A Comparative Study of LoRaWAN, SigFox, and NB-IoT for Smart Water Grid

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***Abstract*—Low Power Wide Area Networks (LPWAN) are becoming the powerful communication technologies of the IoT of tomorrow. LoRaWAN, SigFox, and NB-IoT are the three competing LPWAN technologies. On the other hand, Smart Water Grid (SWG) is an emerging paradigm that promises to overcome issues such as pipes leaks encountered by current water infrastructure by deploying smart devices into the water infrastructure for monitoring purposes. This paper firstly explores the physical and communication features of the above LPWAN technologies and provides a comprehensive comparison between them as well as their suitability for the Smart Water Grid (SWG) use case. The important aspect of SWG is to connect devices such as smart water meters and other tiny devices like sensors installed into the water pipelines for the system monitoring purpose. We consider Advanced Metering Infrastructure (AMI) also called Smart Water Metering when dealing with the water grid, which is the main application of SWG and we study the scalability of LoRaWAN, NB-IoT, and SigFox in such application. Under NS3, the simulation results show that NB-IoT provides the best scalability compared to LoRaWAN and SigFox and thus is able to support a huge number of devices with a low packet error rate.**

***Index Terms*—IoT, LoRaWAN, SigFox, NB-IoT**

I. INTRODUCTION

The Internet of Things (IoT) promises to connect more than 50 billion devices by 2020 in smart cities applications such as Smart Water Grid (SWG), Smart Electrical Grid, Smart Home, etc. SWG is one of IoT applications that integrates into water system, sensors, control devices, real-time monitoring and data visualization tools, data management and storage software, and analytical components that remotely and continuously monitor and diagnose issues in the water distribution system. The IoT devices installed into SWG system need to fulfill some requirements such as long-range communications, long batteries life, low data rate transmission, high level of security, low-cost installation. The short-range networks such as Bluetooth, ZigBee, 6LoWPAN, etc. don't fit best in such a scenario due to their short-range nature. Cellular networks provide long-range connectivity but these technologies deplete quickly the batteries life of devices installed into water grid during communications processes. To overcome the energy issue of cellular networks and the range problem of short-range networks, LPWAN technologies emerge as powerful wireless communication technologies.

LPWAN technologies provide typically low-power consumption up to 10 years and more of battery life [1]. Depending on the technology, they offer generally up to 10-40 km of communication range in rural areas and 1-5 km in the urban area. The cost of a radio chipset is less than 2 € and the subscription of one device per year is 1 € [1]. The data rate varies according to the technology, condition and type of communication (Uplink or Downlink communication). Due to the above interesting features, LPWANs are suitable for SWG. Currently, many LPWANs emerge. Some operate in the licensed and other in the unlicensed bands. Among them, LoRaWAN, SigFox and NB-IoT are the most useful technologies.

LoRaWAN was firstly introduced by a France startup at Grenoble named Cyclo in 2009 and was acquired by Semtech in 2012. It was standardized in 2015 by LoRa-Alliance. LoRaWAN is currently deployed in more than 42 countries and continues to be roll-out in other countries due to many network operators investments such as Orange (France), KPN (Netherlands), Fastnet (South Africa).

SigFox was patented and developed by SigFox start-up (Toulouse, France) in 2010. SigFox is at the same time a company and a LPWAN network operator. It is deployed in more than 31 countries and continues to be roll-out in other countries owing to the partnership with network operators.

NB-IoT is a 3GPP standard based on narrow-band radio published in 2016 in release 13. NB-IoT has started to be deployed in many countries since 2018. In 2016, NB-IoT was used by Vodafone and Huawei to test data transmission in smart water metering application. In fact, these network operators had integrated NB-IoT in Spanish Vodafone to send a message to a device installed into water meter by following NB-IoT specifications [2]. In China, NB-IoT has started used for utilities and smart cities applications.

In this paper: (1) we provide the various communication requirements of SWG, (2) we present the physical and communication features of LoRaWAN, SigFox, and NB-IoT, (3) we compare these technologies in terms of SWG communication requirements, (4) we study the scalability of these technologies for SWG infrastructure.

The remainder of this paper is structured as follow: Section II provides the communication requirements of SWG while section III presents briefly the three competing LPWANs. Section IV compares LoRaWAN, SigFox and NB-IoT in terms of SWG communication requirements. Section V study the scalability of LoRaWAN, SigFox, and NB-IoT by using advanced metering infrastructure as a use case. Section VI provide the related works and finally, section VII concludes the paper.

II. SWG COMMUNICATION REQUIREMENTS

A. Power consumption

SWG end devices are powered by batteries whose replacement may be infeasible due to the hard to access environments in which they are deployed. As the system is very vast and hard to access, devices installed into SWG require maximum lifetime (15 years and more). Therefore, any communication technology used in SWG must consume minimum energy of devices in order to prolong their lifetime.

B. Scalability

Because of the vastness of water infrastructure, SWG require a good scalability to connect a huge number of IoT devices such as sensors, smart meters and integrated more services into it. Therefore, communication technologies which provide the best scalability are required in order to support these devices.

C. Low cost

SWG consists of several components such as reservoirs, pipelines, water treatment plants, etc. From water source to the water treatment plant, water needs to convey over several kilometres through pipelines. In each component, the installation of IoT devices such as sensors, smart meters is required in order to monitor continuously water distribution system. Therefore, this requires a minimum cost of IoT devices, minimum maintenance and installation cost in order to reduce the total cost of the entire system.

D. Reliability

In order to promote SWG for its large adoption, the main goal is to guarantee certain stability of water distribution in SWG by resolving outages and disturbances of traditional water distribution systems. In order to achieve this goal, the communication technologies used in this system must be reliable. In SWG context, the reliability is the ability of such a system to communicate data generate by the system by fulfilling some specific constraints such as latency, data rate, etc.

E. Security

As report by Electric Power Research Institute, the cybersecurity is one emergent requirement of smart grid applications [3]. Thus, protocols that provide high level of security are required in SWG context.

F. Communication range

The IoT devices installed into SWG are remotely located (several kilometres). Therefore, long-range communications are required in order to transmit data effectively. In this context, SWG requires communication technologies that can provide long-range connectivity.

G. Quality of Service (QoS)

The data collected by sensors and meters must be transmitted with low latency in order to take quick decision [4]. In the smart electrical grid, for example, the maximum allowed time is ranging from 12 to 20 ms [3]. SWG integrates Supervisory Control And Data Acquisition (SCADA). The collected data must not be older than 15 s at their arrival to the SCADA center [3]. Water contamination information shall arrive no later than 30 s once water is contaminated [5].

Another important factor related to QoS is bandwidth. As SWG requires the interconnection of several IoT devices, the communication infrastructure must have the capacity to support several messages simultaneously without impacting negatively on the network latency.

III. LPWAN TECHNOLOGIES

A. LoRaWAN

1) Technical features and architecture: LoRaWAN is a communication protocol developed by LoRa alliance around LoRa. LoRaWAN consists of three important components such as end devices, gateways and network server as provide in Fig 1. The EDs are in charge of data collecting and are connected to the network server via gateways (GWs). The GWs relay data between EDs and network server (NS). To provide long-range communication, LoRaWAN uses LoRa modulation which is based on Chirp Spread Spectrum (CSS) with different spreading factors (SF7 to SF12) to adapt the data rate and range trade-off. The lower SF enables shorter range at the expense of higher data rate, and vice versa. LoRa operates in unlicensed sub-GHz ISM bands (i.e. 868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia.). Because LoRa operates in licensed-free bands, the duty cycle is limited (1% for example for European Union regulation). LoRa provides a data rate varying between 300 bps and 50 kbps depending on the SF and the bandwidth. The maximum payload is 243 bytes and the number of message transmitted both in UL and DL per day is unlimited [6]. The battery life of EDs can go beyond 10 years. LoRaWAN network architecture is generally deployed in a star-of-stars topology illustrated in Fig. 1, in which GWs seamlessly relay data between EDs and a NS. According to the application scenario, three classes of LoRaWAN devices can be used:

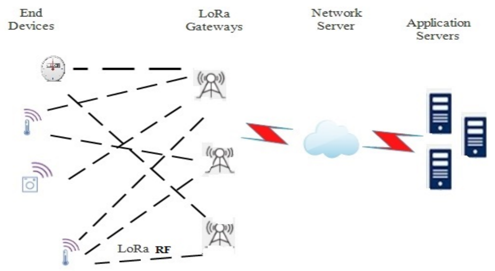

Fig. 1. LoRaWAN Network

- Class A –Bi-directional end-devices: After an UL message, the EDs of this class open two receive windows to enable for DL. For the rest of the time, EDs stay in the sleep mode. The EDs of this class consume less energy but have high latency.
- Class B –Bi-directional end-devices with scheduled receive slots: In addition to the two receive windows, the EDs open extra windows at scheduled times. In order to open extra windows, EDs use time-synchronized beacons send by the GWs. The EDs of this class have a medium energy consumption and medium latency.
- Class C –Bi-directional end-devices with maximal receive slot: The EDs continuously keep receive window open only if they are transmitting. The NS can thus establishes DL communication at any time. The latency problem is overcome but an excessive energy is consumed compared to other classes.

2) Communication principles: The communications over a LoRaWAN network take place after EDs activation. An ED can be activated over the air called Over the Air Activation or by Personalization called Activation By Personalization. Once an ED is activated, it joins a LoRaWAN network and can communicate with NS. LoRaWAN provides two types of communication, UL and DL communications. The UL communication refers to messages send by EDs to NS relayed by one or more GWs. Any message sent by an ED is received by all GWs located in the transmission range. The GWs send the received data to the NS, the NS checks data integrity, removes redundant receptions and finally identifies the corresponding application server (AS) and transmits it the data. The DL communication corresponds to data send by ASs to EDs. This data can be an acknowledgment or a specific message that an AS needs to send to an ED.

B. SigFox

1) Technical features and architecture: SigFox was patented by SigFox company, which is both a company and a network operator. It commercializes its own solutions in many countries and operates in the unlicensed sub-GHz ISM bands (e.g. 868MHz in Europe, 433MHz in Asia, and 915MHz in North America). The EDs connected to SigFox GWs use differential binary phase shift keying (D-BPSK) modulation to transmit data in an ultra narrow band (100Hz). Using ultra narrow band in sub-GHz ISM bands enables SigFox to efficiently exploited the frequency band and provides a very low noise levels, leading to low-power consumption and high receiver sensitivity [7]. The maximum data rate is 100 bps. SigFox supports both UL and DL communications in its later version with 140 messages per day for UL communications and 4 messages per day for DL communications. Therefore, we can see that all UL messages have not acknowledgment. Thus, in order to ensure that all messages have reached the receivers, SigFox uses time/frequency diversity and transmission duplication. In other words, each message sends by a SigFox ED is resent three times on three random carrier frequencies. SigFox base stations are able to receive messages at the same time over all available channels. As SigFox operates in unlicensed bands, the duty cycle restrictions of the utilized sub-band in the EU, for example, is 1%. The maximum payload of each DL message is 8 bytes while this payload is 12 bytes for UL communications. The batteries life of SigFox EDs can go up to 10 years.

Like LoRaWAN network, SigFox network is laid out in a star topology where EDs are connected to SiFox cloud via SigFox base stations.

2) Communication principles: SigFox base stations (BS) listen to all available channels to receive messages. For UL communication, a message sent by an ED is received by any SigFox BS in the range and on average the number of BS which can receive this data is 3. Then the BSs send the same message to the SigFox cloud which is the core of the SigFox network. The SigFox cloud is in charge of messages processing and sends them to customers' message location. It also contains tools that analyze data generated by the network. For DL transmission, the reverse path is adopted.

C. NB-IoT

1) Technical features and architecture: Narrow-Band IoT (NB-IoT) also called LTE Cat NB1 connects up to 100 k EDs per cell by using existing cellular network operators. It provides 8-10 years of battery life, large coverage, low-cost, and high network security [8]. NB-IoT uses a frequency bandwidth of 200 KHz corresponding to one physical resource block in GSM and LTE transmission [8]. With 200 KHz frequency bandwidth, there is three possible operation modes for NB-IoT namely:

- Stand alone operation: It is possible for NB-IoT to use one or more existing GSM carriers.
- Guard band operation: Utilizing the unused resource blocks in LTE spectrum guard-band.
- In-band operation: Utilizing resource blocks within an LTE carrier.

NB-IoT reuses several functionalities of LTE and adapts them as need for IoT applications requirements. For example, NB-IoT reuses the back-end system of LTE to broadcast valid messages for all EDs within a cell. The back-end system was optimized to small data and doesn't include features not required for IoT. The data rate is 200 kbps and 20 kbps respectively for UL and DL communications. The maximum payload of each message is 1600 bytes. NB-IoT uses Quadrature Phase

TABLE I
COMPARISON BETWEEN THE THREE POPULAR LPWAN TECHNOLOGIES

LPWAN Technologies Features	LoRaWAN	SigFox	NB-IoT
Battery Life	$> 10years$	$> 10years$	$10years$
Range	2-5km urban, 10-20km rural	3-10km urban, 20-40km rural	1 km in urban 10 km in rural
Frequency Band	sub GHz ISM bands	sub GHz ISM bands	Licensed LTE bandwidth
Network Topologies	Star-of-stars	Star	Star
Maturity Level	Some deployments	In use commercially	Early stages
Modulation Technique	Chirp Spread Spectrum	Ultra-NarrowBand	LTE-Based
Number of Device per BS	No restriction	only SigFox certified	100 k per cell
Security	AES	Not build in	3GPP (128-256bit)
MAC Layer	ALOHA-based	ALOHA-based	LTE-based
Data rate	between 300bps and 50kbps	100bps	200kbps
Maximum payload	243bytes	12 bytes for UL and 8 bytes for DL	1600 bytes
Adaptive Data rate	Yes	No	No
Latency	Low latency for class C devices	high latency	Low latency
Deployment Model	Operator-based and Private	Operator-based	Operator-based

Shift Keying (QPSK) modulation. For UL data transmission, it uses Single Carrier Frequency Division Multiple Access (SC-FDMA) modulation and Orthogonal FDMA for DL data transmission. The core of NB-IoT architecture is based on the Evolved Packet System (EPS) and two optimization procedures for the Cellular IoT (CIoT). These procedures are User Plane CIoT EPS and the Control Plane CIoT EPS.

2) Communication principles: As we mentioned above, two optimizations named, User Plane CIoT EPS and the Control Plane CIoT EPS are defined to send data to an application in NB-IoT network. With Control Plane CIoT EPS optimization, for UL communication, user equipment (UE) data is sent to Mobility Management Entity (MME) through eNB (CIoT RAN). From MME, there is two way to transmit data according to its type. For IP data packets, data is transferred to Packet Data Network GW (PGW) via Serving Gateway (SGW). Then, the PGW transmits finally data to CIoT services or AS. For non-IP data packets, data is transferred to the Service Capability Exposure Function (SCEF). In fact, SCEF are new nodes conceived specifically for machine type data. It offers an abstract interface for network functionalities such as authentication, discovery, etc. From there, data is sent to CIoT services. With DL communication, data is sent following the same path but just in reverse direction. On the other hand, with User Plane CIoT EPS optimisation, data is transmitted over radio bearers to application server via PGW passing by SGW. Both IP data packets and non-IP data packets are supported by this sequence.

IV. COMPARISON BETWEEN LPWANS IN TERMS OF SWG COMMUNICATION REQUIREMENTS

A. Power consumption

LoRaWAN, SigFox, and NB-IoT provide a long life of EDs battery due to the use of sleep mode, star topology, simplicity of EDs design. However, NB-IoT additionally uses synchronous communication, SC-FDMA modulation and Orthogonal FDMA for UL and DL communications respectively. This consumes additional energy and thus decreases EDs batteries lifetime compared to the two other technologies. Therefore, compared to LoRaWAN and SigFox, NB-IoT provide high energy consumption.

B. Latency

Some SWG applications like smart water metering require sometimes low latency. NB-IoT provided low latency compared to SigFox and LoRaWAN. Additionally, LoRaWAN provides class C to handle low latency. Thus for applications requiring low latency, NB-IoT and LoRaWAN class C are suited. Therefore, in terms of latency, NB-IoT is the best choice.

C. Scalability

SWG infrastructure requires the connecting of the great number of EDs. Thus, the high scalability is mandatory in such a system. LoRaWAN and SigFox are able to support thousands of EDs per GW. However, NB-IoT connects up to 50k EDs per cell.

D. Quality of Service

LoRaWAN and SigFox operate in unlicensed bands and use asynchronous ALOHA-based communication. They can avoid interference but don't provide the QoS. NB-IoT operates in licensed bands and uses synchronous communication based on LTE. Thus, NB-IoT provides optimal QoS but unfortunately, the cost is very high.

E. Cost

The EDs cost, the spectrum cost, and the deployment cost will be taken into account. The NB-IoT base station (BS) has a high cost compared to LoRaWAN and SigFox BS. In terms of EDs cost, NB-IoT has also high cost compared to the others. NB-IoT operates in the licensed band while LoRaWAN and SigFox use the licensed-free bands.

F. Communication range and coverage

IoT devices installed into SWG need to communicate over long-range. SigFox can communicate over 10 km in an urban area and up to 40 km in a rural area. LoRaWAN provides 5 km of communication range in an urban area and up to 20 km in a rural area. However, NB-IoT offers low communication range, 1 km in an urban area and 10 km in a rural area. Therefore, in SWG application requiring long-range communications over 10 Km, NB-IoT is not suitable. Fig. 2 summarize the comparison of some metrics.

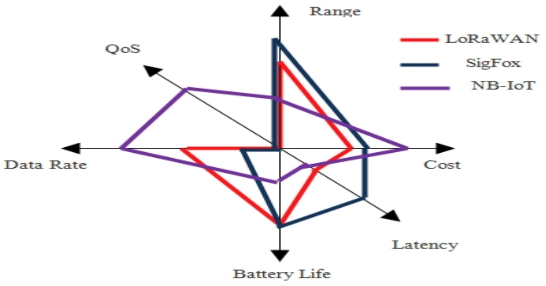

Fig. 2. Comparison of LoRaWAN, SigFox, and NB-IoT in terms of SWG metrics

V. SCALABILITY ANALYSIS IN AMI

In this part of the paper, we analyze the scalability of the three competing LPWANs in order to take a position because the need to connect a great number of devices in SWG is mandatory due to the vastness of the system. Also, according to many forecasting, IoT promises to connect billion even trillion of devices by 2025. Therefore, it is crucial to know which one of these technologies is more scalable to support these devices in SWG context. We consider smart water metering as a use case consisting of smart water meters and gateways in a star topology. The smart water meters are connected to a central network server through gateways. Each gateway can support a great number of smart water meters and is connected to the network server via reliable standards IP. Typically, the number of smart water meters to connect can be very high (a hundred or even thousands). In order to achieve our goal, NS3 which is a discrete-event network simulator is used to perform simulations. The simulations are performed using one, two or four gateways and a configurable number of nodes, all deployed in a circle with a 5000m radius. As smart water meters transmit small amounts of data, in all simulations, the maximum payload is set to 12 bytes. This payload is supported by all the LPWANs describe above. All simulations are performed using 100, 500, 1000, 2000, 5000, 7000, 10000, 15000 or 20000 nodes. The total simulation time is set to 6000 seconds in order to allow all traffic to occur. Each node must send its data to the gateway from every 300 seconds (as smart water metering requirements indicate above). The nodes are distributed uniformly in the circle and keep a fixed position during simulations because, in smart water metering, smart water meters are typically installed in stationary locations and don't need mobility.

For LoRaWAN, we evolved a module developed by authors in [9] in order to simulate LoRaWAN network. In all simulations, all gateways and nodes use the same 125kHz LoRaWAN bandwidth. To transmit, nodes randomly use one of the six spreading factor (SF7 to SF12). We assume that packets are sent as unconfirmed messages because, in smart water metering, smart water meters are typically found in stationary locations, and don't require regular acknowledgments. LoRaWAN class A devices are implemented because smart water metering just needs quasi-real-time communications (latency can be tolerated). For both transmitter and receiver, the transmission power (TP) is set to 14 dbm which is the default TP. The duty cycle is limited to 1% according to EU regulation.

For NB-IoT, we used the LTE module already present in NS3 and we added minor modifications in order to simulate a real NB-IoT network. One, two or four eNodesBs are used as base stations, similar to gateways in LoRaWAN and SigFox networks. A packet data network gateway (P-GW) relays data between eNodesBs and a remote host. The bandwidth used is 180 kHz.

For SigFox, we have followed the lr-pwan module architecture present in ns-3 and developed a module to simulate the SigFox network. The default 868.130 MHz channel is used.

We have performed simulations in three cases according to the number of the gateway. In each case, we have used the packet error rate (PER) as the performance metric. Therefore, scalable technology is one that provides low PER. We define PER as the rate of the packet not successfully received by the gateways (equation 1).

$$PER = \frac{\sum packets \ \ not \ \ successfully \ \ received}{Total \ \ number \ \ of \ \ send \ \ packets} \tag{1}$$

In the first case, we have used one gateway and run simulations using the configurable number of nodes provide above. The results are shown in Fig.3. For the three LPWAN technologies, the PERs increase when the number of nodes increases in the network. Additionally, NB-IoT provides low PERs compared to SigFox and LoRaWAN regardless of the number of nodes. In the second case, we used two gateways, and the results are presented in Fig. 4. Similar to the first case, the PERs increase when the number of nodes increases. but are low for the three LPWANs compared to PERs obtained previously. Always, NB-IoT provides low PERs compared to SigFox and LoRaWAN. Finally, when the number of gateway is set to four in Fig. 5, the PERs for the three LPWANs are very low and always increase when the number of nodes increases. Similar to the two above cases, NB-IoT outperforms LoRaWAN and SigFox in terms of PER.

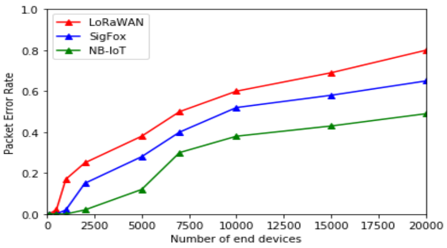

Fig. 3. Packet error rate for one gateway

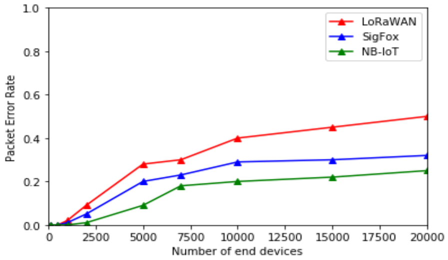

Fig. 4. Packet error rate for two gateways

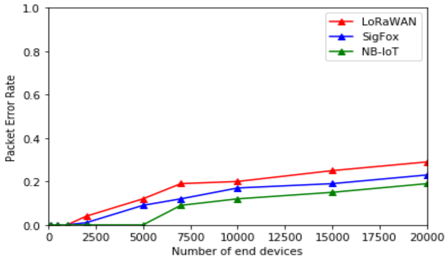

Fig. 5. Packet error rate for four gateways

Looking at the results obtained in Fig. 3, 4 and 5, we can draw three conclusions: (1) The number of gateways used has a great impact on the performance of the network, (2) NB-IoT provides low PER compared to SigFox and LoRaWAN in all the study cases, (3) Through the three different cases, we found out that the three LPWANs are sensitive to the number of nodes and with a high number of nodes we obtain high PERs. On the basis of the obtained results, we can finally conclude that NB-IoT is able to support a great number of devices with low PER compared to LoRaWAN and SigFox and thus is the most scalable.

VI. RELATED WORKS

We found in literature, some research works which tried to compare LoRaWAN, SigFox, and NB-IoT. Mroue et al. [10] compared the MAC layers of LoRaWAN, SigFox, and NB-IoT and concluded that NB-IoT is more robust than LoRaWAN and SigFox in terms of PER. Mekki et al. [11] qualitatively provided a comparative study of LoRaWAN, SigFox, and NB-IoT. Similarly, Gaddam et al. [7] provide a qualitative comparison of LoRaWAN, SigFox, and NB-IoT in terms of battery lifetime, cost, network coverage, latency, range and security. Vejlgaard et al. [12] compared SigFox, LoRa, GPRS, and NB-IoT in terms of network coverage and capacity by using a real site deployment covering 8000 km^2 in Northern Denmark.

VII. CONCLUSION

The current paper has firstly explored the various technical features of LoRaWAN, SigFox, and NB-IoT and has compared these LPWAN technologies in terms of SWG communication requirements. Under the NS3 simulator, we have proved that NB-IoT is a good candidate for the SWG scenario because it provides high scalability compared to LoRaWAN and SigFox. In the future, we plan to compare these technologies in terms of other performance metrics such as latency, security, cost, range, etc. Additionally, the results provide by LoRaWAN are unexpected. May be due to LoRa physical parameters configuration. In the future, we plan to study deeply the configuration of these parameters in order to enhance LoRaWAN performance.

VIII. ACKNOWLEDGEMENTS

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