Enabling LoRaWAN Communication Over Wi-SUN Smart Grid Networks

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***Abstract*—Since Smart Grids, Smart Cities and IoT are in a very active expansion phase, we investigate some of the possibilities of integration between different network technologies to expand the options for the use of Smart End Devices. This work presents a series of improvements made on the communication of LoRaWAN Gateways and their Network Servers that allow these technologies to be installed over Low-Rate Wireless Networks communication channels, such as Wi-SUN Smart Grid Networks. The proposed improvements were validated on a network prototype assembled in a Lactec laboratory. Our results, in addition to supporting the viability of the integration, show that the protocol modifications can yield a reduction of up to 99% in the number of control messages sent through the Wi-SUN network.**

***Index Terms*—LoRaWAN, Wi-SUN, Integration, Smart Grids, Smart Cities**

I. Introduction

In recent years a great deal of research has been carried out on how to take advantage of the high transfer rate and low latency offered by new communication technologies such as 5G and 6G. In developing countries, however, these technologies have not yet been (fully) implemented and even their predecessors have coverage restricted to urban areas of cities. On the other hand, Smart Grids (SG), implemented by utility companies, are being extensively deployed, as their advanced metering infrastructure (AMI) brings about several benefits, such as cost reduction with meter reading, and savings with displacement of service teams. Furthermore, AMIs can be installed and provide coverage wherever there is an energy consumer, including rural areas.

AMIs are usually formed by two layers of communication networks: (i) the *backhaul* which interconnects the data collectors of the AMI network itself and supports automation applications; and (ii) the *Neighborhood Area Network* (NAN) formed by smart meters installed in energy consumers. NANs are a mesh-type network that communicate with data collectors to send and receive their messages. The Wireless Smart Ubiquitous Networks (Wi-SUN) specification has been widely used in the implementation of SGs AMI networks and also in applications for Smart Cities and IoT. The specification is promoted by the Wi-SUN Alliance [1] and follows the IEEE 802.15.4 standard [2], which defines Low-Rate Wireless Networks (LR-WAN).

The first Smart Grid network installed by Companhia Paranaense de Energia (COPEL) is in the city of Ipiranga, Paraná State, Brazil. This SG AMI network has 18 data collectors, 154 routers and 5250 smart meters. The city was strategically chosen because it represents a good test scenario for the technology, has a large territorial extension, has low cell phone coverage, and about half of the energy consumers are located in the rural area [3]. Assessments carried out on this SG proved its economic viability for the company, and thus new installations are being deployed and should cover the entire south of Paraná State in the coming years.

In addition to the economic viability of Ipiranga's SG, a previous study evaluated the network bandwidth usage and presented a framework that allows the integration of different applications on the SG network [4]. Three applications were assessed: weather monitoring, water metering and street lighting. Subsequent studies identified that, although the Wi-SUN radio modules evaluated have strengths such as long range and security, they do have a higher power consumption than desirable for battery-powered devices, which should run for several years without maintenance. This is the case of water metering, smart home devices, and most IoT devices.

This paper presents a series of improvements designed to enable the use of LoRaWAN technology over the communication infrastructure of Smart Grids, which enables the use

This work was supported by COPEL under grant PD-2866-0515/2019 from R&D program of the Brazilian Electricity Regulatory Agency (ANEEL).

of ultra low power devices on SGs. The results demonstrate that this integration is possible if the changes proposed by the authors are adopted between the communication of LoRaWAN Gateways and Network Servers. Among the gains achieved in the tests performed, we observed a reduction of up to 99% in the number of control messages sent through the Wi-SUN network.

The text is organized as follows. Section II discusses related work; section III presents the system architecture; section IV presents the proposed adaptations to the LoRaWAN protocol. Section V shows the results obtained, and in section VI we present the conclusions and indicate areas for future work.

II. Related Work

The necessity of developing low-power devices for Smart Grid applications led to extensive work attempting to assess the viability of the LoRaWAN technology for this purpose. Some studies suggest modifications to the Wi-SUN protocol, and even to the LoRaWAN protocol, attempting to improve energy consumption, and to support the development of ultra low-power applications. However, as far as we know, none have tested the combination of these two technologies.

In [5], the authors compare the establishment of a smart grid system based on LoRaWAN to a mesh solution. In [6], the authors explore the use of LoRaWAN as a smart grid solution through simulation. In [7], the authors evaluated the use of LoRaWAN networks, through simulations, to implement an AMI system. In [8], the authors describe a successfully implemented smart water grid system in Mori, a village in India, with LoRaWAN technology. In [9], the authors propose an alternative to the LoRaWAN Adaptative Data Rate (ADR) mechanism to improve the device consumption for smart water grid applications. In [10], the authors tested a LoRaWAN smart grid solution in southern Brazil in a suburban region. In their work, they assess the costs involved in deploying a LoRaWAN backhaul in a rural environment. In [11], the author proposes the diversification of the Wi-SUN protocol into three categories according to the application: high-capacity data collection network, reinforced mesh network, and ultra low-energy operation network. The latter would allow the leaf router node devices to sleep, enabling ultra low-power applications, such as water metering. In [12], the authors investigate the interference LoRaWAN receives from Wi-SUN, since both technologies operate on unlicensed bands and their networks can interfere with each other, and propose some algorithms to set the best LoRaWAN parameters.

III. System Overview

The system architecture is presented in Fig. 1. The left side of the picture shows the "pure" Wi-SUN Devices (red cones), the LoRaWAN Gateways (blue cones) and the Wi-SUN Border Router. The center of the figure displays the backhaul network, the Meter Data Collection (MDC) system, and a more detailed LoRaWAN Gateway ensemble is shown in the dotted box. The right side contains a representation of the integration server and the LoRaWAN Network Server (NS) – including the protocol converter module – that integrate the application servers. The components are described in what follows.

A. LoRaWAN

LoRaWAN (LW) is a Low Power Wide Area Network (LPWAN) protocol that is intended for communication over long distances with low power consumption. It uses proprietary LoRa modulation and its MAC layer is optimized to reduce power consumption. The use of star topology and short data reception windows after a transmission (operation in class A) allows LW End Nodes to be extremely simple and remain in sleep mode most of the time. In addition, LW has an Adaptive Data Rate (ADR) algorithm to further optimize power consumption [13].

As the main use case of enabling LoRaWAN over Wi-SUN is the connection of battery-powered devices, our tests included only LW Class A devices. Although untested on Class B and Class C, the proposed modifications do not depend on the device class. In practice, it may be necessary to configure the network server to schedule Class B downlinks to later ping slots in order to compensate the high latency of the Wi-SUN network.

A LW network is formed by end node devices that communicate directly with a gateway using the LoRaWAN protocol. The gateway uses the UDP/IP protocol to communicate with the Network Server, which in turn controls security and interconnects the devices with their application servers.

B. Wi-SUN Network

The Wi-SUN network is composed of a border router, which interconnects the mesh network and the backhaul network, and Wi-SUN end nodes, comprised mostly of smart meters and routers. The Wi-SUN network is managed by the MDC system, which collects data from the smart meters, controls the devices that can join the mesh network and allows devices to interconnect with their external applications. To provide for the development of applications other than AMI, it is possible to connect different devices to the smart grid infrastructure using a radio module that is compatible with the Wi-SUN network technology. For that purpose, the MDC provides a software interface that allows external applications to exchange raw data with devices in the mesh network. We developed an integration server that connects to the MDC using this interface to forward LoRaWAN messages between a LW gateway and a network server.

In previous work [4], we used the MDC integration interface to implement the MQTT-SN protocol in the Wi-SUN network, allowing applications to communicate with end devices using MQTT, a widely adopted protocol for IoT. This paper describes a different integration mechanism in which LW End Nodes and Gateways are connected to a LW Network Server using the Wi-SUN network as a backhaul. Although the underlying technologies described here and in [4] are distinct, the application developer is presented with a single abstraction (MQTT), a rather useful feature since most LW NSs implement MQTT integration with other applications.

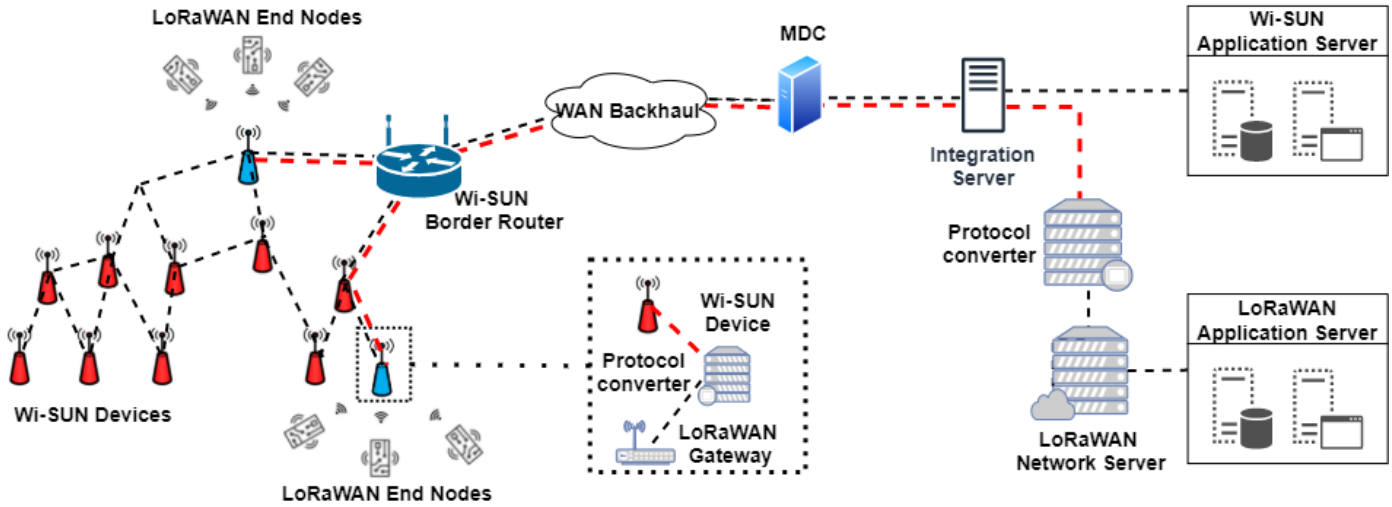

Fig. 1. System integration architecture.

C. LoRaWAN Gateway

The gateway that enables the communication between the LoRaWAN End Nodes and a Wi-SUN Border Router is composed of three elements: a LoRaWAN Gateway, a Wi-SUN Device and software developed by our group for protocol conversion. This structure is shown in the dotted box in Fig. 1.

The assembly of the gateway is shown in Fig. 2. The LW Gateway consists of a Raspberry Pi 3B+ and a RisingHF RHF0M301 Gateway LoRaWAN shield. The Raspberry Pi board runs both Packet Forwarder UDP [14] and LoRa Gateway [15], which are open-source software provided by Semtech for LW Gateway implementations. The protocol converter software we developed also runs in the Raspberry Pi, and is described in Section IV. The Wi-SUN Device is a module that operates in pass-through mode. The module was integrated with the system described above via a USB/serial converter.

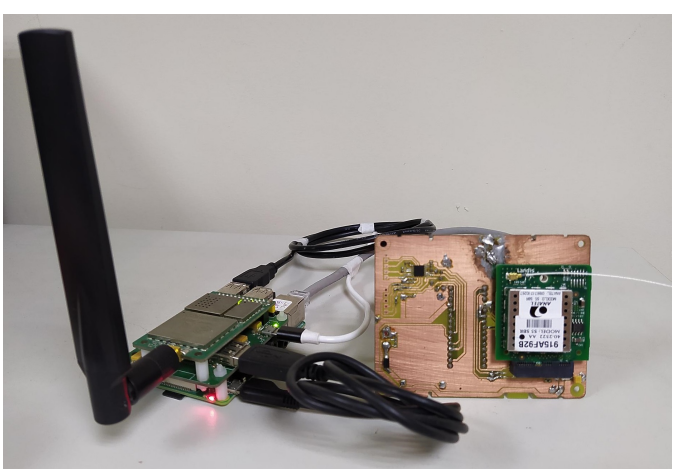

Fig. 2. LoRaWAN/Wi-SUN Gateway hardware.

D. LoRaWAN End Nodes

Commercial LoRaWAN water meters from three manufacturers were employed in our performance tests, and these devices are displayed in Fig. 3. The variety is needed so our test scenarios are closer to actual deployments. While development kits allow the setting almost every LoRaWAN parameter, most of the commercial metering products are very restrict regarding configuration due to security concerns.

The LoRaWAN protocol presents two activation modes: Activation By Personalization (ABP) and Over-The-Air Activation (OTAA). In the former mode, the device does not need to exchange join messages since the cryptography keys, as well as the device address, are static and predefined. In the latter mode, these values are defined during the join procedure.

One of the tested products has extra features such as resetting the device to an initial state and selecting the LoRaWAN activation method (ABP/OTAA). The others have only ABP activation and are fully sealed.

Fig. 3. LoRaWAN End Nodes - commercial water metering solutions.

IV. Protocol Improvements

To enable the communication between the LW Gateway and the LoRaWAN NS via Wi-SUN network, the LoRaWAN protocol had to be adapted. A set of software routines were written

```
JSON up: {"stat":{"time":"2021-04-20 16:52:34 GMT","rxnb":0,"rxok":0,"rxfw":0,"ackr":0.0,"dwnb":0,"txnb":0}}
RCVD UDP:PUSH_DATA
0x02 0x4a 0xec 0x00 0xb8 0x27 0xeb 0xff 0xfe 0xaf 0x79 0xc3 0x7b 0x22 0x73 0x74 0x61 0x74 0x22 0x3a 0x7b 0x22 0x74 0x
69 0x6d 0x65 0x22 0x3a 0x22 0x32 0x30 0x32 0x31 0x2d 0x30 0x34 0x2d 0x32 0x30 0x20 0x31 0x36 0x3a 0x35 0x32 0x3a 0x33
 0x34 0x20 0x47 0x4d 0x54 0x22 0x2c 0x22 0x72 0x78 0x6e 0x62 0x22 0x3a 0x30 0x2c 0x22 0x72 0x78 0x6f 0x6b 0x22 0x3a 0
x30 0x2c 0x22 0x72 0x78 0x66 0x77 0x22 0x3a 0x30 0x2c 0x22 0x61 0x63 0x6b 0x72 0x22 0x3a 0x30 0x2e 0x30 0x2c 0x22 0x6
4 0x77 0x6e 0x62 0x22 0x3a 0x30 0x2c 0x22 0x74 0x78 0x6e 0x62 0x22 0x3a 0x30 0x7d 0x7d

Serial send: 2B 1D 00 34 00 02 4A EC 00 B8 27 EB FF FE AF 79 C3 01 00 00 00 00 60 7F 06 D2 00 00 00 00 00 00 00 00 00
 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 45 FD
***************
```

Fig. 4. Compression of a PUSH_DATA packet.

to convert the Packet Forwarder UDP protocol to a lightweight protocol. The main purpose of the intermediate protocol is to reduce packet size, since the Wi-SUN network has more stringent traffic constraints than IP over Ethernet or Cellular. In Fig. 1, the exchanges through the lightweight protocol are identified by the red dashed lines. After implementing the compression feature, additional requirements were addressed, such as fragmentation, buffering of downlink packets and reduction of traffic. Each of these features is detailed below.

A. Compression

The LoRaWAN Packet Forwarder uses JSON-encoded payloads, which are readable and easy to work with. However, each message is comprised of many bytes because of the text-based serialization. This format is not suitable for communication methods that have a small packet-size limit, or have their performance severely affected by sending long packets.

In order to reduce the number of bytes of the serialized message, each JSON payload was recoded to a binary notation. Numeric fields were modified to be stored as binary numbers, dates in string format were converted to numeric Unix timestamp values, categorical fields were given enumeration values. Furthermore, all fields were given a specific order in the binary payload, allowing the JSON keys to be omitted.

The compressed version of a PUSH_DATA packet is presented in Fig. 4. The time field is highlighted in red. On the first lines, the original message is represented as text and their corresponding octets. The compressed packet is shown on the last line.

The proposed payload format is fixed, meaning that every field has a determined position, data type and size. Fields cannot be added, removed or modified without a complete payload redesign. Despite these shortcomings, we still opted to use a fixed payload over flexible formats (such as BJSON or BSON), because they cannot achieve the data size reduction we were aiming for, especially regarding the removal of string keys and conversion of dates to numeric timestamps.

B. Fragmentation

Most packets defined by the Packet Forwarder UDP have a fixed size and can be reduced to a few bytes; yet a single PUSH_DATA can contain a list of uplink messages send by several nodes. This packet, even after compression, might contain more bytes than the Wi-SUN MTU (Maximum Transmission Unit). In these cases, we implemented a simple fragmentation protocol to break the payload in smaller parts that fit the maximal transmission unit.

C. Downlink Buffer

The latency of the Wi-SUN network is too high to meet the standard RX Delay value of 1 second for LoRaWAN class A reception window [16]. When attempting to send a downlink to the node, the LW Gateway would discard the message since it arrived past the time the node was in reception mode. One workaround would be increasing the reception delay directly in the end device's firmware, but most commercial metering devices disallow firmware modification for security reasons.

The RX Delay can also be set in the NS and issued to the device as part of the Join Accept message or as MAC command. When the device is activated by OTAA, the Join RX Delay (5 seconds) is enough for receiving the Join Accept frame even with higher latency. When activated by ABP, the MAC command downlink does not meet the current RX Delay. In the latter case, the NS keeps trying to send the command indefinitely without success, since the node will never receive the downlink in time.

There are some LoRaWAN metering devices that only accept ABP activation and have the RX Delay fixed on the standard value. For this reason, we implemented a buffer for holding a downlink request and sending it on the next available window. This buffer is selective: not all downlink messages are held, only the ones containing the MAC command responsible for setting the RX Delay (RXTimingSetupReq). As such, the buffer capacity is limited to a single message per device, with no expiration time. Fig. 5 shows the message flow when activating an ABP node.

After receiving the first uplink from the node (orange arrows), the NS generates a downlink containing the RX-TimingSetupReq command (green arrows). This message is forwarded to the LW Gateway. Because of the latency, it would arrive after the node's receive windows (RX1 and RX2), so this message is inserted on the buffer instead of being discarded. The next time this device sends an uplink, the request for setting the RXDelay to a higher value is already on the LW Gateway and can be sent on time. After that, the Wi-SUN

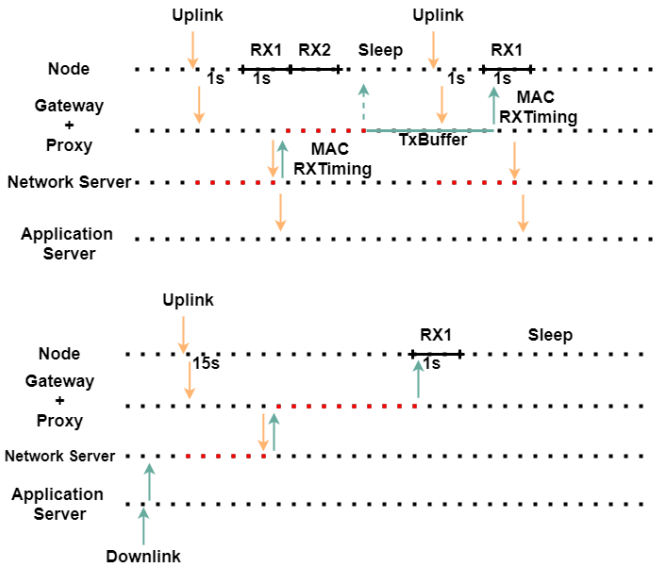

Fig. 5. Downlink bufferization message flow.

backhaul latency is no longer an issue since 15 seconds is enough for the NS to send a frame to the LW Gateway.

The data rate, frequency and timestamp fields of the bufferized downlink need to be updated by the protocol converter software, since these parameters are set according to the uplink preceding the reception window in which it will be sent.

D. Reducing Packet Traffic

Several control messages are exchanged between the LW Gateway and the NS, alongside application data packets. These messages are periodic and their default cycle time is shorter than 1 minute. The daily packet count could amount to more than twenty thousand per day, even without a single active device on the network. This would greatly impact the Wi-SUN network performance, especially in the case of having several LW Gateways, hence we attempted to reduce the frequency of the control messages.

The period of both PUSH_DATA (`stat`) and PULL_DATA can be defined in the Packet Forwarder configuration file, through `stat_interval` and `keepalive_interval` keys, respectively. The period of the `stat` message was increased from 30 to 600 seconds without any issues, whereas increasing the `keepalive_interval` from 10 seconds to any value longer than 60 seconds resulted in malfunctions, albeit only for downlink messages.

The purpose of the PULL_DATA message is to keep a stable connection so that the NS is able to send messages to the LW Gateway [14]. The Chirpstack Gateway Bridge process, running on the server side, keeps track of the messages coming from the LW Gateway and when the "last seen" is longer than 1 minute, it unsubscribes this device from the MQTT topic. Thus, in the absence of a PULL_DATA message, the communication from NS towards the LW Gateway may be compromised, but not on the other way around – only the downlinks are affected.

Since the protocol adaptation proposed here eliminates the end-to-end UDP communication between the NS and the LW Gateway, the PULL_DATA/PULL_ACK mechanism loses its purpose of keeping the UDP channel open. Therefore, we decided not to forward the PULL_DATA packets generated by the LW Gateway to the NS (and subsequent PULL_ACK responses) over the Wi-SUN network. Instead, we generate fake messages on each side of the communication. This keeps both the route open, and the subscription on the MQTT topic, without the overhead of control packet traffic through the backhaul. The reception of `stat` by the NS is used to check if the LW Gateway was communicating properly and if a fake PULL_DATA should be injected.

With these modifications in place, the number of control messages between NS and LW Gateway via the Wi-SUN network was reduced to less than 300 per day.

V. Performance Evaluation

In order to validate and evaluate our proposed protocol modifications, we assembled the LoRaWAN/Wi-SUN gateway prototype into a Wi-SUN network, composed of one border router along with thirty router nodes, at Lactec. This LoRaWAN/Wi-SUN gateway, which is also one of the Wi-SUN router nodes as shown in Fig. 1, communicates with five LoRaWAN devices. Tests were performed to assess device activation and data exchange, both uplink and downlink. We also measured the performance of the new approach at reducing the number of LW control packets.

A. Packet Traffic Reduction

The increase in the time period of the `stat` message and the adaption of the PULL_DATA/PULL_ACK mechanism led to a reduction of nearly 99% in the number of LW control messages sent through the Wi-SUN network. The message counts are presented in Table I. No communication instability was observed that could be attributed to this optimization.

TABLE I
Reduction of LoRaWAN control messages

	Before reduction		After reduction	
Message	**Interval [sec]**	**Packets per day**	**Interval [sec]**	**Packets per day**
PULL_DATA	10	8640	-	-
PULL_ACK	-	8640	-	-
PUSH_DATA (stat)	30	2880	600	144
PUSH_ACK	-	2880	-	144
Total packets per day		23040		288

B. Device Commissioning

Both ABP and OTAA devices are successfully activated on the LW Network. The ABP devices have their `RxDelay` set to 15 seconds after the second uplink sent. This is achieved via MAC command buffering. Currently, this buffer works for devices complying with the recommended regional default for reception delay and data rate offset. Additional functionality is needed in order to support non-standard parameters.

Devices activated via OTAA also had their `RxDelay` set to 15 seconds by means of the join procedure. The 5 seconds join delay can sometimes be too narrow a window for receiving the JOIN_ACCEPT, especially if there is heavy traffic on the Wi-SUN network. This leads to the loss of some accept messages, but eventually the device will join the LW Network.

C. Uplink

After commissioning, uplink statistics were collected based on the `f_cnt_up` field of the LoRaWAN frame. Table II shows the lost number of packets for five ABP devices sending data every hour, except for device 5, which was sending every three hours. This test was conducted for both ABP and OTAA devices, and was repeated with the Wi-SUN node in the layer below, thus communicating to the Border Router indirectly, via another node. There were no significant differences observed in these two scenarios. On average, 96% of the packets were received.

TABLE II
UPLINK STATISTIC FOR LORAWAN END NODES

	Received	**Lost**	**Received [%]**
Device 1	179	6	97
Device 2	183	2	99
Device 3	181	2	99
Device 4	160	21	88
Device 5	57	1	98

D. Downlink

The downlink traffic was not as extensively tested as uplink traffic in the scenarios described above. Twice a day, a confirmed downlink was sent from the LW Application Server towards the LW node. In every test case, the device successfully acknowledged the reception of the message in the following uplink exchange.

VI. CONCLUSIONS AND FUTURE WORK

This paper demonstrates that it is possible to use LoRaWAN technology over Low-Rate Wireless Networks communication channels, such as Wi-SUN Smart Grid Networks, which then serve as a backhaul for the LoRaWAN network.

We describe four improvements to enable this integration, namely: compression, fragmentation, downlink buffering and packet traffic reduction. The performance of our prototype confirms the viability of the integration and that a reduction of up to 99% can be obtained in the number of control messages sent through the Wi-SUN network.

Our proposal greatly extend the possibilities for integrating IoT devices for Smart Grids and Smart Cities, since Smart Grids have large capillarity and will be present in almost all energy consumer's premises, including those in rural areas and small cities, locations where the more modern networks may yet take a long time to arrive.

In regard to potential disadvantages of deploying LoRaWAN in a Wi-SUN AMI network, a point of concern is that the LW Gateway handles numerous LW End Nodes. As such, the gateway generates much more traffic in the AMI than a common smart meter. This can result in congestion, especially if the gateway is located far away from the border router and needs several hops in the mesh network to reach the LW servers. Considering that the AMI itself has a low data rate, in order to support a large number of LW nodes, nodes must not send packets (very) often and should avoid transmitting at the same time. Many applications, such as water metering, tolerate these limitations and are suitable in this scenario.

As future work, we intend to carry out tests with LoRaWAN Gateways and Network Server on other types of networks with low data rates and high latency, such as satellite networks.

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