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LoRaWAN - A Low Power WAN Protocol for Internet of Things: a Review and Opportunities

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***Abstract*—The Internet of Things (IoT) vision requires increasingly more sensor nodes interconnected and a network solution that may accommodate these requirements accordingly. In wireless sensor networks, there are energy-limited devices; therefore techniques to save energy have become a significant research trend. Other issues such as latency, range coverage, and bandwidth are important aspects in IoT. It is considering the massive number of expected nodes connected to the Internet. The LoRaWAN (Low Power WAN Protocol for Internet of Things), a data-link layer with long range, low power, and low bit rate, appeared as a promising solution for IoT in which, end-devices use LoRa to communicate with gateways through a single hop. While proprietary LPWAN (Low Power Wide Area Network) technologies are already hitting a large market, this paper addresses the LoRa architecture and the LoRaWAN protocol that is expected to solve the connectivity problem of tens of billions of devices in the next decade. Use cases are considered to illustrate its application alongside with a discussion about open issues and research opportunities.**

***Index Terms*—Internet of Things; IoT; LoRa; LoRaWAN; Sigfox; Long range; Low power**

I. INTRODUCTION

The growth of the Internet of Things (IoT) has increased the scale of the issues inherent to the energy restricted nodes in wireless sensor networks (WSNs). For better network performance, many studies have been performed to find the optimal transmission power for each network node. They try to perform network connectivity with minimum wasted power, thus, increasing its lifetime [1]. Instead of having each node transmitting with its maximum power, it is possible to redefine the power of nodes in a collaborative way, optimizing the topology of a WSN considering the neighbor nodes under certain criteria [2]. Recent proposals, like Aziz *et al.* [3] present topology control techniques to extend the battery life time and energy efficiency in WSNs [4]. Nevertheless, new challenges arise from keeping communication effective while reducing energy consumption and IoT heterogeneity can be considered as a further open-issue addressed at radio level [5] or gateway level [6]. Other aspects, such as latency, range coverage and bandwidth are also important in IoT to support the massive number of expected nodes connecting to the Internet. For this purpose, LoRa identifies end-devices that have limited energy and transmit few bytes every time [7]. Both a sensor (end-device) and an external entity can initiate a communication (data transfer). End-devices can also be actuators, for example. LoRa is an excellent candidate for being used in many applications in smart environments (such as, smart healthcare, smart cities, environmental monitoring, industry, etc.) given its long range and low power features.

LoRa pursues an approach based on the following two distinct layers: *i*) a physical layer is based radio modulation technique, called CSS (Chirp Spread Spectrum) [8]; and *ii*) a MAC layer protocol (LoRaWAN) that provides access to LoRa architecture. LoRaWAN is an open standard [9]. These LoRa network layers may be seen in Fig. 1.

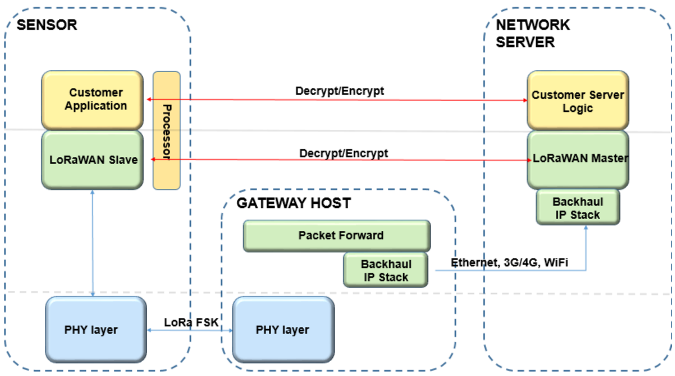

Fig. 1. Illustration LoRaWAN network layers.

The physical layer employs LoRa modulation, which is based on CSS and presents the same characteristics of FSK (Frequency Shifting Keying) regarding communication range [10]. Thus, LoRaWAN will be approached as a communication protocol and network architecture, while LoRa physical layer enables the long range link. The protocol and network architecture have the influence to determine a node's battery life, the network capacity, the QoS (Quality of Service), security and reliability of the applications in the network. LoRaWAN supports virtualized wireless networking technologies, where all base stations collaborate and are collectively seen by end devices. This work focuses on describing and presenting a comparison of LoRaWAN with other standard protocols. The study will consider several network parameters, such as range coverage, power consumption and lower bit rate used to consider the best solution for IoT.

The remainder of this paper is organized as follows. Section II addresses new challenges for MAC protocols regarding IoT. The work related to the most relevant Low power Wide Area Networks (IoT data-link layer protocols) are elaborated in Section III. Section IV describes the LoRaWAN protocol considering its main characteristics and two use-cases using LoRaWAN are presented in Section V. A comparison among LoRa and other available solutions is shown in Section VI, considering several open research challenges and opportunities for further works. Finally, concluding remarks are presented in Section VII.

II. New Challenges for MAC Protocols in IoT

The emergence for IoT introduces new challenges that cannot be addressed by the current available connectivity protocols. Here, several key IoT challenges are discussed [11].

Bandwidth/Data Rate: Bandwidth and data rate are used to determine the amount of data being transferred (bit rate) in a given time unit, normally, seconds. Bandwidth means the spectrum range in Hertz that a system can use for digital communication. Data rate depends on the bandwidth of the Internet connection. If the bandwidth is high, the bit rate tends to be high whether adequate digital communication technologies are employed. In LoRaWAN, the data rate is selected by a trade-off between the communication range and the duration of the message. ”Virtual” ducts (channels) are created with diversified data rates and without any interference due to spread spectrum technologies.

Battery Life: The technical and practical challenges facing energy storage for electronics in IoT cannot be met by any one incumbent technology [12]. Most things are powered by non-rechargeable batteries for reasons of cost, availability and convenience. However, the need for replacement, limited energy resources and ecological implications will become a severe problem when powering billions of IoT devices, which employ non-rechargeable batteries as the primary energy storage. To maximize the life of the final device batteries, the LoRaWAN server controls the RF output (Radio frequency) and an output rate through an adaptive scheme for each end device.

Range: New technologies have the objective to provide information access to the Internet to people/things away from the big metropolis. To achieve greater distances, the power of the radio should be increased, causing greater consumption of the battery. Thus, new protocols aim to obtain greater distances with lower energy consumption, following green energy approach. LoRaWAN and other protocols commercially dispute these ideals. Currently, this protocol obtains about 2-5 km of coverage range in urban perimeters and about 45 km in rural areas.

Latency: Currently, social media like applications demand strict requirements on latency. To build up the fifth generation (5G) architecture, one must rethink about how to employ limited resources to serve different kinds of traffic flows under different environments. There is a trade-off between downlink communication latency *versus* battery life that can be resolved through QoS classes in a LoRaWAN device.

Throughput: LoRa provides a throughput greater than technologies based in ALOHA, with low complexity in the MAC (Medium Access Control), however, LoRa is a communication long range limited for different environments, i.e, 2-5 km urban and 45 km rural, with data rate between 290 bps and 50 kbps.

III. Related Low power Wide Area Networks Solutions

The communication technologies that were proposed and deployed for low power and wireless communications targeted for IoT are classified in the following low power categories:

i) Low power local networks with a range smaller than 1000m - They are applicable to short-range networks, but when organized in a mesh topology, they can be applied to larger areas, *i.e.* IEEE 802.15.4, Bluetooth/LE (low energy), etc.

ii) LPWAN (Low power wide area networks) with a bandwidth exceeding 1000m. This category applies to low power cellular networks, where each base station covers thousands of end-devices, *i.e.* Sigfox, DASH7, etc.

This section focuses on LoRaWAN and overviews the related IoT communication technologies for these considered categories.

A. Bluetooth/LE

With the proposal to replace cables to connect devices used with lower data rates (1Mbps maximum) in a short distance range (in theory, officially up to 100m) with low power consumption, emerged Bluetooth technology. After several releases, appeared the Bluetooth 4.0, *i.e.*, the Bluetooth/LE that provides simpler pairing functions and higher data rate (24Mbps max, Wi-Fi-based) for a lower power consumption, with the purpose of connecting sensors and actuators on IoT environments [13].

B. DASH7

DASH7 is a protocol stack based on the interaction of the OSI model where sensors and actuators operate in the unlicensed bandwidth of 433MHz, 868MHz, and 915MHz [14]. DASH7 aims to provide communication over a range about up to 2km, with low latency, mobility support, multi-layer battery, 128-bit AES encryption, and data rate up to 167Kbps. In addition, DASH7 defines the layered architecture, considering protocols from the physical up to the application layer.

C. Sigfox

Sigfox is a cellular system approach that allows end-devices connecting to base stations equipped with software-defined cognitive radios using the BPSK (Binary Phase Shift Keying) modulation [15]. It uses a frequency band of 868MHz, dividing the spectrum into 400 channels of 100Hz. Its coverage is about 30-50 km in rural areas and about 3-10 km in urban environments. An access point can manage around one million of end-devices and each end-device can send about 140 messages per day with a data rate of 100bps. Downlink communication can only precede uplink communication after each the end-device must wait to hear a response from the base station which makes it interesting for data acquisition. However, for command and control scenarios, it is not interesting.

IV. The LoRaWAN Protocol

LoRaWAN architecture is considered as a "star of stars" where it is a structure that defines the communication protocol and the network system architecture while the physical layer, LoRa, enables the long range link. The protocol influences to determinate a node battery lifetime, the network capacity, QoS, security, and the quantity of applications served by the network.

A. LoRaWAN network

A typical LoRaWAN network is a "star-of-stars" topology, illustrated in Fig. 2.

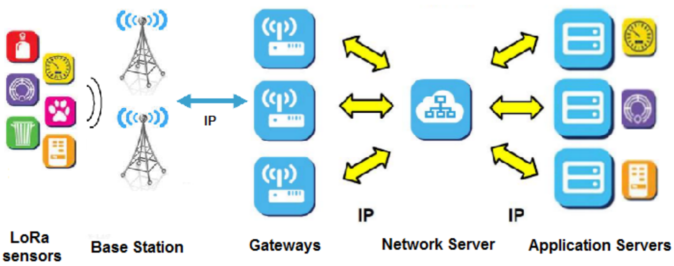

Fig. 2. Illustration of LoRaWAN network architecture.

According to Fig. 2, several components are defined in a LoRaWAN as end-devices, gateways (*i.e.*, base stations), network server, and applications.

1. End-devices perform the communication gateways using LoRa and LoRaWAN technologies.

2. Gateways dispatch the LoRaWAN frames from the end-devices to a network server using a back-haul interface with higher throughput, usually Ethernet, 3G/4G, satellite, or Wi-Fi.

3. The network server decodes the packets sent by the devices, performing security checks and adaptive data rate, thus generating the packets that should be sent back to the devices.

4. Each application receives data from the network server. It should decode the security packets and uses the information to decide the action in the application.

The long-range link, number of antennas (base stations), and device battery life are improvements related to a star network architecture. Communications with different data rates do not have interference between 300bps up to 5kbps to 125kHz bandwidth, as shown Table I and these are distributed in different channels to perform the communication between the connected devices and the gateways.

TABLE I
LoRaWAN Main Characteristics.

Characteristic	LoRaWAN
Topology	Star on Star
Modulation	SS Chirp
Data Rate	290bps - 50kbps
Link Budget	154 dB
Packet Size	154 dB
Battery lifetime	8 $\sim$ 10 years
Power Efficiency	Very High
Security/Authentication	Yes (32 bits)
Range	2-5 km urban 15 km suburban 45 km rural
Interference Immunity	Very High
Scalability	Yes
Mobility/Localization	Yes

The ADR (Adaptive Data Rate) scheme is used for LoRa network infrastructures for manage the individual data rates and maximize the battery life of each connected device through RF output. In traditional cellular networks, end-devices are not associated with a specific gateway, *i.e.*, route the packet received from the end-devices to the network server after adding information about the reception quality (QoS). Therefore, an end-device chooses the appropriate gateway, that is logically transparent to the end-devices, to send a response (if any), to the end-devices.

B. Battery Lifetime

Considering the ALOHA method as a reference [7], the nodes must be available to synchronize with a mesh network or with a synchronous network, *i.e.* a mobile network, and check the messages. This synchronization will consume significant energy and reduces battery life time. Nodes are asynchronous and communicate with LoRaWAN network via events or previous scheduling. This observation is confirmed in Fig. 3. It presents the power consumption of some wireless communication technologies addressed in this study in function of the range coverage and, as may be seen, LoRaWAN covers the largest range with less power consumption, in comparison with Bluetooth/LE, Wi-Fi and cellular networks.

A recent research study performed by Scientific Research Publishing, Inc [16] revealed that LoRaWAN showed an

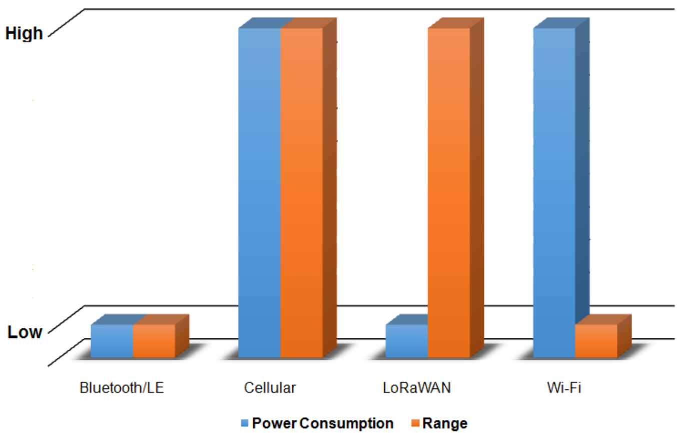

Fig. 3. Power Consumption *vs* Range for Bluetooth/LE, Cellular, LoRaWan, and Wi-Fi technologies (Adapted from [7]).

advantage of 3 up to 5-fold in the energy economy compared to all the others LPWAN technologies.

C. Network Capacity

In a long range network, the gateway must have high availability to receive messages from a large number of nodes. This high capacity is allocated using adaptive data rate and a multi-channel transmitter, in such way that simultaneous messages can be received. Critical factors influencing this capability are the following: *i*) the number of simultaneous channels; *ii*) the data rate; *iii*) the length of the payload; and *iv*) the frequency that the nodes transmit.

The LoRaWAN network can be deployed with a minimal infrastructure and, with the expected capacity achieved in the future, more gateways can be added modifying data rates for reducing the overhearing of other gateways. Then, it turns the network scalable from 6 to 8-fold of the minimum capacity. LoRaWAN performs better in terms of scalability thanks to technology trade-offs, which limit downlink capacity or do the downlink band to be asymmetric to the uplink bandwidth.

D. Device Classes

In end devices, the downlink communication latency is an important factor to decide the quantity of the used power battery. LoRaWAN is an asynchronous protocol based on ALOHA, which means that an end device can "wake up" at programmable intervals to check the downlink and synchronization messages, in a synchronization window with the network, thus reducing communication latency and consumption, respectively. That end, LoRaWAN uses different device classes. The device classes can negotiate network downlink communication latency *versus* battery lifetime.

Taking into account the application needs, LoRaWAN considers three classes of end-devices. These classes are illustrated in Fig. 4 and can be briefly described as follows:

- Class A (bidirectional) - Devices have a scheduled uplink transmission window, followed by two short downlink windows. It has low power consumption and high latency while sending/receiving unicast messages.
- Class B - Devices have additional scheduled downlink windows. It has medium power consumption, low latency at sending/receiving unicast and multicast messages.
- Class C - The devices use receiving windows continuously, similar to the sliding window algorithms. It has high power consumption, lowest latency sending/receiving unicast and multicast messages.

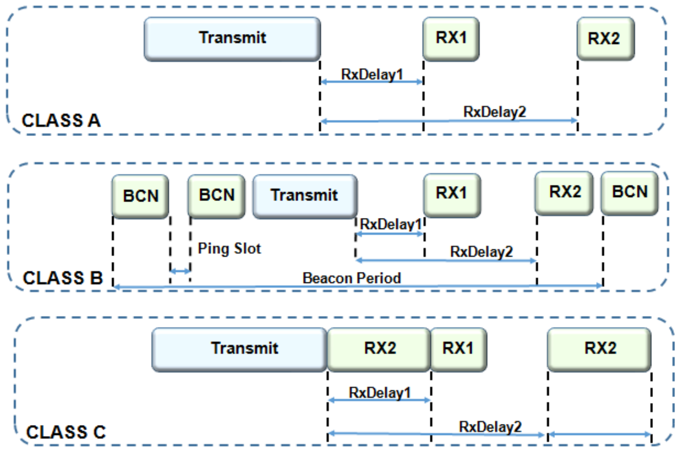

Fig. 4. LoRaWAN communication classes.

E. Security

This feature, the security, is extremely important for the future IoT networks, since it will ensure the operation of the thing without external interruption. LoRaWAN considers two layers of security, one for the network and another for the applications, as shown in Fig. 5.

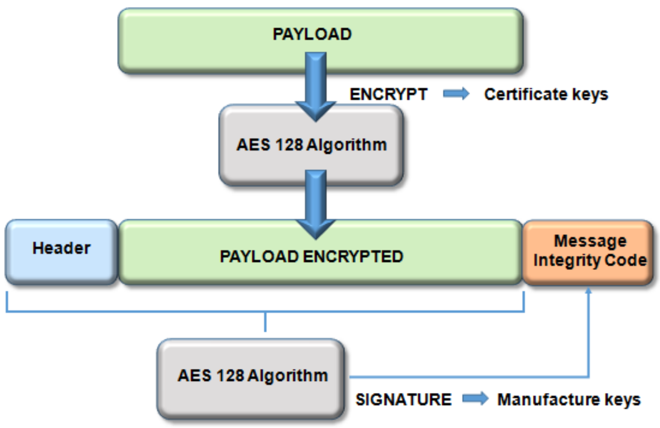

Fig. 5. AES-128 encryption scheme.

The LoRaWAN network solution comes with an authentication framework and a security framework based on the AES-128 (Advanced Encryption Standard) encryption scheme. The AES-128 encrypts the frame for confidentiality and generates a MIC (Message Integrity Code) for integrity. Each end-device has key assignments done by device manufacturers or the application owners. Other systems use a single key for encryption and authentication, compared to LoRaWAN. Authentication and encryption are separate, so it is possible to authenticate packets and provide integrity protection.

V. Examples of LoRaWAN Use-Cases

This section briefly describes two LoRaWAN use-cases to illustrate its potential and show examples of its usage.

A. Renewable energy and health-care solutions

SK Telecom LPWAN covers 99 percent of South Korea's population using Semtech's Lora technology, which enables a sensor network to operate at low power, providing connectivity over a long range. They plan to connect four million things to their LoRa networks by the end of 2017 [17]. The commercial service is planned to be deployed in Daegu, the fourth largest Korean city, in April 2017, and it will be available nation-wide by the middle of 2017. Daegu focus on setting-up and adapting infrastructure for renewable energy solutions, cloud platforms, and big data analytics on healthcare, as well as for infrastructure for autonomous cars. Examples of solutions to be deployed along the city are the streetlights that will collect weather and traffic information using IoT sensors, enabling cost savings by automatically adjusting the lighting level and also sending air pollution status information [18].

B. Cattle Traxx project

This project uses a LoRaWAN mesh topology. Ear tags are the end devices and the use of wireless communication in a single bound to one or many gateways field. Field gateways transmit messages to a server and gateway at the main office via standard IP connections. Ear tags sensors automatically from the nodes of the mesh network. The location of a cow is transmitted through the mesh network to a field gateway. These gateways are battery powered and equipped with solar panels to recharge. Each operation will typically have three or more of these gateways to provide better coverage and allow triangulation to determine the location of a cow [19].

VI. Discussion and Open Research Issues

A. LoRa vs other LPWAN network solutions

Several approaches are being used to benchmark LPWAN solutions commercially available. The NB-IoT (NarrowBand-IoT) focuses specifically on indoor coverage when the LTE-M (LTE-MTC LPWA standard technology published by 3GPP) standard is employed to provide cellular connectivity for a wide range of end devices/sensors with low power consumption and high interoperability in IoT networks [20].

The LoRaWAN protocol has several advantages over other LPWA technologies, namely: the data rate ranges from 300 bps up to 5 kbps (with 125 kHz bandwidth) and 11 Kbps (with 250 kHz bandwidth) allowing for better time-on-air and better battery life; communication is bidirectional and unlimited (subjects to ISM - industrial, scientific and medical band local regulations); native payload encryption able to create public and/or private networks; ADR (Adaptive Data Rate) enables base station addition on a scalable network, decreasing the ADR average and reducing time-on-air that, it is the time taken to send chips at the chip rate around it, allowing more end devices to communicate.

In short, Sigfox may not be a feasible IoT protocol for fast-moving, since in performed experiments, it was shown that communication is unreliable at low speed, and resource-constrained [21]. Thus, the IoT devices need to communicate at high data rates.

Table II summarizes a comparison among the most promising LPWA technologies (LoRaWAN, Sigfox, NB-IoT and LTE-M) regarding security, capacity and battery life-time in order to decide the best for a generic application scenario.

TABLE II
Comparison among LoRaWAN and others LPWA Technologies.

Feature	**LoRaWAN**	**Sigfox**	**NB-IoT**	**LTE-M**
Modulation	SS Chirp	GFSK/ DBPSK	UNB/GFSK/ BPSK	OFDMA
Data Rate	290bps - 50kbps	100bps 12/8bytes Max	100bps 12/8bytes Max	200kbps - 1Mbps
Link Budget	154 dB	146 dB	151 dB	146 dB
Battery life-time	8 ∼ 10 years	7 ∼ 8 years	7 ∼ 8 years	1 ∼ 2 years
Power Efficiency	Very High	Very High	Very High	Medium
Security/ Authentication	Yes(32 bits)	Yes(16 bits)	No	Yes(32 bits)
Range	2-5km urban 15km sub-urban 45km rural	3-10km urban - 30-50km rural	1.5km urban - 20-40km rural	35km - 2G 200km - 3G 200km - 4G
Interference Immunity	Very High	Low	Low	Medium
Scalability	Yes	Yes	Yes	Yes
Mobility/ Localization	Yes	No	Limited, No Loc	Only Mobility

Other LPWA technologies, such as Weightless-N, Weightless-P from Weightless SIG, and RPMA (Random Phase Multiple Access technology) are also commercially deployed and being used to support specific vertical use-cases. There are also several new 3GPP standards, such as EC-GSM, LTE-M, and NB-IoT that are currently being specified to enable future 3GPP networks of support the specific requirements and use-cases of the fast growing IoT markets in the upcoming years.

B. Open issues

Studies about LoRa coverage and the proposal of a channel attenuation model were performed by [22]. Research works comparing several long-range technologies and LoRa are presented in [23], [24]. This later article provides an overview and functional description of LoRaWAN. This is relevant, since LoRaWAN documentation has some imprecisions that difficult understanding. Continuing this work, performance analysis studies of the protocol may consider the following topics: estimation of the collision rate, total capacity, channel load, single device maximal throughput and MTU (Maximum Transmission Unit), scaling networks to a massive number of devices, and mobility/roaming proposing possible solutions for performance enhancement.

VII. Conclusion

This paper elaborated an analysis about LoRaWAN protocol based on its architecture, battery lifetime, network capacity, device classes and security. It was observed that this protocol showed an advantage of about 3 to 5-fold when compared with other LPWAN technologies regarding power consumption for long range communications. Moreover, LoRaWAN networks can be deployed with a minimal amount of infrastructure and with the achieved capacity. Soon, more gateways can be added to reduce the amount of overhearing to other gateways and subdivide the data rate, making the scalable network in 6 to 8-fold of the minimum capacity.

Acknowledgments

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