Long-Range Communications in Unlicensed Bands: The Rising Stars in the IoT and Smart City Scenarios

Marco Centenaro, Lorenzo Vangelista, Andrea Zanella, and Michele Zorzi

Abstract

Connectivity is probably the most basic building block of the IoT paradigm. Up to now, the two main approaches to provide data access to *things* have been based on either multihop mesh networks using short-range communication technologies in the unlicensed spectrum, or long-range legacy cellular technologies, mainly 2G/GSM/GPRS, operating in the corresponding licensed frequency bands. Recently, these reference models have been challenged by a new type of wireless connectivity, characterized by low-rate, long-range transmission technologies in the unlicensed sub-gigahertz frequency bands, used to realize access networks with star topology referred to as low-power WANs (LPWANs). In this article, we introduce this new approach to provide connectivity in the IoT scenario, discussing its advantages over the established paradigms in terms of efficiency, effectiveness, and architectural design, particularly for typical smart city applications.

Introduction

The Internet of Things (IoT) paradigm refers to a *network* of interconnected *things*, that is, devices such as sensors and/or actuators, equipped with a telecommunication interface, and processing and storage units. This communication paradigm should enable seamless integration of potentially any object with the Internet, thus allowing new forms of interactions between human beings and devices, or directly between devices according to what is commonly referred to as the machine-to-machine (M2M) communication paradigm [1].

The development of the IoT is an extremely challenging topic, and the debate on how to put it into practice is still open. The discussion involves all layers of the protocol stack, from physical transmission up to data representation and service composition [2]. However, the whole IoT system rests on the wireless technologies that are used to provide data access to the end devices.

For many years, multihop short-range transmission technologies, such as ZigBee™ and Bluetooth, have been considered a viable way to implement IoT services [3–5]. Although these standards are characterized by very low power consumption, which is a fundamental requirement for many IoT devices, their limited coverage is a major obstacle, especially when the application scenario involves services that require urban-wide coverage, as in typical smart city applications [5]. The experimentation of some initial smart city services has indeed revealed the limits of the multihop short-range paradigm for this type of IoT applications, stressing the need for an access technology able to allow a *place-&-play* type of connectivity, making it possible to connect any device to the IoT by simply placing it in the desired location and switching it on [6].

From this perspective, wireless cellular networks may play a fundamental role in the diffusion of IoT, since they are able to provide ubiquitous and transparent coverage [1, 7]. In particular, the Third Generation Partnership Project (3GPP), which is the standardization body for the most important cellular technologies, is attempting to revamp second generation/Global System for Mobile Communications (2G/GSM) to support IoT traffic, implementing the so-called cellular IoT (CIoT) architecture [8]. On the other side, the latest cellular network standards, such as Universal Mobile Telecommunications Service (UMTS) and Long Term Evolution (LTE), were not designed to supply machine-type services to a massive number of devices. In fact, unlike traditional broadband services, IoT communication is expected to generate, in most cases, sporadic transmission of short packets. At the same time, the potentially huge number of IoT devices asking for connectivity through a single base station (BS) would raise new issues related to signaling and control traffic, which may become the bottleneck of the system [6]. All these aspects make current cellular network technologies unsuitable to support the envisioned IoT scenarios, while, on the other hand,

The authors are with the Department of Information Engineering of the University of Padova. Lorenzo Vangelista and Michele Zorzi are also with Patavina Technologies s.r.l.

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a number of research challenges still need to be addressed before the upcoming 5G cellular networks may natively support IoT services.

A promising alternative solution, standing between short-range multihop technologies operating in the unlicensed industrial, scientific, and medical (ISM) frequency bands, and long-range cellular-based solutions using licensed broadband cellular standards, is provided by so-called low-power wide area networks (LPWANs).

These kinds of networks exploit sub-gigahertz unlicensed frequency bands, and are characterized by long-range radio links and star topologies. The end devices are directly connected to a single collector node, generally referred to as a *gateway*, which also provides the bridging to the IP world. The architecture of these networks is designed to supply wide area coverage and also ensure connectivity to nodes that are deployed in very harsh environments.

The goal of this article is to give an introductory overview of the LPWAN paradigm and its main technological interpretations. We discuss the advantages provided by this new type of connectivity with respect to the more traditional solutions operating in the unlicensed spectrum, especially for applications related to smart cities. To substantiate our arguments, we refer to some preliminary experiments and deployments of IoT networks based on LoRa™, one of the LPWAN solutions available on the market today.

The rest of the article is organized as follows. Current wireless technologies and service platforms for IoT connectivity are reviewed. The potential of LPWANs is discussed, while we describe the commercial LPWAN products available today, focusing in greater detail on LoRa, with characteristics that make it a good representative of the LPWAN family, while its open specifications make it possible to access some details of its most interesting and specific mechanisms. We discuss the experience gained with some experimental deployments of a LoRa network. Conclusions and final remarks are given.

A Quick Overview of Current IoT Communication Standards

Although the IoT paradigm does not set any constraint on the type of technology used to connect the end devices to the Internet, it is a fact that wireless communication is the only feasible solution for many IoT applications and services. As mentioned, the current practice considers either cellular-based or multihop short-range technologies. In the latter case, the connected *things* usually run dedicated protocol stacks, suitably designed to cope with the constraints of the end devices. Furthermore, at least one such device is required to be connected to the IP network, acting as a *gateway* for the other nodes. The architecture is hence distributed, with many "islands" (sub-nets) that may operate according to different connectivity protocols, and are connected to the IP network via gateways. The applications and services are deployed on top of this connectivity level, according to a *distributed service* layer. The applications may run either locally, that is, in the sub-net, or, more and more often (as typical in the smart city scenario), using cloud computing services.

At this level we can find the *IoT platforms* that act as a unifying framework, enabling the service creation and delivery, as well as the operation, administration, and maintenance of the things and the gateways. Nowadays, the most important de facto standards in the IoT arena are the following:

1. Extremely short-range systems, such as near field communications (NFC)-enabled devices
2. Short-range passive and active radio frequency identification (RFID) systems
3. Systems based on the family of IEEE 802.15.4 standards like ZigBee, 6LoWPAN, and Thread-based systems
4. Bluetooth-based systems, including Bluetooth Low Energy (BLE);
5. Proprietary systems, including Z-Wave™, CSRMesh™ (i.e., the Bluetooth mesh by Cambridge Silicon Radio, a company now owned by Qualcomm), and EnOcean™
6. Systems mainly based on IEEE 802.11/Wi-Fi™, such as those defined by the AllSeen Alliance[1] specifications, which explicitly include the gateways, or the Open Connectivity Foundation.[2] The AllSeen Alliance is dedicated to the widespread adoption of products, systems, and services that support the IoT with AllJoyn®, a universal development framework [9]. The Open Connectivity Foundation has a similar aim, but different partners [10].

The vast majority of the connected things at the moment use IEEE 802.15.4-based systems, in particular ZigBee. The most prominent features of these networks are that they operate mainly in the 2.4 GHz and optionally in the 868/915 MHz unlicensed frequency bands, and that the network level connecting these *nodes*[3] uses a mesh topology. The distances between nodes in these kinds of systems range from a few meters up to roughly 100 meters, depending on the surrounding environment (presence of walls, obstacles, etc.).

To better appreciate the comparison with LPWAN technologies, it is worth highlighting the main characteristics of these IoT technologies.

Mesh networking. Multihop communication is necessary to extend the network coverage beyond the limited reach of the low-power transmission technology used. Furthermore, the mesh architecture can provide resilience to the failure of some nodes. On the other hand, the maintenance of the mesh network requires non-negligible control traffic, and multihop routing generally yields long communication delays, and unequal and unpredictable energy consumption among the devices.

Short coverage range–high data rate. The link-level technologies used in these systems tend to favor the data rate rather than the sensitivity, that is, in order to recover from the network delays due to mesh networking, these networks have a relatively high raw link bit rate (e.g., 250 kb/s), but they are not robust enough to penetrate building walls and other obstacles (even in the 868/915 MHz band). In other words, in the trade-off between rate and sensitivity, rate is usually preferred.

Although the IoT paradigm does not set any constraint on the type of technology used to connect the end devices to the Internet, it is a fact that wireless communication is the only feasible solution for many IoT applications and services.

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[1] https://www.allseenalliance.org

[2] http://www.openconnectivity.org

[3] *Node* is a term that is frequently used to indicate a connected thing with emphasis on the communication part.

The combination of the simple but effective topology of cellular systems with a much lighter management plane makes the LPWAN approach particularly suitable to support services with relatively low average revenue per user, such as those envisioned in smart city scenarios.

A New Paradigm: Long-Range IoT Communications in Unlicensed Bands

As a counterpart of the unlicensed short-range technologies for the IoT mentioned in the previous section, we turn our attention to the emerging paradigm of LPWAN.

Most LPWANs operate in the unlicensed ISM bands centered at 2.4 GHz, 868/915 MHz, 433 MHz, and 169 MHz, depending on the region of operation.[4] The radio emitters operating in these frequency bands are commonly referred to as "short-range devices," a rather generic term that suggests the idea of coverage ranges of few meters, which was indeed the case for the previous ISM wireless systems. Nonetheless, ERC Recommendation 70-03 specifies that "*The term Short Range Device (SRD) is intended to cover the radio transmitters which provide either uni-directional or bi-directional communication which have low capability of causing interference to other radio equipment*." Therefore, there is no explicit mention of the actual coverage range of such technologies, but only of the interference caused.

LPWAN solutions are indeed examples of short-range devices with cellular-like coverage ranges, on the order of 10–15 km in rural areas and 2–5 km in urban areas. This is possible thanks to a radically new physical layer design, aimed at very high receiver sensitivity. For example, while the nominal sensitivity of ZigBee and Bluetooth receivers is about –125 dBm and –90 dBm, respectively, the typical sensitivity of a LPWAN receiver is around –150 dBm.

The downside of these long-range connections is the low data rate, which usually ranges from a few hundred to a few thousand bits per second, significantly lower than the bit rates supported by the actual "short-range" technologies (e.g., 250 kb/s in ZigBee and 1–2 Mb/s in Bluetooth). However, because of the signaling overhead and the multihop packet forwarding method, the actual flow-level throughput provided by such short-range technologies may actually be significantly lower than the nominal link-level bit rate. For example, in [11] it is reported that a 6LoWPAN network based on a mesh topology using an IEEE 802.15.4 physical layer, with a nominal link-level bit rate of 250 kb/s, reaches a unicast throughput of about 0.8 kb/s and a multicast throughput lower than 1.5 kb/s.

While such low bit rates are clearly unsatisfactory for most common data-hungry network applications, many smart city and IoT services are expected to generate a completely different pattern of traffic, characterized by sporadic and intermittent transmissions of very small packets, typically on the order of a few hundred bytes, for monitoring and metering applications, remote switching/control of equipment, and so on.[5] Furthermore, many of these applications are rather tolerant to delays and packet losses, and hence are suitable for the connectivity service provided by LPWANs.

Another important characteristic of LPWANs is that the things, that is, the end devices, are connected directly to one (or more) gateway(s) with a single-hop link, very similar to a classic cellular network topology. This greatly simplifies the coverage of large areas, even nationwide, by reusing the existing infrastructure of the cellular networks. For example, LoRa systems are being deployed by telecommunication operators like Orange and Bouygues Telecom in France, Swisscom in Switzerland, and KPN in the Netherlands, while SIGFOX™ has already deployed a nationwide access network for M2M and IoT devices in many central European countries, from Portugal to France. Furthermore, the star topology of LPWANs makes it possible to have greater control of the connection latency, thus potentially enabling the support of interactive applications that require predictable response times, including the remote control of streetlights in a large city, the operation of barriers to limited-access streets, intelligent control of traffic lights, and so on.

Besides the access network, the similarity between LPWANs and legacy cellular systems further extends to the bridging of the technology-specific wireless access to the IP-based packet switching core network. Indeed, the LPWAN gateways play a similar role to the gateway GPRS support node in general packet radio service (GPRS)/UMTS networks, or the Evolved Packet Core in LTE, acting as the point of access for the end devices to the IP-based core network and forwarding the data generated by things to a logic controller, usually called a *network server*.

Therefore, LPWANs inherit the basic aspects of the legacy cellular systems architecture, but stripped of its most advanced features, such as the management of user mobility and resource scheduling. The combination of the simple but effective topology of cellular systems with a much lighter management plane makes the LPWAN approach particularly suitable to support services with relatively low average revenue per user, such as those envisioned in smart city scenarios.

A clear evidence of the appeal of LPWAN technologies in the IoT arena is given by the ever increasing number of products and applications that rely on these technologies for communication. For example, Sensing Labs[6] produces sensors for telemetry and metering to enable smart building applications. Enevo[7] uses wireless devices to monitor the fill level of waste containers. Sayme[8] provides a street lighting remote management system that increases energy efficiency and reduces maintenance expenses. Turbo Technologies[9] designed a wireless geomagnetic detector for smart parking purposes. Elmar[10] is implementing a smart grid network across the entire island of Aruba. Finally, Mueller Systems[11] developed a communication network that fully automates the management of water resources.

A Review of Long-Range IoT Communications Systems in Unlicensed Bands

In this section we quickly overview three of the most prominent technologies for LPWANs: SIGFOX, Ingenu™, and LoRa. In particular, we describe in greater detail the LoRa technology, which is gaining more and more momentum, and with specifications that are publicly available, thus making it possible to appreciate some of the technical choices that characterize LPWAN solutions. In Table 1 a comparison between these LPWAN radio technologies can be found.

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[4] A further set of bands that is suitable for the implementation of LPWANs is the TV white space (TVWS) spectrum. These frequencies are made available for unlicensed users when the spectrum in not being used by licensed services. The most prominent LPWAN technology that jointly exploits ISM bands and TVWS bands is Weightless™ (www.weightless.org).

[5] See, for example, 3GPP Technical Report 45.820, November 2015.

[6] http://sensing-labs.com

[7] http://www.enevo.com

[8] http://www.sayme.es

[9] http://www.turboes.com/english/

[10] https://www.elmar.aw

[11] http://www.muellersystems.com

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™Ingenu is a trademark of On-Ramp Wireless.

SIGFOX

SIGFOX, the first LPWAN technology proposed in the IoT market, was founded in 2009 and has been growing very fast since then.[12] The SIGFOX physical layer employs ultra narrowband (UNB) wireless modulation, while the network layer protocols are the "secret sauce" of the SIGFOX network and, as such, there is basically no publicly available documentation. Indeed, the SIGFOX business model is that of an operator for IoT services, which hence does not need to open the specifications of its inner modules.

The first releases of the technology only supported unidirectional uplink communication, that is, from the device toward the aggregator; however, bidirectional communication is now supported. SIGFOX claims that each gateway can handle up to a million connected objects, with a coverage area of 30–50 km in rural areas and 3–10 km in urban areas.

Regarding the security aspects of SIGFOX networks, very few comments can be made as the SIGFOX protocols are proprietary and therefore closed. However, as a general approach, SIGFOX focuses on the network security itself, leaving the payload security mechanisms to the end users at both the transmitting side, that is, the SIGFOX node, and the receiving side, that is, the applications linked to the SIGFOX cloud via application programming interfaces (APIs) or callback functions.

Ingenu

An emerging star in the landscape of LPWANs is Ingenu from On-Ramp Wireless, a company headquartered in San Diego, California.[13] On-Ramp Wireless has been pioneering the 802.15.4k standard [12]. The company developed and owns the rights to the patented technology called Random Phase Multiple Access (RPMA®) [13], which is deployed in different networks. Conversely to the other LPWAN solutions, this technology works in the 2.4 GHz band but, thanks to a robust physical layer design, can still operate over long-range wireless links and under the most challenging RF environments.

From a security point of view, RPMA technology offers six state-of-the-art guarantees:

- Mutual authentication
- Message integrity and replay protection
- Message confidentiality
- Device anonymity
- Authentic firmware upgrades
- Secure multicasts

The LoRa System

LoRa is a new physical layer LPWAN solution, designed and patented by Semtech Corporation, which also manufactures the chipsets.[14]

LoRa PHY: The PHY is a derivative of chirp spread spectrum (CSS) [14], which has been innovated in order to ensure the phase continuity between different chirp symbols in the preamble part of the physical layer packet, thus enabling simpler and more accurate timing and frequency synchronization, without requiring expensive components to generate a stable local clock in the LoRa node.

	SIGFOX	Ingenu	LoRa
Coverage range (km)	Rural: 30–50 Urban: 3–10	≈ 15	Rural: 10–15 Urban: 3–5
Frequency bands (MHz)	868 or 902	2400	Various, sub-gigahertz
ISM band	✓	✓	✓
Bidirectional link	✓	×	✓
Data rate (kb/s)	0.1	0.01–8	0.3–37.5
Nodes per gateway	≈ 10^6	≈ 10^4	≈ 10^4

Table 1. Comparison between LPWAN radio technologies.

The technology employs a spreading technique, according to which a symbol is encoded in a *longer sequence of bits*, thus reducing the signal-to-noise-plus-interference ratio required at the receiver for correct reception, without changing the frequency bandwidth of the wireless signal. The length of the spreading code is equal to 2^{SF}, where SF is a tunable parameter, called *spreading factor* in the LoRa jargon, that can be varied from 7 up to 12, thus making it possible to provide variable data rates, giving the possibility to trade throughput for coverage range, link robustness, or energy consumption [15].

The system works mainly in the 902–928 MHz band in the United States and in the 863–870 MHz band in Europe, but can also operate in the lower ISM bands at 433 MHz and 169 MHz. According to the regulation in [16], the radio emitters are required to adopt duty cycled transmission (1 or 0.1 percent, depending on the sub-band), or the so-called listen-before-talk (LBT) adaptive frequency agility (AFA) technique, a sort of carrier sense mechanism used to prevent severe interference among devices operating in the same band. LoRa (as well as SIGFOX) uses the duty cycled transmission option only [17], which limits the rate at which the end device can actually generate messages. However, by supporting multiple channels, LoRa makes it possible for an end node to engage in longer data exchange procedures by changing carrier frequency while respecting the duty cycle limit in each channel. Furthermore, channels with carrier frequencies from 869.4 to 869.650 MHz fall in band g3.1 of Table 1 of the ERC Recommendation 70-03, for which a 10 percent duty cycled transmission and a much higher transmit power (27 dBm vs. the standard 14 dBm) are allowed. Therefore, this channel can be exploited for communications of longer messages over larger distances.

LoRaWAN™ : While the PHY layer of LoRa is proprietary, the rest of the protocol stack, known as LoRaWAN, is kept open, and its development is carried out by the LoRa Alliance,[15] led by IBM, Actility, Semtech, and Microchip.

As exemplified in Fig. 1, the LoRa network is typically laid out in a *star-of-stars* topology, where the end devices are connected via a single-hop LoRa link to one or many gateways that, in turn, are connected to a common network server (NetServer) via standard IP protocols.

[12] http://www.sigfox.com

[13] http://www.onrampwireless.com

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[14] F. Sforza, "Communications system," Mar. 2013, US Patent 8,406,275.

™LoRaWAN is a trademark of Semtech Corporation.

[15] https://www.lora-alliance.org/

The NetServer is hence in charge of filtering duplicate and unwanted packets, and of replying to the end devices by choosing one of the in-range gateways, according to some criterion. The gateways are thus totally transparent to the end devices, which are logically connected directly to the NetServer.

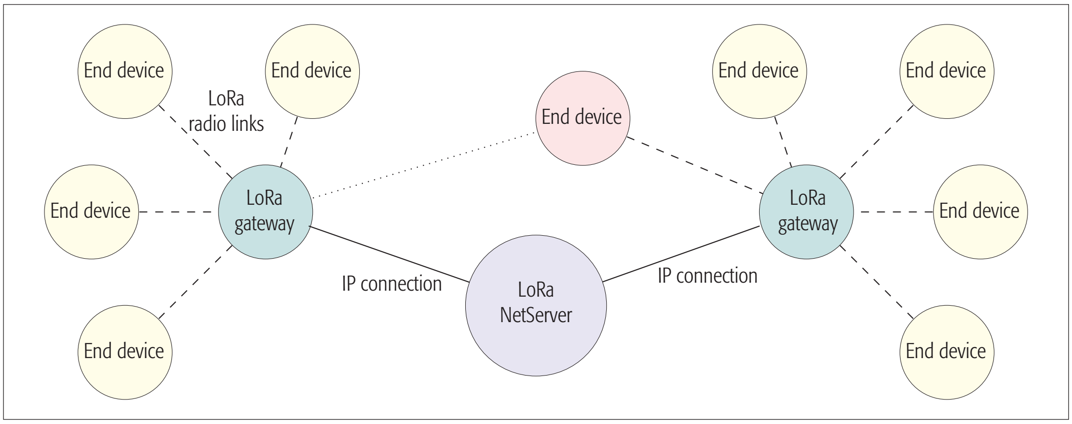

Figure 1. LoRa system architecture.

The gateways relay messages between the end devices and the NetServer according to the protocol architecture represented in Fig. 2. Unlike in standard cellular network systems, however, the end devices are not required to associate with a certain gateway to get access to the network, but only to the NetServer. The gateways act as a sort of relay/bridge and simply forward to their associated NetServer all successfully decoded messages sent by any end device, after adding some information regarding the quality of the reception. The NetServer is hence in charge of filtering duplicate and unwanted packets, and of replying to the end devices by choosing one of the in-range gateways, according to some criterion (e.g., best radio connectivity). The gateways are thus totally transparent to the end devices, which are logically connected directly to the NetServer. Note that current full-fledged LoRa gateways allow the parallel processing of up to nine LoRa channels, where a channel is identified by a specific sub-band and spreading factor.

This access mode greatly simplifies the management of the network access for the end nodes, moving all the complexity to the NetServer. Furthermore, the end nodes can freely move across cells served by different gateways without generating any additional signaling traffic in the access network or the core network. Finally, we observe that increasing the number of gateways that serve a certain end device will increase the reliability of its connection to the NetServer, which may be interesting for critical applications.

LoRa Device Classes: A distinguishing feature of the LoRa network is that it envisages three classes of end devices, *Class A* (for *All*), *Class B* (for *Beacon*), and *Class C* (for *Continuously listening*), each associated with a different operating mode [17].

Class A defines the default functional mode of LoRa networks, and must be mandatorily supported by all LoRa devices. In a Class A network, transmissions are always initiated by the end devices in a totally asynchronous manner. After each uplink transmission, the end device will open (at least) two reception windows, waiting for any command or data packet returned by the NetServer. The second window is opened on a different sub-band (previously agreed on with the NetServer) in order to increase the resilience against channel fluctuations. Class A networks are mainly intended for monitoring applications, where the data produced by the end devices have to be collected by a control station.

Class B has been introduced to decouple uplink and downlink transmissions. Class B end devices, indeed, synchronize with the NetServer by means of beacon packets, which are broadcast by Class B gateways and can hence receive downlink data or command packets in specific time windows, irrespective of the uplink traffic. Therefore, Class B is intended for end devices that need to receive commands from a remote controller (e.g., switches or actuators).

Finally, Class C is defined for end devices without (strict) energy constraints (e.g., connected to the power grid), which can hence keep the receive window always open.

LoRa MAC: The medium access control (MAC) layer, according to the LoRaWAN specifications [17], is basically an ALOHA protocol controlled primarily by the LoRa NetServer. A description of the protocol is beyond the scope of this article and can be found in [17]. Overall, the LoRa MAC has been designed attempting to mimic as much as possible the interface of the IEEE 802.15.4 MAC toward the higher layers. The objective is to simplify the accommodation, on top of the LoRa MAC, of the major protocols now running on top of the IEEE 802.15.4 MAC, such as 6LoWPAN and Constrained Application Protocol (CoAP). A clear analogy is the *authentication* mechanism, which is taken directly from the IEEE 802.15.4 standard using the 4-octet message integrity code.

LoRa IP Connectivity: LoRaWAN employs the IEEE 64-bit extended unique identifier (EUI) to automatically associate IPv6 addresses with LoRa nodes. Therefore, IPv6/6LoWPAN protocols can be deployed on LoRaWAN networks, thus enabling transparent interoperability with the IP-based world.

Security in LoRa: Security aspects are taken into account in the LoRaWAN specifications as well [17]. Several layers of encryption are employed, using:
- A unique network key to ensure security at the network layer
- A unique application key to ensure end-to-end security at the application layer, and finally
- A device-specific key to secure the joining of a node to the network.

Some Experimental Results Using a LoRa Network

In this section, we corroborate the arguments of the previous sections by reporting some observations based on some initial deployments of LoRa networks.

A LoRa Deployment Test

A LoRa private network has been installed by Patavina Technologies s.r.l. in a large and tall building (19 floors) in Northern Italy for a proof of concept of the capabilities of the LoRa network. The objective is to monitor and control the temperature and humidity of different rooms, with the aim of reducing the costs related to heating, ventilation, and air conditioning. To this end, different wireless and wired communication technologies (including powerline communication) had been tried, but these solutions were mostly unsatisfactory, requiring the installation of repeaters and gateways on basically every floor to guarantee mesh connectivity and access to the IP backbone. Instead, the LoRa technology has made it possible to provide the service by installing a single gateway on the ninth floor and placing 32 nodes all over the building, at least one per floor. The installation included the integration of the NetServer with a monitoring application and with the databases already in use. At the time of writing, the installation has been flawlessly running for a year and is being considered as the preferred technology for the actual implementation of the energy saving program in many other buildings.

We want to remark that the LoRa network connectivity has been put under strain by placing nodes in elevators and other places known to be challenging for radio connectivity. All the stress tests have been passed successfully. The envisioned next step is to install a gateway on an elevated site to serve multiple buildings in the neighborhood.

This proof of concept is particularly relevant as it provides, on one hand, interesting insights on how pertinent and practical the LPWAN paradigm is for a smart city scenario and, on the other hand, some intuition from the economic point of view. Indeed, although extremely limited in its extent, the positive experience gained in the proof-of-concept installation of the LoRa system in a building bodes well for the extension of the service to other public and private buildings, at the same time realizing an infrastructure for other smart city services. According to Analysis Mason 2014 data, the number of LPWAN smart building connections is projected to be 0.8 billion by 2023 [18], and, according to the McKinsey Global Institute analysis, the potential economic impact of IoT in 2025 for homes and cities is between \$1.1 and \$2.0 trillion [19]. Thus, LPWAN solutions appear to have both the technical and commercial capabilities to become the game changer in the smart city scenario.

LoRa Coverage Analysis

One of the most debated aspects of LPWAN is the actual coverage range. This is crucial for a correct estimation of the costs for citywide coverage, which clearly have an important impact on the capital expenditure of the service providers.

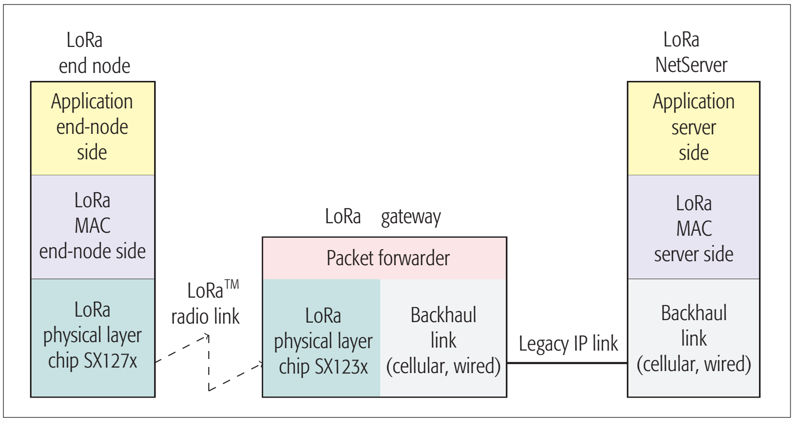

Figure 2. LoRa protocol architecture.

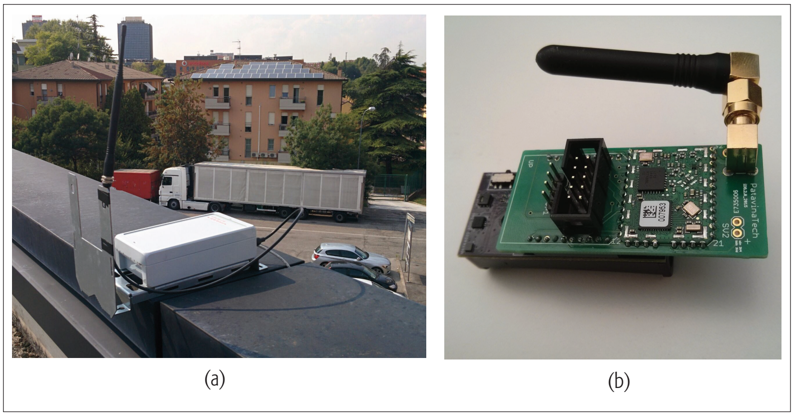

Figure 3. Experimental setup to assess LoRa coverage: a) the gateway, a Kerlink LoRa IoT station model 0X80400AC (www.kerlink.fr); b) a Patavina Technologies node mounting an IMST iM880A-L LoRa module.

To gain insight in this respect, we carried out a coverage experimental test of LoRa networks in the city of Padova, Italy. The deployment area consists of an urban environment, which resembles a typical commercial area of a big Italian city, crossed by a busy six-lane two-way street, with office buildings and shopping malls (up to 5–6 floors) on both sides, and intersections with secondary roads regulated by traffic lights and roundabouts. The aim of the experiment was to assess the worst case coverage of the technology and have a conservative estimate of the number of gateways required to cover the whole city. To this end, we placed a gateway with no antenna gain at the the top of a two storey building, without antenna elevation, in an area where taller buildings are present.

Figure 3 shows the experimental setup, while Fig. 4 shows the results of the test. It can be seen that in such harsh propagation conditions, the LoRa technology was able to cover a cell of about 2 km radius. However, the connection at the cell edge is guaranteed only when using the lowest bit rate (i.e., the longest spreading sequence, which provides maximum robustness), with low margin for possible interference or link budget changes. For this reason, we assumed a nominal coverage range of 1.2 km, a value that ensures a reasonable margin (about 14 dB) to interference and link budget variations due, for example, to fading phenomena.

Using this parameter, we attempted a rough coverage planning for the city of Padova, which extends over an area of about 100 km^2. The resulting plan is shown in Fig. 5, from which we observe that with the considered conservative coverage range estimate, coverage of the entire municipality can be achieved with a total of 30 gateways, which is less than half the number of sites deployed by one of the major cellular operators in Italy to provide mobile cellular access over the same area.

Finally, we observe that Padova accounts for about 200,000 inhabitants. Considering 30 gateways to cover the city, we get about 7000 inhabitants per gateway. The current LoRa gateway technology claims the capability of serving 15,000 nodes per gateway, which accounts for about 2 things per person. Considering that the next generation of gateways is expected to triple the capacity (by using multidirectional antennas), in the long term we can expect that basic coverage of the city may grant up to 6–7 things per person on average, which seems to be adequate for most smart city applications. Any further increase in the traffic demand can be addressed by installing additional gateways, a solution similar to densification in cellular networks.

Figure 4. LoRa system single-cell coverage in Padova, Italy. Colored dots represent some of the measurement spots, which are associated with the minimum LoRa SF required for robust communication. The dash-dotted circle and the dashed circle enclose the coverage edge area, where communication is only possible at the minimum transmit rate (i.e., using LoRa SF12).

Figure 5. Coverage plan using LoRa system for the city of Padova, Italy.

Conclusions

In this article we have described the new emerging LPWAN paradigm for IoT connectivity. This solution is based on long-range radio links, on the order of tens of kilometers, and a star network topology with peripheral nodes directly connected to a concentrator, which acts as the gateway to the Internet. Therefore, LPWANs are inherently different from usual IoT architectures, which are typically characterized by short-range links and mesh topology. The most prominent LPWAN technologies, SIGFOX, Ingenu, and LoRa, have been introduced and compared to the current short-range communication standards. The experimental trials performed employing LoRa technology have shown that the LPWAN paradigm has the potential to complement current IoT standards as an enabler of smart city applications, which can greatly benefit from long-range links.

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Biographies

Marco Centenaro [S] (marco.centenaro@dei.unipd.it) received his Bachelor's degree in information engineering in 2012 and his Master's degree in telecommunication engineering in 2014, both from the University of Padova, Italy. Since November 2014 he has been a Ph.D. student at the Department of Information Engineering of the University of Padova. His research interests include next generation cellular networks (5G), particularly machine-to-machine communication.

Lorenzo Vangelista [SM] (lorenzo.vangelista@unipd.it) received his Laurea and Ph.D. degrees in electrical and telecommunication engineering from the University of Padova in 1992 and 1995, respectively. He subsequently joined the Transmission and Optical Technology Department, CSELT, Torino, Italy. From December 1996 to January 2002, he was with Telit Mobile Terminals, Trieste, Italy, and then, until May 2003, he was with Microcell A/S, Copenaghen, Denmark. In July 2006, he joined the Worldwide Organization of Infineon Technologies as program manager. Since October 2006, he has been an associate professor of telecommunications with the Department of Information Engineering, Padova University. His research interests include signal theory, multicarrier modulation techniques, cellular networks, and wireless sensor and actuator networks.

Andrea Zanella [SM] (zanella@dei.unipd.it) received his Laurea degree in computer engineering and Ph.D. degree in electronic and telecommunications engineering from the University of Padova in 1998 and 2000, respectively. He was a visiting scholar with the Department of Computer Science, University of California, Los Angeles (UCLA), in 2000. He is an associate professor with the Department of Information Engineering, University of Padova. He is one of the coordinators of the Signals and Networking (SIGNET) research lab. His long-established research activities are in the fields of protocol design, optimization, and performance evaluation of wired and wireless networks.

Michele Zorzi [F] (zorzi@dei.unipd.it) received his Laurea and Ph.D. degrees in electrical engineering from the University of Padova in 1990 and 1994, respectively. During academic year 1992–1993 he was on leave at the University of California, San Diego (UCSD), working on multiple access in mobile radio networks. In 1993 he joined the faculty of the Dipartimento di Elettronica e Informazione, Politecnico di Milano, Italy. After spending three years with the Center for Wireless Communications at UCSD, in 1998 he joined the School of Engineering of the University of Ferrara, Italy, where he became a professor in 2000. Since November 2003 he has been on the faculty of the Information Engineering Department at the University of Padova. His present research interests include performance evaluation in mobile communications systems, random access in wireless networks, ad hoc and sensor networks, the Internet of Things, energy constrained communications protocols, cognitive networks, and underwater communications and networking. He was Editor-In-Chief of *IEEE Wireless Communications* from 2003 to 2005 and Editor-In-Chief of *IEEE Transactions on Communications* from 2008 to 2011, and is currently the founding Editor-In-Chief of *IEEE Transactions on Cognitive Communications and Networking*. He has also been an Editor for several journals and a member of the Organizing or Technical Program Committees for many international conferences, as well as Guest Editor for Special Issues in *IEEE Personal Communications*, *IEEE Wireless Communications*, *IEEE Network*, and the *IEEE Journal on Selected Areas in Communications*. He served as a Member-at-Large of the Board of Governors of the IEEE Communications Society from 2009 to 2011, and as its Director of Education and Training in 2014–2015.