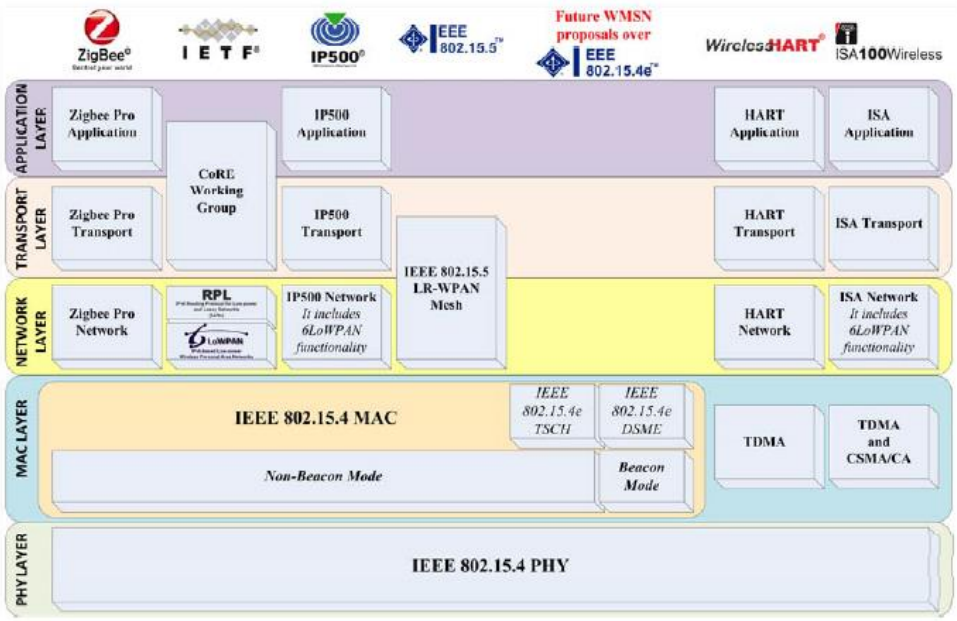

Figure 4: LR-WPANs protocol stack [LP02].

3.1.1 IEEE 802.15.4 Standard

IEEE 802.15.4 uses a Direct Sequence Spread Spectrum (DSSS) access mode and operates in the 2450 MHz, 915 MHz, and 868 MHz ISM bands working with 16 channels, 10 channels, and one channel, respectively. The combination of an Orthogonal QPSK modulation and a DSSS technique enables the coexistence with other wireless systems and increases transmission robustness. The indoor

nominal communication range of standard IEEE 802.15.4 nodes transmitting with power levels of 0 dBm and 20 dBm is of 10 and 100 meters, respectively. Depending on the environment characteristics and the maximum transmission power levels, it is possible to obtain bit rates from 20 to 250 kbit/s. The IEEE 802.15.4 standard defines a minimum output power of -3 dBm in most bands. This standard allows 10 dB difference between the required receiver sensitivity level and the required energy detection level. However, the use of Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism for collision avoidance in the MAC layer reduces the maximum bit rate in the 2450 MHz frequency band to 150 kbit/s. The maximum-length frame is 127 bytes, where a payload length is between 86 and 116 bytes, depending on the content of the frame. An IEEE 802.15.4 device address has either short 16-bit or 64-bit address. When using the 64-bit addressing mode, the maximum payload is 102 bytes. The IEEE 802.15.4 standard defines several symmetric-key cryptographic mechanisms to support security services.

All nodes from an IEEE 802.15.4 network use the same radio channel. The MAC sub-layer provides mechanisms for channel access, guaranteed time slots management, frame validation, delivered frame acknowledgement, and association/disassociation activities. Two types of channel access mode are supported in the MAC layer: beacon and non-beacon. In the non-beacon mode, the unslotted CSMA/CA mechanism waits for a random period and senses the channel before a packet is transmitted. The node can transmit the packet only when the channel is detected to be idle. Otherwise, it waits for another random period and senses the channel again. The non-beacon mode is useful for low traffic between the network nodes. In a beacon-enabled network, the coordinator sends periodic beacons containing information that allows network nodes to synchronise their communications, and information on the data pending for the different network nodes. In this mode, a superframe structure is utilized to organize the communications over the wireless medium.

The standard defines two classes of devices: Fully Function Devices (FFD) and Reduced Function Devices (RFD). The FFD provides capabilities such as routing, association and formation of a network. The PAN coordinator is an FFD that acts as the main controller to which other devices may be associated. It is also responsible for the time synchronization of the entire network.

More details about IEEE 802.15.4 standard parameters can be found in the following table.

Table 4: Summary of IEEE 80215.4 key parameters.

Key Parameters	***Values***
Bit Rate	*20 kbit/s @ 868 MHz* *40 kbit/s @ 915 MHz* *250 kbit/s @ 2.4 GHz*
Frequency Bands	*Global: 2.4 GHz* *EU: 868 MHz* *North America: 915 MHz*
Bandwidth	*868 MHz band: 0.3 MHz* *915 MHz band: 0.6 MHz* *2.4 GHz band: 2 MHz*
Topology	*star, mesh, tree*
Transmission Range	*10 - 100m @ 2.4 GHz*
Tx Power	*0-20 dBm*
Current consumptions *(in active states)*	*5–20 mA at* *3.6 V, depending on the vendor*
Security	*AES-128*

3.1.2 IEEE 802.15.4 Key Performance Indicators

Since the first release of the IEEE 802.15.4 standard in 2003 and several revisions and amendments in 2006, 2011, and 2015, respectively, many performance evaluation studies have been published, including analytical models [LP14-LP17], simulations [LP18-LP20] and experimental campaigns [LP21, LP22], to assess key performance metrics such as throughput, reliability, latency, power consumption, etc.

The mechanisms at MAC layer are crucial for reliable and energy-efficient network operations. If the radio were switched on all the time (corresponding to 100% radio duty cycle), it would deplete a typical pair of AA batteries (holding 2200 mAh of charge) in around one week. Turning the radio duty cycle down to 25% extends the lifetime to about a month, whereas a duty cycle of 1% yields years of lifetime [LP23]. Various algorithms were proposed to adapt the MAC parameters of the IEEE 802.15.4 protocol to broad range of applications [LP21, LP24]. Authors in [LP25] propose a novel modeling and adaptive tuning of the IEEE 802.15.4 MAC for reliable and timely communication while minimizing the energy consumption. They investigated the performance of adaptive MAC algorithm under both stationary and transient conditions by experiments and Monte Carlo simulations. Numerical results showed that the proposed scheme ensures a longer lifetime of the network, and allows the system to recover quickly and operates at its optimal parameter by estimating just the busy channel and channel access probabilities. Authors in [LP26] quantify the behavior of key networking metrics (throughput, delay, power consumption, collision probability, and packet-discard probability) of IEEE 802.15.4 beacon-enabled nodes under typical operating conditions, with the inclusion of packet retransmissions. It has been shown that the probability of sensing a free channel experience large deviations from one backoff stage to another and that these differences have a noticeable impact on backoff delay,

packet-discard probability, and power consumption. Likewise, the probability of obtaining transmission access to the channel depends on the number of nodes that is simultaneously sensing it. Authors in [LP27] evaluated the efficacy of time, space, and frequency diversity in cooperative IEEE 802.15.4 wireless networks. They demonstrated a wireless sensor network topology that achieved 99.99999% of reliability bounded by a worst case end-to-end latency of 3 ms. This network topology can scale up to more than 8 simultaneous networks if channel occupancy and throughput are adjusted accordingly.

A considerable number of studies have addressed the problem of coexistence from the perspective of the 802.15.4 PHY layer [LP28]. Authors in [LP29] present the first analytical model for predicting saturation throughput in symmetric coexisting 802.11 and 802.15.4 networks. They have proposed a performance tuning method that ensures Quality of Service (QoS) and a distributed Nash-equilibrium-based method that provides fairness. The model was validated using a coexistence simulator previously developed and this approach demonstrated a fast and scalable way to predict saturation throughput with a low average error smaller than 10%.

3.1.3 IEEE 802.15.4e Standard

The limitations of IEEE 802.15.4 MAC layer in mesh-networking mainly appear due to the use of a single channel, and the high energy waste resulting from the fact that relay nodes are always on. To overcome these limitations, the IEEE 802.15.4e Working Group has published an amendment of the IEEE802.15.4-2011 standard to support the low-power multi-hop networks and fulfil industrial communication requirements [LP30]. The IEEE 802.15.4e defines five MAC behavior modes to support specific application domains: Deterministic and Synchronous Multichannel Extension (DSME), Time Slotted Channel Hopping (TSCH), Low Latency Deterministic Network (LLDN), asynchronous multi-channel adaptation and radio frequency identification Blink. The improvements of IEEE 802.15.4e include support to multi-channel communication, more flexible superframe (DSME), and the use of a contention-free channel access mechanism based on Time Division Multiple Access (TDMA) (it decreases the number of collisions, and allows minimizing the energy consumption) and frequency hopping, such in TSCH.

Based on the research papers and proposals in last few years, the TSCH mode is one of the most promising ones for radio embedded devices, particularly in harsh environments (e.g., industrial applications), where the network performance needs to be predictable. TSCH combines time-slotted access with channel hopping capabilities, thus providing predictable latency, ultra-low-power operations (< 1% duty cycle), communication reliability (immunity to interference and multipath fading), and high network throughput. TSCH is topology-independent (i.e. suitable for star, tree, partial mesh, or full mesh topologies). All nodes in a TSCH network are globally synchronised and can achieve over 99.999% end-to-end reliability. In TSCH, the superframe concept used in DSME, LLDN and its parent standard IEEE 802.15.4 has been replaced with the concept of slotframes, comprising a fixed number of timeslots. A slotframe consists of a matrix of cells,

being each cell defines by a pair of timeslot (typically 10 ms) and a channel offset (see Figure 5). TSCH defines two types of cells: dedicated and shared. A dedicated cell is contention-free providing that only one transmitter can send a packet. If cells are shared between multiple nodes, then a random access mechanism is applied.

The IETF 6TiSCH working group defines mechanisms to combine the high reliability and low-energy consumption of IEEE 802.15.4e TSCH with the ease of interoperability and integration offered by the IP protocol. Current 6TiSCH implementations use the 2.4 GHz band, with 16 frequencies available. The scheduling in 6TiSCH networks has attracted considerable research interest. The 6TiSCH architecture defines several approaches for resource allocation: static scheduling, centralized monitoring and schedule management, neighbor-to-neighbor scheduling, and hop-by-hop scheduling [LP31-LP33]. In order to provide QoS guarantees for sensitive flows, the scheduling function enables to reserve end-to-end resources hop-by-hop through the distributed Resource Reservation Protocol (RSVP).

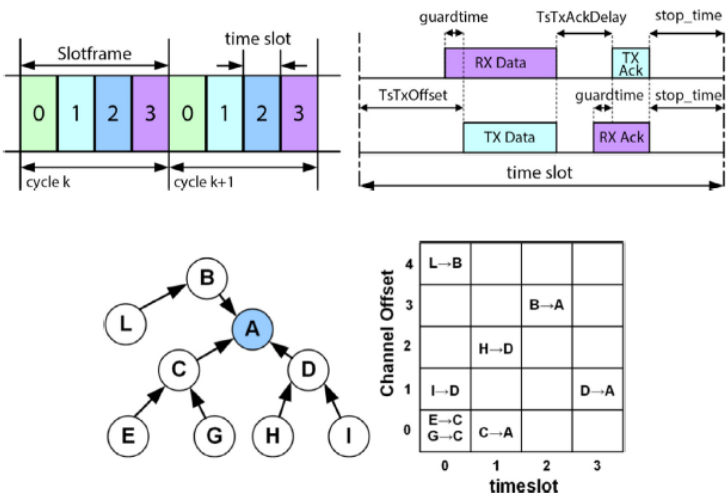

Figure 5: Organization of TSCH transmission [LP32].

3.1.4 IEEE 802.15.4e Performance

Authors in [LP34] analyzed the network statistics generated by two low-power wireless mesh networks deployed in real-world conditions. Based on collected extensive network statistics, results confirmed that TSCH is very suitable for smart agriculture and smart building applications (close to 100% packet delivery ratio and 4-8 years of battery lifetime).

In paper [LP35], two novel contributions are presented: the recurrent traffic problem is defined formally as an Integer Linear Program, and the Recurrent Low-Latency Scheduling Function (ReSF) that reserves minimal-latency paths from source to sink and only activates these paths when recurrent traffic is expected. Extensive experimental results show that using ReSF leads to a latency improvement up to 80% compared to state-of-the-art low-latency scheduling functions, with a negligible impact on power consumption of, at most, 6%.

Recent trends in IoT activities are directed towards open-hardware and open-software prototyping and development. This has been recognized as an important step in terms of standardization activities and new applications for Industrial IoT (IIoT) purposes. Authors in [LP36] implemented the algorithm based on joint scheduling and routing on top of IEEE 802.15.4e, where the performance evaluation in terms of PDR and throughput was performed. The obtained results indicate that 6TiSCH provides close to 100% packet delivery rate.

An autonomous version of 6TiSCH where each device uses only local information to select their timeslots is presented in [LP37]. The paper exploits the concept of 6TiSCH tracks to guarantee flow isolation, defining the concept of shared (best-effort) and dedicated (isolated) tracks. The experimental performance evaluation campaign, conducted over the open and large scale FIT IoT-LAB testbed (by employing the OpenWSN), highlights the visibility of this solution to provide reliability and low delay while not relying on any centralized component.

3.1.5 802.15.4e Future Development

The IEEE 802.15.4e standard does not specify details of mechanisms that must be implemented, leaving many aspects to protocol designers, such as TSCH scheduling and resource allocation. There are still open issues in terms of MAC scheduling strategies, as well as the optimal coexistence of scheduling and routing protocols. There is a strong need for a cross-layer design and re-modeling of existing solutions for the MAC and network-layer protocols. A convergent protocol-stack with clean and well-defined structure is thus required. Nowadays, the most common application scenario implies the network of nodes that are sending data to coordinator. Future applications, on the contrary, will require complex scenarios with dynamic topologies and heterogeneous traffic with different QoS requirements. The rapid evolution of hardware solutions fosters the development of multi-protocol platforms and systems, multi-band radio interfaces with adaptive and opportunistic techniques. Emergence of IEEE 802.15.4g standard for smart utility networks indicates the importance of IEEE 802.15.4 MAC design in reliable operation and maintenance of power grid systems. Moreover, the possible extension of IEEE 802.15.4 for future scenario suggests for inter-technology mobility and new roaming policies. A Fast Attachment has been proposed as an amendment for IEEE 802.15.4e [LP38], to reduce the number of control messages when a mobile device has to attach with the network. Security is another critical service in emerging IoT environments that must be taken into account not only as an added functionality but also as a baseline requirement for future IIoT. The current manufacturing industry is undergoing new technology-driven change such as Industry 4.0. However, the lack of open, reliable and deterministic wireless communication solutions prolongs the realization of fully connected and digital industrial spaces.

3.2 Wi-Fi Low Power

The 802.11 standard is one of the most successful standards under the 802 LAN/MAN standardization committee. When the initial standard was published in 1997, as the first wireless network standard from IEEE 802 the main design goal was realizing wireless local area networks up to 100 meters range [WiFi01]. In 2010, a new amendment to 802.11 standard, called 802.11ah, was approved, and Wi-Fi Alliance has introduced Wi-Fi HaLow as the designation for products incorporating IEEE 802.11ah technology [WiFi02]. Main use cases of the 802.11ah is stated as sensors and meters, backhaul sensor and meter data, and extended range Wi-Fi.

3.2.1 IEEE 802.11ah Technology

801.11ah PHY design is based on a former 802.11 amendment 802.11ac. The signal waveforms from 20 to 160 MHz channel bandwidths of 802.11ac are scaled down by 10 times to 802.11ah 2 to 16 MHz signal waveforms. OFDM is utilized and there are 64 subcarriers for a 2 MHz channel. Subcarrier spacing is 31.25 kHz. inverse/discrete Fourier transform period is set as 32 μs. The guard interval of 8 μs brings the total OFDM duration to 40 μs. To improve communication range, 1 MHz bandwidth is added to the bandwidth options. Since the robustness and the range of the link is more important, a rate ½ Low Density Parity Check (LDPC) code with 2 times repetition is included in the forward error correcting schemes. Other code rates are 1/2, 2/3, 3/4 and 5/6. Either convolutional or LDPC codes are used to achieve those rates. To increase data rate Multiple-Input-Multiple-Output (MIMO) transmission up to 4 spatial streams can be used. According to [WiFi03], total link budget enhancement of 802.11ah compared to 802.11n in 2.4 GHz is 24.5 dB. Since a typical 802.11 device operates at 15-17 dBm, such a link budget gain enables to reduce the transmit power below 0 dBm without sacrificing transmission range. One drawback of reducing the bandwidth is that the signal may observe fading in all of its subcarriers. System designers solve it by selective subchannel transmission. For example, the best 1 MHz subchannel can be selected from a 4 MHz channel bandwidth. This can improve signal power by approximately 7 dB for an indoor channel model with 50 ns root mean square delay spread as shown in [WiFi04]. Another physical layer feature of 802.11ah is traveling positions of the pilot subcarriers. In previous amendments such as 802.11n and 802.11ac, channel estimation sequences and fixed positions of pilot subcarriers are used, however such a scheme is not enough to track outdoor channels. 802.11ah supports a traveling pilot scheme that shifts pilot tones every OFDM symbol such that the traveling pilot tones over multiple OFDM symbols can cover all subcarriers.

Table 5: Summary of IEEE 802.11ah key parameters.

Key Parameters	***Values***
Bit Rate	*150 kbit/s (1 MHz bandwidth, BPSK, ½ rate coding with repetition)* *to 347 Mbit/s (16 MHz bandwidth, 256 QAM, 5/6 rate coding with 4 spatial streams)*
Frequency Bands	*614 MHz - 787 MHz (China),* *863 MHz - 868MHz (Europe),* *902 MHz - 928 MHz (US),* *917.5 MHz - 923.5MHz (Korea),* *916.5 MHz - 929.7 MHz (Japan)*
Bandwidth	*1 MHz, 2 MHz, 4 MHz, 8 MHz, 16 MHz*
Topology	*Star topology with relay support*
Transmission Range	*Up to 1km*
Maximum transmit power	*1W(US), 250 mW(Japan)*
Number of devices which can be supported by 1 AP	*8191*

Main goals of the 802.11ah MAC design is enhancing the efficiency of the MAC layer to reduce energy consumption and to increase total number of devices which can be served by an access point. One of the main reasons of increased energy consumption in 802.11 network is the hidden node problem, where signals from two stations interfere and result in retransmissions. Since many 802.11ah will operate outdoors, previous solutions for indoor 802.11 is not effective. 802.11ah mitigates the hidden node problem by restricting the time at which a station can start to contend for the medium so that packet transmissions from stations do not overlap with each other. 802.11ah defines a time window called a Restricted Access Window (RAW) during which only a group of stations that are associated with an Access Point (AP) are allowed to access the medium. A RAW is divided into RAW slots, and each RAW slot is typically allocated to one station. The maximum number of slots in a RAW is 64. A RAW slot may also be allocated to more than one station to achieve statistical multiplexing among the stations in the RAW slot. Another important feature of 802.11ah for IoT applications is increased sleep time. The baseline 802.11 standard was allowing only 18 hours of sleep for devices, since the BSSMaxIdlePeriod field is an unsigned 16bits value. 802.11ah redefined it such that the two most significant bits of the BSSMaxIdlePeriod field is used as a scaling factor. The longest sleep period for a station is now 5.2 years without disassociation [WiFi05]. Another energy consumption related property of 802.11ad is the Target Wake Time. Normally, a station has to consume energy while waiting for transmission if AP's Beacon indicate that there is buffered data. The AP has to process the buffered data after receiving a signal that the station ready is receive. Target Wake Time (TWT) addresses this problem by having an AP and a station schedule a future wake-up time (i.e., a TWT) of the station so that the AP knows when the station will be awake. AP readies data at the scheduled time and transmit without delay. Another energy minimization feature is bidirectional TXOP, which allows an AP and a station to exchange one or more uplink and downlink packets separated by a short inter frame space (SIFS).

3.2.2 IEEE 802.11ah KPI and Future Development

IoT applications are often characterized by small data packets, whereas legacy 802.11 had a 14 bytes long acknowledgement (ACK) frames. In [WiFi05], it is shown that to transmit 100-byte data, 23% of time should be allocated for ACK frame at 2 MHz bandwidth and 650 kbit/s data rate. 802.11ah introduced a null data packet carrying MAC frame format that consists of only the PHY preamble and no data field. In the above example, the total duration to send ACK frame is reduced by 45%. Another reduction in overhead is obtained by introducing a short 12 byte MAC frame header compared to the normal 30 byte MAC frames [WiFi05].

As discussed earlier, one of the use cases of 802.11ah is a smart grid use case where an AP has to support as many as 6000 stations within a 1 km^2 area [WiFi06]. Developers increased the number of stations that an AP can support from 2007 to 8191. To indicate every station in beacon's traffic identification map four encoding schemes have been introduced.

802.11ah is the answer of 802.11 to long range IoT application demands. It operates in lower frequency bands in different countries. However, there is no harmonization around the globe. In addition, it has to compete with other low-energy long-range IoT systems, mentioned in this work. On the other hand, 802.11 continues to develop new amendment in the 2.4 GHz and 5 GHz bands, in which WiFi dominates the market. 802.11's major amendment in those bands 802.11ax (Wi-Fi 6) could be a contender for low range IoT applications. Although the primary channel of 802.11ax is 20 MHz, thanks to OFDMA, 2 MHz resource units can be reserved to IoT stations. The data rates can be as low as 375 kbit/s. In conclusion 802.11 universe provides solutions for IoT both for long range applications with less complex stations and also short-range but legacy stations.

3.3 Bluetooth Low Energy

Bluetooth Low Energy (BLE), also known Bluetooth Smart, was first introduced in 2006 as "Wibree" and in 2010 merged into the main Bluetooth standard with the adoption of the Bluetooth Core Specification Version 4.0 [BLE01]. In contrast to other wireless technologies targeting the IoT market, BLE 4.0 only offered a star network topology with no multi-hop capabilities. Due to the demand for more services requiring mesh topologies, e.g., Wireless Home Automation Networks (WHANs) and broader coverage areas, e.g., urban and agricultural applications, the core specifications of BLE were reviewed and resulted into a number of enhancements [BLE02].

Table 6 summarizes the main parameters and characteristics of the BLE4.0 and BLE5.0 standards. Besides the higher data rates, wider transmission range and the inclusion of the mesh topology, BLE 5.0 introduces novel features.

Table 6: Summary of the BLE key parameters.

Key Parameters	***BLE 4.0***	***BLE5.0***
Symbol Rate	*1 Msymbol/s*	*1 and 2 Msymbol/s*
Data Rate	*1 Mbit/s*	*1 and 2 Mbit/s*
Frequency Bands	*2.400 GHz – 2.483 GHz*	*2.400 GHz – 2.483 GHz*
Bandwidth	*40 channels, 2MHz each*	*40 channels, 2 MHz each*
Topology	*Star*	*Star –Broadcast - Mesh topology*
Transmission Range	*10 meters (indoor)* *350 meters [BL03]*	*40 meters (indoor)* *4x at 128 kbit/s*

Among the main novel features, the latest BLE specifications, BLE5.1, incorporates a direction finding feature to determine the direction of a BLE signal transmission [BLE03]. This allows developers to create high accuracy, interoperable positioning systems such as real-time locating systems and Indoor Positioning Systems (IPS) [BLE04].

The BLE specification of the Mesh Networking solution is another of the major tasks currently undertaken by the Bluetooth Special Interest Group [BLE05]. The mesh networking specifications define the requirements to enable interoperable many-to-many mesh networking solution for BLE wireless technology. The specifications define basic functionality and properties of nodes and devices on a BLE mesh network.

The above two features, BLE-based IPS and Mesh Networking solutions, will enable the development of many end-user applications. The specifications of the main building blocks will enable the interoperability of BLE devices developed by different vendors.

3.3.1 Bluetooth Low Energy Key Performance Indicators

Most works reported in the literature focusing on BLE-based IPS have incorporated the use of machine learning principles or signal processing techniques. In [BLE06], the authors first present a review of different IPS BLE-based systems reported in the literature. Then they proposed three different techniques to enhance the precision of a BLE indoor positioning system: channel diversity, Kalman Filtering and a weighted trilateration method. All those techniques address the major challenges faced on the analysis of the Received Signal Strength Indication (RSSI) measurements: the use of multiple channels, channel diversity, to reduce the dispersion of the RSSI measurements inherent to

BLE signals; a Kalman Filter to mitigate the effects of unlikely location estimations due to wrong RSSI measurements; and a weighted trilateration algorithm.

In [BLE07], the authors conduct an experimental study using 19 BLE4.0 beacons. Their study included an analysis of the transmission power used by the BLE4.0 beacons over the accuracy of a BLE-based indoor localization scheme. Results show that their initial power setting, set at the highest available level, was unnecessarily high for their deployment and that an attenuation of up to 25 dB would have had a low impact on the positioning accuracy.

In [BLE08], Castillo et al. focus on the tuning of the RSSI fingerprint to be used in the implementation of a BLE4.0 localization mechanism. They evaluate the relevance of the RSSI fingerprint reported by each BLE4.0 beacon operating at various transmission power levels using feature selection techniques. They use two classification algorithms, namely the k-Nearest Neighbors and the Support Vector Machine algorithms, in order to improve the setting of the transmission power levels of each of the BLE4.0 beacons. Finally, the authors show that the use of an asymmetric power level setting can greatly improve the localization accuracy of a BLE4.0-based IPS.

In [BLE09], Huang et al. explored the challenges on developing BLE-based indoor positioning in a dense Bluetooth environment. The authors point out that in a dense Bluetooth environment, the received signal strength indication exhibits a high RSSI variation requiring a longtime interval collection of the BLE signal samples. Hence, to mitigate the effects of the dense Bluetooth environment, their proposal introduces a hybrid method combining sliding-window filtering, trilateration, dead reckoning and Kalman filtering to improve the performance of the BLE indoor positioning.

Due to the great interest in comparing the performance of BLE-based IPS, various research groups have produced rich datasets [BLE010][BLE11]. Due to the large variety of end-user applications, e.g. health, ambient assisted living, some of the datasets being produced may not only provide the means of positioning a BLE-equipped device, but moreover, the dataset may provide rich social interaction information [BLE11]. Such studies are motivated by the fact that BLE is implemented in smartphones and a wide variety of consumer electronics gadgets, ranging from leisure to health monitoring devices.

Another major research line focuses on the evaluation of the capabilities of Machine Learning algorithms to mitigate the multipath effect encountered in indoor environments. In [BLE12], Lovón et al. investigate the characterization of Bluetooth signals behavior using twelve different supervised learning algorithms as a first step towards the development fingerprint-based localization mechanisms. They also explore the use of metaheuristics to determine the best radio power transmission setting evaluated in terms of accuracy and mean error of the localization mechanism. They also tune-up the supervised algorithm hyper parameters. Their main contribution is centered on a comparative evaluation of twelve supervised learning and two meta-heuristics algorithms under two different system parameter settings as a means to provide valuable insights on the

use and capabilities of the various algorithms on the development of indoor localization mechanisms

Regarding the mesh network mechanism, in [BLE02], Darroudi and Gomez review the many challenges facing the development of reliable and robust communications mechanism, mainly routing mechanisms. Their study includes a comparative analysis of academic and proprietary proposals and points out the relevance of the mesh networking mechanism on the development of BLE-based applications. They characterize two major routing approaches and point out the suitability on supporting two data collection paradigms. They point out the many open issues to be addressed on developing routing mechanisms provided added-value services, such as, security, privacy and multicast. They also point out the need of ensuring the interoperability of the various solutions: a topic often left out by many research proposals.

In [BLE13], Baert et al. carried out an in-depth evaluation of the BLE Mesh Standard. Their study comprises an experimental evaluation, a statistical approach and a graph-based simulation model. Among the metrics reported in their study, they show that the backoff mechanism used by the access mechanisms, has a major impact on the round trip time (RTT) of the network. Since node density is expected to increase in the near future, the number of medium access conflicts (collisions) is expected to become a major issue. Further studies will be required to examine the tradeoff between the number of hops and the backoff mechanism.

3.3.2 Bluetooth Low Energy Future Development

As the deployment of IoT services continues to grow, BLE with an IoT market share of 30% [BLE14] has become a key player. In order to meet the needs of IoT, key market solutions, such as audio streaming, sports and health monitoring devices, location services and monitoring systems, the BLE SIG has focused their efforts on enhancing the topology and radio technologies [BLE15]. The latest specifications define novel features facilitating the development of location systems and control, monitoring and automation systems. The implementation and capabilities of the proposed features will require an in-depth evaluation of the various options included in the BLE specifications, such as, three different physical layers, the use of error detection and correction mechanisms, advertising (signaling) extensions, frequency hopping. Furthermore, the expected growth of industrial wireless networks and smart city solutions will require the deployment of dense BLE networks. Power-efficiency, robustness and quality of service guarantees will be three key performance indicators to be addressed [BLE15].

4. Vehicular technologies

Vehicular networks are also part of the IoT scenario. Vehicles themselves can be nodes of a vehicle sensor network. Transportation might become a means not only to transmit safety data to other vehicles, but also a means to increase wireless coverage and move data to different areas. Furthermore, it also fosters use cases for other traffic participants, like cyclists and pedestrians.

4.1 IEEE 802.11p

The current state-of-the-art systems for vehicle-to-anything (V2X) communication, ITS-G5 in Europe and DSRC in the US, are based on the IEEE 802.11p MAC and PHY layers [Veh01, Veh02]. The 802.11p amendment to the 802.11 standard was approved back in 2010 and is heavily studied in the literature---both experimentally and by computer simulations. Moreover, hardware has been available for some time. In spite of this, large-scale deployments are still lacking.

The main innovation brought by 11p is the possibility to communication "outside the context of an BSS (OCB)". This change was made to remove the time it takes for an 802.11 station to attach to a network. In other words, stations that communicate OCB can transmit and receive frames without prior authentication, which allows for short latency communication even when the network topology changes quickly, as is the case in high-mobility scenarios. Security needs to be handled by higher layers.

The physical layer changes due to 802.11p are minor. Indeed, the PHY layer is regular 802.11 OFDM (802.11-2016, Clause 17 [Veh03]) with the 10-MHz channel spacing option. The default coding and modulation scheme, QPSK with rate ½ convolutional coding, yields a data rate of 6 Mbit/s. MIMO for the purpose of enabling spatial multiplexing is not used. However, receiver hardware can use multiple antennas to improve reliability through receive-antenna diversity.

The main reason for using the 10 MHz channel spacing option is to be robust against delay spread. The 802.11 OFDM cyclic prefix (guard interval) is determined only by the channel spacing: for 20 MHz it is 0.8 μs and for 10 MHz it is doubled to 1.6 μs. An increased cyclic prefix leads to an increased robustness against delay spread. However, also the OFDM symbol duration is determined by the channel spacing: for 20 MHz it is 4 μs and for 10 MHz it is doubled to 8 μs. An increased OFDM symbol duration leads to a decreased robustness to Doppler spread (i.e., time-variations) of the channels. Even in high-mobility scenarios, the

resulting ICI is limited. The problem is more related to the placement of pilot signals in the 802.11 frame. In 802.11p, the pilots are concentrated in the beginning of the frame, as shown in Figure 6. Since the channel frequency response can vary quite significantly over a frame duration, channel estimates from the frame beginning are outdated at the end of the frame, which will cause increased frame error probability if not counter-acted. Advanced channel estimation, iterative channel estimation and detection, and other ways to include extra training in the 802.11p frame (while remaining standard compliant) have been proposed to tackle this problem [Veh04].

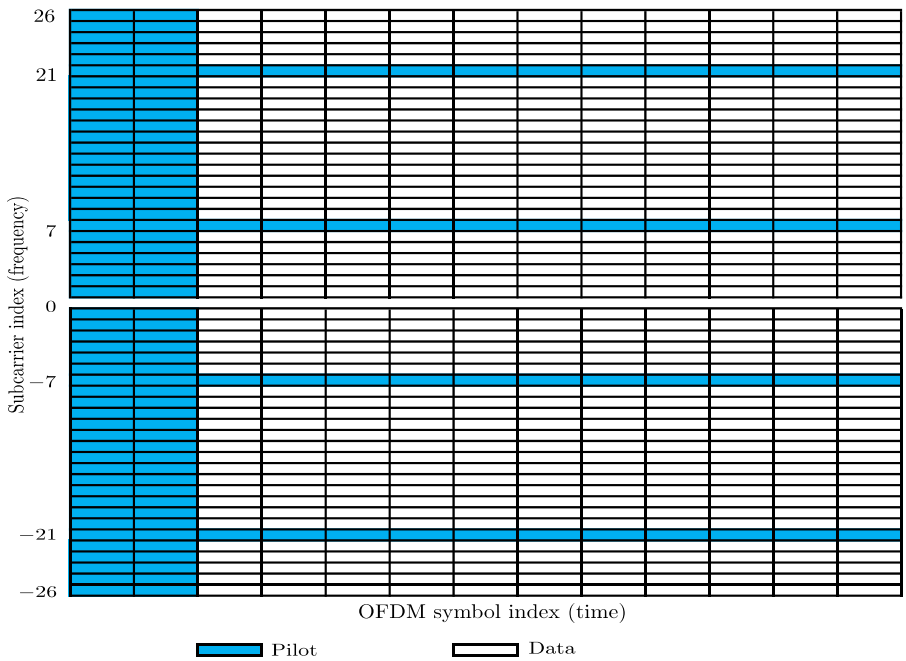

Figure 6: 802.11 OFDM frame format. Note that pilots are concentrated to the beginning of the frame.

The medium access control is Enhanced Distributed Channel Access (EDCA), which is an enhanced version of the 802.11 Distributed Coordinating Function (DCF). EDCA is, just as DCF, based on Carrier-Sense Multiple Access (CSMA). CSMA performs quite well for low to modest channel loads. However, as the channel load increases, channel access delays and packet collisions increase quite rapidly. For this reason, ITS-G5 mandates the use of so-called Decentralized Congestion Control (DCC) with the aim to avoid high channel loads. This is achieved by regulating the CAM repetition rate based on the vehicle dynamics and the measured channel load [Veh05]. A number of alternatives to CSMA have been proposed. In fact, the literature on this is quite extensive. However, none of the proposed enhancements, e.g., self-organised time division multiple access or mobile slotted ALOHA, have made it into the standard.

4.1.1 IEEE 802.11p KPI and Future Development

Motivated by the push of the Cellular Vehicle-to-Everything (C-V2X) community (see next section) and about 10 years of development of 802.11, including the completion of 11n and 11ac and the ongoing work on 11ax, some work has started towards the update of the 802.11p standard. The new foreseen amendment is

called 802.11bd, which has the goal to define at least one mode to provide 12 Mbit/s with 10 MHz channel spacing in a high mobility scenario (500 km/h relative speed, corresponding to vehicles traveling at 250 km/h in opposite directions) in the 5.9 GHz band [Veh06]. Moreover, the project aims at specifying a mode for increased range, targeting a 3-dB sensitivity improvement compared with the current standard BPSK rate-½ mode (i.e., the mode providing 3 Mbit/s in 10 MHz). A final project aim is to provide at least one form of positioning in conjunction with V2X communication. Needless to say, the changes should be backwards compatible and interoperable with deployed OCB devices.

Table 7: Summary of the IEEE 802.11p key parameters.

Key Parameters	***Values***
Bit Rate	*Default 6 Mbit/s with 10 MHz bandwidth*
Frequency Bands	*5.9 GHz*
Bandwidth	*10 MHz*
Topology	*Ad hoc (OCB)*
Transmission Range	*About 1 km*

4.2 C-V2X

Given the relevance of the vehicular scenario and the enormous market potential, in Release 14 (2015-2017) 3GPP started working on specific features to be added to the cellular technology in the so-called C-V2X. Even if that was not the first time the cellular technology considered communications with highly mobile nodes, a new perspective was introduced. Starting from that release, two aspects started paving the way for vehicles towards 5G: 1) new components in the core network, specifically addressing that "vertical"; and 2) enhancements to the radio protocols in order to enable short range direct vehicle-to-vehicle (V2V) communication.

In parallel with the standardization process at the 3GPP, all the major players of the automotive sector have formed the 5G automotive association (5GAA), which has the stated aim to promote this new technology as a complete solution for any situation, thus making all alternatives (and especially IEEE 802.11p) outdated.

C-V2X thus intends to cover with a single technology both kinds of connections; first, the classical infrastructure-based communications, hereafter denoted as long-range, where vehicles directly connect to the base stations (deployed on purpose or already existing); second, a newly defined short-range solution allowing devices to directly communicate to each other, with or without the support of the infrastructure. Main parameters of this technology are reported in Table 8.

Table 8: Summary of C-V2X key parameters.

Key Parameters	***Short-range C-V2X (sidelink)***	***Long-range C-V2X***
Bit Rate	*Up to 22 Mbit/s with 10 MHz bandwidth*	*More than 1 Gbit/s in 4G*

Frequency Bands	*5.9 GHz*	*Various, from sub-GHz (700, 800 MHz) to tens of GHz in 5G*
Bandwidth	*Typically 10 or 20 MHz, carrier aggregation possible*	*Typically 20 MHz, with carrier aggregation*
Topology	*Ad hoc*	*One-hop connection with base stations*
Transmission Range	*Expected more than 2 km*	*Up to tens of km*

4.2.1 Long-range C-V2X, from 4G to 5G

The long-range C-V2X is basically a customized management of the legacy cellular network for the specific vertical of the automotive sector. What Release 14 introduces in this case is a new network element, called "V2X control function", which is devoted to the management of all operations involving vehicular communications (3GPP TS 23.285).

Actually, long-range cellular support to vehicular communications has started to rely on the paradigms of network slicing, network virtualization, and software defined networking, which are the main keywords for the evolution of cellular core networks towards 5G.

Regarding the radio access of long-range communications, no particular changes have been introduced and the advanced features of LTE/LTE-advanced are exploited, including multicarrier based multiple access mechanisms (orthogonal frequency division multiple access, OFDMA, in downlink and single carrier frequency division multiplexing, SC-FDMA, in uplink), a large number of Modulation and Coding Schemes (MCSs) based on advanced coding, MIMO techniques, and carrier aggregation. Like for other services, both unicast and multicast (i.e., Multimedia Broadcast/Multicast Service, MBMS) can be used in downlink.

The range granted by a single base station can be from tens of meters to several km, depending on the installation, and the maximum data rate can exceed the Gbit/s in good channel conditions within an unloaded cell. The main issues when the mobile nodes are vehicles are related to strict requirements on latency and the potential high number of nodes at the same time in the same cell. The former point is indeed debated, since the current network allows 10 to 100 ms of delay and it is not overall agreed that a lower latency is really beneficial, at least in a first phase. The latter appears instead as a critical point, given that for safety applications all vehicles are supposed to continuously share information with periodic messages to all neighbors, also known as cooperative awareness service; considering the baseline of 200-300 bytes every 100 ms, which could increase to 1200 bytes and even 50 Hz of periodicity in specific cases, collecting everything in uplink and redistributing in downlink appears very challenging, even considering multicast via MBMS in downlink.

This point is indeed one of the main motivations for the development of the short-range option discussed in the next subsection. In order to give example numbers, in Figure 7, the probability to successfully allocate all users attempting to transmit periodic messages of 100 bytes every 100 ms is shown assuming short-range or

long-range communications, with either unicast or MBMS in downlink. In this example, it is assumed that one cell covers up to 1 km of a highway segment, where vehicles are randomly distributed. Furthermore, 340 packets can be concurrently allocated in downlink, 200 in uplink, and 100 in the case of short-range (we have used the same approach and settings as in [Veh07]). Even if the figure corresponds to specific settings, the message is that the service is hardly possible on a large scale using unicast downlink and that the spatial reuse of short-range significantly increases the supported density.

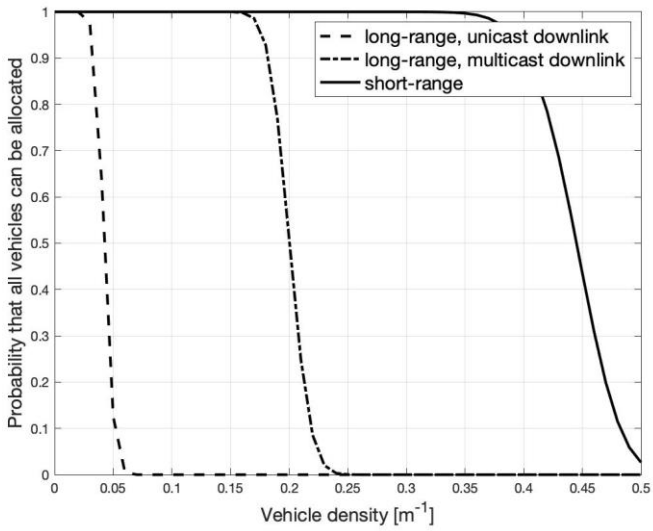

Figure 7: Probability that all vehicles can be allocated varying the vehicle density with long-range and short-range C-V2X applied for the cooperative awareness service

5.2.2 Short-range C-V2X, sidelink

Whereas long-range is overall a customization of the network towards specific needs, the short-range solution appears as something new, which might mean new issues to be raised, investigated, and solved.

The early specifications on direct device-to-device (D2D) communications, started with Release 12, were enriched in Release 14 with specific parts dealing with the vehicular scenario, thus addressing V2V, vehicle-to-pedestrian (V2P), and possibly vehicle-to-roadside units (V2R). More precisely, the terminology applied by 3GPP to indicate the short-range direct communication is sidelink, to distinguish it from the downlink/uplink used by a mobile node from/towards a base station.

Short-range C-V2X uses SC-FDMA (same as the uplink) and exploits a subset of the features designed for long-range communications. For example, the allowed MCSs are a slightly reduced subset of those possible in LTE and a limited use of multiple antennas and carrier aggregation is defined. The main differences with respect to the legacy specifications are that more pilot symbols are introduced, leaving just 9 of every 14 OFDM symbols at the physical layer for the transmission of data (compared to 12 data symbols used by long-range), that the control part associated to the data is revised in order to reduce the transmission delay, and

that new solutions for the radio resource allocation have been introduced, as hereafter detailed.

In particular, regarding the resource allocation, Release 14 introduces the so-called Mode 3 and Mode 4. Mode 3 is the infrastructure-based radio resource assignment to be used when vehicles are under cellular coverage and the operator wants to take control of the allocation process; the standard in this case does not define a specific algorithm, which is left to the operator. Differently, Mode 4 is the allocation process performed directly by the vehicles based on local measurements. A specific algorithm is defined in this case by 3GPP, in order to make products from various vendors interoperable. In addition to this, the standard leaves the door open to a geo-based resource allocation, where the selection is constrained to some sub-pools based on the position of the vehicles (assumed known thanks to some global navigation satellite system, GNSS).

4.2.2 Short-range C-V2X Performance

Regarding the performance of short-range, it must be remarked that commercial devices are still not available, and results have been mostly obtained via simulations. A few measurements, with promising results, are only provided by 5GAA based on prototypal components.

One possibly weak aspect is that all vehicles must be synchronized in order to ensure orthogonally among resources. Such aspect does not appear critical when GNSS signals are received with good quality, but doubts arise in the other cases, despite the efforts made by 3GPP to add other mechanisms, both involving the base stations or not. Actually, this is one of the main points remarked by those against C-V2X in favor of IEEE 802.11p.

Being short-range C-V2X initially conceived for safety purposes, normally a high throughput is not considered as a relevant objective. For this reason, although in principle more than 2 Mb/s per each MHz (net MAC, considering control channels, reference signals and other redundancy at the PHY layer) can be reached using 16 Quadrature Amplitude Modulation (QAM) and a coding rate approximating 1, typically more reliable combinations are preferred, with around 0.5 Mbit/s per each MHz obtained with a lower-order modulation and more protected coding.

The carrier frequency is fixed around 5.9 GHz and the bandwidth is normally assumed of 10 MHz, in compliance with IEEE 802.11p. These values are indeed those reserved in most countries for safety applications of connected vehicles. Channels of 20 MHz are also possible.

The high carrier frequency clearly implies severe path loss and high impact of all kinds of impairments. Still a range longer than 2 km in line of sight conditions is estimated by preliminary measurements conducted on field by 5GAA, if the transmit power is 21 dBm. A longer range compared to IEEE 802.11p is indeed expected, given the use of more advanced physical layer techniques and the possibility to use only a portion of the 10 MHz bandwidth (meaning lower noise at the receiver).

Example results obtained via simulations (using LTEV2Vsim [Veh08]) are provided in Figure 7, where the packet reception ratio is shown varying the transmitter-receiver distance. The cooperative awareness service, with 300 bytes packets every 100 ms is simulated. Results compare short-range C-V2X Mode 3, short-range C-V2X Mode 4, and IEEE 802.11p. Regarding C-V2X Mode 3, the algorithm detailed in [Veh09] is adopted. In Mode 4 the 3GPP algorithm is used with the same parameters as in [Veh10], which are indeed shown not to be optimal from the packet reception ratio point of view (for example in [Veh11]). In all cases 4-QAM is used, with a coding rate 0.33 in LTE and ½ in IEEE 802.11p. Simulations refer to a highway scenario, where vehicles are randomly distributed with a density of 0.1 vehicles/m. Also in this case, results refer to specific settings, but allow to appreciate at least the following aspects: 1) C-V2X outperforms IEEE 802.11p due to improved physical layer and the use of orthogonal resources; 2) exploiting the larger scale knowledge of the network in Mode 3 allows better performance than with the local view of Mode 4; 3) the specific allocation algorithm in LTE can lead to very different results.

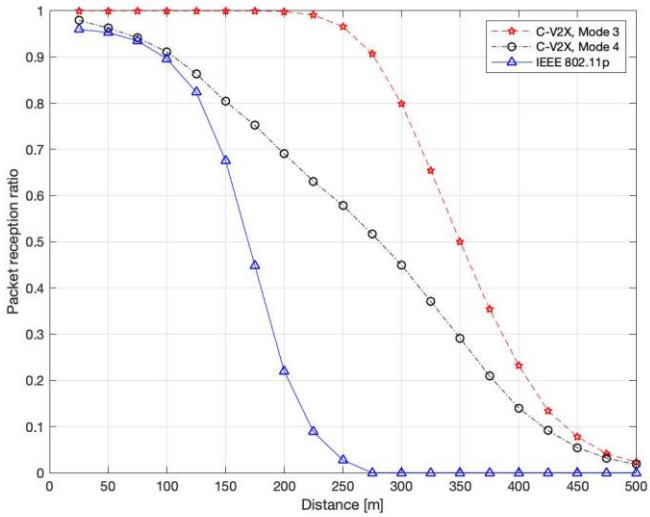

Figure 8: Packet reception ratio varying the distance with short-range C-V2X in Mode 3 and Mode 4 and with IEEE 802.11p.

4.2.3 C-V2X Future Development

C-V2X is one of the verticals targeted by 5G and as such it will continue its evolution within the 3GPP standardization process. The first complete set of functions of 5G is planned in Release 16, expected by 2020, even if some aspects are already defined in Release 15. As a preliminary work in this direction, 3GPP has specifically dedicated attention to the identification of advanced use cases that are hardly supported by current technologies. In particular, within Release 15 (3GPP TS 22.186) a number of applications have been defined for the so-called eV2X, including dense platooning, remote driving, see-through for advanced driving, and extended sensing. To address these scenarios, stringent requirements in terms of throughput, latency and reliability are identified.

Looking at the radio access, New-Radio in 5G will add capacity and flexibility to C-V2X. Still, the promise made by 3GPP is that future enhancements will be retro-

compatible with Release 14, at least when safety applications are addressed. In any case, the baseline technology itself is relatively new and a number of issues have not been fully investigated or might have even not been noted yet. Just as an example, algorithms for power control or data generation adjustment have been widely studied in IEEE 802.11p, while they need further discussion with C-V2X. As another example, the use of half-duplex devices might cause non-negligible message losses even with perfect channel conditions, due to the granularity of 1 ms of the time axis.

5. Future Architectures for IoT

The most commonly used architecture for IoT is composed of the following layers [Arch01, Archi02]:

- The **Perception or Sensing layer**: It is the physical component composed of sensors, which collect physical instances from the environment and convert them into useful data, and actuators, which intervene to change the physical conditions that generate the data.
- The **Transmission or Network layer**: It connects the smart things to the network devices and servers and basically transfers the sensor data from perception to the processing layer. This transmission may happen via gateways that connect the perception layer to the Internet, or there might be a direct access to the Internet of the perception layer, in case an IPv6 based protocol is implemented at the sensors/actuators. Gateways are generally located near the perception layer, and can possibly realize further functionalities.
- The **Processing layer**: It stores, analyses and processes data and may employ different technologies and paradigms (see below).
- The **Application layer**: It delivers application-specific services to the user.

As far as the processing is concerned, there are essentially two visions from the architectural viewpoint: i) cloud-based system architecture, where data processing is largely done in a centralised fashion by cloud computers, where the cloud is in between the network and the application layers; ii) edge (or fog) computing, where the processing and network layers are exchanged. Indeed, edge (fog) computing is a distributed paradigm, which serves as a middle layer in between cloud database and IoT sensors. Mobile Edge Computing (MEC) has proposed to describe the execution of services at the edge of environment and cloud-computing capabilities at the edge of MEC reference architectures and frameworks have the functional elements that support services such as location awareness, radio network information, and application execution. The advantages of expanding cloud services at the edge of mobile networks include lower latency, higher bandwidth, and access to radio network information and location awareness.

Besides the classical architecture briefly described above, the advent of 5G and of the emerging paradigms of Wireless Software-Defined Networking (WSDN) and Network Function Virtualisation (NFV), will most probably play an important role in future architectures for IoT.

The SDN paradigm initially designed for wired networks (e.g., data centers), has recently gained a lot of interest into the wireless environment [Archi03], and it is seen as a key technology enabler for 5G networks [Archi04]. SDN separates the data plane (i.e., the traffic forwarding between network devices, such as switches, routers, end hosts) from the control plane (i.e., the decision making about the routing of traffic flow - forwarding rule) [Archi05]. SDN centralizes network control into a logical entity, namely the SDN controller, in change of programming the IoT network. The SDN controller with its centralised view of the network (topology, active flows, etc.), allows dynamic, flexible, and automated reconfiguration of the network. SDN will be able to address flexibility and interoperability challenges of future multi-vendor, multi-tenant 5G scenarios, such as allow the coexistence of different services with different QoS requirements [Archi06].

Different works in the literature already applied Wireless SDN approaches to IoT and demonstrated its efficacy [Archi07, Arch08, Archi09]. Also the IETF 6TiSCH architecture presented in Section 4.1 defines a centralised scheduling, which implements SDN concepts to provide spatial and frequency diversity within IEEE 802.15.4-2015 IIoT networks.

NFV is a complementary technology of SDN, destined to impact future 5G networks. NFV aims to virtualize a set of network functions, by deploying them into software packages, which can be assembled and chained to create the same services provided by legacy networks. The NFV concept comes from the classical service whereby many virtual machines running different operating systems, software and processors, can be installed on the same server. By moving network functions from dedicated hardware into general purpose computing/storage platforms (e.g., servers), NFV technologies will allows to manage many heterogeneous IoT devices. Moreover, by implementing the network functions in software packages that can be deployed in virtualized infrastructure, NFV offers scalability and large flexibility in operating and managing mobile devices.

Table 9: Characteristics of the different architectures.

Architecture	***Low Latency***	***Robustness of connection***	***Reconfigurability***	***Wide coverage***	***Support of different QoS data***
Four-level architecture with Gateways at Network Layer	*Yes*	*No*	*No*	*No*	*No*
Four-level architecture without GWs at Network Layer (IP-v6 sensors)	*Yes*	*No*	*No*	*Yes*	*No*
Edge/Fog Computing	*Yes*	-	-	-	*No*
Cloud Computing	*No*	-	-	-	*No*

SDN / NFV Architecture	*No*	*Yes*	*Yes*	-	*Yes*

6. Mapping Applications to Air Interfaces

In this section we identify for each of the applications introduced in Section 1 the most suitable technologies among those described above. This mapping is provided in Table 10 and Table 11.

Bluetooth Low Energy is not considered since it is mainly suitable for health and in general body area networks applications, not considered in this white paper.

Smart Cities

While LoRaWAN is currently deployed in many cities for the provision of remote metering services (and other), there is a general thread: as long as the traffic generated by IoT devices in cities will increase significantly, LoRaWAN network might saturate owing to the lack of reserved frequency bands and the long ranges covered by LoRaWAN gateways. This will make room to NB-IoT and/or LTE-M success.

Smart Buildings

ZigBee is the most suitable candidate for smart home applications. One of the major advantages of ZigBee is that, as an open global wireless standard, it provides the open source software stack for developers to freely access the network and application layer. It uses mesh networking and may associate many devices. Also Wi-Fi can be used in some applications.

Smart Agriculture

The energy efficiency of the technology used must be extremely high, to ensure long lifetime for devices embedded in terrain or on trees. Moreover, there is no need for high throughput technologies, since even though many devices are generally deployed, the offered traffic is very low. From all the above, LoRa technology seems to be the most suitable one.

Industry 4.0

The application of 5G radio technologies to industry plants might introduce a number of benefits to automation systems, as long as the stringent requirements set in terms of reliability and latency will be met. In particular, making wireless the links between sensors and actuators on robotic machines, will simplify their maintenance and design, and will permit to add monitoring devices on components currently unreachable because of the impossibility to deploy wires. While the due levels of link reliability might be achieved through the application of proper transmission techniques, the requirements on maximum latency might

still be a limit; some industrial applications require control loops with maximum delays in the order of tens of microseconds, a level unreachable even by 5G NR. On the other hand, wire replacement is a significant advantage, and for those applications where extreme low latency is not an essential requirement, 5G will be an enabler of increased process efficiency.
Which Radio Access Technology (RAT) will best fit to the user needs is difficult to predict; 5G NR promises to deliver low-latency high reliability services, but at the cost of implementation of a SIM card in UEs. Will the industry managers accept this step?

Automotive Applications

For several years, car makes have wondered whether to rely on ad-hoc networking approaches (like, ITS-G5 and DSRC, based on 802.11p), or wait for 5G deployment. Now, C-V2X (Cellular Vehicle to Everything) promises to enable most of services needed for connected cars. For long-range communication, it is most likely that C-V2X will be the dominant standard. For short-range, it is less clear. For less demanding services, today's 802.11p or the recent short-range LTE-V2X will suffice in many cases. For more demanding services, evolved 802-11p (i.e., 802.11bd) and evolved short-range C-V2X, including 5G NR, will be required.

Table 10: Applications vs technologies mapping.

	LoRa	NB-IoT / LTE-M	Zigbee	6TiSCH	Wi-Fi	5G
Smart City						
Metering of utilities consumption	Yes	Yes	No	No	No	Yes
Smart Parking	Yes	Yes	Yes	No	No	Yes
Waste Management	Yes	Yes	No	No	No	Yes
Smart Lighting	Yes	Yes	Yes	No	No	Yes
Smart Buildings						
Home automation	No	No	Yes	No	Yes	-
Microgeneration (photovoltaic cells, solar panels, etc.)	No	No	Yes	No	Yes	-
Smart Agriculture						
Crops Monitoring	Yes	Probably yes	In some cases, yes	No	No	-
Environmental Monitoring (soil, air)	Yes	Probably yes	In some cases, yes	No	No	-
Industry 4.0						
Monitoring	Yes	No	No	Yes	No	Yes
Controlling	No	No	No	No	No	Probably yes, but still not clear

Table 11: Automotive applications and technologies mapping.

	IEEE 802.11p	**Short-range LTE-V2X**	**Long-Range LTE-V2X**	**5G**
Cooperative awareness	Yes	Yes	Probably No	Yes
Platooning	Probably Yes	Probably Yes	Yes (if covered)	Yes
Lane merging	Probably Yes	Yes	Yes (if covered)	Yes
See through	No	Probably Yes	Probably No	Yes
Extended sensing	No	Probably No	Probably No	Yes
Remote Driving	No	No	Probably No	Probably Yes

7. Conclusions

Based on the analysis reported above, the 5G ecosystem will optimally serve the various IoT application domains with different RATs. Mobile Network Operators will need to be able to offer services based on a multi-RAT approach comprising non-3GPP solutions. Among the latter ones, which use ISM bands, LoRaWAN is becoming more and more successful; it works mostly on the 868 MHz band, though recent releases of LoRa chipsets operating at 2.4 GHz will make the adoption of this frequency band feasible. In any case, its use for long-range applications in densely populated areas might encounter problems in terms of saturation of the frequency bands. One option to solve this issue might rely on the identification of separate frequency bands specifically for smart city scenarios (as done for other application domains, like e.g. for health).

In any case, what the 5G ecosystem might bring as strong support tool to the IoT world, lies mostly in the cloud computing component, the adoption of artificial intelligence approaches, the development of digital twin technologies. MNOs will work in that direction. What RAT is used by things, should be transparent to such elements of the ecosystem. Nevertheless, the availability of different RATs, each one being optimal for a different IoT application domain, is an essential aspect of the 5G ecosystem.

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