# Chapter 8
# IoT Communication Technologies for Smart Cities

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## 8.1 Introduction

According to the latest studies, by 2050 70 % of the world population will be living in towns and cities which are responsible of 75 % of GreenHouse Gas (GHG) emissions even if they only cover 2 % of the Earth surface [6, 45]. In this context, the vision of Smart City entails the development of methodologies, solutions, and procedures to improve the efficiency of urban environments and facilitate their sustainable development. Realizing such a vision calls for the active participation of different stakeholders which naturally share/use the urban ecosystem, including city governing bodies, law-makers, utilities, Information and Communication service providers/producers and citizens.

In particular, the capillary use of Information and Communication Technologies (ICT) will provide the backbone for improving the efficiency of existing services and for fostering the creation of new ones in the urban environment. Among the ICT solutions which can make our cities smarter, the Internet of Things (IoT) paradigm is one of the most promising ones [17]. The IoT envisions scenarios where everyday-life objects equipped with sensing peripherals, processing/storage units and communication technologies have a "presence" on the Internet, that is, they can be reachable from the Internet and they can further deliver data up to the Internet on the surrounding environment they are immersed in.

The IoT paradigm finds application in many different domains which are relevant to the vision of Smart Cities including home automation, industrial automation, med-

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ical aids, mobile health care, elderly assistance, intelligent energy management and smart grids, automotive, traffic management, and many others [15].

The concepts of IoT and Smart Cities have become more and more coupled in the last few years. On the one hand, such connection has been stimulated by the strong push from local and national governments to adopt ICT solutions oriented to the urban administration. The possibility of connecting urban objects, resources and services to the Internet in order to facilitate their management and utilization is a great plus for both the citizens and the governments, as it allows for better quality of services for the one and lower administrative costs for the others. On the other hand, Smart Cities offer a perfect application scenario for many IoT solutions: therefore, many technological advancements in different areas related to the IoT paradigm have been motivated, designed, and tested expressly for such a scenario.

This chapter provides a general overview of the main communication technologies in the field of the Internet of Things which can have a beneficial impact in the realization of Smart Cities. We focus here on the available solutions to provide connectivity to/from smart objects, and propose a classification of the different technologies based on the reference network architecture used to “cover” the urban environment; the alternative solutions are critically categorized on the basis of quantitative/qualitative key performance indicators including supported data rate, communication latency, coverage width, cost, flexibility, robustness and maturity/availability/diffusion.

We start off by analyzing the most promising application domains for Smart Cities in Sect. 8.2; Sect. 8.3 provides the reference classification of the most common alternatives of IoT architectures for Smart Cities, which are then described and evaluated in Sects. 8.4–8.6. Finally, Sect. 8.7 reports a discussion on the open challenges of the presented technologies, together with our concluding remarks.

## 8.2 IoT-Based Services for Smart Cities

We organize the plethora of IoT services/applications for Smart Cities which are envisioned to be implemented in the near future in three main categories, namely (i) smart urban mobility, (ii) services for urban sustainability and (iii) services aimed at enhancing the quality of life of citizens. In the following, we provide details and give examples for each one of these macro-areas.

### *8.2.1 Smart Urban Mobility*

Management and optimization of urban mobility is one of the main challenges that any municipal administration has to face. It includes all the activities related to the management of vehicular traffic within the urban boundaries, with the ultimate goal of allowing easy and smooth mobility to anyone, anywhere and at any time. This requires not only a careful planning of urban spaces devoted to vehicular traffic (i.e., offline management), but also the capacity to quickly operate when needed, in an "online" fashion. Having such a capacity is clearly connected to the availability of real-time data of various types from the urban vehicular environment, and this is where the IoT plays a key role. In the following, we list several IoT applications and services that will be or have already been implemented to support smart urban mobility:

- **Traffic monitoring**: the ability to monitor traffic congestion and detect traffic incidents in real time is crucial for obtaining safer roads and smoother traffic flows. Such capability may be achieved either with the use of statically deployed cameras or other sensors [23], or using real-time measurements coming from the vehicles themselves [25, 33].
- **Smart parking**: cameras or other sensors [27] may be used to monitor the availability of vacant parking lots in the city, in order to direct drivers along the best path for parking. Such a service may produce many benefits, such as lesser traffic congestion, fewer emissions and less stressed citizens.
- **Smart traffic lights**: communications between traffic lights and vehicles may be established to inform the latter of the optimal speed in order to e.g., hit a green light or other important information [44]. Also, specific traffic lights in the city may be controlled in real time to facilitate the mobility of emergency vehicles.

### *8.2.2 Services for Urban Sustainability*

Having "greener" cities have nowadays become not only a good intention, but a global goal regulated by international agreements. While part of the transition to environmentally aware cities will be pursued through fairly easy technological improvements (e.g., switching to energy-efficient LED lighting) and administrative regulations (e.g., creating low-emission zones), the role of information and communication technologies, and the IoT in particular, is of key importance. Several examples falls within the area of environmental-aware IoT services:

- **Smart lighting**: adapting the intensity of public lights to movement of pedestrians and cars may allow for notable energy saving, reduction of light pollution and increased safety. Also, specific sensor for detecting malfunctioning may be installed in order to reduce the maintenance costs. The same ideas may be also applied in indoor scenarios [46].
- **Waste management**: capacity sensors may be used to disseminate the status of each trash bin in the city, and such information may be used to optimize routing and scheduling of vehicles deputed to waste collection [14].
- **Energy consumption monitoring and optimization**: future Smart Cities electricity services will be based on the concept of Smart Grid, where smart meters and devices will operate to control and optimize the production and distribution of

electricity. In this context, the IoT paradigm is expected to play a key role, especially for the integration of customers' premises and appliances with the smart grid owned by power distributors [42].

### *8.2.3 Services Aimed at Enhancing the Quality of Life of Citizens*

Cities are made of citizens, whose quality of life (QoL) is critical for the success of the city itself. The IoT will play a major role in the development of services and applications to enhance the quality of life of citizens. Besides improvements in urban mobility and a cleaner environment, the IoT may enable additional services, such as

- **Noise monitoring**: exposure to excessive noise levels is known to negatively impact the quality of life, producing annoyance, sleep disruption, anxiety and other disturbances. Noise data coming from several sound sensors dislocated in the city may help municipalities in monitoring the level of noise [26].
- **Air quality monitoring**: sensors for monitoring the quality of air and the level of pollution may be deployed in public spaces and such data distributed publicly to citizens [28].
- **Automation of public buildings**: the IoT paradigm may also be employed to implement building automation systems, supporting applications such as electronic devices management and maintenance, energy monitoring, smart rooms and many others [29].

**Table 8.1** Qualitative comparison of Smart City services requirements

| Application | Coverage | Range [m] | # of devices | Tolerated delay | Rate |
|---|---|---|---|---|---|
| Traffic monitoring | Full | ∼1000 | ∼1000 | Minutes | Low |
| Smart parking | Hotspot | ∼100 | ∼100 | Seconds | Med-high |
| Smart traffic lights | Full | ∼10 | ∼1000 | Seconds | Med-high |
| Smart lighting | Full | ∼1000 | ∼1000 | Seconds | Low |
| Waste management | Full | ∼1000 | ∼1000 | Minutes | Low |
| Smart grid | Full | ∼10 | ∼100 | Seconds | Med-high |
| Noise monitoring | Full | ∼1000 | ∼1000 | Minutes | Low |
| Air quality monitoring | Full | ∼1000 | ∼1000 | Minutes | Low |
| Home automation | Hotspot | ∼10 | ∼10 | Seconds | Low |

Table 8.1 briefly summarizes the requirements of each of the aforementioned services in terms of degree of coverage (full or hotspot), transmission range, number of devices, tolerated delay and produced traffic rate. As one can see, such requirements may vary a lot from case to case, justifying the adoption of different communication technologies, tailored to the particular application scenario. Such communication technologies are detailed in the following sections.

## 8.3 Interconnecting Objects in Smart Cities: Working Architectures

Urban environments are extremely complex and heterogeneous in terms of available communication technologies and architectures. The plethora of IoT services and applications envisioned for Smart Cities and described in Sect. 8.2 requires the interplay of different communication technologies and different system's architectures. Regardless of the specific application/service, Smart Cities generally require some type of ICT infrastructure to support the exchange of information among the different agents in the urban environment.

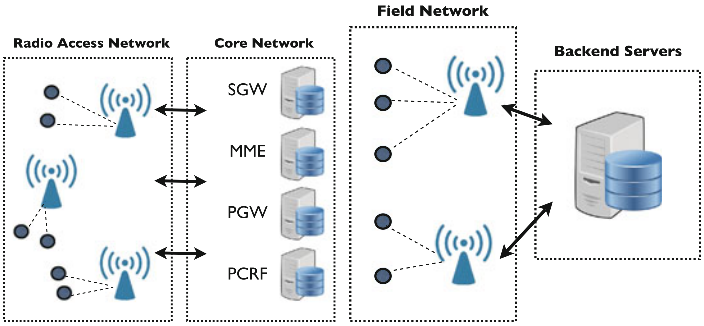
As far as the communication is concerned, data must travel from devices which are immersed in the urban environment toward information sinks, and vice versa. Generally speaking, there are three most commonly used ways to realize such communication patterns: (i) through **Cellular Mobile Networks**, (ii) through **IoT-Dedicated Cellular Networks**, (iii) through **Multi-Tier Networks**.

Figure 8.1 reports the main layout for the three different architectures.

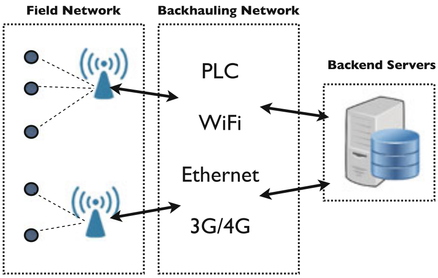
In the case of **Cellular Mobile Networks**, the reference architecture is the one of "legacy" mobile radio networks (2G/3G/4G) with a Radio Access Network (RAN) in the front end and a Core Network (CN) at the backhand. The RAN often works over licensed spectrum bands and the CN includes several entities to manage users mobility, registration, etc. As an example, Fig. 8.1a reports some of the entities in the CN of the Long Term Evolution (LTE) system including the Serving Gateway (SGW), the Packet Data Network Gateway (PGW), the Home Subscriber Server (HSS), the Mobility Management Entity (MME) and the Policy and Charging Rules Function (PCRF) server.

Whilst cellular mobile networks are designed to serve primarily human-to-human and human-to-machine traffic, **IoT-Dedicated Cellular Networks** are stand-alone networks dedicated to service only data traffic to/from unmanned field devices. The "last-mile" connection to the field devices is implemented via long-range transmission technologies over unlicensed spectrum bands, and the backhand infrastructure is much simpler than the CN of mobile radio networks.

**Multi-Tier Networks** feature traffic concentrators or gateways which, on one side, collect the traffic from the field devices through short/medium-range wireless technologies, and on the other side deliver the collected traffic to the backhand via long-range backhauling communication technologies.



(a) Cellular Architecture (b) IoT-dedicated Cellular Architecture



(c) Multi-tier Architecture

**Fig. 8.1** Architectures to support M2M communications in Smart Cities

The following sections describe the main technologies which are available in all the three architectural classes.

## 8.4 Cellular Mobile Networks

Current cellular mobile networks were mainly designed for human-to-human and human-to-machine interactions targeting specific applications/services like telephony, SMS/MMS exchange, multimedia download and streaming. The device ecosystem of Smart Cities further includes unmanned devices which are immersed in the environment for monitoring and reaction functionalities, thus requiring data exchange capabilities to/from the backend. This de facto defines a new communication paradigm which involve little or no human interaction, and thus it is often referred to as Machine-To-Machine (M2M) communications or Machine-Type Communications (MTCs).

M2M communications are characterized by distinctive features with respect to "legacy" human-to-human communications including larger number of devices, periodic or intermittent network access and small amount of data per device [13].

Although most of M2M communications is currently serviced by legacy 2G cellular technologies (GSM, GPRS), the massive growth of the M2M traffic poses specific challenges both in the RAN and CN of cellular mobile networks [38]. To this extent, efforts are in place to improve the cellular architectures to effectively accommodate M2M communications.

According to the Third Generation Partnership Project (3GPP) which is standardizing the future generation mobile cellular networks, the main distinctive features of MTCs with respect to human-based communication include [11, 24]:

- different market scenarios; MTC can be actually used to support diverse applications in different market fields. Sample use cases include the support for smart metering/smart grid applications, environmental monitoring and crowdsensing applications;
- lower costs and effort: the user equipment must be much cheaper than the “legacy” devices with extreme capabilities in terms of energy efficiency;
- a potentially very large number of communicating terminals;
- to a large extent, little traffic per terminal: MTC mainly required the exchange of very small and intermittent data from the field devices to the network.

On the user equipment’s side, the main open issues deal with the cost reduction and the definition of network-assisted power saving functionalities to prolong the device lifetime; on the network’s side, the major issues include coverage enhancement, the definition of lightweight signaling procedure for M2M devices to avoid problems of overload and congestion at the radio and core network levels [16, 48] and the study of effective radio resource allocation techniques to manage the interplay between M2M communication and human-to-human ones [50]. To this extent, the technical specification groups of 3GPP has launched several initiatives to define specific modifications to support MTCs in the Global System for Mobile communications (GSM) and the Long-Term Evolution (LTE) standards. Table 8.2 reports an overview of the main features of the upcoming standardization efforts in the field of cellular IoT.

### *8.4.1 GSM Evolutions*

The working groups dealing with the management of the GSM/GPRS and Edge Radio Access Networks (GERAN) are focusing on two complementary approaches to make GSM more efficient for M2M [24]: an *evolutionary* approach and a *clean-slate* one; the evolutionary approach targets the modification of the legacy GERAN architecture to increase uplink capacity, extend downlink coverage for both control and data channels, and reduce power consumption/complexity of M2M devices while maintaining full compliancy with the current GERAN structure; two proposals are currently competing within the evolutionary approach, the most promising one, according to the latest plenary meeting of GERAN working groups [36], being the so-called Extended Coverage GSM (EC-GSM). In EC-GSM, the uplink uses Frequency Division Multiple Access overlaid with Code Division Multiple Access, that

**Table 8.2** Evolution in the cellular technologies to accommodate M2M/MTC

| | Release 8 | Release 8 | Release 12 | Release 12/13 | Release 13 | | |
|---|---|---|---|---|---|---|---|
| | Cat-4 | Cat-1 | Cat-0 | LTE-M | NB LTE-M | EC-GSM | CS IoT |
| Spectrum (MHz) | 700–900 | 700–900 | 700–900 | 700–900 | 700–900 | 800–900 | 700–900 |
| Channel width | 20 MHz | 20 MHz | 20 MHz | 1.4 MHz | 200 kHz | 200 kHz | 5 kHz (UL)<br>3.75 kHz (DL) |
| TX Rate DL | 150 Mb/s | 10 Mb/s | 1 Mb/s | 200 kb/s | 200 kb/s | ~300 kb/s[a] | 200 kb/s |
| TX Rate UL | 50 Mb/s | 5 Mb/s | 1 Mb/s | 200 kb/s | 144 kb/s | ≤10 kb/s | ~48 kb/s[b] |
| Duplexing | Full duplex | Full duplex | Half duplex | Half duplex | Half duplex | Half duplex | Half duplex |
| TX power UL (dBm) | 23 | 23 | 23 | 20 | 23 | 23–33 | ≤23 |
| Cost[c] | 1.4 | 1 | 0.4 | 0.2 | <0.15 | <0.15 | <0.15 |
| Availability | Available | Available | Available | 2016 | 2016 | 2016 | 2016 |

[a] Peak rate of the EC-PDTCH when base station is transmitting at 43 dBm [24]
[b] Peak rate of the PUSHC with a bonding factor of 8 [24]
[c] scaling factor w.r.t. Release 8 Cat-1

is, in order to allow more devices to transmit at the same time in the same frequency multiplexing based on overlaid code division multiple access technique is proposed to separate the users simultaneously transmitting in the same time slot. Coverage extension for all the transport channels is essentially achieved through blind repetition, that is, the same data block is repeated several times by the transmitter, thus allowing higher receiving gains; different repetition levels are defined based on the coverage class the device belongs to. Other enhancements include definition of new control messages with smaller payload sizes and introduction of a new lower power class.

The *clean-slate* approach targets the re-farming of the GSM spectrum to support a brand new narrowband air interface compatible with GSM channelization of 200 kHz. Four proposals are under investigation, even if the one which seems to be reaching the largest consensus is called NarrowBand Cellular IoT (NB-CIoT) and is based on asymmetric narrow band channels in the downlink and in the uplink; in the downlink, each chunk of 200 kHz is subdivided into 48 narrowband sub-channels of 3.75 kHz width, whereas the uplink defines 36 sub-channels of 5 kHz width. The downlink adopts Orthogonal Frequency Domain Multiple Access modulation, whereas the uplink sub-channels are “assigned” according to a Frequency Division Multiple Access scheme. Sub-channel bonding is further allowed in the uplink to increase the nominal uplink throughput. The reference spectrum bands include the GSM spectrum and the guard bands of the LTE. The base station operates in RF full duplex mode in order to maximize network capacity while the devices operate in half duplex mode to reduce the RF cost.

### *8.4.2 LTE Evolutions*

As far as the evolution of LTE is concerned, LTE Rel-11 has focused on RAN overload functionalities to handle the access of large numbers of M2M devices, and on device power differentiation. The Release 12 of LTE introduces low-cost M2M devices with reduced capability, Category 0 devices, whose cost is approximately 40–50 % of regular LTE Release 8 Cat1 devices. Cost/complexity reduction is mainly achieved by reducing the number of radio transceiver (1 receiving antenna versus 2 receiving antennas of legacy LTE devices), by limiting the maximum transport block sizes (up to 1000 bits per sub-frame) and by further allowing an optional FDD half duplex operation mode. Moreover, to improve the lifetime of Cat 0 devices, a device power saving mode is introduced, which is mainly intended for user equipment with infrequent uplink (mobile-originated) traffic. Devices in power save mode remain registered to the network but are not reachable as they do not check for paging. The device remains in power saving mode until it needs to initiate a "session" toward the network (e.g., issue a tracking area update or start a new uplink transmissions). In addition, scheduling prioritization and service differentiation solutions have been introduced to minimize the impact of MTC data on human-based traffic.

The Release 13 is in the works for better response to M2M requirements leading to the so-called LTE for M2M (LTE-M) [9, 10]. The main improvements at the physical layer include the definition of narrowband channels for transmission of 1.4 MHz and 200 KHz which allow the use of less expensive (and more energy-efficient) hardware at the UE side while improving on the coverage; moreover, features which are already available in the Release 12 are being further improved and extended including an Enhanced Power Saving mode (EPS), and an Extended Discontinuous Reception (DRX) functionality.

## 8.5 IoT-Dedicated Cellular Networks

IoT-dedicated cellular networks are taking pace to fill in the need of designing low-cost, low-energy M2M applications with limited traffic requirements. IoT-dedicated cellular operators often share the same proposition value which includes reduced energy consumption and Total Cost of Ownership (TCO) with respect to classical cellular operators, global reach and plug-and-play connectivity.

As far as the architecture is concerned, IoT-dedicated cellular networks share a common star topology with base stations serving wide areas and large numbers of unmanned field devices, mostly targeting new uses (smoke alarms, parking sensors, maintenance alerts, environmental monitoring) that have not been viable with GPRS/GSMs higher silicon costs, subscription prices, and power consumption [22]. The different IoT-dedicated cellular technologies mainly differ in the used spectrum band, in the capability to supporting bidirectional traffic and in the

**Table 8.3** Comparison of different short-range communication standards for multi-tier IoT architectures

| | SigFOX | LoRaWAN | | Weightless | | | Ingenu |
|---|---|---|---|---|---|---|---|
| | | EU | US | -W | -N | -P | |
| Spectrum | 868–902 MHz | 863–870 MHz 433 MHz | 902–928 MHz | 470–790 MHz TV white spaces | Sub GHz (ISM) | Sub GHz (ISM) | 2450 MHz |
| Channel width | 100 Hz | 125–250 kHz | 125–500 kHz | 6–8 MHz | 200 Hz | 12.5 kHz | 1 MHz |
| TX Rate UL | ≤100 b/s | 250–50 b/s | 980 b/s–kb/s | 250 b/s–50 kb/s | 250 b/s | 200 b/s–100 kb/s | 624 kb/s |
| TX Rate DL | 256 b/day | 250 b/s–50 kb/s | 980 b/s–21.9 kb/s | 2.5 kb/s–16 Mb/s | None | 200 bytes –100 kb/s | 156 [kb/s] |
| Packet size | ≤12 bytes | ≤222 bytes | ≤222 bytes | ≥10 bytes | ≤20 bytes | ≥10 bytes | 6 bytes–10 kbytes |
| Max range (km) | 10–50 | 2–15 | | 5 | 3 | 2 | 100 |
| TX power UL | 10 μW–100 mW | 14 dBm | 20 dBm | 17 dBm | 17 dBm | 17 dBm | 20 dBm |
| Standard (if any) | Proprietary | Standard available | Standard available | Standard available | Standard available | Standard in the works | Proprietary |

maturity/availability of the proposed solutions. In the following, we briefly overview the major technologies and commercial solutions which are compared at glance in Table 8.3.

### 8.5.1 SigFOX

**SigFOX** uses ultra-narrowband (UNB) radios which are built in the field devices and talk directly to a SigFOX base station according to a star-like network topology [40]. Reliability is enhanced by making each device reachable by multiple base stations. The communication protocols at the Physical and MAC layers are proprietary and leverage 100 Hz channels out of a 200 kHz spectrum around 868 or 902 MHz, depending on the region of use. The communication pattern is mostly uplink (from the field devices to the base stations) with the possibility of activating a tiny downlink channel for control purposes. The data exchange protocol is based on messages with payload up to 12 bytes. The very same message is repeated multiple times over different frequency channels to make reception more robust. The message rate can be customized on the specific application needs with a maximum number of per day, per device messages equal to 140 which leads to a maximum uplink throughput of 100 bps. As for the coverage characteristics, SigFOX transceiver generally feature a maximum output power of 15 dBm with a receiver sensitivity of −126 dBm. The claimed coverage is up to 10 km in urban areas and up to 50 km in rural ones.

SigFOX operates by providing the reference technology including base station development/upgrade, and methods/tools for deployment to SigFOX Network Operators (SNOs) in return of a monthly/yearly fee which depends on the specific traffic and coverage requirements of the reference market segment. The SNOs are usually responsible for the upfront investments to build up, plan and maintain the low power network, as well as the business development in the reference market sector [4]. SigFOX is, at the moment, the market leader in the provision of low-power, low-cost IoT connectivity with partnerships of several SNOs across Europe and the US.

### *8.5.2 Weightless*

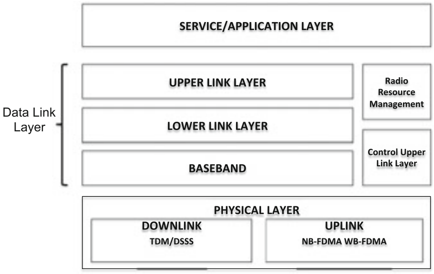
**Weightless** Special Interest Group (SIG) [5] is a nonprofit standard organization created to manage the standardization activities of low-power, wide-area technologies. The Weightless system is represented in Fig. 8.2 [7]. Going bottom-up, uplink and downlink transmissions are distinguished at the physical layer through time division duplexing transmissions; downlink transmissions are multiplexed on a time division manner and leverage a Direct Sequence Spread Spectrum (DSSS) approach. The uplink is operated according to a Frequency Division Multiple Access (FDMA), that is, multiple uplink concurrent transmissions may be operated over different noninterference frequency channels. Besides FDMA, the concurrent access of multiple uplink transmissions is mostly managed in a time-scheduled way with the base station notifying the field devices the proper time slots for transmission.

Two modulation/physical layer approaches are further introduced for the uplink: Narrow Band FDMA (NB-FDMA) with a reference channel bandwidth of 200 kHz and Wide Band FDMA (WB-FDMA) with reference channel bandwidth of 6 or 8 MHz.

The data link layer includes different sub-layers

- the *Baseband* which is responsible for multiplexing and de-multiplexing, further managing the send/receive data for the field devices.
- the *Lower Link Layer* which is responsible for acknowledgements/retransmissions and data fragmentation/de-fragmentation.

**Fig. 8.2** Weightless reference architecture



- the *Upper Link Layer*, responsible for encryption and sequencing and delivery of data to and from the service layer.
- the *Radio Resource Manager* is responsible for managing the Radio resources of the MAC layer, including network configuration.

Differently than SigFox, Weightless system is richer in functionalities at the data link layer as it currently supports acknowledged transmission, data fragmentation/defragmentation, multicast transmissions from the base stations and interrupt capabilities which allow devices to raise alarms for specific events such as power outage.

Weightless includes, at the moment of writing, three different solutions for low-power wide-area networks. The **Weightless-W** is designed primarily to operate in unlicensed spectrum including the white space spectrum frequencies between 470 and 790 MHz previously allocated solely for TV broadcast and wireless microphone applications. Unlike 3G and LTE spectrum, these frequencies are not being auctioned by government communications regulators and are being offered license- and cost-free for use.

The **Weightless-N** is the standard version targeting low-cost applications needing only unidirectional data transmission. It operates in sub-GHz spectrum using the NB-FDMA physical layer described above. Pilot networks operated with the Weightless-N standard have been deployed in the cities of London, UK , Copenhagen and Esbjerg, Denmark.[1]

The **Weightless-P** version proposes itself as a solution targeting reliability and performances similar to cellular systems at a fraction of the cost. The standard uses the narrow band modulation scheme offering bidirectional communications capabilities with fully acknowledged two-way communications. The standard is currently in the works; base stations, endpoints and development kits are expected to be available in the second half of 2016.

### *8.5.3 LoRAWAN*

The LoRa Alliance [1] has been created with similar objectives as Weightless SIG, that is, standardizing low-power, wide area communication technologies for the Internet of Things. The reference architecture of LoRa communication protocol stack, *LoRaWAN*, is reported in Fig. 8.3. The standard is frequency-agnostic in the sense that it can operate in different ISM band portions depending on the specific regional rules. The key technology at the physical layer is a proprietary Chirp Spread Spectrum (CSS) modulation scheme which allows to set up bidirectional connections between the end devices and the base stations/gateways [41].

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[1] See Weightless SIG web site, press release section, http://www.weightless.org/news/type/press-releases.

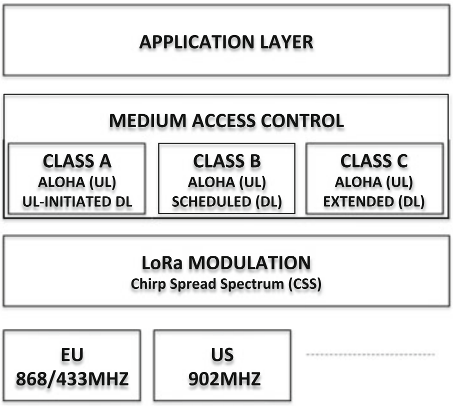

**Fig. 8.3** LoraWAN reference architecture

At the Medium Access Control layer, LoRaWAN defines three operation modes which entail different medium access control modes and different balance between uplink and downlink transmission capabilities;

- the Class A operation is the standard baseline meant for the lowest power end device requiring limited downlink communications from the base stations; devices of Class A may initiate uplink transmissions according to an ALOHA-like access protocol; conversely, downlink transmissions from the base station are allowed only in two short receiving time-windows which follow each uplink transmission. Class A devices can optionally require an acknowledgement to their uplink transmissions.
- Class B devices share the same ALOHA-like access protocol for the uplink, but they have additional receiving time windows with respect to class A devices. In Class B operation mode, the base station periodically broadcast a beacon message to synchronize the field devices so that they can schedule in time the required additional receiving time-windows. Devices of Class B can further support downlink multicast transmissions.
- Class C devices share the same ALOHA-like access protocol for the uplink, but they have almost continuous receiving time windows. Like devices of Class B, Class C devices can support multicast transmissions.

Network pilots using LoRa technology are already active in Europe[2] and US.[3]

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[2] See press release at http://www.semtech.com/Press-Releases/2015/Semtech-LoRa-based-Internet-of-Things-Wide-Area-Network-to-Deploy-with-Telecom-Operator-Orange.html.

[3] See press release at https://www.semtech.com/Press-Releases/2015/Senet-Deploys-First-Low-Power-Wide-Area-Network-in-North-America-for-IoT-Applications-Based-on-Semtech-LoRaT-RF-Platform.html.

### 8.5.4 Ingenu

*Ingenu*[4] (formerly On-Ramp) targets the application segments of smart grids/smart metering, asset tracking, usage-based insurance and critical infrastructure monitoring. The reference communication technology is based on the Random Phase Multiple Access (RPMA) protocol [35] operating in the unlicensed 2.4 GHz band. The coverage performance is similar to those of the other IoT-Dedicated cellular technologies with a receive sensitivity of −142 dBm and a maximum transmit power of 20 dBm which allows to have up to 400 square miles of coverage with a single basestation if properly placed. Capacity can be tens of thousands of devices per basestation. Ingenu is one of the founding members of the IEEE 802.15.4k standardization working group which is currently working to extend the IEEE 802.15.4 PHY and MAC layer for the support of Low Energy Critical Infrastructures (LECIM) [8].

## 8.6 Multi-tier Architectures

Differently from the cellular scenario, multi-tier architectures are characterized by a layered design in which Things are used both to sense data and to form the network infrastructure, in a multi-hop/mesh fashion. Data collected from such devices is then generally forwarded to a central collection point (gateway, concentrator), which then conveys such data to the Internet through other technologies. Multi-hop transmission is generally needed to compensate for the limited communication range achievable by the radio technologies used in such scenarios. On the one hand this is a consequence of the extremely low power consumption exhibited by such solutions, which is key for certain applications. On the other hand, the limited radio range may cause to use more devices than what is actually needed, just for ensuring connectivity. In the following, we give details on the main technologic solutions proposed so far in the field of short-range, multi-tier architectures for supporting IoT applications in Smart City scenarios. The main features of each solution are compared in Table 8.4.

### 8.6.1 Solutions Based on IEEE 802.15.4

The IEEE 802.15.4 standard, specified for wireless personal area networks, offers the fundamental lower network layers for low-cost, low-rate, and low-power communication. The standard specifies only the PHY and MAC layers of the protocol stack: at the physical layer, three unlicensed frequency bands may be used (868/915/2450 MHz). Originally, the direct sequence spread spectrum (DSSS) modulation scheme was specified, allowing a data rate of 20, 40 and 250 kbps for the three bands, respectively. The 2006 revision improved the data rates in the 868/915 bands to 100 and

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[4] http://www.ingenu.com/.

**Table 8.4** Comparison of different short-range communication standards for multi-tier IoT architectures

| Standard | Frequency bands | Max Tx rate | Max range (m) | TX power | Application |
|---|---|---|---|---|---|
| ZigBee (802.15.4) | 868/915/2450 MHz | 250 kbps | 100 | 1–100 mW | Home automation<br>Backhaul for WSN |
| WI-SUN (802.15.4g) | sub-1 GHz, 2.4 GHz | 1 Mpbs | 200 | 1–100 mW | Home automation<br>Backhaul for WSN |
| ULP (802.15.4q) | 868/915/2450 MHz | 100 kbps | 100 | 5–15 mW | Ultra low power applications |
| Wireless M-Bus | 169/433/868 MHz | 100 kbps | 300 | 1–100 mW | Metering |
| Z-Wave | 908 MHz | 100 kbps | 100 | 1–100 mW | Home automation |
| Bluetooth Low Energy (BLE) | 2450 MHz | 1 Mbps | 30 | 1–100 mW | e-Health, Sport, Multimedia |
| WiFi Low Power (802.11ah) | Sub-1 GHz | 7.8 Mbps | 1000 | 10 mW–1 W | Long range WSN<br>Backhaul for WSN |

250 kbps, respectively. Other amendments were made to the standard in the following years, all targeted to expand the available PHYs with several additions. The MAC layer employs the CSMA-CA mechanism for channel access and is responsible for maintaining the connectivity (beacons transmission and synchronization, PAN association/disassociation, etc.). The frame size is generally 127 bytes. On top of the PHY and MAC layers defined by the IEEE 802.15.4 standard, several solutions have been proposed to enable communication between smart devices, which are briefly addressed in the following.

#### 8.6.1.1 ZigBee

Zigbee [2] is probably the most known high-level communication protocol based on IEEE 802.15.4. It supports star, tree and mesh topologies, and two types of devices. The coordinator (full-function device, FFD) is responsible for maintaining the network, composed by routers and end devices (reduced-function devices, RFD). ZigBee supports both non-beacon and beacon-enabled networks. In the former type, medium access is achieved through the IEEE 802.15.4 CSMA-CA mechanism. In the latter, beacons are used to schedule the transmissions of network nodes, thus lowering their duty cycle and consequently extending their battery. At the application layer, ZigBee also includes methods for secure communication, such as key establishment and transport and frame protection.

#### 8.6.1.2 6LoWPAN

6LoWPAN (IPv6 over Low Power PAN) specifies a set of rules to apply the IP protocol to low-power devices for the Internet-of-Things. Clearly, such integration allows for easy interoperability with other types of IP-enabled devices (e.g., WiFi based) and the Internet. Mapping the IP network layer to the 802.15.4 lowest layers requires several functionalities, all provided by 6LoWPAN: packet size adaptation, header compression, address resolution and management, routing and security.

#### 8.6.1.3 802.15.4 Amendments and Other Protocols

The IEEE 802.15.4 standard has been used as starting point for several working solutions, and it is still being refined in order to support full interoperability.

Examples include WirelessHART and MiWi. The former uses the 802.15.4 PHY layer and redefines the upper layer. In particular, it is based on a TDMA protocol and allows to create self-organizing and self-healing mesh networks [20]. The latter is a trimmed-down, economical version of ZigBee, proprietary of MicroChip, which uses low data rates and very short communication distances [21].

It is also worth mentioning two amendments of the IEEE 802.15.4 protocol, namely WI-SUN and Ultra Low Power (ULP). WI-SUN is under study by the 802.15.4g Task Group, and focuses on Smart Utility Networks (SUN) with the objective to provide a standard that facilitates very large-scale process control applications. In particular, 802.15.4g includes operation in ISM bands (700 MHz–1 GHz and the 2.4 GHz band), data rates from 40 kbps to 1 Mbps and a PHY frame size up to a minimum of 1500 octets to support IP packets without fragmentation. Different multi-rate and multi-regional (MR) PHYs are specified, in order to ensure interoperability with existing systems [19]. The Ultra Low Power version (ULP, 802.15.4q Task Group) explicitly focuses on ultra low power applications, with a target peak power consumption for the PHY layer of maximum 15 mW.

### *8.6.2 Z-Wave*

Developed by the Z-Wave alliance [3], this protocol defines all layers of the protocol stack and targets mainly home automation applications. Z-Wave operates at 908 MHz and uses GFSK encoding as modulation scheme. Different data rates are available (9.6/40/100 kbps) and the communication range is comparable to 802.15.

4-based solution (tens of meters). Similarly to ZigBee, Z-Wave utilizes a mesh network architecture and provides basic routing and security functionalities. Differently from the "open" 802.15.4, Z-Wave is a proprietary system made and licensed by one single company (Sigma Designs): this is not necessarily a drawback, since the tight control on how devices should communicate may facilitate interoperability between products from different vendors.

### *8.6.3 Wireless M-Bus*

The Metering Bus (M-Bus) is a field bus specialized for transmission of metering data from gas, electricity, heat, and other meters to a data collector. The Wireless M-Bus is a radio variant of M-Bus: it can work within three bands (169/433/868 MHz) and allows the creation of star and mesh topologies with the help of a time synchronized TDMA source routing protocol. Data transmission rate can be as high as 100 kbps for a communication range up to 300 m. Many off-the-shelf commercial products based on such protocol are already available on the market with a claimed lifespan of more than 10 years with a single battery.

### *8.6.4 Bluetooth Low Energy*

Stimulated by the popularity Bluetooth recently enjoyed in the field of audio streaming, Bluetooth Low Energy (BLE, also called Bluetooth Smart) was introduced in 2010 to be suitable for M2M and IoT applications. As its name says, the main focus is on the reduction of the power consumption so that such protocol may be used in battery-powered devices for a long period of time. BLE uses GFSK modulation with rate data rate of 1 Mbps in the 2.4 GHz ISM band. 40 different channels are available, divided in 3 advertising channels (carefully chosen in order to minimize interference with WiFi) and 37 data channels. The BLE protocol stack is tailored to easy integration with IPv6, supporting packet fragmentation and providing basic security primitives. The biggest drawback of BLE is that it supports only star topology (not mesh networks), therefore limiting its application to real-life scenarios. Recently, the Bluetooth SIG launched a study group to define an industry standard BLE mesh protocol. This should close the gap between BLE and mesh-capable protocols such as IEEE 802.15.4 and Z-Wave. [18]

### *8.6.5 WiFi Low Power*

IEEE 802.11ah operates in the sub 1 GHz band (900 MHz) and provides extended range WiFi networks with an eye on reducing power consumption. Therefore, it is particularly tailored to IoT and M2M applications. At the PHY layer, 802.11ah uses OFDM-based waveforms and supports BPSK, QPSK and 16 to 256-QAM modulations. This allows to have data rates from 150 kbps to nearly 8 Mbps. The MAC layer is designed to maximize the number of connected devices (up to 8191) and includes power saving modes to reduce the energy consumption by deactivating the radio module during non-traffic periods. The protocol also includes optimizations for small data transmission and long sleeping periods [12, 32]. Due to their large coverage, IEEE 802.11ah networks may be also used as backhaul, acting as an intermediate step between device (e.g., 802.15.4 nodes) and data collectors.

### 8.6.6 Gateway-to-Internet

As mentioned before, multi-tier architectures generally deliver data from Things (sensing domain) to a central collection point which bridges such data to the Internet (network domain). Such gateway should have specific features, such as support for multiple sensing domain protocols (e.g., ZigBee, Z-Wave, BLE, etc.), protocol translation and conversion and easy manageability. Connection to the Internet may be provided using different technologies, namely (i) classic access through an ISP, (ii) access through cellular architecture, or (iii) access through Power Line Communication (PLC).

### 8.6.7 Multi-tier Network Testbeds and Realizations

In parallel with the development and standardization of the different IoT communication technologies mentioned in the previous sections, in the last few years there has been an increasing interest for the realization of demonstrators and testbeds of IoT solutions for the Smart City scenario.

Probably, the most interesting example is given by the *SmartSantander* project [39], which propose a unique city scale experimental research facility. The testbed, deployed in the city of Santander, is composed of around 3000 IEEE 802.15.4-compliant devices and 200 devices (mostly mobile) with GPRS communication capabilities. Such devices are used to test different use cases developed within the project, including static and mobile environmental monitoring, parking management, traffic monitoring and irrigation management. These applications share a three-tiered architecture in which 802.15.4-compliant nodes transmit the sensed information to gateways equipped with several communication interfaces (IEEE 802.15.4, WiFi, GPRS, Bluetooth and Ethernet). Such gateways have either a local database accessible remotely or transmit all the data to a central server using Internet connection. Such a testbed has been developed not only for demonstrating the benefits of IoT solutions in a smart city scenario, but also for giving researchers the possibility of testing experiments (e.g., routing protocols) with the deployed nodes. The project envisions the deployment of a total of 20,000 sensors in Santander, Belgrade, Guildford and Lbeck, exploiting a large variety of technologies.

The *Padova Smart City* project [47] uses IEEE 802.15.4-compliant nodes placed on streetlight poles and connected to the network of the city municipality by means of a gateway. Each node is equipped with different sensors, including photometer, temperature, humidity, and benzene sensors for monitoring the environment. Data is delivered to the gateway using 6LoWPAN and the RPL routing protocol. Several considerations and inferences were possible from the analysis of the collected data.

The *Smart Berlin Testbed* [30] is composed by nearly 300 IEEE 802.11-compliant nodes organized in a mesh topology and support WSNs operated by 6LoWPAN. The testbed is remotely manageable and has been used to perform white space detection in the area of deployment.

Finally, an interesting example is given by the work in [31], where a city scale mobile sensing infrastructure that relies on bicycles is proposed. The *NITOS BikesNet* architecture consists of fixed gateways (WiFi access points and custom-made ZigBee gateways). Bikes in the city are equipped with both WiFI and Zigbee interfaces and several sensors (GPS, temperature humidity and light-intensity). All data is stored locally on the bike memory and delivered to the gateways when in range. The testbed has been implemented in the city of Volos (Greece) and used to populate a database of the available WiFi networks in the city.

## 8.7 Discussion and Concluding Remarks

Smart Cities are complex environments with diverse applications, stakeholders, and governing bodies which lead to the coexistence of different business propositions and value chains for different services. Such complexity and heterogeneity is reflected also in the technological offer to support wide are coverage and connectivity in urban environment, which is vast and diverse. In the following, we summarize the high-level features and discuss the main challenges of the three architectural alternatives explained in the previous chapters:

- **Cellular Mobile Networks** are particularly fit for Smart City applications requiring high coverage and flexibility in terms of supported data rate. Moreover, cellular architectures can leverage the embedded support for worldwide mobility and security. On the other hand, the integration of MTC into cellular architectures opens up new technical challenges including the differentiation of traffic at the RAN and CR and the management of massive access loads in the RAN and the CN. In terms of nontechnical challenges, the standardization activities to support massive MTC in mobile cellular networks are relatively "young", due to the unavoidable inertia the mobile operators have in enhancing their complex network architectures and technologies to accommodate tiny M2M traffic. Such inertia has opened up business opportunities for different technological solutions to support M2M communication which have quickly spread out in the last few year and will be described in the next section.

- **IoT-dedicated Cellular Network** operators have a clear time advantage over cellular operators in offering IoT-specialized connectivity solutions. Cellular IoT architectures are in general characterized by lower costs, both in the network equipment and in the network devices, compared to classical cellular IoT architectures, which, at the moment, allows them to be extremely aggressive in their business models. On the other side, IoT-dedicated architectures generally target low-rate applications with highly customized network deployment with scarce flexibility. Moreover, IoT-dedicated architectures are often asymmetric in the supported channel rate at the air interface, with limited downlink channels.
- **Multi-tier Architectures** are particularly tailored to those applications characterized by limited number of nodes and low communication range. Such requirements are typically encountered in indoor scenarios like home automation or industrial control/metering, where multi-tier architectures are generally preferred to cellular-based solutions. On the one hand, multi-tier architectures allow for very flexible setups, easily customizable based on the customer's needs (in terms of transmission rate, delay and power consumption). On the other hand, the low transmission range sometimes constitutes a drawback, and more devices than needed have to be installed just to provide the required communication coverage. The standards presented in the previous sections all constitute a possible solution for implementing personal area networks (PAN), which form the basis of IoT applications for Smart Buildings and Smart Homes. Solutions based on IEEE 802.15.4 (e.g., ZigBee) and Z-Wave, which were specifically designed to overcome the power and range limitations of traditional WiFi and Bluetooth solutions, are still struggling to find their way on the market and to become a widely used standard. At the time of writing, no clear winner is emerging in such a battle of standards. On the one hand Z-Wave, being controlled by a single company, allows for easy interoperability between different products and it is thus very attractive to manufacturers. Also, working in the 900 MHz band allows to reduce the number of collisions and transmission retries compared to the 2.4 GHz band and that may translate in lower power consumption. On the other hand, the IEEE 802.15.4 open-standard has clear advantages (e.g., global standardization, products can be made by a variety of manufactures, etc.) but still lacks full interoperability, although several efforts are being made in this direction (e.g., ZigBee 3.0, will provide seamless interoperability among products from different manufacturers). Between the two dogs striving for the bone, WiFi and Bluetooth are trying to close the gap with their low-power versions. Interestingly, the solutions proposed by mobile giants such as Samsung, Apple and Google do not give any hint on the final outcome of such battle: Samsung's Artik chip supports WiFi, Bluetooth Low Energy, Zigbee but not Z-Wave; Google's Thread standard is based on 802.15.4 and 6LoWPAN, while Apple's HomeKit proposes a completely different solution based on either WiFi or Bluetooth Low Energy, so that all smart devices can be controlled directly from a smartphone without the need of installing a hub or an additional radio interface. In the long run, it is unclear which standard will emerge as a clear winner, and it is possible that they will coexist for a long period, making product developers continually reevaluate which wireless standard is the best for their needs.

As it emerges from our previous discussion, it is likely that diverse communication technologies and architectures for IoT in Smart Cities will forcedly coexist in the same environment serving different subsets of applications. In such ecosystem, besides the challenges related to the improvement of the specific communication technologies which have been already discussed in the previous sections, the additional challenge will be to exploit such coexistence to make smart cities even smarter. In this view, three factors will likely play a key role:

- the definition of **unifying architectures** to orchestrate the interplay among different communication technologies through the definition of proper abstraction layers that can be readily embedded within various hardware and software, and relied upon to connect the myriad of devices in the field with Smart Cities. Efforts in this respect are already in place in the research community and in standardization bodies [37, 43];
- the **interconnectedness** between applications and services operated by diverse stakeholders through different communication technologies/architectures; related to the previous item, data coming from diverse Smart City applications and services should be exposed and made available to foster the creation of novel composed value added services through proper **programming interfaces** [34];
- the availability of **easy-to-use management platforms** to build-up novel applications for Smart Cities [49]; the final users of smart city applications are heterogeneous and diverse (citizens, group of citizens, governing bodies, law enforcement bodies) which call for different types of interaction with the application/service itself; as an example, citizen-oriented applications may require simple but effective data visualization plug-ins, whereas, services targeting urban efficiency and sustainability may require, besides data visualization, advanced data analytics and business intelligence tools. To this extent, the design and availability of management platforms for Smart Cities will be central.

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