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A Comprehensive Study on LPWANs With a Focus on the Potential of LoRa/LoRaWAN Systems

Christos Milarokostas, Dimitris Tsolkas, Nikos Passas, and Lazaros Merakos

Abstract—The Internet of Things (IoT) ecosystem is emerging rapidly. From the connectivity perspective, it is the vehicle towards connecting massive number of devices to the Internet; whereas, from the application perspective, it paves the way towards collecting huge amounts of data and enabling novel information-based services. The connectivity infrastructure that will support the IoT ecosystem is composed of both expansions applied in the well-deployed mobile network infrastructures, and dedicated deployments provided by vertical-specific setups. In the latter case, the Low-Power Wide Area Networks (LPWANs) have become a cost-effective solution, incorporating efficient technologies for wireless connectivity and control. In this context, a comprehensive study is provided to assist on the currently increasing research and development interest in the area of LPWANs. The study provides state-of-the-art work as well as research directions and tools for the most representative LPWAN technologies. Supporting the concept of openness in the IoT ecosystem, the study targets connectivity solutions that operate in unlicensed spectrum bands, such as the LoRa/LoRaWAN systems, and describes the most recent cloud and open-sourced solutions for IoT service and data management.

Index Terms—IoT, WSN, LPWAN, LoRa, LoRaWAN

I. INTRODUCTION

ONE of the key targets of beyond 2020 networks is the interconnection of numerous devices to support innovative applications with heterogeneous requirements. This target has been described in the International Mobile Telecommunications 2020 (IMT-2020)¹ report [1] as one of the three most demanding scenarios for the 5G era; under the term: massive Machine Type Communications (mMTC). In this context, Internet of Things (IoT) technology [2] serves as key enabler for the realization of the mMTC scenario.

Primarily, IoT has been defined as *a global infrastructure for the information society, enabling advanced services, by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies* [3]. Based on this definition, various terms have been coined to highlight i) the application perspective, as for instance, the terms Broadband IoT and Critical IoT, and ii) the network perspective, as for instance, the terms Massive IoT [4] and Network of Things (NoT) [5], [6]. In all the cases, the message is one: in the coming years, the massiveness of IoT devices is expected to be a major challenge. Recent estimations foresee that by the end of 2030 about 500 billion IoT devices will be deployed [7].

In this context, two main approaches are developed. On the one hand, mobile networks (having high coverage from multiple Base Stations (BSs) already in the field) and local area networks (covering well-enough indoor deployments) expand their capabilities, towards including in the pallet of their services IoT communications. 5G New Radio for Reduced Capability (NR RedCap) devices is the most recent advancement of that expansion [8]. On the other hand, the domain of developing IoT dedicated networks, having as main representative the Low-Power Wide Area Networks (LPWANs) [9], is evolving notably.

LPWANs target mainly the deployment of Gateways (GWs), operating as access points, to support End Devices (EDs) that mainly act as sensors (for gathering data of interest) and/or as actuators (for performing an action). As such, LPWANs can be considered as a type of Wireless Sensor and Actuator Networks (WSANs) [10]. From the application perspective, LPWANs support applications with low rate requirements, which can be provided by EDs with low energy demands that remain operational in the field for a long term (a few years), with no charging or battery replacement [11]. Since limited functionality is requested for the EDs and long range (wide area) is covered (hence, a small amount of GWs is required), the LPWANs have become a cost-effective solution for IoT.

The scope of this paper is to present LPWANs as major candidates for the support of the IoT ecosystem, by decomposing various related technologies and revealing research challenges and directions. To this end, extra focus is applied on the Long Range (LoRa)/LoRa Wide Area Network (LoRaWAN) systems, which appears to be the most prominent solution for unlicensed wireless connectivity in LPWANs. With initial velocity from existing surveys in the area, ([12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22]), we strive for an up-to-date comprehensive review on LPWANs, by providing valuable insights on the underlay technologies and state-of-the-art directions for research and development. The adopted approach is reflected in the diagram of Fig. 1; with the solid-colored path the adopted presentation approach is indicated, where each box represents a core section of the survey, whereas the auxiliary tabular boxes represent self-contained overviews (provided in separated sections) to support the main path.

The remaining of this paper is organized as follows. In Section II, fundamental characteristics of LPWANs are described. Those characteristics are positioned against characteristics of other networking families. In Section III, the key technologies that support LPWANs are presented. In Section IV, a comprehensive comparison of those technologies is provided, in terms of achievable performance and supported capabilities.

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¹Manuscript to be submitted for review.

¹The full list of acronyms used in this document is provided in an annex.

Fig. 1. Block diagram of the structure of this survey. Solid-colored boxes represent the content in the core sections, whereas the tabular boxes reflect self-contained supporting overviews provided in separated sections.

Section V focuses on LoRa/LoRaWAN systems, delivering an overview of the related protocol stack. Section VI and Section VII delve more into those systems, providing an overview of LoRaWAN and LoRa, respectively. In Section VIII, key considerations in LoRa/LoRaWAN research and development studies are presented. Section IX and Section X include directions for conducting simulations and utilising cloud services for LPWAN, respectively. Section XI, deals with data management for LPWANs. Conclusions are drawn in Section XII.

II. BACKGROUND ON LPWANs

LPWANs define a wireless networking family, supported from various technologies, separated from the other well-established wireless networks technologies developed for mobile communications and short range communications. As such they have been considered as part of the 3rd generation of IoT networking, focusing on communication of things with cloud services [23]. Fig.2 compares the key wireless technology families in terms of range, data rate and power efficiency. As it can be observed in Fig.2, LPWAN technologies are the winners in terms of range and energy consumption.

Fig. 2. Wireless technology families with respect to range, data rate and power efficiency

Well established LPWAN technologies are: the Extended Coverage-Global System for Mobile communications-IoT (EC-GSM-IoT), the Long Term Evolution-Machine type communication (LTE-M), the Narrowband-IoT (NB-IoT), the MY IoT (MIOTY), the Random Phase Multiple Access (RPMA), the Wize, the Weightless, the Sigfox and the Long Range (LoRa). The first three technologies (i.e., EC-GSM-IoT, LTE-M, NB-IoT) have been defined by 3rd Generation Partnership Project (3GPP), whereas the rest ones are non-3GPP standardized. This splitting criterion also splits the technologies

to those that use the licensed part of the spectrum (3GPP technologies) and those that operate in licensed-free spectrum (non-3GPP technologies).

From the architectural perspective, LPWANs are mainly composed of three types of nodes, namely the EDs and the GWs that compose the access-side of the system, as well as the Network/Application Servers, that compose the server-side of the system. EDs are deployed in massive numbers and tend to broadcast their messages in the hope of being received by a GW that covers the area. GWs forward these messages to the server-side of the system, where numerous functions at network and application level take place. At the server side, a security server can also be present along with the application server. Although, nomenclature might be different from one technology to another, an LPWAN system architecture can be usually described by a structure similar to the one depicted in Fig.3.

Fig. 3. A generic LPWAN system architecture

From the functional perspective, all LPWANs technologies need to meet certain demands in order to be acknowledged as such. Energy efficiency, long range communication, low-cost operation and up-link dominance are the main demands (or operating characteristics) of all LPWAN technologies.

A. Energy Efficiency

For all LPWAN technologies the main energy draining factor is the transmission process, hence an appropriate radio interface and a careful transmission planning is essential for the longevity of the system. Furthermore, lightweight protocols are needed to achieve not only minimization of the number of transmissions, but also minimization of each transmission length. For specific scenarios, EDs are powered by solar panels, moving towards an energy harvesting approach, off-boarding an important factor of the network management functionality.

B. Long Range

As expected by the networking paradigm's name, long range support is a prerequisite for an LPWAN technology. Practically, LPWANs refer to systems that establish links in the order of 10^3 and 10^4 meters. Furthermore, experimental setups have seen communication in the order of 10^5 meters. Such distances are achieved thanks to robust Physical layer protocols and tolerant behavior in the receiving side of the link.

C. Low cost

Focusing on the access part of the network, on the one hand, the GWs are deployed in low numbers (due to the long range) and operate as packet forwarders, pushing the main functionality back to the server-side. This minimizes the cost of the GWs. On the other hand of the access network, EDs are deployed in massive numbers and, thus, the minimization of their development cost is performed by constraining the functionality and limiting the hardware/software needs. Indeed, EDs can be built from scratch using the appropriate radio module and a common development board like Arduino, Raspberry Pi and BeagleBoard.

In the server/control-side of the network, for the LPWANs various server components (e.g., application server, security server) are expected, having, however, low impact on the overall cost since the development approach is based in-principle in open source technologies and integrates code snippets and stacks that are available in public software repositories.

D. UL dominance

LPWAN access part borrows the principles of the Wireless Sensor Networks (WSNs) [24] and as such it is characterized as UL dominant; that is, the most transmissions are performed from EDs to GWs. Typically, EDs are deployed on the field and are expected to provide the server-side of the system with information obtained by their sensors, based on a periodical or event-driven scheme. It should be noted that contrary to the typical mesh or ad-hoc network topology that is used in WSNs, LPWANs follow a star system development [25].

III. LPWAN TECHNOLOGIES

A. EC-GSM-IoT

EC-GSM-IoT technology was first introduced by 3GPP in Release 13, and further improvements have been added in recent Releases. The main target of the technology was to use existing mobile network infrastructure and functionality (mainly 2G/GSM) for establishing long range IoT communications.

Key point in developing the technology was to maintain advanced features of GSM and General Packet Radio Service (GPRS), while extending the coverage area of these systems and optimizing the protocol for IoT devices [26]. More specifically, EC-GSM-IoT is based on Enhanced GPRS (EGPRS), a wireless cellular technology of '2.75G' that serves as an improvement of GSM in terms of data rate. GSM as a system

offers extended coverage compared to other cellular technologies. Its improvement, eGPRS, maintains this advantage and increases system's data rate. EC-GSM-IoT utilizes the two cellular technologies pros, by exploiting the coverage benefit with the sufficient data rates of EGPRS or Enhanced Data rates for Global Evolution (EDGE). Data rate of EDGE is placed at 384kb/s, which is beyond EC-GSM-IoT's maximum data rate of 240kb/s.

Contrary to GSM and EDGE, EC-GSM-IoT uses enhanced Discontinuous Reception (eDRX) of 52min compared to GSM's DRX of 11min, performs less operations during inactive periods and utilizes a Power Saving Mode (PSM), leading to extended ED lifetime [27]. Other features of EC-GSM-IoT are the optimization of system's information that is used and the nonexistence of redundant re-transmissions; factors that are considered critical in the effort to reduce device complexity and further improve the battery usage [27]. Also, EC-GSM-IoT is equipped with additional channels to achieve greater coverage and overlaid Code Division Multiple Access (CDMA) scheme for increased capacity [28]. Security improvements on the areas of integrity, authentication of both ends and the ciphering algorithms that are used, classify EC-GSM-IoT as LTE-level secure [28].

In the deployment field, EC-GSM-IoT is supported by low-cost EDs that can operate for up to 10 years with an average of 5W/h battery usage. These EDs transmit in multiple GSM frequency bands according to deployment area, from 395MHz to 1960MHz, using 200kHz Bandwidth (BW) channels. The deployment of EC-GSM-IoT's channels is performed in a GSM in-band scheme. Message transmissions are performed in two power classes; one being at 23dBm and the other at 33dBm. The two classes define the two coverage areas cases, with the former having a Maximum Coupling Loss (MCL) of 154dB and the latter of 164dB. Data rate depends on modulation type. Gaussian Minimum Shift Keying (GMSK) offers data rates between 0.35kb/s and 70kb/s, while 8-Phase Shift Keying (8PSK) can go up to 240kb/s. These data rates correspond to UL as well as DL. Time Division Multiple Access (TDMA)/Frequency Division Multiple Access (FDMA) are used as multiple access schemes in both DL and UL.

B. LTE-M

Another Cellular IoT (CIoT) technology that can satisfy the needs of low power and extended coverage is LTE-M. We note that, in the context of this paper, with the term LTE-M, we refer to the common characteristics of LTE-MTC, LTE Cat M1 and LTE-M technologies. LTE-M as CIoT technology utilizes the LTE spectrum for establishing wireless communication links allowing coexistence with other cellular technologies such as 2G, 3G and especially advantages of the 4G standard.

LTE-M deployment cost and time-to-market is reduced, since LTE's BSs can be used for LTE-M links with a software upgrade. Security and privacy benefits from LTE also exist in LTE-M and issues like confidentiality of end user's identity (practically ED), authentication, integrity of messages and identification of EDs are tackled successfully. Moreover, with improvements added in 3GPP Releases 14 and 15, LTE-M EDs

with mobility capabilities can be supported, since in-band LTE operation permits handovers from one cell to the other. Other improvements added in 3GPP's Releases 14, 15 and 16 include the standardization of a new device category; namely Cat. 2, that offers substantial enhancements in ED's performance. Furthermore, Voice Over LTE (VoLTE) features were added in Release 14 [29]. Release 15 built upon these improvements and presented new use cases, supporting higher ED mobility, adding a new power class of 14dBm, reducing latency and ED's power consumption, increasing spectral efficiency and improving access control [26]. The evolutionary approach of the technology was continued in Release 16. Worth mentioning enhancements include new power saving techniques for EDs, extended support of EDs' mobility and improvements that targeted coexistence with New Radio (NR), i.e., the 5G radio interface [30].

Overall, LTE-M is based on a simplified version of LTE protocols and functionality towards reducing ED complexity and cost, and improving power consumption. More precisely, in LTE-M, there is no control channel for wideband operation, Transmission Modes (TM) support is reduced and Hybrid Automatic Repeat Request (HARQ) is also reduced [28], since message size is already limited and the addition of large number of redundant bits for error detection purposes should be restricted.

In the deployment field, LTE-M EDs are able to operate in low power modes and utilize power saving techniques like PSM, eDRX and Connected mode DRX (C-DRX) to live up to 10 years with a 5W/h battery consumption. The frequency bands that are used for message transmissions are cellular, ranging from 462.5MHz to 2655MHz and their selection is based on each area's spectrum regulation and operators' decision. The BW is 1.08MHz and the in-band LTE operation is applied. LTE-M defines two power classes: the class of 23dBm and the class of 20dBm. Both classes result in the same coverage area, with an MCL of 155.7dB. Despite the extended area that the system can cover, data rates are the greatest among other LPWAN solution, reaching 1Mb/s for both streams. Especially for Cat. 2 devices, data rates of 7Mb/s in UL and 4Mb/s in DL using 5MHz BW, can be reached. For both UL and DL, Quadrature Phase Shift Keying (QPSK) and 16-Quadrature Amplitude Modulation (16-QAM) are utilized for modulation purposes. In UL, Single Carrier-FDMA (SC-FDMA) is used as multiple access scheme, whereas in DL the use of Orthogonal FDMA (OFDMA) is preferred; same as in LTE networks. It is worth mentioning, that in both UL and DL techniques like 15kHz tone spacing and Turbo codes are utilized to increase system's performance [28].

C. NB-IoT

NB-IoT is one of the most prominent LPWAN CIoT technologies. NB-IoT defines a radio interface for IoT communications, moving one step further from the EC-GSM-IoT and LTE-M technologies which are solely based on the GSM and LTE radio interfaces, respectively.

NB-IoT is specified in 3GPP Release 13, but much like EC-GSM-IoT and LTE-M, future improvements of the technology

are included in Releases 14, 15 and 16. More precisely, in Release 14, a new device power class was established at 14dBm, mobility improvements were introduced and enhancements in power consumption and latency were proposed among other upgrades of the technology [29]. Data rate was also improved to reach the scale of 250kb/s for both UL (for multi-tone deployment) and DL. Release 15 brought further improvements, with system's range increase to 120km, support of micro-cells, pico-cells and femto-cells, wake-up enhancements for EDs that operate in DRX or eDRX and other upgrades [26]. Release 16 expanded the technology even further, with key improvements among others being power saving techniques in wake-up procedure of EDs, directions towards Self Organizing Networks (SONs), greater mobility support and coexistence of the technology with NR [30].

As a 3GPP CIoT technology, NB-IoT utilizes bands in the licensed part of the spectrum, both in the sub-GHz region, like B8 or B26 and above 1GHz, like B66 or B74. The BW of the system is 180kHz. Three modes of operation are defined as depicted in Fig.4 [31]. In the *stand alone* mode, NB-IoT utilizes part of the spectrum that is used for GSM EDGE Radio Access Network (GERAN) by operating in a GSM carrier. In the *guard-band* mode, unused resource blocks inside an LTE's carrier are utilized. These blocks are at the edges of the carrier and are typically used for tackling interference issues. Finally, in *in-band* operation, NB-IoT uses an LTE Physical Resource Block (PRB) for its needs; hence the size of 180kHz BW, since LTE uses 12 subcarriers of 15kHz width each. The mode of operation is agnostic to ED when it connects to the network [32].

Fig. 4. NB-IoT modes of operation

In the deployment field, NB-IoT uses the same power saving techniques as in LTE-M; namely PSM, eDRX and C-DRX. Battery life is calculated to approximately 10 years, with solutions being designed to last even more with the typical 5W/h battery usage. Key advantage of NB-IoT is its MCL value, that can go up to 164dB for standalone deployment, allowing extremely extended coverage. Supported modulation schemes include QPSK in both UL (multi-tone) and DL, and $\frac{\pi}{4}$ -QPSK or $\frac{\pi}{2}$ -Binary PSK (BPSK) in UL (single-tone) [20]. Being able to coexist and utilize LTE bands, NB-IoT uses SC-FDMA in UL and OFDMA in DL for multiple access, however the area of access mechanisms in NB-IoT is undergoing extensive research [33]. Again, to improve system's performance, techniques like 15kHz tone spacing in both streams (or even 3.75kHz tone spacing in single-tone UL operation) and Turbo coding in UL are used.

D. MIOTY

Moving to non-3GPP technologies that operate in unlicensed bands, the first examined candidate is MIOTY. MIOTY

is an LPWAN standard that follows one of the 3 European Telecommunications Standards Institute (ETSI) specifications for the so called Low Throughput Networks (LTN). In [34], ETSI defines 3 LTN protocol families; namely Lora family, Telegram Splitting Ultra Narrow Band (TS-UNB) family and Dynamic Downlink Ultra Narrow Band (DD-UNB) family. MIOTY is a realization of the 2nd protocol family, TS-UNB, mainly implemented by BTI.

MIOTY can offer communications services to EDs with high mobility, of up to 120km/h. The underlying LTN protocol, i.e., the TS-UNB, offers great advantages in the area of robustness against co-channel interference; a factor highly critical for links operating in the unlicensed part of the spectrum. This robustness is achieved thanks to GW's ability to decode the entire message using a portion of the received packets. Adding to Telegram Splitting (TS) benefits, the split messages require less time to transmit, resulting in reduced Time On Air (ToA), and, hence, an improvement in battery usage. As a TS-UNB technology, MIOTY uses Telegram Splitting Multiple Access (TSMA) for allowing more than one EDs to access the communication channel. TS as a concept is explained in [34], [35] and [36]. In TS, the packets to be transmitted are first divided into several smaller sub-packets and then they are sent in a non-continuous fashion, with each transmission being separated by the other in time domain. The sub-packets are distributed pseudorandomly in both time and frequency within a certain radio frame.

In the deployment field, two power classes are supported by MIOTY, based on the frequency band that is used for the communication; either 868MHz in Europe or 915MHz in North America. That leads to the 14dBm power class for the European band and the 23.3dBm class for the North American band. With these power classes and proper configuration, EDs can operate in the field for about 20 years. The link budget of a MIOTY link is calculated at 154dB, with a receiver sensitivity of 139dBm [34]. Data rate by official statement is 0.514kb/s, but estimations set it at 0.4kb/s using a BW of 200kHz.

E. RPMA

RPMA was invented and patented [37] by Theodore J. Myers with On-Ramp assignee; the company that is now called Ingenu. RPMA, is explained as a concept in [16] and [38]. It is actually a Direct Sequence Spread Spectrum (DSSS) technique that pseudorandomly delays the transmissions of EDs to minimize overlapping occurrences, resulting in increased Signal to Interference and Noise Ratio (SINR) value for every node.

Contrary to other popular LPWAN technologies and especially the unlicensed ones, RPMA does not make use of the sub-GHz frequency bands for link establishment. RPMA utilizes the globally available 2.4GHz band for wireless transmission. Despite not having the added advantage of high penetration due to low frequency that other LPWAN solutions have, RPMA behaves extremely well in terms of coverage. For tackling the issue of interference in a band that operates also one of the most widely used wireless technologies, i.e., WiFi (IEEE 802.11), RPMA utilizes its high robustness and

a frequency plan that assigns small channels in-between the channels of WiFi [39]. To provide multiple access in the wireless channel, RPMA uses the namesake multiple access scheme.

Another key feature of RPMA is its solid security and privacy support. EDs communicate with RPMA's BSs having ensured authentication for both end points of the link, messages are sent encrypted by the EDs and the backhaul communication of the system is achieved via secure Secure Sockets Layer (SSL)/Transport Layer Security (TLS) connections.

In the deployment field, the BW that is used by RPMA is significantly higher than the typical case of LPWANs, reaching the size of 1MHz [40]. Regarding transmission power, EDs transmit at a maximum of 21dBm in both US and Europe, while RPMA BSs can transmit at 30dBm in US and at 21dBm in Europe [41]. In this power class and by optimizing the usage of EDs for longevity, nodes can last on the field for more than 10 years, while estimates state that can last for about 20 years with rare message transmissions and small-sized packets. A key advantage is its extremely high link budget as well. It can reach 168dB, with a receiver sensitivity of 142dBm for BSs and 133dBm for EDs. However, the data rate is estimated to be 8kb/s at maximum [21].

Interestingly, as of 2018, Ingenu has decided to offer RPMA as a Platform-as-a-Service (PaaS) solution [42].

F. Weightless

Weightless Special Interest Group (SIG) started developing 3 solutions for LPWA networks; namely Weightless -W, -N, -P. Weightless-W operates in the TV White Space (TVWS) region, making it a worth examining solution, but the different regulations in different parts of the world regarding TVWS spectrum complicate its deployment. Weightless-N operates in the sub-GHz unlicensed region and seems as a promising solution due to its numerous similarities with Sigfox; one of the most popular LPWANs. The technology is used by NWave, however Weightless-N's link budget is considered to be floating [43], leading Weightless SIG to another alternative. The suggested solution is Weightless-P [44], a technology that this paper focuses on.

Weightless-P as a technology supports fully acknowledged (ACK) bi-directional links and various techniques can be used among others to offer Quality of Service (QoS), like Forward Error Correction (FEC) in block interleaving mode, Cyclic Redundancy Code (CRC) and ARQ. It, also, offers various advanced security and privacy features, with mutual authentication via Advanced Encryption Standard (AES) 128/256, message integrity, confidentiality via AES 128/256 and secure Over The Air (OTA) key exchange being supported [45].

In the deployment field, the BSs that implement Weightless-P standard transmit at a typical power of 27dBm, while being able to transmit also at 30dBm. EDs have a lower transmit power, at 14dBm, being also capable for 30dBm transmissions. What is more important, is the power consumption of EDs at idle state, which is placed at 100μW. With this power usage, an ED can last for 3-8 years [46]. Even though the technology can theoretically operate at both licensed and unlicensed spectrum,

for the time being, it operates at unlicensed bands in the sub-GHz region. These bands are: 138MHz, 433MHz, 470MHz, 780MHz, 868MHz, 915MHz and 923MHz. The choice of band is subjected to each area's frequency regulation. BW is set at 12.5kHz or 100kHz for UL, while at DL broadcast, unicast and multicast channels exist, using 100kHz, 50kHz or optionally 12.5kHz.

Link budget of Weightless-P can reach at most 153dB, assuming an Additive White Gaussian Noise (AWGN) channel. Its value depends on transmission parameters, with the highest figure being obtained for UL transmissions when the receiver sensitivity is set at -135.5dBm, with a required Signal to Noise Ratio (SNR) of -17.5dB, for a typical Bit Error Rate (BER) of 10^{-4} , while Coding Rate (CR) is set at $\frac{1}{2}$ and Spreading Factor (SF) at 8. The 153dB value is true, if Offset QPSK (OQPSK) is used as a modulation method. The other modulation method that the technology utilizes is GMSK with a Bandwidth-symbol Time (BT) product of 0.3. These modulations are used in both UL and DL. For multiple access, UL messages use TDMA and FDMA combined, whereas in DL only FDMA is utilized. Considering the data rates, the maximum value is 100kb/s in both streams for 100kHz BW, GMSK modulation and proper CR selection, but falls to 10kb/s at max in UL for 12.5kHz BW. OQPSK performs worse in terms of data rates; a penalty that has to be paid for the great system range it offers.

G. Wize

Different from the techniques presented so far, Wize provides, in addition to the Physical layer functionality, a full protocol stack. It also adopts the conventional LPWAN architecture; however the server-side is a data collection system called Head-End, and between the GWs and the EDs, LAN modems could be used to serve multiple EDs. The Wize protocol stack includes four layers; namely the PHY, the Data Link, the Presentation and the Application (APP) layer. Wize specification is supported by Wize Alliance and can be found in [47]. Based on this specification we describe below (following a bottom-up approach) the main aspect of each layer.

In the deployment field, the related PHY layer parameters are described in [48]. Practically, the 169MHz Industrial, Scientific, Medical (ISM) band is utilized and targets deployments in European region. Six channels are defined, each 12.5kHz wide, permitting transmissions with a power of up to 27dBm with the necessity of respecting a duty cycle of 10%. The modulation that is used is either Gaussian Frequency Shift Keying (GFSK) or 4GFSK, both with a BT product of 0.5. The former modulation can give data rates of either up to 2.4kb/s or 4.8kb/s, while the latter can go as high as 6.4kb/s. Optimal sensitivity by popular market products is achieved with the 2.4kb/s PHY layer, giving a value of -119dBm [49], resulting in a maximum link budget of 146dB.

On top of PHY layer resides the Wize Data Link layer. Two different packet formats are defined; the DL broadcasting format and the default UL/DL format. In the UL (i.e., the dominant communication direction) multiple transmissions of the same message (repetitions) are allowed to increase the

probability of message reception. Possible duplicates that may appear due to time redundancy or broadcasting nature of UL messages are resolved in Head-End. In the DL, unicasting transmissions for device-specific commands or broadcasting software update commands are sent to EDs. As in the most related systems, the DL messages are UL-initiated. Practically, this behavior can be translated into great power management device-wise, since EDs remain idle during non-UL periods (with the exception of waiting for a software update broadcasting), allowing a DL message in a small communication window only shortly after the UL broadcast.

Security aspects and metadata management are performed at the Wize Presentation layer. Regarding system's security, Wize supports both access authentication using AES Cipher-based Message Authentication Code (CMAC) for ED - GW communication and end-to-end authentication using AES CMAC. Encryption using AES Counter (CTR) mode is also provided.

The data plane of the APP layer, is related to the use case supported. Wize targets mainly smart city applications, with gas metering and water management verticals being the most adopted ones. Regardless the use case, application administration options (control plane) are offered as well.

H. Sigfox

Sigfox is one of the widely adopted non-3GPP technologies for LPWA networks, that owes its name to the namesake company, Sigfox, that first introduced the technology. A comprehensive review of the technology can be found in [50]. Based on the Sigfox set of specifications, EDs can be developed, while the server-side system is also provided by Sigfox and Sigfox Cloud. EDs communicate with BSs via Sigfox links and the backhaul communication is performed within a Virtual Private Network (VPN), via fixed cable links (Digital Subscriber Line (DSL)) as a primary solution and cellular technology as a backup. Satellite support can act as an alternative solution as well [51].

In the deployment field, Sigfox defines three power classes for EDs, according to the region that the technology is used. Currently, there are 7 region zones, named RC1-7. 1st zone consists mostly of European countries and parts of Africa and Middle East, 2nd zone includes North America and parts of South America, 3rd zone is dedicated to Japan, zone 4 covers some other countries of South America and the Asia-Pacific area and zones 5, 6 and 7 are exclusive for South Korea, India and Russia respectively. For RC1, RC3, RC6, RC7 the maximum TP is set at 16dBm, for RC5 is at 14dBm, whereas in RC2, RC4 is at 24dBm. However, TP can differ based on device class. In Sigfox, 4 device classes are defined; namely U0-U3, with U0 being the strongest and U3 the weakest. For U1 devices, TP is in the range of $[TP_{U0}-9dB, TP_{U0}-4dB]$, for U2 the range is $[TP_{U0}-14dB, TP_{U0}-9dB]$ and for U3 we have a TP below $TP_{U0}-14dB$. This TP, along with other technology parameters, allow battery powered EDs to have an autonomy at the scale of a decade.

Sigfox's frequency plan is also region based and utilizes ISM parts of the spectrum. Devices that operate in RC1 areas transmit at 868.130MHz, in RC2 at 902.200MHz, in RC3 at

923.200MHz, in RC4 at 920.800MHz, in RC5 at 923.300MHz, in RC6 at 865.200MHz and in RC7 at 868.800MHz. The total BW used in a region is 192kHz and transmission BW is only 100Hz, thus implementing an Ultra Narrow Band (UNB) scheme.

The transmission rate for Sigfox is 600b/s in the DL and either 100b/s or 600b/s in the UL, depending again on the region. RC2 and RC4 support the 600b/s data rate, while the rest of the regions allow UL transmissions of 100b/s. These data rates might seem extremely low, but in reality are sufficient enough considering the information that is transmitted and the size of the packets. In Sigfox, packets have a payload size of 0-12Bytes and a total size of 26Bytes for the UL, and a fixed payload size of 8Bytes for the DL. As a result, transmission of 26Bytes with a 100b/s rate needs only 2.08s. To transmit their messages, devices utilize the available channels in a Random-FDMA (RFDMA) scheme. EDs choose three channels in a pseudo-random fashion to transmit their message 3 times in 3 different frequencies in an effort to increase the chance of their message to be receipt by at least one BS, thus decreasing the amount of lost information and improving the QoS.

The total number of messages that an ED can send in one day depends on several parameters including the region, the payload size and the bit rate. In RC1 and RC7 a duty cycle of 1% is imposed due to regulations, in RC2 and RC4 a Frequency Hopping (FH) scheme is adopted as described earlier with the 3 times transmission approach and in RC3 and RC5 Listen Before Talk (LBT) is preferred. Shortly examining the European region case, for a 12Bytes payload (26Bytes total size) message transmissions in 100b/s with a 1% duty cycle, an ED can transmit 6 messages an hour and 140 messages a day. In DL, messages are less often and are initiated by a UL message, with DL duty cycle being at 10% and the maximum number of messages per day and per device being 4. The sensitivity of a Sigfox BS is also region depended and for a typical RC1 transmission can reach -142dBm, resulting in a theoretical link budget of 163.3dB. However, a typical link budget of 156dB can be considered reasonable.

I. LoRa/LoRaWAN

LoRa as a technology refers to the Physical (PHY) layer of the protocol stack, and more precisely, to a proprietary Chirp Spread Spectrum (CSS) modulation, that has been developed by Semtech as described in [52]. Despite being tightly connected with LoRaWAN, it should be noted that, while LoRa is the PHY layer technology, LoRaWAN is an open Medium Access Control (MAC) protocol residing on top of it and maintained by LoRa Alliance.

LoRa EDs may transmit at a maximum power of 16dBm, whereas GWs have two power classes; one defined by the same maximum TP with the EDs and the other at a maximum value of 27dBm. Chipsets built by Semtech support transmission of packets at ISM bands, on a region-depended fashion or by utilizing universally available bands, like 2.4GHz. Transmission frequencies are set by the protocol used in MAC layer. LoRaWAN, which is the main proposal in this area, defines 8 ISM regions [53], as described later. Bandwidth is also non

fixed and can be either at 125kHz, 250kHz or 500kHz in several widely used chipset implementations, while others can go down to 7.8kHz [54].

A number of LoRa parameters, like BW, might differ from one link to another, resulting in a link budget that can be adapted to each use case, with its maximum value reaching 154dB. Other parameters that can be configured in a LoRa link include CR, SF, Carrier Frequency (CF) and TP [55], which can be set in a value lower than the maximum allowed if the channel quality permits it. CF refers to the band used to carry the information and although typically adjustable, due to the extended usage of LoRaWAN protocol, the CF is dictated by deployment region. Regarding SF, the options are 6; from SF7 to SF12, while CR should be selected from the set $\{\frac{4}{5}, \frac{4}{6}, \frac{4}{7}, \frac{4}{8}\}$. Data rate is variable and can take values in the area of [0.162kb/s, 50kb/s], however LoRaWAN-based systems that implement LoRa in PHY layer can achieve data rates of up to 5.47, 11 or 21.9kb/s according to deployment region (despite Semtech chipsets having greater capabilities), whereas the maximum value of 50kb/s is achieved via Frequency Shift Keying (FSK) modulation. LoRaWAN supports also Long Range - Frequency Hopping Spread Spectrum (LR-FHSS) for some regions, with a maximum bit rate of either 0.162kb/s or 0.325kb/s, again in a region-based fashion [53].

Since LoRa operates in ISM bands, transmissions should respect the use of medium by other technologies. Common regulations regarding LoRa is the moderation of duty cycle, i.e: percentage of time that an ED is active (where active refers to transmitting), with values of 0.1%, 1% and 10% being common. Practically, duty cycle regulates the ToA of a LoRa transmitted packet for several regions. The ToA regulator role may also be performed by dwell time, whereas some regions are subjected to both regulations. Instead of duty cycle, LBT is also an option in a few occasions.

Multiple access is subjected to the protocol used above LoRa. Considering the typical case of LoRaWAN protocol, EDs are accessing the transmission medium in an ALOHA scheme with variable frame sizes [56], however its performance has been measured to be greater than ALOHA either due to SF orthogonality, other transmission characteristics (e.g., capture effect) or due to improvements suggested [57], [58]. SF orthogonality in LoRaWAN should be taken into account when discussing about multiple access due to its imperfect nature [59], [60]. Several research efforts examine different approaches to the field of multiple access [61], [62], [63], [64], [65]. DL is also permitted in LoRaWAN, either in unicast form for every ED class specified in protocol (Class A, B, C) or multicast for some ED classes (Class B, C).

J. Other LPWAN technologies

The LPWAN area is developing at such a rapid pace, that more technologies are emerging. As discussed, one of Weightless SIG proposals is Weightless-N, which is implemented by a smart cities oriented system, called Nwave [66]. Major industry players, like Sony and Amazon, offer their solutions; namely Eltres [67] and Sidewalk [68] respectively (Sidewalk operates with LoRa and/or FSK and/or Bluetooth

Low Energy (BLE)). Sensor Networks Over White spaces (SNOW) [69] is another worth considering option for LPWAN deployment, while Wi-Fi HaLow [18], [70] is gaining more and more attention. DASH7 [71] is a well-established protocol, supported by DASH7 Alliance. The interested reader can also search for alternatives like Telensa, NB-Fi, iQRF, Thingstream, Helium, SAT4M2M, Hiberband and Wi-SUN.

IV. CHOOSING THE APPROPRIATE TECHNOLOGY

A. Operational characteristics

Based on the presentation of the main LPWAN technologies, provided in the previous section, TABLE I summarizes their key characteristics. As it can be observed in TABLE I, all the technologies have a link budget of over 146dB, justifying their capabilities of covering the needs of LPWAN systems, while they share very common operational characteristics with some little variations.

B. Existing deployments

Besides the very common operational characteristics that are shared among the LPWAN technologies, four candidates are currently showing the greatest acceptance, namely: LTE-M, NB-IoT, Sigfox and LoRa. This trend is backed up by market research conducted by IoT Analytics [72]. According to their estimates, in 2019, more than 9 out of 10 LPWAN systems (92%) were deployments based on those four technologies. An analysis of how this percentage of 92% is distributed among the 4 dominant technologies is provided in Fig.5.

Fig. 5. Number of operators and countries covered by the top 4 LPWAN technologies as of July 2021

As it can be observed in Fig.5, LoRaWAN technology dominates against the other technologies, regarding both the number of LoRaWAN network operators and the number of countries with established LoRaWAN networks. Part of that domination should be attributed to cost reasons, since NB-IoT and LTE-M utilize the licensed spectrum and make use of more computing capable and energy demanding BSs, while Sigfox networks operate on a subscription-based scheme. Another reason could be the publicly available LoRaWAN protocol, which contradicts the typical approach for non-3GPP technologies. In contrary, NB-IoT seems to be a very popular option among the 3GPP technologies, which are deployed by network operators. Focusing on the Sigfox's number of operators, 23 out of the 82 depicted in Fig.5 are a Sigfox

carrier, distinguishing itself country-based (e.g., Sigfox France, Sigfox USA, Sigfox Hellas, etc.). That leads to 59 Sigfox operators that are not immediate derivatives of Sigfox.

In Fig.5 an interesting pattern can be observed as well. For the LoRaWAN technology the number of countries covered exceeds the amount of network operators, revealing the higher applicability of licence-free LPWAN technologies in cross-country deployment scenarios. Interestingly, in Fig.5 the depicted numbers of the LoRaWAN technology refer to deployments where LoRaWAN MAC on top of LoRa PHY is used, meaning that there might be even more LoRa systems established, with other protocol stacks on top of them, highlighting the lead of LoRa in the course of LPWAN PHY technologies.

C. Key performance indicators

Continuing with the study of the main LPWAN technologies, a comparison between the two main non-3GPP candidates and also between the two main candidates in general, would lead to even more conclusions. To start of, an examination of how LoRa and Sigfox perform in key IoT areas is depicted in Fig.6, as described in [19].

Fig. 6. Comparison of LoRa and Sigfox regarding IoT KPI's [19]

Fig.6 showcases the superiority of Sigfox systems in the areas of range, which is backed up by TABLE I data, where Sigfox has a slightly higher link budget; and coverage, which is justified by the widely deployed Sigfox's BSs. On the other hand, LoRa outperforms or matches Sigfox in the remaining 7 examined KPIs. LoRa is considered optimal in terms of system deployment, whereas it performs more satisfactory in terms of scalability, latency, amount of information carried in each packet and QoS. Both technologies perform the best in the areas of battery life and cost, however research conducted in [19] takes into account issues like spectrum usage, BS or GW cost and ED cost, which are in the same scale for these two technologies. Should we examine other cost factors, then

TABLE I
COMPARISON OF LPWAN TECHNOLOGIES

Technology	Modulation [UL / DL]	Multiple Access [UL / DL]	Frequency (MHz)	Bandwidth (kHz) [UL / DL]	Maximum Data Rate (kb/s) [UL / DL]	Maximum Transmission Power (dBm) [UL / DL]	Maximum Link Budget (dB)
EC-GSM-IoT	GMSK or 8PSK	TDMA, FDMA or CDMA	cellular bands	200	GMSK: 70 8PSK: 240	23, 33	164 [MCL]
LTE-M	QPSK or 16-QAM	SC-FDMA / OFDMA	cellular bands	1080 or 5000	1000 or 7000 / 1000 or 4000 (3GPP Release dependent)	14, 20, 23 (3GPP Release dependent)	155.7 [MCL]
NB-IoT	$\frac{\pi}{4}$ -QPSK or $\frac{\pi}{2}$ -BPSK or QPSK / QPSK	SC-FDMA / OFDMA	cellular bands	180	250	14, 23 (3GPP Release dependent)	164 [MCL]
MIOTY	TS-UNB	TSMA	ISM region dependent	200	0.4	14, 23.3 (region dependent)	154
RPMA	DSSS (RPMA)	RPMA	2400	1000	0.01 - 8	21 / 30 21 / 21 (region dependent)	163
Weightless-P	OQPSK or GMSK	TDMA and FDMA / FDMA	ISM region dependent	12.5, 100 / 12.5, 50, 100	10 or 100 / 100 (BW and modulation dependent)	14 or 30 / 27 or 30	153
Wize	GFSK or 4GFSK	ALOHA-like (unslotted)	ISM 169	12.5	GFSK: 2.4, 4.8 4GFSK: 6.4	27	146
Sigfox	DBPSK / GFSK	ALOHA-like (unslotted), Random-FDMA	ISM region dependent	0.1	0.1 or 0.6 / 0.6 (region dependent)	14, 16, 24 (region dependent)	156
LoRa/LoRaWAN	LoRa (CSS) or FSK or LR-FHSS	ALOHA-like (unslotted)	ISM region dependent	125 250 500	LoRa: 5.47, 11 or 21.9 (region dependent) FSK: 50 LR-FHSS: 0.162 or 0.325 (region dependent)	16 / 16 or 27 (chipset and region dependent)	154

LoRa might seem as a more attractive solution, since Sigfox is a purely subscription-based system. In reality, both LoRa and Sigfox can be commercialized, but LoRa gives the option for cost-free operation deployments.

Moving to the comparison of LoRa and NB-IoT, we can observe an interesting behavior while looking at Fig. 7 [17], [19]. It can be seen that where LoRa lacks performance, NB-IoT excels and vice versa. LoRa systems offer great coverage, are easy to deploy, cost efficient and support EDs that can operate for multiple years while being powered by simple batteries. On the other hand, NB-IoT deployments, can reach great distances, are able to scale easier, perform superbly in terms of latency and QoS offered and have a greater payload length. These indicators lead to the conclusion that LoRa and NB-IoT are more of a complementary technologies than competitors.

V. LORA/LORAWAN SYSTEMS

The combination of LoRa PHY along with LoRaWAN MAC seems to be a highly efficient and preferable solution for the establishment of LPWAN systems. This is due to the key characteristics of the underlay combined technologies, i.e., the LoRa modulation and the LoRaWAN protocol. Below the LoRa/LoRaWAN systems are further analysed.

A. Architectural view

From the architectural perspective, a star-of-stars topology is followed in the deployment of the LoRa/LoRaWAN systems,

Fig. 7. Comparison of LoRa and NB-IoT regarding IoT KPI's [17], [19]

as it can be observed in Fig. 8.

EDs are deployed in a star topology around GWs, and they broadcast their messages by using single-hop LoRa links defining the **network access side** of the architecture. GWs are deployed in a star topology around a central node, called

Fig. 8. Architecture and topology of a LoRa/LoRaWAN system

Network Server (NS). The main role of the GWs is to forward UL messages to an NS and distribute DL messages to EDs.

Once the messages arrive to an NS, packet deduplication is applied and then the data are forwarded to an Application Server for application-layer processing of the payload. For the ED to NS connection a separated authentication server can be used, called Join Server. All the entities of the **server side** of the system (Network, Application, and Join servers) can be hosted either in a single location (single point of presence) or in a distributed cloud platform.

1) *Server side*: The NS is the core component of the architecture, containing the intelligence of the deployed network. NS usually resides in a computer system with full computing capabilities, although the advancements in single board computers (like Raspberry Pi) over the recent years, has lead to NS implementations in such systems. The current trend dictates the deployment of NS in a cloud infrastructure along with the rest of architecture's server-side.

NS can be either public or private. A number of industry partners and network operators have allowed access to their public NS, with most-known solution in this area being the NS offered by The Things Network (TTN). However, in many occasions it is preferred to develop a private NS, for managing devices and applications. Solutions by TTN, Chirpstack, Lorient, ResIoT, Actility and others are widely used. These solutions might offer additional components of LoRaWAN system, like an application server, a security or authentication server, a geolocation server and a managing platform.

NS, as the central point of the star-of-stars topology (Fig. 8), is responsible for a number of operations, including: node activation, message deduplication, direct communication with applications or with the application server (should it exists), enforcing ED updates via Firmware Update Over The Air (FUOTA) messages, sending MAC commands, and the Adaptive Data Rate (ADR) algorithm. Node activation can be performed either using the Over The Air Activation (OTAA) method or the Activation By Personalization (ABP) method. Both of them are explained later.

Packet deduplication is a critical operation, since arrival of duplicate packets is a commodity. EDs transmit their messages via broadcasting. With GWs' deployment becoming denser, a

UL message can be received by more than one GWs. GWs are designed with no intelligence by default, meaning that they act as plain packet forwarders regarding the upstream traffic. As a result, duplicate packets appear in the NS, adding to its responsibilities the identification and resolution of them. Another possible way of duplicate packets appearance is the loss of ACK packets from NS to ED, i.e., an ED sends UL that requires acknowledgment, NS receives that UL and transmits ACK but ACK never reaches ED, resulting in ED re-transmitting the same UL that already exists in NS. Duplicate packets can also emerge due to QoS policy, i.e., an NS may instruct an ED to broadcast the same frame up to 15 times, in an effort to increase its reception probability; a scheme reminiscent to Sigfox's triple UL. A Received Signal Strength Indication (RSSI) deduplication policy is described in [73].

The data received by NS are destined to be used in an application. In this context, NS should be able to provide these data to applications built on top of the network infrastructure. Usually, an application server is deployed for handling such operations, which offers significant advantages i) in terms of NS performance and complexity, since NS has to communicate only with the application server and not with each application separately, and ii) in terms of system scalability, since the addition of a new application requiring a dedicated application server will have no impact on the configuration of NS other than establishing a new communication channel between it and the new application server.

Apart from UL traffic, LoRaWAN supports message transmission from NS to ED. An example of such DL traffic are FUOTA messages. FUOTA [74], a process running on the APP, allows EDs to update their firmware without the need of physical access to the device. Usually, it is supported by a firmware update server and the application server, however the distribution of the update file to EDs is performed by the NS. Another example of DL traffic are the MAC commands initiated by NS for Class A and Class B EDs, as described later. These commands may ask an ED for its state or modify its transmission parameters. For Class B EDs, there are additional beacon-related commands.

Another operation performed by NS is ADR algorithm [75]; an effort to offer the best trade-off of data rate to range for EDs, maximize the capacity of the network and minimize the need for UL ACK messages. When an ED sends UL packets to the GW, the GW forwards them to NS using Internet Protocol (IP) links. The GW does not act on the packet, but it does attach some additional information, like timestamp, RSSI value and SNR level. Based on these metadata for all UL packets from all EDs, NS can have a holistic view of the network and thus decide what is the best SF configuration for each ED.

The selection of SF follows a simple approach: for high link budget, use smaller SFs, thus increasing data rate and reducing link range, message airtime and energy consumption. The opposite is the case with low link budget, where higher values of SF have to be used to achieve longer range communication, with lower data rates and greater energy consumption. The impact of SF configuration in the discussed trade-off will become evident when the performance metrics of a LoRa link

will be presented. The underlying logic of ADR is based on the position of each ED. An ED that sends messages via a high link budget connection is either positioned in close proximity of GW or has an obstacle-free path, allowing higher data rates and better energy management, without the need of increasing link's range. On the other hand, distant EDs or EDs with established links unfavorable to successful communication with GW, have to sacrifice data rate for a more robust SF configuration.

It should be noted that this ADR scheme with fixed positioned EDs is performed by NS (network-managed); if an ED is in motion, the notion of Blind ADR is utilized [76]. In general, non-stationary EDs decide whether to implement ADR or not, since they have greater knowledge on the current link state compared to the NS. For high mobility EDs, ADR is preferably disabled due to highly variable communication channel. Valuable insights in ADR are given by [77] and [78], whereas an extensive discussion on the topic and the different implementations of ADR can be found in [79].

2) *Network access side*: EDs and GWs are the components of the access part of the architecture. EDs are usually small-sized, energy-constrained devices with low computing capabilities. These characteristics are imposed by the need to be cost-effective, since they are deployed in massive numbers. EDs can be stationary or perform operations while on move.

Typical building blocks of an ED are: the power unit, the radio module, the memory block, the processor and the sensor(s). EDs can either rely on a fixed power scheme for their operation or be battery-operated. The latter approach is usually preferred, although recent proposals discuss the utilization of small solar panels on top of EDs as a main or supplementary energy solution, towards the realization of energy harvesting WSNs. The radio module has the greatest energy needs relative to other operations like sensing and acting, and as a result the selection of the suitable radio technology and a careful transmission planning are considered essential. An antenna is another component of an ED, but it is common to be considered as a part of its radio interface. In market devices, antenna can be printed.

A memory unit in the order of few MBs or even KBs is considered adequate for satisfying the needs and the constraints of such a device. The processor of an ED has rather limited capabilities compared to modern processors used in home or enterprise computing systems, but is sufficient enough for an ED and its required operation. Finally, an ED may have multiple sensors, being able to perform several measurements, varying from temperature sensing to position awareness. Sensing is the main operation of EDs, hence the WSN characterization of the access part of IoT systems. The main modules of an ED can be observed in Fig.9. A more sophisticated view of a smart sensor's architecture can be found in [24] and [80]. Recent advancements in microelectronics have lead to the development of chips that can incorporate both radio transceiver and microprocessor for LoRa EDs².

Fig. 9. Main modules of an LPWAN ED

As for GWs, they rely on a fixed power source for their operation. They also have a radio module for LoRa communication, however several other network interfaces, which can be either wireless (e.g., cellular, IEEE 802.11) or wired (e.g., Ethernet) may be a GW component. Of course, an antenna is present, usually being significantly more powerful than EDs' antennas. Computing capabilities are higher than that of EDs. A GW can receive and decode messages by more than one EDs and more than one GWs may receive the messages broadcast by an ED. GWs can receive simultaneously data in different frequencies and different SFs.

B. Protocol stack view

The LoRa/LoRaWAN protocol stack fits to the main elements of the architecture as described in Fig.10. In Fig.10 the well-known layers of Open Systems Interconnection (OSI) stack, used both for the IP communication between the GW and the network side internal communication, are also depicted.

1) *Server side*: It is apparent that NS participates in both data and control flows. NS's functionality starts by receiving from GW an APP payload encapsulated in a LoRaWAN frame, which is encapsulated in appropriate types of packets regarding the rest of the OSI protocol stack (L4 to L1). NS performs the necessary decapsulation and according to the type of the message, either it remains in NS (control messages that are not related to authentication actions, and application messages in an architecture that does not include an application server) or it is further forwarded to the server-side: i) to an application server (data flow) or ii) to a join server (authentication-related control flow). The reverse order of encapsulation and decapsulation takes place in DL messages.

A key observation is that LoRaWAN resides above transport layer in NS; that is expected since GW to NS and vice versa communication is achieved via links that transfer APP messages encapsulated in transport layer protocol segments (User Datagram Protocol (UDP) is preferred), encapsulated in NET layer protocol datagrams (IP), encapsulated in Data Link layer protocol frames (Ethernet, cellular, IEEE 802.11). A complete definition of system's backend is given in [81].

2) *Network access side*: The stack in an ED is simpler than that in NS, as expected. In the case of information belonging to data flow, an APP message is encapsulated in a LoRaWAN MAC frame, which is then encapsulated in a LoRa PHY packet to be broadcast via the LoRa radio interface. The broadcast LoRa packets are received by a GW, which performs decapsulation operations to extract the APP payload. The extracted payload is placed in a typical transport layer protocol

²https://www.thethingsnetwork.org/article/breaking-down-stm32wl-the-central-element-of-generic-node-sensor-edition-and-first-dual-core-lorawan-system-on-chip-soc?mc_cid=57d7f74b8f&mc_eid=8698751288, Accessed: 04 October 2021

Fig. 10. LoRa/LoRaWAN protocol stack mapped in the main elements of the architecture

segment, then it is encapsulated in an IP datagram, and finally, it is encapsulated in the desired Data Link layer protocol frame (Ethernet, cellular, IEEE 802.11) to be transmitted to NS. The reverse operation takes place during DL. For control flow information the APP-related encapsulation and decapsulation may be skipped.

Fig. 11. Protocol stack at a LoRaWAN-enabled End Device [56]

More precisely, at the ED side, the protocol stack can be seen in Fig. 11 [56]. A 4-layer stack can be observed, namely the APP, the LoRaWAN, the Regional Parameters and the PHY, which practically can be narrowed down to 3 layers since the Regional Parameters (TABLE II) actually defines which PHY can be supported at which bands. In the PHY layer, LoRa modulation is the main choice. The FSK modulation is supported as well, based on [53]. LR-FHSS [82] is also an option. On top of the PHY, LoRaWAN MAC layer describes 3 device classes, which define the available DL windows and ultimately determine the power consumption scheme of ED.

TABLE II
LORAWAN FREQUENCY PLANNING BASED ON DEPLOYMENT REGION

Region	Frequency band (MHz)	Abbreviation
Europe & some African countries	863 - 870, 433	EU868, EU433
North America	902 - 928	US915
China	779 - 787, 470 - 510	CN779, CN470
Australia	915 - 928	AU915
Asia	923	AS923
South Korea	920 - 923	KR920
India	865 - 867	IN865
Russia	864 - 870	RU864

The full frequency plan documentation can be found in [53]. In Europe, no plan for the use of the EU433 band exists. On the other hand, EU868 is used extensively for LoRa transmissions. In all regions other than US915 and AU915, 16 communication channels may be used with 3 of them being mandatory to implement, since they can be used for ED join-request messages. In TABLE III, the mandatory channels of EU868 for UL transmission are depicted.

TABLE III
EU868 MANDATORY CHANNELS FOR UL TRANSMISSIONS

Channel (MHz)
1. 868.1: LoRa (SF7BW125 up to SF12BW125)
2. 868.3: LoRa (SF7BW125 up to SF12BW125, SF7BW250)
3. 868.5: LoRa (SF7BW125 up to SF12BW125)

Regarding DL transmissions, the same channels as UL transmissions may be available, however the default DL channel is set at 869.525MHz (LoRa, SF9BW125), which permits transmission for GWs operating in higher TP, 27dBm (0.5W).

On top of LoRaWAN MAC layer stands the APP. This is where the applications that are built on top of LoRaWAN infrastructure reside, utilizing the services offered by the layers

below. A number of use cases can be discussed on this area, and protocols intriguing to be studied do exist. LoRa Alliance has established 6 Working Groups (WGs), that are responsible for the further development of the according vertical sectors. These include all the familiar "smart" applications like agriculture, buildings, cities, industry, logistics and utilities [83].

VI. AN OVERVIEW OF THE LORAWAN MAC PROTOCOL

LoRaWAN is an open protocol being developed by LoRa Alliance. The protocol is officially defined as:

"LoRaWAN[®] specification is an LPWA networking protocol designed to wirelessly connect battery operated 'things' to the internet in regional, national or global networks."

LoRa Alliance is an association that has been established since 2015, having Semtech as a founding member and being supported by numerous industry players. More on LoRa Alliance can be found in the corresponding website [84].

A. LoRaWAN device classes

The main characteristic of the LoRaWAN layer is the establishment of 3 device classes; namely Class A, Class B and Class C. An ED has to transmit in a scheme described by one of these 3 classes in order to be considered as a LoRaWAN device.

Class A stands for *All*, meaning that all EDs have to be able to implement at least this class to perform LoRaWAN transmissions. Class A defines two open DL windows with a maximum of 15s and 16s delay respectively after a UL transmission (typical values are 1s and 2s or in case a join-request UL message has been preceded 5s and 6s), in which an ED may receive messages from NS for data or control reasons. The 2nd receive window opens in case there was no successful reception during the 1st window. Regarding the UL, Class A EDs can transmit either a data message, a MAC command (initiated by ED or an answer to a previous NS-initiated MAC command) or a combination of them. The transmission scheme can be seen in Fig.12.

Fig. 12. LoRaWAN Class A

Class B stands for *Beacon*, meaning that EDs open additional receive windows, based on synchronization beacon frames that are sent either from NS to ED via GW or directly from GW to ED. Differentiating from Class A, messages received in Class B's supplementary DL slots can be only data-related, however additional Class-B specific MAC commands exist that are sent by NS to ED during Class A receive windows. For UL, again there is a set of MAC commands available either as an ED-originated request or as an answer to an NS-originated MAC request. Class A to Class B switching decision originates from ED's APP layer. The transmission scheme can be seen in Fig.13.

Fig. 13. LoRaWAN Class B

Class C stands for *Continuous*, meaning that an ED implementing Class C approach is constantly waiting for DL transmissions between its UL transmissions. Class C adds no extra MAC commands and any of Class A MAC commands have to be transmitted in the related available windows and not in the continuous reception window. Should an ambiguity occur with a Class A receive window and Class C continuous reception in a Class C-enabled ED, Class A DL messages are prioritized. If a Class A successful reception took place in the 1st window, no 2nd window is opened, as mentioned earlier, meaning that the continuous DL window will take its place. The transmission scheme can be seen in Fig.14.

Fig. 14. LoRaWAN Class C

Naturally, Class A is the best option power-wise, but forces the NS to wait for the next UL transmission if it can't be served by the two open windows. On the other hand, Class C reduces latency for NS to ED communication and practically communication ceases being UL-initiated (except for the first transmission which must be a UL), but ED has to be ready to receive DL messages all the time, resulting in greater energy demands. Class B stands in the middle point of Class A and Class C.

B. LoRaWAN messages & node activation

Using the functionality offered by the lower LoRa PHY layer, LoRaWAN formats its packets to support message exchange between EDs and GW. The format of LoRa PHY layer packet is discussed on the corresponding section. The format of the LoRaWAN MAC frame can be seen in Fig.15.

Fig. 15. LoRaWAN frame format

The frame has three main fields. *MHDR* field is the header field for MAC layer, the payload of MAC layer resides inside the *MAC Payload* field and the *MIC* field stands for Message Integrity Code. In the latter field, the MIC is calculated using the fields of the frame and AES CMAC algorithm. Considering the *MAC Payload* field, it may either include the payload of a message, *Join-Request/Join-Accept* messages for EDs trying

Fig. 16. Packet encapsulation in LoRaWAN

to join the network or other MAC commands. In Fig.16, a deeper view of packet encapsulation process in LoRaWAN is given³.

An extensive analysis of each field is not in the scope of this paper. The interested reader can find more in official documentation [56]. In this context, we focus on the 3-bit *MType* field in an effort to present the different types of messages supported by the protocol. In LoRaWAN, 8 types of messages are supported as shown in TABLE IV.

TABLE IV
MESSAGE TYPES SUPPORTED BY LORAWAN

MType field	Message Description
000	Join-Request
001	Join-Accept
010	Unconfirmed Data Up
011	Unconfirmed Data Down
100	Confirmed Data Up
101	Confirmed Data Down
110	Reserved (v1.0.x) / Rejoin-Request (v1.1)
111	Proprietary

Messages with an *MType* field value of 010 and 011 represent UL and DL traffic with no ACK respectively. An *MType* field of 100 and 101 is used for UL and DL messages that require ACK. 111 value is proprietary, in a sense that it can be used to describe messages that do not follow the standard format. Messages 000, 001 and 110⁴ are used for activation of ED via OTAA process.

In LoRaWAN two activation processes are distinguished: OTAA and ABP. In OTAA, ED has to first be "personalized", meaning that a device ID, called *DevEUI*, a join ID, called *JoinEUI*⁵ and an application key, called *AppKey* have to be

defined. With these values set, ED can send a *Join-Request* message with *DevEUI* and *JoinEUI* values included in it along with a *DevNonce*. Should the network accept this request, NS sends a *Join-Accept* message, consisted of the fields of *JoinNonce*⁶, *NetID*, *DevAddr*, *DL settings*, *Rx delay* and optionally a channel list field relevant to transmission regulations in each area. With these fields and the *AppKey* value, the *NwkSKey* and *AppSKey* can be derived using AES 128. These keys are used for security purposes as described at the end of this LoRaWAN section. The OTAA process is described in Fig.17.

Considering ABP procedure, the join accept/request messages are bypassed and the user stores directly to ED the required keys and device address. As a method, it might seem simpler, but has two serious drawbacks. Firstly, the ED is associated with the specific network through which has been activated. Secondly, the keys are derived by the user, which involves the danger of non-careful selection of them, thus risking the security of the device or even of the entire WSN⁷.

After successful activation of the device with either of these two methods, *DevAddr*, *NwkSKey* and *AppSKey* are set to ED.

C. Security in LoRaWAN

In LoRaWAN, security is provided via the use of two of the keys described in the previous subsection; namely *NwkSKey* and *AppSKey*. *NwkSKey* stands for Network Session Key, although it refers to security aspects in LoRaWAN MAC. *NwkSKey* is used by ED and NS for encryption and decryption processes of the LoRaWAN MAC payload, as well as for ensuring integrity (*MIC* field in frame format). On the other hand, *AppSKey*, an abbreviation of Application Session Key,

³In DL messages the field of *Payload CRC* (*PL CRC*) does not exist.

⁴In Specification version 1.0.x, 110 value is described as RFU, meaning Reserved for Future Use. In Specification version 1.1, 110 value is used for Rejoin-Request messages by the ED.

⁵To avoid confusion, in older versions of the protocol *JoinEUI* is mentioned as *AppEUI*. As of 1.0.4 and 1.1, versions the former nomenclature is adapted.

⁶To avoid confusion, in older versions of the protocol *JoinNonce* is mentioned as *AppNonce*. As of 1.0.4 and 1.1 versions, the former nomenclature is adapted.

⁷Due to the importance of that risk, [56] emphasizes the necessity of proper key derivation.

Fig. 17. OTAA sequence diagram (ED: End Device, GW: Gateway, NS: Network Server, JS: Joint Server, AS: Application Server)

is used for encryption and decryption processes regarding the APP payload.

It can be inferred that encryption is guaranteed end to end, but that is not the case with integrity. Encryption is vital for network's sustainability, due to the broadcasting nature of UL transmissions that can be captured by any GW in proximity; even GWs that are not part of the system. On the topic of integrity, NS is considered as a trusted entity in general, however a user may implement additional confidentiality and integrity mechanisms for the applications. A reference on the topic of system's security in a LoRaWAN deployment can be found in [85]. Even broader discussions encompassing the entirety of IoT field can be found in [86], [87].

VII. AN OVERVIEW OF THE LORA MODULATION

In contrast to LoRaWAN, LoRa is a proprietary PHY layer modulation being developed by Semtech. Its definition follows:

"LoRa® is a modulation technique, suitable for interconnecting things with energy constraints in long range wireless environments, with low needs of data rate."

LoRa development as a technology started from a French company called Cycleo and eventually was patented by O. B. A. Seller and N. Sornin [88], [89] with Semtech assignee. Cycleo was acquired by the USA-based company named Semtech, in 2012. Since then, LoRa is maintained and developed by Semtech. A brief history of LoRa can be found in [90].

A. Implementation of LoRa in chipsets

Semtech is responsible for the development of chipsets that are capable of interconnecting EDs with GWs, via an established LoRa link. A number of chipsets are in use today

inside LoRa EDs; families of SX1261/62/68, SX1272/73, SX1276/77/78/79 are considered the most common, LLCC68 is the preferable option in smart home applications due to lower maximum link budget and worse receiver sensitivity and SX1280/81 is a chipset that can offer LoRa connectivity in the 2.4GHz band. These chipsets can be found inside LoRa modules built by other hardware manufacturers, like Microchip Technology (RN2483 is one of the most widely used modules and is based on SX1276/77/78/79 family), Murata Manufacturing (its CMWX1ZZABZ-078/-093 module uses SX1276 chipset), STMicroelectronics, HopeRF, Gemtek, AcSiP and others. A comparison among Semtech's chipsets can be found in TABLE V. Values of TABLE V are nominal, as provided by Semtech.

On the area of GWs, a number of chipsets are also available. SX1250, which works along with SX1302, SX1255/57/58 (frequency: 400MHz-510MHz / 860MHz-1000MHz / 779MHz-787MHz), SX1301, SX1302, SX1308 are common options. Major companies develop their own GWs based on these chipsets, like Cisco (GW based on SX1301), Kerlink, Multitech and others who are operating in this field.

B. Performance metrics of a LoRa link

The main metrics regarding a LoRa link are the maximum achievable bit rate and the maximum range supported. The former can be calculated by taking into account 3 of the key performance factors (SF, CR, BW), while the latter is depicted in receiver's sensitivity or link budget equations and is related to the 4th factor (TP). For the interested reader, Appendix A provides a further mathematical definition of BW, SF, chirp and chip in the context of LoRa. The bit rate of a LoRa link is given by the formula:

$$R_{b(b/s)} = SF * RateCode * \frac{BW_{(Hz)}}{2^{SF}} \quad (1)$$

The fact that R_b is proportional to SF linearly and inversely proportional with it in an exponential way, leads to the conclusion that an increase of SF will have a negative impact on data rate. On the other hand, regarding the receiver's sensitivity we have the following formula:

$$S_{(dBm)} = -174 + 10 * \log_{10}(BW_{(Hz)}) + NF_{(dB)} + SNR_{(dB)} \quad (2)$$

where BW is the bandwidth in Hz, NF is the receiver Noise Figure in dB (which for certain LoRa implementations can be fixed at 6dB) and SNR is the signal to noise ratio threshold for a given spreading factor in dB.

The opposite is the occasion with receiver's sensitivity. An increase of SF will lead to a lower receiver sensitivity threshold, leading to a receiver being able to decode signals received with less power. The relationship between sensitivity and SF is not clear in equation 2, but can be derived when examining equation 3. In LoRa, 6 SFs are in use, from SF7 to SF12 and the selection of SF defines the value of SNR threshold. Interestingly, all the nominal values of SNR threshold are negative, which reveals another benefit of LoRa: the fact that receiver can decode signals even below the noise floor.

$$SNR_{threshold(dB)} = -7.5 + (7 - SF) * 2.5 \quad (3)$$

TABLE V
COMPARISON OF LoRa CHIPSETS BY SEMTECH

Feature Chipset	Frequency (MHz)	Maximum Transmission Power (dBm)	Rx Sensitivity (dBm)	Maximum Link Budget (dB)	Supported Modulation	Bit Rate (kb/s)
LLCC68	150 - 960	22	-129	151	FSK, GFSK, MSK, GMSK, LoRa	Programmable bit rate from 1.76 up to 62.5 LoRa and 300 FSK
SX1261/62/68	150 - 960	22	-148	170	FSK, GFSK, MSK, GMSK, LoRa	Programmable bit rate up to 62.5 LoRa and 300 FSK
SX1272/73	860 - 1000	20	-137	157	FSK, GFSK, MSK, GMSK, LoRa, OOK	Programmable bit rate up to 300
SX1276/77/78/79	137 - 1020 137 - 525 (for SX1278)	20	-148	168	FSK, GFSK, MSK, GMSK, LoRa, OOK	Programmable bit rate up to 300
SX1280/81	2400	12.5	-132	144.5	LoRa, FLRC, (G)FSK	Programmable

$$P_{Rx(dBm)} = P_{Tx(dBm)} + SystemGains_{(dB)} - SystemLosses_{(dB)} - ChannelLosses_{(dB)} - M_{(dB)} \quad (4)$$

The relationship between sensitivity and SF has an impact on the potential range of the system, since a lower sensitivity threshold permits an ED to communicate with a more distant GW. The trade-off of range and bit rate can be quantified through equations 1-3.

Moreover, link budget can be defined by calculating the expected power on the receiver's end as described in equation 4, where P_{Rx} is the expected power in receiver's end in dBm, P_{Tx} is the transmitted power in dBm, $SystemGains$ is the gain in link's ends in dB (practically Tx and Rx antenna gains), $SystemLosses$ is the loss in link's ends in dB (practically loss due to connection of antennas to radio modules via e.g., wiring), $ChannelLosses$ is the loss in link's channel in dB (practically referring to all the phenomena affecting wireless signal transmission, i.e., reflection, refraction, diffraction, scattering and absorption) and M is the fading margin in dB. We can also calculate the link budget of a link with respect to transmitted power and receiver sensitivity, as follows:

$$P_{Rx(dBm)} = P_{Tx(dBm)} - S_{(dBm)} \quad (5)$$

A visualization of the inversely proportional and proportional relationship between SF and bit rate, and SF and range respectively is given in Fig.18. Naturally, an increase of SF results in linear increase of system's range, whereas the decrease of supported data rate is exponential.

Ending this quantitative section, we examine the regulations of ISM transmission by exploring the concepts of ToA and duty cycle. LoRa as a technology utilizes the ISM bands in a region-based scheme, although chipsets that support globally free bands like the 2.4GHz exist. Due to the use of these bands, LoRa links have to comply with a number of regulations:

- change transmission channel in a pseudorandom fashion in every transmission,
- respect the maximum duty cycle (or dwell time) and the maximum transmitted power (Effective Isotropic Radiated Power (EIRP) and Effective Radiated Power (ERP)),

Fig. 18. Trade off between data rate and range (BW = 125kHz)

Compliance to these regulations is necessary, since a plethora of technologies reside in ISM bands. Focusing on European region, the duty cycle imposes the maximum time allowed to transmit, with common maximum values being 0.1%, 1% and 10%. In North American region, dwell time is the regulated value.

The structure of a LoRa PHY packet can be viewed in Fig.19.

Fig. 19. LoRa packet format [54]

A *Preamble* being transmitted in the form of a number of up-chirps followed by two and a quarter down-chirps indicates the start of the packet. After that, the *Header* and *CRC* fields are included if explicit mode is used. The size of these fields depends on CR, and a typical rate code of $\frac{4}{5}$ with an 8Bytes *Payload* plus *Payload CRC* field size, would result on a combined size of *Header* and *CRC* of 2Bytes. In the example of Fig.19 packet formatting, we observe that the size

$$T_{payload} = T_s * \{SW + \max[\text{ceil}(\frac{8 * PL - 4 * SF + 28 + 16 * CRC - 20 * H}{4 * (SF - 2 * DE)}) * (CR + 4), 0]\} \quad (9)$$

$$ToA = \frac{2^{SF}}{BW_{(Hz)}} * \{\{n_{preamble} + 4.25\} + \{SW + \max[\text{ceil}(\frac{8 * PL - 4 * SF + 28 + 16 * CRC - 20 * H}{4 * (SF - 2 * DE)}) * (CR + 4), 0]\}\} \quad (10)$$

of Header and CRC fields are half the size of Payload and Payload CRC, indicating a CR of 4. The *Payload* field includes the payload information that the ED broadcasts, assuming a UL transmission.

Based on Fig.19, the transmission time of a PHY layer packet can be split in the time needed for preamble and the time needed for payload. We can easily infer that ToA will be:

$$ToA = T_{preamble} + T_{payload} \quad (6)$$

The formula for calculating $T_{preamble}$ is given by equation 7:

$$T_{preamble} = (n_{preamble} + 4.25) * T_s \quad (7)$$

where $n_{preamble}$ is fixed for EU868 band in 8 symbols and T_s is transmission time for one symbol, as expressed in equation 8 and derived in Appendix A (equation A5):

$$T_s = \frac{2^{SF}}{BW_{(Hz)}} \quad (8)$$

On the other hand, the time to transmit payload is given by equation 9, where T_s is the time for a symbol transmission in s, SW is synchronization word and has a fixed value of 8, PL is the number of payload bytes, SF is the spreading factor, CRC is a one-bit flag that can be set at 1 if the used protocol above is LoRaWAN, H is the header type as discussed in Fig.19 (0: explicit, 1: implicit), DE is a one bit flag that notifies for low data rate optimization when SF11 or SF12 is used (0: high data rate, 1: low data rate) and CR is coding rate.

Finally, equation 10 provides the total ToA, taking into consideration equations 6, 7, 8 and 9.

Having regulated the percentage of time that an ED can transmit, we clearly see a pattern being shaped in UL transmissions. A node can transmit, then it has to wait for at least a minimum amount of time during which it may or may not receive DL messages and after that it can re-transmit. We refer to this waiting time as $T_{interval}$. If we examine the relationship between ToA and $T_{interval}$ and taking into account the regulation about duty cycle, we have:

$$T_{interval} = \frac{ToA}{DutyCycle} - ToA \quad (11)$$

This results in $T_{interval}$ being orders of magnitude greater than ToA .

VIII. RESEARCH ON LORA/LORAWAN SYSTEMS

There are various open research topics related to the implementation, usage, and optimization of the LoRa/LoRaWAN networks [91], [92]. The major ones are listed below:

- Power consumption, energy management and lifetime of the system (e.g., [40])

- Range management and link-level behavior (e.g., [14])
- Network performance validation and evaluation metrics (e.g., [12])
- Multiple Access (e.g., [58])
- Security in PHY, MAC and NET layers (e.g., [93])
- ADR algorithm (e.g., [77])
- ED mobility support and roaming (e.g., [78])
- Optimal GW placement and localization challenges (e.g., [94])
- Data-based decision making by incorporating Machine Learning (ML) (e.g., [95])
- Meeting recent advancements from Information Technology (IT) and Telco domains, e.g., Software-Defined Networking (SDN), Blockchain and network slicing (e.g., [96])

The research work on addressing challenges related to the above-listed topics includes approaches for all the well-known steps in research methodology [97], [98]; namely: mathematical analysis, simulation study, and real-life system implementation.

TABLE VI
LIST OF RELATED SURVEYS

Target of the Survey and Tutorial	References
IoT	[2] (full overview), [5] (definitions and characterization), [10] (IIoT full overview), [38] (full overview with focus on specific vertical), [87] (security aspects), [99] (Blockchain applicability), [100] (Blockchain applicability), [101] (technologies & verticals), [102] (DT full overview), [103] (DT full overview), [104] (DT full overview), [105] (DT full overview), [106] (IIoT edge computing), [107] (IIoT security aspects)
WSN	[24] (full overview), [97] (WSN evaluation methodology)
LPWAN	[13] (LoRa & Sigfox comparison), [15] (comparison, verticals, research challenges), [16] (design considerations, comparison, research challenges), [17] (LoRa & NB-IoT comparison), [18] (overview, comparison, research challenges), [19] (Sigfox, LoRaWAN & NB-IoT comparison), [20] (LoRaWAN, DASH7 & NB-IoT comparison and mobility support), [21] (verticals, comparison), [22] (full overview), [45] (ISM LPWAN security aspects)
LoRa/LoRaWAN	[79] (ADR algorithm), [82] (LR-FHSS), [85] (LoRaWAN v1.1 security aspects), [91] (LoRa research challenges), [92] (LoRaWAN full overview), [98] (LoRa research challenges), [108] (full overview), [109] (LoRaWAN full overview), [110] (LoRaWAN simulators)

A set of surveys has also been published ([2], [5], [10], [13], [15]-[22], [24], [38], [45], [79], [82], [85], [87],

[91], [92], [97]-[110]) examining IoT, WSN, LPWAN and LoRa/LoRaWAN from various perspectives, one of which is the research challenges. This set of publications is summarized in TABLE VI. Indicative research contributions that target specific problems and challenges are studied in the following subsections.

A. Analytical approaches

The first step towards the study of LoRa/LoRaWAN networks is to evaluate the performance and the behavior of the system using mathematical tools. Such tools include but not limit to methods like: calculation of performance metrics in probabilistic manner and comparison with well-known results (e.g., performance of LoRaWAN throughput in comparison with protocols like ALOHA, Carrier Sense Multiple Access (CSMA) and variations of them), modeling of the system with stochastic tools under various scenarios and assumptions (e.g., Poisson process, Markov process, stochastic geometry) and others.

In [60], the authors provide an analysis for the probability of successful UL transmissions when taking into account co-SF interference, inter-SF interference or both of them. The imperfect orthogonality of SF is proven to affect UL LoRa links. In [78], a statistical approach to the effect of SF selection and different levels of mobility in ADR is presented. The authors gather UL data based on a real testbed and with these data they perform a Kruskal-Wallis non-parametric test. Their analysis exposes a high correlation between SF selection dictated by Blind ADR and performance, especially in lower mobility experiments (p-value is always at least at 2 significant digits between increment pairs of SFs).

The modeling of interference in LoRa networks either in the form of inter-SF or in the form of intra-SF is of great interest. For the latter case, the authors in [111] derive an interference model based on their proposal for a coherent LoRa transceiver. They calculate the necessary expressions for Symbol Error Rate (SER) and Frame Error Rate (FER) utilizing the Discrete Fourier Transform (DFT). Due to heavy computational complexity, they also use Q-functions for approximation purposes and later they compare their theoretical model with simulation results for the typical non-coherent transceiver and their proposed coherent one. In [112] the performance of CSS is examined in regard to SF orthogonality with the derivation of closed form expressions, whereas in [113] the author gives insights in LoRa modulation examining it by a quantitative signal processing perspective, while also coming up with an optimal receiver based on Fast Fourier Transform (FFT). Results are drawn by comparing the optimal receiver with the typical FSK modulation in terms of BER versus SNR.

In [114], the authors propose their own MAC solution in order to alleviate the low Packet Delivery Ratio (PDR) problem of pure ALOHA-based approach in LoRaWAN. They name their protocol Lightweight Carrier Sensing (LCS) and evaluate it by comparing it with pure ALOHA in a three-fold way: mathematical approach, simulation and small scale implementation. LCS has two main features: i) a hardware

level "hearing" mechanism, which is called Channel Activity Detection (CAD), and ii) a packet drop mechanism when the channel is sensed busy instead of random backoff. For the initial evaluation part, they derive a probability model for the PDR of their mechanism and compare it with the known PDR of pure ALOHA. The results showcase a considerable improvement in PDR for the proposed mechanism over pure ALOHA, especially for large numbers of EDs. Another MAC suggestion can be found in [65], where the alternative of slotted ALOHA is discussed. The proposed protocol is based in FM-RDS broadcasting for time dissemination and the authors explore the applicability of the protocol in all 3 possible research steps. For the mathematical approach, they derive closed form expressions for Type-A and Type-B uncertainty of the transmission time of packets, which is caused due to a packet moving among the stacks of the entire protocol stack inside a node.

In [115] the authors present an analytical approach to the topic of LoRa networks scalability based on stochastic geometry. In essence, their efforts target the derivation of closed form expressions for outage probability regarding to two events: i) the event of a packet having SNR below the required threshold in the receiver, and ii) the event of less than 6dB difference between the interested signal and the interferers (practically capture effect). For these two events the probabilities are calculated and the results are further validated with Monte Carlo simulations. In [116], the OTAA activation mechanism of Class A EDs in LoRaWAN is evaluated. The authors formulate the problem as a discrete time Markov Chain (MC) and derive the transition probabilities for all the possible transitions between states, in an effort to estimate the energy that an ED consumes when it tries to get activated and the delay that exists until successful activation.

Reference [117] examines the topic of energy harvesting in the more general context of WSNs, providing analytical expressions for power consumption and throughput of the system when realistic assumptions are taken, such as battery inefficiencies. To provide these analytical expressions, the authors formulate the problem as a Markov Decision Process (MDP). In [118], the same problem of energy harvesting is discussed, but this time in specific for LoRaWAN systems. An MC model is presented and results are drawn regarding PDR for Class A EDs. These results are later compared to simulation experiments. Energy issues are also discussed in [119], in which the authors derive analytical expressions for energy consumption, ED lifetime and energy cost for different types of UL transmissions, and propose their own energy models. Their analysis is based on measurements from an experimental testbed, as described later. The same approach can be found in [80]; a derivation of analytical expressions for energy consumption. These expressions are validated through simulations and the results are discussed further in the corresponding simulation studies subsection that follows.

A resource allocation framework based on a Network Slicing scheme orchestrated by a Deep Federated Reinforcement Learning (DFRL) system architecture is presented in [95]. The authors focus their efforts on providing different network slices for Industrial IoT (IIoT) use cases. The slices are

allocated thanks to GWs acting as agents, TP and SF acting as environmental parameters and QoS being the reward that needs to be maximized, according to the typical agent–environment interaction in reinforcement learning problems [120]. The algorithm that is developed maximizes the QoS reward, which can be interpreted as slice delay, energy consumption, throughput and Packer Loss Rate (PLR).

Network slicing for resource allocation purposes is also considered in [96]. The authors distinguish application scenarios according to their QoS needs in 3 slices and formulate the problem of network slicing for each ED with a game theoretic approach. The slicing is performed in a distributed way at the GW level. 3 games are designed: the first one between GWs for cell edge EDs assignment, the second for physical channel reservation for each slice in each GW and the final for channel assigning in each ED of each slice for each GW. Both the former and the latter game are designed as matching theory problems (one-to-many and one-to-one respectively), whereas the second game is formulated as a bankruptcy game. Their model is further validated via simulations as explained in the next subsection.

B. Simulation studies

Simulation-based research dominates the area of WSNs and consequently LPWANs, due to simulators capability to support experimentation with crowded networks. To this end, numerous simulation environments can be utilized, with main considerations being the ones presented in a comprehensive overview in Section IX later. This subsection presents indicative research work conducted with the aid of LoRa/LoRaWAN dedicated simulators as well as other, yet more generic network simulation frameworks like OMNeT++ and NS-3.

In [12], the authors develop a simulator to compare LoRaWAN capacity with pure ALOHA, with the results depicting an equivalent performance of the two protocols. Further tests they perform, are based on a testbed as described in the corresponding section that follows. In [40], a comparative study is provided for several LPWAN solutions, with LoRa being among them. The study includes simulations conducted in Matlab with realistic assumptions, in an effort to estimate the performance of all of these solutions in terms of coverage and energy consumption and consequently the impact on EDs' lifetime. In [58], the authors quantify the throughput of pure ALOHA, which is supposed to be the multiple access mechanism performed by LoRaWAN. They also propose a slotted ALOHA mechanism built in top of LoRaWAN protocol and based in a synchronization procedure, in an effort to improve throughput. To validate their results they conduct Matlab simulations and real testbed experiments as described later. In [59], the authors develop two endpoints of a LoRa transmission (a modulator and a demodulator) in Matlab, in an attempt to estimate the impact of SF's imperfect orthogonality in BER and Packet Error Rate (PER) with respect to Signal to Interference Ratio (SIR), for various combinations of useful transmissions' SF and interferers' SF.

The analytical results provided in [60] are further validated with simulations that extract system throughput under different

conditions. Simulation details are given, but no further elaboration on the simulation environment is available. In [80], the authors propose an energy model for LoRaWAN EDs and validate their model via simulations. Again, simulation details regarding the environment are not given, however the parameters of the tested scenarios are provided. Results follow intuition regarding the effects of SF and CR selection on the energy consumption, the relationship between range and energy consumption and the most demanding tasks energy-wise for an ED. Regarding the topic of multiple access, a proposal can be found in [62], in which a variant of CSMA/Collision Avoidance (CSMA/CA) is examined as an option, instead of pure ALOHA that LoRaWAN is thought to be. Experiments in crowded OMNeT++ simulations are performed, which reveal a sizeable improvement in successful packet reception and consequently system's throughput.

In [55] a discrete event simulator based on Python is described, called LoRaSim. The simulator is used to obtain results that are related to scalability potential of a LoRa system and Data Extraction Rate (DER); a metric that compares the total number of received messages to the total number of sent messages. The discrete event simulator of LoRaSim is used and modified extensively and one such example is [63], where a new MAC layer approach is examined, called MAC on Time (MoT). The authors compare their proposed protocol, which is a combination of TDMA and contention-based schemes, with the ALOHA-based LoRaWAN protocol. The results reveal a superiority of MoT both in throughput and in latency performance metrics. Moreover, in [121] the same simulator is used for DER measurements and the impact that directional antennas on EDs and an increase on the number of GWs may have on the topic of interference scaling. In [122] the LoRaSim simulator is extended with MAC layer considerations, as described in the corresponding subsection of the simulator (Section IX). Results include evaluation of successful transmissions as goodput and energy consumption, while insights on the impact of ACK packets in LoRaWAN systems scaling are given.

The same extended simulator is used to evaluate the ADR algorithm described in LoRaWAN 1.1. The study in [77] reveals a slow convergence of the algorithm, which deteriorates the energy consumption and PDR. A further extension, called LoRaEnergySim, is provided in [123], where realistic assumptions are taken regarding energy consumption and results are drawn for both energy and DER. The same simulator (LoRaEnergySim) with the necessary modifications [124] is used to evaluate the proposed slotted ALOHA MAC described in [65]. Results depict a clear improvement in both PDR and energy efficiency, especially when high SFs are used and/or payload length is long. For the combination of SF7 and small packets, pure ALOHA seems the preferable option, at least energy-wise.

LoRa-MAB is another SimPy-based discrete event simulator. The simulator examines the energy consumption per node per successful sent packet and the successful packet transmissions for a proposed algorithm discussed in [125], which focuses on an intelligent distributed resource allocation mechanism that is designed via utilization of Exponential-

weight for Exploration and Exploitation (EXP3) algorithm to solve the Multi-Armed Bandit (MAB) problem. LoRa-FREE completes the presentation of SimPy-based simulators and is described in [126], where a mechanism of transmitting buffered data in scheduled bulk UL, contrary to transmitting data at the time of generation is investigated. Key metrics include Data Delivery Ratio (DDR) -a metric similar to PDR- and energy, but also collision-related metrics and study of ACK-related transmissions. The same simulator is used in order to evaluate Time-slotted LoRaWAN (TS-LoRa) protocol, as discussed in [64].

In [127], the authors present their LoRaWAN simulator implemented in Matlab. After validating the accuracy of their simulator against results of analytical models, they perform several experiments to examine the relation among UL delivery rate (practically PDR), energy consumption, range and number of EDs. In all the occasions, an increment in range or number of EDs affects negatively PDR and energy consumption. Similarly, a stricter duty cycle worsens the DL response rate, however it is more beneficiary for energy consumption. The parameters of the simulations are well provided by the authors.

Another simulator development contribution is described in [128], where a simulator using Java is implemented. With this simulator, the authors perform numerous scalability analysis tests by calculating the PDR with respect to the number of EDs. Their study reveals an unfavorable effect of SF's increase, inter-arrival time decrease and (in the case of high numbers of EDs) payload size increase. CR seems to have no impact on PDR, whereas GWs with multiple channels tend to provide higher PDR, as expected. The capture effect that is present in LoRa transmissions improves the PDR of LoRaWAN when compared to pure ALOHA protocol. QoS requirements are also examined in terms of required PDR for vastly populated LoRa networks. More work with the same simulator includes the further evaluation of the LCS protocol proposed in [114]. The authors perform comparative experiments between LCS and pure ALOHA in terms of energy consumption (based on their proposed energy models) and supported EDs; LCS appears to be superior in both metrics.

OMNeT++ is one of the de-facto simulation environments used extensively in academic research. The framework supports experimentation with a vast type of networks and LoRaWAN simulations are supported by the FLoRa framework. In [129], the authors elaborate on the development of the framework and showcase the potential of the implemented simulator with ADR-related simulations. Three types of experiments are distinguished with ideal path loss, moderate variability of path loss and highly variable path loss for urban and sub-urban environments. ADR clearly improves the performance of the network in terms of PDR and energy consumption when path loss is not taken into consideration, but with path loss present the results depend on the environment and the level of path loss variability. To this end, an improved ADR+ algorithm is proposed, which excels both no-ADR implementation and ADR implementation in the two aforementioned metrics.

ns-3 is one of the most widely used simulators in networking research, and regarding the topic of LoRa/LoRaWAN connectivity several references exist. In [57], the required modules for simulating such networks in ns-3 are presented and simulations are developed in order to assess throughput and coverage. [130] and [131] further discuss these modules and provide results regarding PDR. One more research team has extended these ns-3 modules for simulations focusing on energy consumption, as described in [132]. In [133], another effort on developing the necessary modules for LoRa/LoRaWAN simulations in ns-3 is described providing insights in PDR, whereas a different research group discusses in [134] the development of necessary ns-3 modules for LoRa connectivity and examines energy consumption, PDR and feasibility of CSMA protocol on top of LoRa, when taking into account these two metrics plus the collision rate. Another research topic is the optimization of GW placement, which is presented in [94]. The authors utilize Gap statistics method, K-means clustering and Fuzzy C-means to derive their own model; namely DPLACE. The model is tested and compared with other GW placement methods in ns-3 simulations, showing promising results in terms of Capital Expenditure (CapEx), Operational Expenditure (OpEx), number of required GWs and PDR.

Work [111] has already been mentioned in mathematical approach subsection, however the authors go a step further by putting their proposed interference model for coherent LoRa transceiver to the test via Monte Carlo method. The approximation from Q-function, the coherent transceiver and the non-coherent one are examined, with twofold result: i) the approximations are proven to be extremely close to the simulation results (in many occasions identical), and ii) in terms of SER and FER the coherent transceiver outperforms the non-coherent one. Metrics for SNR and SIR are also provided. Same validation approach for the mathematical analysis of the problem can be found in [115]. The authors confirm their results via Monte Carlo simulations, with the outcomes of their experiments being almost identical to the ones of the numerically calculated outage probabilities.

The mathematical analysis of [116] is also tested via simulations. The proposed MC for the OTAA procedure in LoRaWAN is tested via Scilab simulations with the parameters of the simulations being well described. Results reveal that high channel quality and the existence of multiple available channels have a positive impact in delay and energy metrics, whereas crowded networks are unfavourable to the aforementioned performance factors. Again, the mathematical formulation of the problem is validated through simulations in [112], where the authors set up experiments in Matlab to estimate the performance of CSS in terms of BER and throughput and compare it with BPSK performance, which is used extensively in narrowband solutions.

In [118], simulations are performed based on a discrete event simulator developed in C++ by the authors, in an effort to compare results extracted from an MC formulation of PDR estimation problem in energy harvesting LoRaWAN Class A EDs, as described in the previous subsection. Extending the lifetime of an LPWAN system is an area of extensive research

and [135] proposes the innovative *Long-Lived LoRa* MAC protocol to be used in LoRa networks, composed of energy harvesting Class A EDs. The longevity of the system can be further improved via offloading EDs with drained energy to EDs with higher energy load and via parameter selection based on heuristic methods. The proposed model is evaluated via ns-3, in terms of network lifetime and throughput. Results are also compared to a real testbed.

Blockchains are the most widely researched realization of distributed ledgers and their applicability in several networking paradigms is investigated constantly. The intersection of Blockchains protocols with IoT solutions is summarized in [99] and [100]. Related work focusing on LoRa/LoRaWAN connectivity exists both in simulation environments and in real testbeds. In [93] the authors propose a system architecture with a Blockchain network running in parallel with the typical LoRaWAN system architecture. The Blockchain network is deployed to improve OTAA process and secure the join messages against replay attacks and jamming, thanks to the proposed two-factor authentication mechanism. The mechanism is examined in a virtualized environment with Ethereum client and showcases great results in terms of throughput, however the increase in latency is considerable as the number of EDs rises.

IIoT is one of the main use cases of LoRa/LoRaWAN and a key research area in this frame is resource allocation as mentioned in [95] and described earlier in mathematical approach subsection, where the authors developed a DFRL framework to handle such needs. Their model is tested in Tensorflow (Python) with results being drawn regarding slice delay, energy consumption, throughput and PLR, compared with another network slicing approach and showing considerable improvements in all 4 factors. Network slicing in the context of LoRa/LoRaWAN connectivity is also examined in [96], where the authors perform ns-3 simulations to validate a multi-game theoretic model that they developed for resource allocation. Results are drawn from experiments with different network configuration and slicing strategies and reveal great performance in terms of delay, energy consumption, throughput and PLR.

C. Real system implementations

Implementations of IoT systems with the support of LPWANs include: i) small-scale research-oriented testbeds with a few EDs, and ii) large scale deployments serving verticals in the "smart" paradigm.

One of the pioneering works on the topic of system evaluation by means of an experimental testbed is [25] where a LoRa-specific path loss model based on real measurements is derived. The testbed consists of 1 Kerlink GW and 2 SX1272-based EDs; one mounted on top of a moving car and one on a boat. The results are promising in terms of range for both cases, assuming lenient requirements for PDR. Regarding the path loss model, it is coined to fit the performed measurements, with different formula parameters for each mobility scenario. Recent publications on the topic of coverage also exist, with [136] examining indoor scenarios using at most 10 SX1272-based EDs and at least 2 devices of this type to communicate

with 1 GW. Results are drawn for path loss, RSSI, energy consumption and Packet Reception Rate (PRR) (practically PDR).

References [12] and [14] are two more of the earliest works in LPWAN systems. The former work focuses on LoRa connectivity and evaluates some of the specified nominal values. 1 SX1276-based ED and a Cisco GW in an urban environment are used to evaluate the RSSI metric, which is calculated slightly higher than the specified, the coverage in terms of PDR, where the system performs satisfactory and the throughput, which is close to nominal values at the time of that reference's publication. The latter work provides a quick overview of Sigfox and RPMA, whereas sketches in greater detail LoRa/LoRaWAN connectivity. The authors conclude their work with some coverage tests for two use cases. Considering the smart buildings vertical, a successful coverage test is conducted in a 19-store building, placing the GW in the middle point of it and 32 EDs scattered in different places inside of it. Smart city application scenarios are also examined with a Kerlink GW providing connectivity to IMST iM880A-L-based EDs as far as 2km.

More on the topic of measurement campaigns can be found in [137]. The authors perform extended LoRa measurements in urban and rural scenarios thanks to a combination of both a well-established and an experimental deployment. The entire system is consisted of 3 Kerlink GWs and multiple EDs, but for the needs of the experiments 2 EDs are utilized. Range and coverage are proven feasible even in the 10³m scale as depicted by RSSI and SNR values, having lenient PER requirements. Part of author's work is also the proposal of a reference architecture which is close to the typical LPWAN case, but with slightly different terminology and a protocol stack, that relies on IEEE 802.15.4 above LoRa and Constrained Application Protocol (CoAP) in APP layer.

As described in the previous subsection, [58] proposes a slotted ALOHA access method on top of LoRaWAN. Apart from Matlab simulations, the authors deploy a real system to perform several tests consisted of a maximum of 24 RFM95W EDs and a GW from Multitech based on a SX1301 and two SX1357 in an indoor environment. The experiments verify the improvement of their slotted ALOHA proposal compared to pure ALOHA. Same is the approach in [59], with the authors validating their Matlab simulation results via the establishment of a link between a USRP and an SX1276-based transceiver. Another MAC consideration is given in [65], where a slotted ALOHA scheme is examined. Mathematical approach and simulation study have already been discussed, but a testbed consisted of 2 SX1272-based ED and 2 Si4703 FM-RDS decoder for time dissemination purposes is also developed.

An innovative approach to the topic of multiple access is given in [61]. The authors propose a new architecture for the access part of the system containing an extra component; namely the Cluster Head (CH). EDs' UL messages can be received by the distant GW or by the near CH and then forwarded to GW, whereas the CH is responsible for distributing DL messages to the EDs of its cluster. To ameliorate the energy consumption of EDs, a TDMA-based scheme is also proposed. Findings from testbed experiments, containing 1 GW, 1 CH

and 9 SX1276-based EDs showcase enhancements in PDR, latency and EDs' lifetime.

The deployment presented in [128] is consisted of 3 GWs in urban placement and 4 RFM95W-based (or SX1276-based) EDs with different boards. Experiments are conducted for fixed position indoor, fixed position outdoor and moving EDs, resulting in throughput characterization in PHY layer (similar to theoretical) and APP layer (about 10x decrease). Also, coverage estimation based on PDR is provided, resulting in an optimal 7.5km range with >95% PDR, an unsatisfactory behavior in indoor scenarios and a non-critical role of velocity in mobility cases, at least not as much as other propagation factors like Line of Sight (LOS). Part of the discussed testbed is also utilized to evaluate the LCS mechanism, presented in [114]. Two of the RFM95W-based EDs and 1 GW were used in an indoor environment to test the transmissions detection precision of the protocol, which proved to be highly accurate.

In [134], the results of the energy-oriented simulation study conducted in [132] are validated thanks to a measurement campaign that includes a Kerlink GW and 4 SX1272 EDs in an outdoor environment with several distances being examined. Energy considerations appear to be a topic of intense research in the area of LPWANs and in [138] the authors deploy a real network in an indoor environment to control a Heating, Ventilation and Air Conditioning (HVAC) system according to room occupation. The network consists of 1 GW and 1 RFM95W-based ED, plus 1 ISM radio ED for comparative reasons. The decision for on/off switching of HVAC is left to a Random Neural Network (RNN) controller, residing in the GW (in the context of that reference the GW is the BS) with the model being trained on a cloud infrastructure. Results are promising in terms of ED's and building's energy consumption, range and path loss, especially when compared to the ISM transceiver.

Energy is a principal consideration in LoRa/LoRaWAN deployments and work in [119] is an example of rigorous analysis of energy consumption in the context of LoRaWAN. The testbed used by the authors is consisted of an SX1272-based ED and a Kerlink GW deployed in an indoor environment. Thanks to the taken measurements and analytical formulas numerous results regarding energy consumption, ED's lifetime and energy cost of UL transmissions are drawn. Most surprisingly, the ACK ULs are more energy effective than the non-ACK ones, an outcome that can be attributed to the fact that if a class-A ED receives an ACK in the 1st receive window then it goes to idle state without opening the 2nd receive window. The proposed *Long-Lived LoRa* protocol is evaluated via simulations as discussed in [135], however a real testbed is also deployed to further investigate the model regarding extended lifetime and system throughput. The testbed is consisted of 1 Raspberry Pi 3 GW based on well-known RAK2245 HAT solution, 15 EDs operating with SX1276 chipset and the open source solution of ChirpStack NS. Both GW and EDs are placed indoor.

Blockchain applicability in LoRa/LoRaWAN is examined not only via simulations but also in testbeds. In [139], the authors propose the HyperLoRa framework, an innovative approach that ameliorates NS workload by exploiting GWs

capabilities. A central cloud service that processes all the data is prone to data falsification or loss. With the proposed solution, a Blockchain network at the edge with different ledgers for different types of data (application data at the server-side, OTAA join-request messages at the GW cluster) is built. The network is tested with Hyperledger Fabric (HyperLoRa is the proposed system), 4 GWs (2 SX1255 and 1 SX1301 in each) and 1 ED SX1276, whereas the proliferation is achieved with Locust framework for up to 2000 EDs. Results are promising: amelioration of CPU utilization in NS thanks to distributed message processing between server-side and GW cluster is achieved, improvement in BW utilization between GW and NS is accomplished, whereas throughput is practically the same with or without HyperLoRa. In short, HyperLoRa has close to no HyperLoRa implementation performance but with greater resource utilization.

Further investigation of Blockchain integration in LoRaWAN systems can be found in [140]. The authors are exploring alternative approaches to the topic of data storage and accessibility. To this end, they propose a LoRaWAN-based system, where the data are stored to a Swarm storage space and the access to them is provided via Ethereum smart contracts. Validation of their proposed system is achieved with a testbed that includes 1 Raspberry Pi 2-based ED with Dragino LoRa/GPS Hat, 1 Raspberry Pi 3-based GW with iC880A module, a local proxy server, Swarm storage system and Ethereum client. Results reveal a viable memory utilization for all entities (cloud server-side, GWs and EDs), but throughput appears to be an issue due to EDs proliferation. However, Blockchain's transactions are focused on GWs, which are fewer in numbers in real systems and can aggregate the traffic of multiple EDs.

Finally, in [141] a Blockchain-based architecture for IIoT is proposed. Authors address the problem of data manipulation and the integration of Blockchain protocols to IIoT as a solution to it. The suggested Blockchain IIoT architecture is called BIIT and targets data reliability and improved energy efficiency with little computational overhead. To validate their architecture, the authors set up a testing platform, that includes 1 Arduino-based ED with Dragino LoRa for the LoRa-related experiment and the same ED with Sixfab Cellular IoT Application Shield for the LTE-M-related experiment, a Raspberry Pi acting as a local TTN GW and a Raspberry Pi 3 having a threefold purpose: a Blockchain plugin for TTN, a Blockchain client and a Blockchain miner. The results on packet overhead are very promising, when the number of signed packets is high.

D. Summary of research points

Published research in the area of LoRa/LoRaWAN connectivity showcases:

- 1) The contribution approach may be categorized as analytical, simulation or field deployment. Mathematical analysis is needed to optimize system deployment and operation, field tests are permitted thanks to low CapEx and OpEx, whereas simulations are needed to examine the behavior of the system in terms of ED proliferation.
- 2) Substantial effort from the research community is allocated on two directions:

- examine well-known wireless connectivity issues in the context of LoRa/LoRaWAN systems, that affect mainly signal propagation in PHY layer and network access in Data Link layer
- explore the applicability of next generation networks key features and technologies, like ML, SDN, Blockchain and network slicing.

In TABLE VII, recent research work in the area of LoRa/LoRaWAN is classified using as criterion the type of contribution provided. While the references depicted in that table are a meaningful set that can provide the reader with a complete view of the state-of-the-art work, the interested reader is encouraged to check for more work from the authors of the cited publications.

IX. AN OVERVIEW OF LPWAN SIMULATION TOOLS

The proliferation of EDs in WSNs dictates the simulation of the interested system to be rolled out, in an effort to estimate its performance, locate any flaws and try to optimize its development. In this context, the available simulators can assist network engineers job, since they allow them to test the system to be deployed, using virtual system components and examining several use cases and scenarios. Among the great advantages of simulation environments is their lack of need to physically deploy devices which might be proved costly in the case of sub-optimal deployment, and their ability to easily scale up the system by just adding virtual nodes.

Focusing on IoT systems and especially on the area of LPWANs and their main representative, LoRa, the target of these simulations is threefold:

- 1) evaluate the number of devices that can be part of the system, especially in terms of EDs, to estimate the capacity of the system and the margin for upscale,
- 2) position EDs and GWs in a way that the system's coverage is optimized and
- 3) use appropriate radio parameters in terms of SF, CR, BW, TP to estimate the performance of the system.

Other common simulation use cases in the area of IoT include the estimation of EDs' longevity, mobility of EDs and applicability of common WSN algorithms in the examined system.

A number of commercially available and also free and/or open source simulation environments are able to perform the required simulations for a wireless system. Some indicative simulators are [142]:

- The RF design system *Planet* by Infovista, which allows the design and optimization of wireless cellular networks that have been standardized by 3GPP.
- The software suit *Signal Pro* by EDX, which includes several modules of widely used networks (e.g., LTE, WiMAX) and provides the necessary tools for RF analysis with the use of propagation models for both indoor and outdoor environments.
- The cellular radiocommunication design tool *ASSET Radio* by TEOCO, which comes with capabilities of analyzing the coverage of wireless systems, their capacity

and the configuration of several parameters in the case of cellular networks.

- The software *HTZ Communications* by ATDI, that can be used in designing several different wireless systems, like cellular networks, IoT deployments, satellite systems and others.
- A number of software suites by CelPlan, which are applicable in a number of simulation use cases, like design and optimization of an outdoor wireless system, design of a network in an indoor environment, analysis of P2P links and others.
- Several network design tools from Siradel, that include tools for cellular system design, WiFi networks, specialized tools for modeling the signal propagation in 5G networks and the tool *S_IoT*, which can be used for LPWAN design.
- The *Pathloss* platform, which can assist the design of radio links that operate in a wide area of spectrum; from 30MHz up to 100GHz.

Despite the usefulness of these tools, in the rest of this section we will focus on simulation environments that are free to use and support the LoRa modulation and/or the LoRaWAN protocol either in their core codebase or via the use of extensions. The tools that will be shortly examined are: COOJA, TOSSIM, CupCarbon, LoRaWANSim (Matlab), LoRaSim (Java), LoRaSim / MoTSim / LoRaWANSim / LoRaEnergySim / LoRaMACSim (Python), LoRa-MAB, LoRaFREE, OMNeT++ and NS3. Along with the discussion of these simulators, references of published work with the utilization of them are given. An overview of the available open source LoRaWAN simulators can be found in [110]. Additional information on the broader topic of WSN simulators and on the evaluation methodology for such networks is available in [97].

A. COOJA

Contiki OS Java (COOJA) [143], [144] is a network simulator developed for WSNs. The simulator is used for the study of the behavior of EDs that are called motes and run the Contiki Operating System (OS) [145]. COOJA is an open source simulator and can be found in [146].

Contiki is an OS that finds usage in devices operating under power restrictions. It is an open source software and additional information can be found in the official software repository [147]. Recently, a new branch has been developed, called Contiki NG [148], that is gaining increasing attention and can support several protocols frequently examined in WSNs, like (CoAP), Simple Network Management Protocol (SNMP) and Routing Protocol for Low-Power and Lossy Networks (RPL).

Keeping in mind the advantages of Contiki, it is only natural to be used by numerous EDs that are distinguishing themselves as IoT components and consequently as LPWAN components. Networks that are consisted of such nodes, can be simulated with the aid of COOJA simulator. In the simulator environment, one may analyze the message exchange between EDs and the aggregator, obtain information about the state of the nodes and the communication and also adjust communication parameters. Important aspect of the environment is its

TABLE VII
A CLASSIFICATION OF THE LoRa/LoRaWAN RESEARCH WORK

Ref.	Contribution Approach			Evaluation Process		
	Algorithm or Process Design	Performance Analysis	System Implementation (Hardware, Software, Protocol Development)	Mathematical Approach	Simulation	Experiment
[12]		RSSI, Capacity PDR, Throughput			✓(no info)	Urban, 1 ED, 1 GW
[14]		Coverage				Indoor & Urban, 32 EDs, 1 GW
[25]	Path loss model	RSSI, Path loss				Urban, 2 EDs, 1 GW
[40]		Coverage, Energy, Lifetime			Matlab	
[55]		Scalability, DER	Simulator development		LoRaSim	D2D link
[57]		Throughput, Coverage	Simulator development		ns-3	
[58]	Synchronization procedure	Throughput	slotted ALOHA on top of LoRaWAN		Matlab	Indoor, 24 EDs, 1 GW
[59]		BER to SIR, PER to SIR			Matlab	USRP to transceiver
[60]		Throughput, Successful UL		Successful UL probabilities	✓(no info)	
[61]		PDR, Latency, Lifetime	Network architecture, TDMA-based MAC			Indoor, 9 EDs, 1 CH, 1 GW
[62]		Throughput	CSMA/CA		OMNeT++	
[63]		Throughput, Latency	MAC protocol, Simulator extension		MoTSim	
[64]		PDR, Energy	TS-LoRa		LoRaFREE	
[65]		PDR, Energy	slotted ALOHA, Simulator extension	Type-A, -B uncertainty	LoRaEnergySim (LoRaMACSim)	2 EDs, 2 FM-RDS decoders
[77]		ADR			LoRaWANSim	
[78]		ADR		Kruskal-Wallis		Urban
[80]	Energy model	Energy		Analytical models	✓(no info)	
[93]	OTAA two-factor authentication	Throughput, Latency	Blockchain-based architecture		Ethereum client	
[94]	GW placement model	CapEx, OpEx, PDR, # of GWs			ns-3	
[95]	Resource allocation	Energy, Delay, Throughput, PLR	DFRL architecture	DFRL optimization	Tensorflow (Python)	
[96]	Resource allocation	Delay, Energy, Throughput, PLR	Network slicing architecture	Game theory	ns-3	
[111]	Interference model	SER, FER, SNR, SIR	LoRa transceiver with coherent detection	DFT, Q-function	Monte Carlo simulations	
[112]		SF orthogonality, BER, Throughput		Closed form expressions	Matlab	
[113]		BER v SNR	Optimal receiver	FFT		
[114]	2 energy models	PDR, Energy, Scalability	LCS MAC protocol	PDR probabilities	LoRaSim (Java)	Indoor, 2 EDs, 1 GW
[115]		Scalability		Stochastic geometry	✓(no info) Monte Carlo	
[116]		Energy, Delay		MC	Scilab	
[117]		Energy, Throughput		MDP		
[118]		PDR		MC	C++	
[119]	Energy models	Energy, ED lifetime		Analytical models		Indoor, 1 ED, 1 GW
[121]		DER, Scalability			LoRaSim	
[122]		Goodput, Energy	Simulator extension		LoRaWANSim	
[123]		Energy, DER	Simulator extension		LoRaEnergySim	
[125]	Resource allocation	PDR, Energy	Simulator development		LoRa-MAB	
[126]	UL scheduling	DDR, Energy	Simulator development		LoRaFREE	
[127]		PDR, Energy, DL response rate	Simulator development		LoRaWANSim (Matlab)	
[128]		Throughput, QoS, PDR, Coverage	Simulator development		LoRaSim (Java)	Urban & Indoor, 4 EDs, 1 GW
[129]	ADR+	PDR, Energy	Simulator development		OMNeT++	
[130]		PDR	Simulator extension		ns-3	
[131]		PDR	Simulator extension		ns-3	
[132]		Energy	Simulator extension		ns-3	D2D link
[133]	Error model	PDR	Simulator development		ns-3	
[134]		PDR, Energy	Simulator development, CSMA enhancement		ns-3	4 EDs, 1 GW
[135]	Heuristic parameter selection	Throughput, System Lifetime	<i>Long-Lived LoRa</i> MAC protocol		ns-3	Indoor, 15 EDs, 1 GW
[136]		Path Loss, PRR, Energy, RSSI				Indoor, 2 - 10 EDs, 1 GW
[137]		RSSI, SNR, PER	Architecture, Protocol stack			Urban & Rural, 2 EDs, 3 GWs
[138]		Range, Energy, Packet loss				Indoor, 1 ED, 1 GW
[139]	Edge computing, 2 ledgers	Throughput, CPU, BW utilization	Blockchain-based architecture: HyperLoRa			HyperLedger Fabric 1 ED (2000 virtual), 4 GWs
[140]	Data storage and retrieval	Throughput, Memory	Blockchain-based architecture			Swarm storage, 1 ED, 1 GW
[141]	Management architecture	Overhead	Blockchain-based architecture			1 ED, 1 GW 1 Edge Node

graphical interface, where the topology of the network and nodes' measurements can be visualized. Key asset of COOJA is its high extension capability, which can provide insights in energy consumption and coverage (e.g., WSN-Maintain [149]), apart from the built-in results on network behavior and IoT-related protocols performance. Plugins that support ED mobility also exist [150]. Motes in COOJA are programmed either using C or Java.

B. TOSSIM

A similar approach to COOJA, is TinyOS Simulator (TOSSIM) [151], a discrete event simulator for EDs running TinyOS [152]. TOSSIM is also open source and its repository can be found in [153].

TinyOS can be found in devices that are operating under power and computing constraints in a concurrent way, while being easily modular. These 4 aspects are the main motivation points behind TinyOS development. TinyOS is open source itself and its main repository can be found in [154]. TinyOS, and as a result TOSSIM, are based on network embedded systems C (nesC) [155], [156], a limited dialect of C. Protocols that are of interest in the area of WSNs are supported, like Destination-Sequenced Distance-Vector Routing (DSDV) and Directed Diffusion.

As expected, TinyOS has been used extensively in IoT EDs, the behavior of which can be simulated via TOSSIM. In TOSSIM, the user can simulate the behavior of virtual EDs or even real motes (TOSSIM uses the same notation for EDs as COOJA) and the fact that deployed EDs run nesC permits the loading of code that runs in real deployment. Visualization is supported by TinyViz, with JTOSSIM being an alternative. TOSSIM is highly extensible with an example of this being the modeling of energy consumption by PowerTOSSIM [157]. Mobility support also exists [158] and numerical results about the performance of the network can be obtained. Regarding the coverage estimation of the network, there are no options for importing real map data in the simulator, to the best of our knowledge.

C. CupCarbon

A different approach to the previous simulators is CupCarbon [159], [160], [161]. The simulator focuses on simulating WSNs in the context of smart cities, supporting 3 of the most widely used technologies: ZigBee, LoRa and WiFi networking. CupCarbon can be found in [162].

CupCarbon as an environment comes with a number of advantages. Its Graphical User Interface (GUI) is one of its main benefits, providing visualizations with the use of multiple mapping methods, like Google Maps and Open Street Map. Simulator's documentation is fully explanatory [163] and includes all the mapping options, description of the GUI, presentation of the scripting language used in the simulator and a vast amount of examples that can be used in an effort to get familiar with the simulator environment or start examining WSNs and related algorithms, like Low-Energy Adaptive Clustering Hierarchy (LEACH) and Distributed Least Polar-angle Connected Node (D-LPCN). The scripting language that

is used is called SenScript and can be considered rather simple. It is based on a small number of commands for creating simple and more complex scenarios. Programming of EDs using Python is also supported in the latest version of the simulator.

Another important aspect of CupCarbon is the utility of event creation and integration in a simulation, which can be observed and reported by the nodes. Regarding the storage, extraction and visualization of the results, the user can rely on Comma Separated Values (CSV) files, log files in the form of text and the console of the simulator. Furthermore, graphs can be drawn inside the simulator, focusing on power consumption of the nodes.

D. LoRaWANSim (Matlab)

A recently proposed simulator called LoRaWANSim [127] has been implemented in Matlab. Due to name conflict with a simulator discussed in *Subsection F*, we will refer to the current simulator as LoRaWANSim (Matlab). Simulator's code is accessible via [164].

LoRaWANSim (Matlab), as its name suggests, focuses solely on LoRa/LoRaWAN systems. It can simulate both LoRa PHY layer and LoRaWAN MAC layer while considering EU868 limitations. The simulator offers many advantages in terms of accurate result extraction, most notably the support of numerous GWs and the account of interference of all types (among EDs, among GWs and a mixture of these types). Since the simulator is implemented in Matlab, this is the programming language used to setup the simulations.

There is no GUI implemented, but a mapping is drawn with no real terrain, serving mainly as a visualization of EDs and GWs position relative to each other. Results include performance of the network in terms of PDR and energy consumption and are accurate when compared to analytical models that are discussed in [127]. Being a simulator focused on LoRaWAN, it supports the key algorithmic function of the protocol: ADR performed by NS. Mobility is not supported.

E. LoRaSim (Java)

Another simulator dedicated to studying LoRaWAN systems is presented in [128], developed using the Java programming language. In *Subsection F* a simulator with the same name is described, so we refer to the current simulator as LoRaSim (Java).

LoRaSim (Java) is a discrete event simulator. It has been developed to simulate devices operating in US915 band. Configuration files for GW, EDs and the network can be used as input to the simulator, where the typical parameters of TP, SF, CR and BW are among those that can be described in these files. Results about network performance can be obtained, such as PDR. Algorithmic issues can be examined as the one described in [114], where a proposed carrier sensing mechanism is compared to pure ALOHA in terms of power consumption and system capacity, using the developed simulator.

No GUI details are provided, however LoRaSim (Java) supports the placement of all LoRa systems nodes (GW and

EDs) in a coordinated system, but not using a real map. EDs' mobility is not examined in the corresponding references.

F. LoRaSim / MoTSim / LoRaWANSim / LoRaEnergySim / LoRaMACSim (Python)

LoRaSim is a discrete event simulation environment for LoRa networks. The simulator has been developed using the Python programming language and the simulation framework SimPy and thus it should not be confused with the namesake simulator discussed earlier. Its main target is to examine the collisions in LoRa systems and provide insights on the topic of scaling such networks.

Relevant published works for LoRaSim are [55], [121]. In these references, the capabilities of the simulator are discussed, while the various simulations along with their setups are presented. The simulator can support the creation of multiple LoRa EDs and their communication with one or more GWs. LoRa EDs are simulating the behavior of an element that is based on SX1272 chipset, while LoRaSim's GWs are based on SX1301. The adjustable parameters in LoRaSim are: TP, CF, SF, BW and CR. Results can be obtained about the network performance, like DER. A map with the relative positions of GWs and EDs can be drawn, however it is not based on real environment. There is no further visualization and mobility is not supported. Simulator can be found in [165].

LoRaSim proved to be a big success and several research teams work on the simulator, in an effort to modify or extend the environment to suit their needs. One such research contribution can be found in [63], where the authors base their MoTSim simulator in LoRaSim, trying to examine their proposed MAC layer protocol. Subsequently, another research team has extended the LoRaSim simulator via implementing the necessary support for LoRaWAN protocol [122]. The extended version of the simulator is called LoRaWANSim (not to be confused with the previously discussed simulator). Extensions are focused on MAC layer with the support of DL data and ACKs, duty cycle limitations, collision models, re-transmissions and data rate adaptation based on unsuccessful packet transmissions. Results include energy consumption and network performance indicators.

A further improvement to the original simulator came from a third research team and is described in [123], named LoRaEnergySim. Simulations are organized in a framework that contains three main entities: ED, air interface and GW. Important aspect of air interface class is the consideration of known propagation models, like log-distance model and the COST-231 model, which fits nicely the European deployments. For ED, a realistic energy model is considered based on LoRaWAN_EFM32, whereas the GW is based on an iC880A module. Algorithmic-wise, the ADR algorithm as implemented by TTN is also included. Simulator is available in [166].

Based on LoRaEnergySim, another research contribution is described in [65], with additional capabilities for the simulator. The LoRaMACSim takes into account two more well-known propagation models; the Rayleigh fading and the ETSI TR 136 942. Moreover, the topic of multiple access can be studied

thoroughly due to the consideration of the slotted ALOHA and CSMA/CA protocols, apart from the usual approach of pure ALOHA. LoRaMACSim is also available, in [124].

G. LoRa-MAB

One more discrete event simulator built with the Python programming language and the SimPy framework is LoRa-Multi-Armed Bandit (LoRa-MAB) [125]. The goal of the simulator is to provide an environment for estimating resource allocation in LoRa networks in an intelligent distributed way and analyze the scalability potential of a LoRa network.

To this end, the authors have developed a simulator that has multiple input parameters, supporting a plethora of EDs and GWs, while assuming real radio propagation models and other realistic impact factors like capture effect. EDs are distinguished to normal EDs and smart EDs, with the latter being able to perform the proposed intelligent distributed algorithm for resource allocation. Results can be drawn for energy and other performance metrics, like packet reception rate which can be thought as PDR, whereas coverage can be examined but not with the use of a real map.

EDs' mobility is not discussed and a GUI is not provided. LoRa-MAB is available in [167].

H. LoRaFREE

The final discrete event simulator built with the Python programming language and the SimPy framework to be discussed in this paper is LoRa Fine-Grained Scheduling for Reliable and Energy-Efficient Data Collection in LoRaWAN (LoRaFREE) [126]. This simulator targets the validation of the namesake, *FREE* algorithm.

The authors in [126] have developed a highly configurable simulator with several input parameters, including the usual SF, BW, CR and TP, which can support multiple EDs. LoRaFREE uses realistic assumptions in a number of areas, like a packet error model, the imperfect orthogonality of spreading factors, fading events and duty cycle limitation for EDs and GWs (European deployments). Results can be drawn for numerous performance metrics, with the most important of them being the DDR, collisions and several ACK-related metrics. Energy consumption can be measured thoroughly in the simulator environment. EDs and GWs can be drawn in a non-real map. Algorithmic issues can be examined, as depicted by the study of the proposed mechanism.

No additional GUI is provided apart from the projection of EDs and GWs in a coordinated system. Mobility is not taken into consideration. LoRaFREE can be found in [168].

I. OMNeT++

The Objective Modular Network Testbed in C++ (OM-NeT++) is a simulation environment that is based on modules written in C++. With these modules, simulations for various networking systems, both wireless and wired, may be created. It follows the discrete event simulation pattern, as many other simulators on the field.

Its popularity among other simulation environments is justified by the numerous available frameworks. The INET

framework, which is the most widely used, includes models for examining several known protocols from all the layers of the known TCP/IP protocol suite, for nodes that can be both at fixed position or in motion. Other commonly used frameworks are SimuLTE, which is based on INET and is used for evaluating the behavior of LTE and LTE-A networks, as its name suggests, Simu5G, which extends the simulation capabilities to 5G networks, the Artery framework that targets Vehicle to Everything (V2X) simulations, Castalia framework [169], which targets the simulation of networks consisted of energy-constrained devices like WSNs, and PAWiS simulation framework [170], which also strives for WSN simulations and others.

With the increasing adoption of LoRa networks, it was expected that a framework for such systems would be developed. The Framework for LoRa (FLoRa) [129] simulates the behavior of EDs, GWs and NS in a LoRa network. The adjustment of parameters is an option and a dynamic scheme of parameter modification reminiscent to ADR is supported. Details about the framework can be found in the corresponding web page [171] and its repository [172], since FLoRa follows the open source approach. The capabilities of gathering statistics regarding the transmissions (PDR) and the power consumption are of great importance for its usage. FLoRa supports an energy model based on power consumption of SX1272/73 chipset.

It is worth to mention that OMNeT++ (and as a result FLoRa) provides an intuitive GUI that offers visualization of the network and even simulations based on realistic physical environment, whereas tools to log events and analyze them also exist.

J. ns-3

Final simulator to be discussed, with extensive use in networking research, is network simulator 3 (ns-3) [173]. It is part of the simulator series ns, with its core being based on C++ programming language, supporting also the development of simulations using Python. ns-3 utilizes built-in libraries, which can be combined for developing various networking systems, IP-based or not.

Simulations in ns-3 are performed with the use of 5 main Abstract Data Types (ADTs): the *node*, the *application*, the *channel*, the network device (*netdevice*) and the *topology helper*. More information can be found in the official documentation [174]. The vast amount of libraries assists the development and simulation of different kinds of networks; from 3GPP networks to IEEE 802.11 systems and from networks that are based on modern paradigms like SDN to systems that experience intense heterogeneity with new and old technologies coexisting. In this context, LPWANs can be considered and more specifically LoRaWAN systems, which are subject of intense research.

As a result, a module able to simulate LoRaWAN networks is available and can be found in [175], while published works [57], [130] and [131] explore and greatly extend the LoRaWAN capabilities of ns-3. In the same frame, work published in [132] extends these modules for realistic energy

consumption estimation. Other efforts on ns-3 LoRaWAN modules development also exist, with [133] focusing on PDR using newly developed applications in ns-3 implemented by another research group, whereas another research team investigates the feasibility of CSMA protocol on top of LoRa in [134]. Moreover, several recording commands and log file creation commands can aid the analysis of network's behavior, whereas the input of a simulation is highly configurable. Simulations to log any interested network performance metric can be developed. Algorithmic processes are regularly simulated in ns-3 and in the context of LoRaWAN module such efforts do exist, ranging from the common ADR algorithm to typical WSN-related algorithms, like Pruning algorithm [175].

Considering the graphical interface, NS-3 is a terminal-based simulator. However, visualization can be achieved with the use of an animator like NetAnim or PyViz. ns-3 provides several mobility models and coverage can be examined, while the use of reminiscent to real environments further improves the validity of the extracted results. ns-3 is an open source project [176].

K. Summary of Simulation Environments

A comprehensive summary of the presented simulation environments is given in TABLE IX. The simulators are examined in terms of programming languages supported, the existence or not of a GUI and the capabilities of them in terms of EDs' energy consumption, network coverage, network performance (throughput, data rate, PDR or related metrics), ED mobility and the support of simulating algorithmic processes or protocols. A performance factor that could have also been discussed is scalability, i.e., the number of EDs that can be simulated, however there is no apparent distinction in this area; all of these simulators are able to provide results in simulations crowded with EDs.

X. AN OVERVIEW OF CLOUD PLATFORMS FOR THE SERVER SIDE OF LPWANs

From user's perspective, most of operations in IoT systems and consequently in LPWAN systems, follow the cloud paradigm. In recent years, the Everything-as-a-Service (XaaS) approach has established itself as a growing field in the area of cloud computing. Cloud computing refers to the offering of virtualized computing resources, with several cloud models in exist. The three main representatives, according to NIST, are Software-as-a-Service (SaaS), PaaS and Infrastructure-as-a-Service (IaaS). NIST definitions for all three of them are inclusive [177], however we provide our own definitions here:

- SaaS: The ability of an end user to use existing applications developed by the cloud service provider, via an Application Programming Interface (API) or a client request. End user might be granted authorization to configure a few parameters of the application, but neither user-developed applications are allowed nor access to the underlying platform or hardware infrastructure is permitted.
- PaaS: The ability of an end user to deploy its own software, assuming software's technology can be supported by the cloud environment (e.g., Java applications

TABLE IX
OVERVIEW OF SIMULATION ENVIRONMENTS WITH A LoRA/LoRAWAN FOCUS

Simulation Environment	Ref.	Target	Programming	GUI	Energy	Coverage (Map)	Network Performance	ED Mobility	Algorithmic Processes
COOJA	[143] [144]	IoT generic (Contiki EDs)	C, Java	Built-in	✓	✓ (real)	✓	✓	✓
TOSSIM	[151]	IoT generic (TinyOS EDs)	nesC, C, C++	TinyViz, JTOSSIM	✓	-	✓	✓	✓
CupCarbon	[159] [160] [161]	EDs with Zigbee, WiFi, LoRa radio	SenScript, Python	Built-in	✓	✓ (real)	✓	✓	✓
LoRaWANSim	[127]	LoRa/LoRaWAN specific	Matlab	-	✓	✓ (not real)	✓	-	✓
LoRaSim	[114] [128]	LoRa/LoRaWAN specific	Java	-	✓	✓ (not real)	✓	-	✓
LoRaSim, LoRaWANSim, MoTSim, LoRaEnergySim, LoRaMACSim	[55] [63] [65] [121] [122] [123]	LoRa/LoRaWAN specific	Python	-	✓	✓ (not real)	✓	-	✓
LoRa-MAB	[125]	LoRa/LoRaWAN specific	Python	-	✓	✓ (not real)	✓	-	✓
LoRaFREE	[126]	LoRa/LoRaWAN specific	Python	-	✓	✓ (not real)	✓	-	✓
OMNeT++ (FLoRa)	[129]	Network generic (LoRa/LoRaWAN specific)	C++	Built-in	✓	✓ (real)	✓	✓	✓
NS-3	[57] [130] [131] [132] [133] [134] [175]	Network generic (LoRa/LoRaWAN specific)	C++, Python	NetAnim, PyViz	✓	✓ (partly real)	✓	✓	✓

will require a certain environment to run in the cloud infrastructure). End user might be granted authorization to configure a few parameters of the environment, but has no control over the underlying platform or the hardware infrastructure.

- IaaS: The ability of an end user to deploy entire platforms in the cloud environment, assuming the platform's components can be supported by the cloud infrastructure (e.g., a system component requiring a minimum amount of memory to run). End user is given the option to configure the platform as needed, e.g., OS, storage, but has no control over the underlying hardware infrastructure.

More on the concept of cloud computing can be found in [178], in which the Database-as-a-Service (DBaaS) model -an emerging service model in the area of cloud support to IoT systems- is presented. An informative resource is also [87], where the topic of IoT forensics (Forensics-as-a-Service (FaaS)) is discussed, giving valuable insights in security aspects of IoT networking based on cloud computing.

Such a cloud service paradigm has already been discussed. RPMA is characterized as a PaaS LPWAN solution, meaning that Ingenu offers the required tools to end users for developing their own applications on top of RPMA platform. Apart from RPMA, a number of companies offer SaaS and IaaS solutions in the LPWAN domain, by allowing access to backend servers, storage space or deployed infrastructure.

Numerous key industry entities operating in this area could be mentioned [179]. Amazon's Amazon Web Services (AWS)

is a well-established platform offering cloud solutions and in the context of IoT, IoT Core has great interoperability with LoRaWAN systems. Microsoft provides similar capabilities with its Azure IoT platform. Google, also invests heavily in such a platform with Google Cloud Platform (GCP). Alibaba shows substantial momentum in this field with its Alibaba Cloud and the corresponding IoT platform. IBM serves IoT Cloud needs with its IBM Watson IoT Platform. Tencent runs the namesake cloud platform and offers solutions via its IoT Hub. Finally, Oracle is another option to be considered in this area, with Oracle Cloud Infrastructure (OCI) and IoT Intelligent Applications Cloud.

XI. DATA MANAGEMENT IN LPWANS

LPWAN systems are part of the 3rd IoT generation [23], which focuses on cloud storage and processing, by following data-centric management [24] and data-driven networking [180]. The entirety of data-driven networking in the context of LPWANs faces the key data challenges of the five "V"s of big data -as they are mentioned in the literature- namely: data generated in high Volumes, with extreme Velocity, having intense Variety, being Valuable and needed to check their Veracity. To address those challenges, LPWAN architectures have already emerged [181], [182]. For the definition of such architectures common reference models [183] from the broader Industry 4.0 sector are used, namely: the Reference Architectural Model Industrie 4.0 (RAMI4.0) [184], the Industrial Internet Reference Architecture (IIRA) [185], the International Data Spaces

Reference Architecture Model (IDS-RAM) [186] and the IoT World Forum's (IoTWF) Reference Model [187]. While for the lower layers of such models (covering the communication and connectivity aspects) any of the LPWAN technologies provided in previous sections can be used, in this section the focus is on operations upon data.

Fig. 20. IoTWF Reference Model [187]

A. Fundamental data processes for LPWANs

Data management in LPWANs includes all the fundamental processes that are applied on data when it comes to communications systems; namely: data acquisition, data storage, data visualisation, and data analysis.

Data acquisition is at the heart of sensing and actuating systems, since EDs' main operation is collecting and/or acting on data. Two distinct approaches exist: the pull model and the push model. The pull model expects from the user (usually sitting beyond the server-side part of the system) to ask for the data. Key representative of pull model is HyperText Transfer Protocol (HTTP), where a user can apply the GET method to retrieve information. On the other hand, the push model supports the dispatch of data to the interested user by the time the data are transmitted by EDs. Message Queuing Telemetry Transport (MQTT) protocol and Webhooks are well-established and widely used push methods. Due to the increasing interest in WSN, Organization for the Advancement of Structured Information Standards (OASIS), which develops MQTT, is working towards the standardization of MQTT for Sensor Networks (MQTT-SN).

Data storage is also of vital importance for the successful setup of an LPWAN system. An initial approach is to store data in plain files of .txt (less frequently used), .csv or .json extension. JavaScript Object Notation (JSON) has gained a lot of attention in recent years and along with CSV are considered the main human-readable data representation today. eXtensible Markup Language (XML) is another option and its applicability in semantic web and Web of Things (WoT) [188] context can be proven useful to system developers focusing on such data inter-exchange. Efficient XML Interexchange (EXI) is another step towards this direction [189], having been developed for computationally constrained devices. However, a more sophisticated approach would dictate the utilization of a database paradigm. Several options exist, with the main

considerations being: a document-oriented database (e.g., Dynamo DB) that may also export data in the form of popular representations like .csv and .json extensions files, a timeseries database optimized for the flow of IoT data (e.g., Influx DB), or a graph-based database where each node could be a UL transmission distinguished by the reception time from the GW, with the sequence of transmissions creating a chain (e.g., Dgraph, Neo4j).

Data visualisation and analysis is applied in the stored data, in order to transform them to information. Grafana is an open platform that is utilized in numerous established projects. Mathworks has developed a solution that not only offers visualization capabilities but also supports other operations upon data: the ThingSpeak platform. In the same field, platforms like TagoIO are also widely used. Matlab is used in ThingSpeak platform for data analysis and processing, whereas TagoIO supports Javascript (Node.js) and Python. Naturally, LPWANs support the current evolution in IoT data analysis (and especially in industrial data management), towards exploiting Artificial Intelligent (AI) toolkit. In this context, ML models can be utilized, based on well-established toolboxes or frameworks like PyTorch and Tensorflow. ML models can be deployed not only in system components with high computing capabilities, like a GW, an NS or a monitoring platform, but also in EDs themselves, thanks to TinyML [190].

B. Advanced data-driven services on top of LPWANs

Beyond the fundamental data processes, innovative data-driven concepts have emerged (especially in the industrial sector). Some of the most critical ones are: i) common frameworks for representation of the nodes of a network, referring mainly to the concept of Asset Administration Shell (AAS) [191], including common data formats and communication protocols, referring mainly to the work conducted by Open Platform Communications (OPC) Foundation and especially the OPC-Unified Architecture (OPC-UA) group, and ii) the potential of exploiting the common representation and data modeling schemes towards the digital twinning of LPWAN systems.

Representation and Data modeling. The term "assets" (as defined within the manufacturing sector) refers to any inter-connected device, sensor, actuator, machine, or even processes and systems, inside a controlled communication environment (e.g., inside a manufacturing plant). Considering this, AAS is the basis on top of which *discovery*, *access* and *description* of an asset are made [102]. The specifications of the AAS are defined in IEC 63278 [192], while its implementation is a subject of many open source approaches such as the AASX [193] and the Eclipse Basyx [194]. **Discovery** is a fundamental mechanism in AAS, and a prerequisite for any communication establishment. There are different approaches for that, including the use of directories-style systems, search engines, crawlers, networking protocols, etc. **Access** refers to a set of APIs used for accessing the assets. The use of APIs is selected in an effort to ensure unified access, at the cost of requesting every resource to implement them. **Asset description** refers to data models for describing the asset

procedures and status, as for instance the OPC-UA models, defined by the OPC Foundation. The communication model of OPC-UA fits well to the LPWAN networks since it is a pub/sub protocol as described in open62541 [195].

One step beyond the default data models of OPC-UA, new information models are created which are called Companion Specifications and they are specific to vertical industries (as for instance those defined by the Mechanical Engineering Industry Association VDMA). In addition, the Digital Twin (DT) community has built related tools and models like the DT Definition Language (DTDl) [196] that specifies an Industry 4.0 language used for inter-AAS communication.

The digital twin concept [102]-[105]. DT refers to the digital presence of any "asset" enriched with full administration capabilities. It is based on the concept of emulation, but is fed with real data and is able to affect the real processes among the "assets". With its ability to interconnect a physical entity with a digital one and allowing the flow of data between them, the DT concept is expected to play a major role in the realization of IIoT [106], [107] and Industry 4.0. AAS, as presented above, is the key enabler of the DT provisioning. The realization of a DT could be based on emulation-oriented systems, such as that provided by the Emulated IoT (ELIoT) [197], [198]. In ELIoT, EDs can be abstracted as clients and NS as server and an LPWAN system can be emulated as a client-server model. However, already dedicated cloud-based tools on digital twinning have emerged, as for instance the PaaS solution of Azure DT [199]. For the communication part of a system, and its data flows, the NodeRed tool is also considered as a DT-enabler.

XII. CONCLUSION

LPWAN systems is an emerging connectivity solution looking to embrace the challenge of satisfying the needs of the 3rd generation of IoT networking. Their main target is to serve connectivity demands in terms of long range, low power and low data rates, with low setup and operational cost. LPWAN-related technologies have already been established in several (3GPP and non-3GPP) standards, covering various application demands and network performance requirements. As revealed from the technology comparison study presented in this paper, a standout solution for LPWANs in unlicensed bands is the LoRa/LoRaWAN networking approach, referring to systems that use LoRa PHY and LoRaWAN MAC technologies. Overviews of both technologies are provided, in an effort to serve as reference points to fundamental processes and performance capabilities of LoRa/LoRaWAN-enabled LPWANs.

In this framework, the research area of LPWANs is flooded with a plethora of approaches and studies, which are classified to *analytical* approaches, *simulation* studies and *real implementations/measurement* campaigns. Based on the state-of-the-art study and assessment in this paper, the majority of the research approaches in the area is built around the choice/adaptation of the re-configurable parameters at PHY and MAC layers. In addition, LPWANs have been proven to be good candidates for applied research, targeting real

measurements and setups. This is mainly due to the low establishment cost and the rich open source solutions available. In the case of field implementations, LPWAN systems tend to be supported by cloud infrastructures; an observation that confirms the current trend on virtualizing as much as possible of the LPWANs' functionality. However, due to the massiveness characteristic (a key aspect of IoT EDs), large scale research studies still need to be conducted via simulations. Considering this, a point-to-point comparison of the available simulators for LPWANs has been provided, revealing the pros and cons of the (already long list of) available tools.

Finally, it is apparent that the LPWANs are not only about connectivity; they are actually one of the key features of the broader evolution towards a data-driven IoT world. As such, they can be considered potential candidates for industrial solutions, where advanced data-driven services are designed based on recent advancements, like the AAS and the Digital Twinning.

APPENDIX A

A QUANTITATIVE STUDY ON LoRa MODULATION

LoRa is an implementation of CSS⁸, which is a member of Spread Spectrum (SS) family [200]. SS as a technique strives to spread the signal over a wider BW, achieving better performance in terms of jamming resistance, interference, unintended signal detection and eavesdropping [201].

The spreading process is based in two main elements: coding and pseudorandomness. The block diagram can be seen in Fig.21.

Fig. 21. Spread Spectrum block diagram [201]

Several SS approaches have been proposed over the years, with Direct Sequence SS (DSSS) and Frequency Hopping SS (FHSS) being the main representatives. Other methods include Time Hopping SS (THSS) and Hybrid SS (HSS). LoRa CSS implementation is considered a DSSS alternative [73].

⁸LoRa networks are not the only WSN approach that is relying on CSS for its PHY layer. IEEE 802.15.4a is another example of CSS utilization and can be used for Zigbee connectivity.

The amount of BW spread is denoted by SF. Assuming an input BW R , one can spread the signal transmission over a BW W . Then W is equal to R times the SF, so:

$$W = SF * R \Leftrightarrow SF = \frac{W}{R} \quad (A1)$$

For an $SF = 3$, it means that the signal is transmitted over a BW that is 3 times wider than the input BW, as depicted in Fig. 22. It is worth to mention that if we calculate the integrals of the two areas in Fig. 22, depicting the initial input and the spread one, they should be equal.

Fig. 22. Power Spectral Density with respect to BW for an input signal and a spread signal

We proceed by defining the term of chip, which is the way to encode information in SS systems. Practically, the spreading factor is a chip sequence, so it indicates the number of bits used for a symbol. If we define that the symbol is a chirp in CSS modulation, then for a known SF the ways to encode information in a symbol are 2^{SF} .

The next step is to define the terms of rate and duration for chip and symbol, and eventually bit rate. The chip rate will be equal to the spread BW W , so:

$$R_c = W \quad (A2)$$

The symbol rate will be equal to the chip rate divided by the number of ways to encode information in one symbol, so:

$$R_s = \frac{R_c}{2^{SF}} \quad (A3)$$

In this context, the reciprocal of rate is duration, so we can also define T_c and T_s as⁹:

$$T_c = \frac{1}{R_c} = \frac{1}{W} \quad (A4)$$

$$T_s = \frac{1}{R_s} = \frac{2^{SF}}{W} \quad (A5)$$

Finally, the bit rate will be equal to the number of bits used for a symbol divided by the duration of a symbol (or equivalently multiplied with the rate of a symbol):

$$R_b = \frac{SF}{T_s} \quad (A6)$$

⁹If we define the bit duration in the same way, we get the fraction $\frac{W}{R} = \frac{T_b}{T_c} = SF$. This quantity can also be found in literature as *processing gain*.

However, the bit rate in LoRa is slightly lower than that, due to the inclusion of a FEC scheme. LoRa defines a 4-value Rate Code, picking an element from the set $\{\frac{4}{5}, \frac{4}{6}, \frac{4}{7}, \frac{4}{8}\}$. Rate code is a fraction that has as nominator the amount of useful information carried to a message and as a denominator the total number of bits, i.e., information bits plus redundant bits for error correction.

$$RateCode = \frac{4}{4 + CR} \quad (A7)$$

Ultimately, the bit rate in LoRa considering FEC and equations A5, A6, A7 will be the one given in the corresponding LoRa section (Section VII, equation 1):

$$R_b = SF * \frac{4}{4 + CR} * \frac{W}{2^{SF}} \quad (A8)$$

In CSS modulation, information is carried using the notion of chirp signal. A chirp is a signal that its frequency is changing over time, either moving from lower frequencies to higher (up-chirp) or the opposite direction (down-chirp). The waveforms of an up-chirp and a down-chirp can be seen in Fig. 23.

Fig. 23. Spectrogram for an up-chirp (up) and a down-chirp (down)

LoRa uses a scheme of cyclic shifting when reaching the upper bound in the case of up-chirp (or lower bound in the case of down-chirp).

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ACRONYMS

TABLE X
ACRONYMS TABLE

Acronym	Definition
16-QAM	16-Quadrature Amplitude Modulation
3GPP	3rd Generation Partnership Project
8PSK	8-Phase Shift Keying
AAS	Asset Administration Shell
ABP	Activation By Personalization

TABLE X
ACRONYMS TABLE (CONT'D)

ACK	Acknowledgment
ADR	Adaptive Data Rate
ADT	Abstract Data Type
AES	Advanced Encryption Standard
AI	Artificial Intelligent
API	Application Programming Interface
APP	Application layer
AWGN	Additive White Gaussian Noise
AWS	Amazon Web Services
BER	Bit Error Rate
BLE	Bluetooth Low Energy
BPSK	Binary Phase Shift Keying
BS	Base Station
BT	Bandwidth-symbol Time
BW	Bandwidth
C-DRX	Connected mode DRX
CAD	Channel Activity Detection
CDMA	Code Division Multiple Access
CF	Carrier Frequency
CH	Cluster Head
CIoT	Cellular IoT
CMAC	Cipher-based Message Authentication Code
CR	Coding Rate
CRC	Cyclic Redundancy Code
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
CSS	Chirp Spread Spectrum
CSV	Comma Separated Values
CTR	Counter (AES mode)
CapEx	Capital Expenditure
CoAP	Constraint Application Protocol
D-LPCN	Distributed Least Polar-angle Connected Node
DBaaS	Database-as-a-Service
DD-UNB	Dynamic Downlink Ultra Narrow Band
DDR	Data Delivery Ratio
DER	Data Extraction Rate
DFRL	Deep Federated Reinforcement Learning
DFT	Discrete Fourier Transform
DL	Downlink
DSDV	Destination-Sequenced Distance-Vector Routing
DSL	Digital Subscriber Line
DSSS	Direct Sequence Spread Spectrum
DT	Digital Twin
DTDl	DT Description Language
EC-GSM-IoT	Extended Coverage-GSM-IoT
ED	End Device
EDGE	Enhanced Data rates for Global Evolution
ELIoT	Emulated IoT
ETSI	European Telecommunications Standards Institute
EXI	Efficient XML Interexchange
EXP3	Exponential-weight for Exploration and Exploitation
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FER	Frame Error Rate
FFT	Fast Fourier Transform
FH	Frequency Hopping
FSK	Frequency Shift Keying
FUOTA	Firmware Update Over The Air
FaaS	Forensics-as-a-Service
GCP	Google Cloud Platform
GERAN	GSM EDGE Radio Access Network
GFSK	Gaussian Frequency Shift Keying
GMSK	Gaussian Minimum Shift Keying
GPRS	General Packet Radio Service
GUI	Graphical User Interface
GW	Gateway
HARQ	Hybrid Automatic Repeat Request
HTTP	HyperText Transfer Protocol
HVAC	Heating, Ventilation and Air Conditioning
IDS-RAM	International Data Spaces Reference Architecture Model
IIRA	Industrial Internet Reference Architecture
IIoT	Industrial IoT
IMT	International Mobile Telecommunications

TABLE X
ACRONYMS TABLE (CONT'D)

IP	Internet Protocol
ISM	Industrial, Scientific, Medical
IT	Information Technology
IaaS	Infrastructure-as-a-Service
IoT	Internet of Things
IoTWF	IoT World Forum
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
LBT	Listen Before Talk
LCS	Lightweight Carrier Sensing
LEACH	Low-Energy Adaptive Clustering Hierarchy
LOS	Line of Sight
LPWAN	Low-Power Wide Area Network
LR-FHSS	Long Range - Frequency Hopping Spread Spectrum
LTE-M	Long Term Evolution-Machine type communication
LTN	Low Throughput Networks
LoRa	Long Range
LoRaWAN	LoRa Wide Area Network
MAB	Multi-Armed Bandit
MAC	Medium Access Control
MC	Markov Chain
MCL	Maximum Coupling Loss
MDP	Markov Decision Process
MIOTY	MY IoT
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
MQTT-SN	MQTT for Sensor Networks
MoT	MAC on Time
NB-IoT	Narrowband-IoT
NIST	National Institute of Standards and Technology
NR	New Radio
NS	Network Server
NoT	Network of Things
OASIS	Organization for the Advancement of Structured Information Standards
OCI	Oracle Cloud Infrastructure
OFDMA	Orthogonal-FDMA
OPC	Open Platform Communications
OPC-UA	OPC-Unified Architecture
OQPSK	Offset Quadrature Phase Shift Keying
OS	Operating System
OSI	Open Systems Interconnection
OTA	Over The Air
OTAA	Over The Air Activation
OpEx	Operational Expenditure
PDR	Packet Delivery Ratio
PER	Packet Error Rate
PLR	Packet Loss Rate
PRB	Physical Resource Block
PRR	Packet Reception Rate
PSM	Power Saving Mode
PaaS	Platform-as-a-Service
QPSK	Quadrature Phase Shift Keying
QoS	Quality of Service
RAMI4.0	Reference Architectural Model Industrie 4.0
RFDMA	Random-FDMA
RNN	Random Neural Network
RPL	Routing Protocol for Low-Power and Lossy Networks
RPMA	Random Phase Multiple Access
RSSI	Received Signal Strength Indication
RedCap	Reduced Capability
SC-FDMA	Single Carrier-FDMA
SDN	Software-Defined Networking
SER	Symbol Error Rate
SF	Spreading Factor
SINR	Signal to Interference and Noise Ratio
SIR	Signal to Interference Ratio
SNMP	Simple Network Management Protocol
SNR	Signal to Noise Ratio
SON	Self Organizing Network
SS	Spread Spectrum
SSL	Secure Sockets Layer
SaaS	Software-as-a-Service

TABLE X
ACRONYMS TABLE (CONT'D)

TDMA	Time Division Multiple Access
TLS	Transport Layer Security
TM	Transmission Modes
TOSSIM	TinyOS Simulator
TS	Telegram Splitting
TS-UNB	Telegram Splitting Ultra Narrow Band
TSMA	Telegram Splitting Multiple Access
TTN	The Things Network
TVWS	TV White Space
ToA	Time On Air
UDP	User Datagram Protocol
UL	Uplink
UNB	Ultra Narrow Band
V2X	Vehicle to Everything
VPN	Virtual Private Network
VoLTE	Voice Over LTE
WG	Working Groups
WSAN	Wireless Sensor and Actuator Network
WSN	Wireless Sensor Network
WoT	Web of Things
XML	eXtensible Markup Language
XaaS	Everything-as-a-Service
eDRX	enhanced Discontinuous Reception
mMTC	massive Machine Type Communications

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