Low Voltage Grid Control Using Low Power Wireless Technologies

André Rabaça
Instituto Superior Técnico
Lisbon, Portugal
andre.rabaca@ist.utl.pt

***Abstract*— In this paper is analyzed and discussed the implementation of LoRaWAN for Low Voltage Grid sensors against other multi-hop technologies that use IEEE802.15.4 in the physical and MAC layers. It was developed the LoRaWAN protocol in the OMNeT++ simulator. OMNeT++ has already an implementation of the IEEE 802.15.4. It was added a static routing, on top of the IEEE802.15.4, to recreate a multi-hop scenario, like one using Routing over Low Power Lossy Networks (RPL).**

Keywords— LoRaWAN, OMNeT++, IEEE 802.15.4.

I. Introduction

Low Power Wireless Network (LP-WAN) are a group of technologies for IoT that provides long range and low power consumption. This is used in many sensors in many different fields, such as the industry or the agriculture. The transmissions occur occasionally, when there is useful information to be sent, and with long dwell times, due to low physical bit rate. This is very different from other technologies like WiFi. LP-WAN operate on the Industrial, Scientific and Medical (ISM) band which is a free region of the frequency spectrum. This has allowed a steady growth of this kind of technologies, such as LoRaWAN.

Our main contribution is an evaluation of LoRaWAN versus protocols that use IEEE802.15.4 in the physical and MAC layers. This evaluation was based on a scenario of an electrical grid with sensors on it. Some statistics regarding the end-to-end delay, energy per bit and throughput were taken and discussed.

This paper is organized as follow: Section II describes the LoRa and LoRaWAN protocol, Section III describes the IEEE802.15.4 protocol, Section IV describes the LoRaWAN protocol implement in the OMNeT++, Section V describes the scenario employed. Section VI shows some results taken from a low voltage grid scenario in Batalha. Section VII presents some conclusions are summarized.

II. : LoRa and LoRaWAN

A. LoRa

LoRaWAN stands for Long Range Wide Area Network which employs LoRa as modulation scheme. LoRa is a proprietary modulation owned by the company Semtech. It uses the Chirp Spreading Spectrum (CSS) as the Spread spectrum technique [1]. As a spectral spectrum technique, it is resistant to multipath, fading, Doppler effect and jamming. It is characterized by using a much larger

$$R_s = \frac{1}{t_s} = \frac{BW}{2^{SF}} \; [baud/s] \tag{3}$$

bandwidth than the one necessary to transmit the information. Due to this large bandwidth and low bit rate we can communicate through a channel without the need of a high signal to noise ratio, as stated by Shannon-Hartley theorem.

The Chirp Spreading Spectrum codes the information using a signal in which the frequency varies in a constant way. This is like a sweep tone. The information is coded into a discontinuity of the signal in a specific frequency. This frequency corresponds to the frequency used in the beginning of the signal. This coded signal is called chirp and is represented in Figure 1. A chirp corresponds to a symbol composed by several bits. These bits are given by the value of the Spreading Factor (SF). The information coded in this initial frequency corresponds to a specific symbol with a number of SF bits.

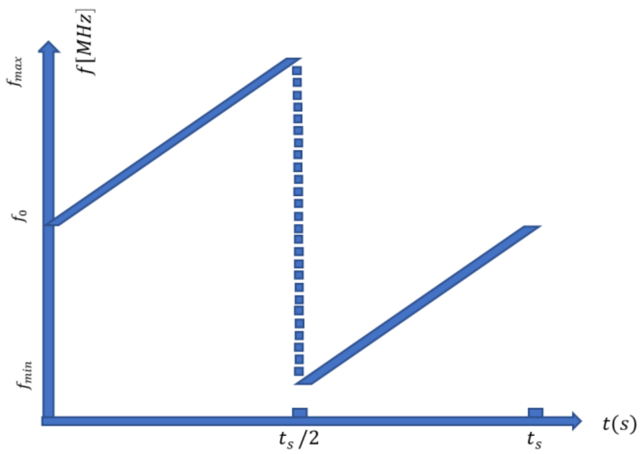

Figure 1: Chirp signal representation.

$$M = 2^{SF} \tag{1}$$

The number of different symbols is given by M Eq. (1):

The period of the chirp, t_s ,is given by the time that it takes

$$t_s = \frac{2^{SF}}{BW} \; [s] \tag{2}$$

to sweep the frequency, Eq. (2):

Where BW is the bandwidth of the signal.

We can conclude that the symbol rate, R_s, is given by Eq. (3):

So, the bit rate is given by Eq. (4):

$$R_b = R_s * SF\ [bits/s] \tag{4}$$

To send more bits in a chirp a higher SF must be employed. This also means that the chirp takes more time to be transmitted (an increase of the SF by one implies that the chirp takes twice the time to be transmitted). The SF used in LoRaWAN can go from 7 to 12. The corresponding bit rate is in the Table I.

If a higher SF corresponds to a lower bit rate why employ it? If the SF becomes higher, the sensitivity of the receptor becomes lower, which means higher communication range. Table I shows some sensitivity values for a channel with 125 KHz bandwidth. If two transmissions of different SF collide in a given channel, both the packets will probably be received (if the power received is higher than the sensitivity) , due to quasi-orthogonality property of the two signals[2]. The LoRaWAN specifies an Adaptive Data Rate (ADR) scheme where the device can increase or decrease the SF.

TABEL I. BIT RATE AND SENSITIVITY FOR EACH SF. VALUES FOR A CHANNEL WITH 125 KHz BANDWIDTH.

SF	Bit rate [bits/s]	Sensitivity [dBm]
7	5470	-124
8	3125	-127
9	1760	-130
10	980	-133
11	440	-135
12	250	-137

B. LoRaWAN

The network elements of LoRaWAN are:

- the device which is a simple sensor with LoRa capabilities
- the gateway which translates packets (chirps) coming from the device to a specific server via IP connection. Reciprocally it has the capability of translating IP Packets to LoRa chirps.
- The network server is responsible for the network's MAC. This includes routing, management of the gateways and forwarding of the downlink messages coming from the Application server
- The join server has an important role on device´s activation in the network and it also delivers several keys to other elements for security and integrity purposes.
- The application server generates information to be included in the payload of the downlink messages.

A new document about the backend [3] was only included in the new specification dating from October 2017 [4]. In that specification the application server, network server and the join server can also be viewed as network elements, as depict in Figure 2.

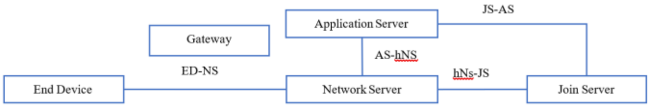

Figure 2: Network elements and respective interfaces.

LoRaWAN specifies three functionality modes for the end device:

• Class A – It transmits whenever is necessary. These transmissions only need to respect the channels´ duty-cycle restrictions. After some delay and after the transmission, it opens two reception windows, as represented in Figure 3. These windows are used by the network server to send Downlink messages to the device via gateway. It is the most used mode and the most power efficient.

• Class B – This mode has the same functionality as the class A. It also opens extra periodic reception windows called pings.

• Class C – This mode has the same functionality as the class A. Most of the times has opened reception windows, only closing them when is necessary to transmit a packet. This mode is used for devices that don't have energy restrictions.

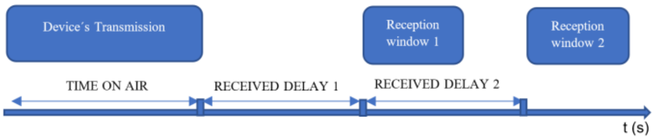

Figure 3: Class A device functionality.

The device needs to be personalized and activated. It must be personalized with two unique identifiers: the device Unique Identifier (DevEUI) and the Join Unique Identifier (JoinEUI). It also needs to have two keys: The Application Key (AppKey) and the Network Key (NwkKey). These keys are important to derive other session keys. These session keys are used to encrypt messages that are exchanged between the device and the backend. They can also be used for integrity purposes.

There are two activation modes: The Over-The-Air Activation (OTAA) and the Activation by Personalization (ABP).

In the OTAA the different session keys are configured with the exchange of a join request message and join accept message. The device must exchange these messages before it starts to send data to the backend. This process adds some delay.

In the ABP there isn't a prior exchange of messages. The session keys must be already configured in the backend and in the device. This mode allows the device to send data to the network without further ado. The drawback is that someone with access to the device can reconfigure those keys and use it to gain access to the device data.

C. Adaptive data Rate

LoRaWAN explores a functionality to increase or decrease the SF used in the transmission of its packets. This mechanism is the Adaptive Data Rate (ADR). This is usually employed when the devices are fixed in a location. ADR can be set or unset by the device, but it is recommended to be always on. In this way a better network overall performance can be achieved. ADR also helps the end devices´ to reduce its energy consumption. Higher SF means higher transmission duration, which means higher energy consumption. If a device transmits with a higher SF, the network can detect if a lower SF can be employed. This information can be transmitted to the device thought a MAC command. MAC commands are useful commands which are included in the packets. These commands can be sent by the network or the gateway to change some parameters in the device or the network

This ADR is activated by a specific bit in a field of the uplink and downlink messages. ADR might be enabled by the device or the network. Only the device can increase its SF. The network is responsible to decrease the device's SF.

The device has a counter named ADR_ACK_CNT. Each time the device sends an uplink message, this counter is incremented (retransmissions don't increase this counter). Each time the network sends a Downlink frame, the counter resets to zero. If there is no downlink received, this counter will always increase. If it reaches a point where it exceeds the ADR_ACK_LIMIT limit, in the next uplink frame a specific bit will be activated to require a downlink message (if SF > 7). If the device after ADR_ACK_LIMIT + ADR_ACK_DELAY hasn't received any frames, it reconfigures its power to its highest value (if isn't already in its maximum value). The ADR_ACK_LIMIT and the ADR_ACK_DELAY are chosen according to the ISM band used. After ADR_ACK_LIMIT + ADR_ACK_DELAY + ADR_ACK_DELAY the SF will increase (if it is less than the maximum (12)). If there is still no downlink frame received, at each step of ADR_ACK_DELAY the SF will be incremented. In this way we can increase the frame reception probability, because a higher SF means a higher receiver´s sensitivity (less reception power required).

When the ADR bit is active the network will gather the Signal-to-Noise Ratio (SNR) of the received packets. After twenty measurements the network will update the transmission power and the SF used by the device. According to the Eq. (5) a margin of the SNR will be calculated [5] :

$$SNR_{margin} = SNR_{mean} - SNR_{req} - M \qquad (5)$$

M is a margin given. It is usually 10 dB. SNR_{mean} is the mean value of the SNR gathered.

SNR_{req} is the SNR required for a given SF, like presented in the Table II.

TABEL II. SF AND RESPECTIVE BIT RATE.

SF	Bit rate [bits/s]
7	-20
8	-17,5
9	-15
10	-12,5
11	-10
12	-7,5

After SNR_{margin} is calculated, a given number of steps is calculated using the Eq. (6):

$$N_{steps} = round(\frac{SNR_{margin}}{3}) \qquad (6)$$

when N_{steps}> 0 the SF will be decremented in N_{steps} to a minimum of SF = 7. The power configuration Tx decremented by $N_{steps}$to a minimum of Tx = 0.

When N_{steps} case < 0 power configuration Tx is incremented in N_{steps} to a minimum of Tx = 5.

The power configuration Tx is represented in the Table III. EIRP stands for Equivalent Isotropic Radiated Power.

These new configurations are then sent to the device via MAC commands. In this way the network can reduce the SF of the device and increase its transmission power.

TABEL III. TX CONFIGURATION AND RESPECTIVE POWER VALUE.

Tx Configuration	Value [dB]
0	EIRP -2
1	EIRP -4
2	EIRP -6
3	EIRP -8
4	EIRP -10
5	EIRP -12
6	EIRP -14
7…15	RFU

III. IEEE802.15.4

The first edition of the IEEE802.15.4 protocol is dated of 2013 [6,7]. This protocol uses channels with 2 MHz bandwidth, spaced 5 MHz, especially in the 2.4 GHz band. It also specifies one channel in the ISM Band specifically in the 868 MHz frequency. Its physical layer is characterized by a bit rate of 250 Kb/ s, which allows the application to send information at a bit rate of 50 Kb/s. IEEE 802.15.4 uses Direct Spreading Spectrum (DSSS) as the Spreading Spectrum technique. The DSSS allows the device to send the data bits on a signal whose bandwidth is greater than that required. This is possible by mapping the data bits with a chipping code bit sequence. The receivers, who know this chipping code, can extract the information, which makes this mechanism resilient to noise and interference. The IEEE 802.15.4 medium is shared by multiple devices. For this reason, its MAC layer uses Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA). This mechanism allows to reduce the probability of packets collision. The different devices can listen to the transmissions that are active on a specific channel. This way devices know when a channel is active or idle.

IV. LoRaWAN in OMNeT++

The OMNeT ++ simulator is an open source event simulator with an Integrated Development Environment (IDE) based on Eclipse[8]. This IDE contains a graphical environment for simulation execution. In OMNeT++ can be seen different packets being exchanged and the modules' state. The simulator also includes several packages with different functionalities. These packages contain modules programmed in C ++ language. The combination of several modules together allows the creation of complex modules. Putting together different complex modules allow the creation of different networks to simulate. There is a package with some modules and protocols. This package is named INeT and can be install together with OMNeT++[9].
In OMNeT++, it was implemented the protocol LoRaWAN. Some C++ and NED files from INET were used or overwritten. Only the class A device functionalities where implemented. The application server and the network server where joined together in a unique module. No join server was implemented. The ADR scheme was programmed according to The Things Network (TTN)[5]. In the MAC layer there are different commands than can be exchange between the network server and the application of the end device. Only ADR MAC commands were implemented and always added in the Fopts field of the packet. In the end device´s application several timers where implemented to emulate data being generated from the sensor. Different send interval can be employed, but the MAC layer always respects the channels' duty-cycle restriction. After a packet is send a back off time given by Eq. (7) must be respected:

$$T_{off_{channel}} = \frac{TimeOnAir}{DutyCycle_{channel}} - TimeOnAir \qquad (7)$$

According to the EU 863-870 band, channels with a 1% duty-cycle were implemented. The TimeOnAir is the transmission duration[4].
Packets that are ready to be send but waiting some back-off time in the MAC layer are stored in a queue.
In the network side packets are deduplicated according to the signal to noise ratio. These duplications occur because different gateways can receive the same packet. The gateway which receives the packet with higher signal to noise ratio is the one that is picked by the network server to perform the next downlink transmission. The gateway routes the packet to the application server via an IP connection. This IP connection is held through a 100 Gbit Ethernet cable.
Packets are named as the correspondent packet field Mtype. They can be send and received by both the gateway and the device. In the beginning of the simulation, the device sends the Join Request in one of the three default channels. This was made according to the EU 863-870 MHz Band[10]. With this Join Request we can emulate the OTAA process. If the packet isn't received, the device is going to increase the power of transmission. If the transmitter is already at its maximum value of transmitting power, it will try to increase the Spreading Factor. This is done cyclically until the SF it reaches 12. After the join request is received, the network sends the join accept. In this join accept it's possible to configure some extra channels in the end device. The user can select the frequency for each channel in the configuration file .ini of OMNeT++. There is also an option to create channels at random frequencies within the limits imposed by the EU 863-870 MHz Band [10].

Packets transmitted on the same channel collide if the SF used is equal. As stated in [2] ,two packets that collide can still be received. If the signal to noise plus interference ratio (SNIR) of one packet i in relation to the other packet j is higher than the threshold $T_{i,j}$. The matrix T in Eq. (8) represents this thresholds [2]:

$$T = \begin{bmatrix} 6 & -16 & -18 & -19 & -19 & -20 \\ -24 & 6 & -20 & -22 & -22 & -22 \\ -27 & -27 & 6 & -23 & -25 & -25 \\ -30 & -30 & -30 & 6 & -26 & -28 \\ -33 & -33 & -33 & -33 & 6 & -29 \\ -36 & -36 & -36 & -36 & -36 & 6 \end{bmatrix} [dB] \qquad (8)$$

$T_{i,j}$ represents the elements of the matrix of the thresholds T, where the value of the line , i, represents the SF of a packet incremented by six . Similarly, the value of the column, j, represents the SF of the packet that collided with i, incremented by six.
For example, if a packet with SF=7, i=1, collide with other with SF=8, j=2, this means that the packet i will be received if:

$$SNIR_i < -24 \qquad (9)$$

Reciprocally, packet j will be received if:

$$SNIR_j < -16 \qquad (10)$$

A. Log Normal Shadowing Model

The aspects of the medium where modulated according to the Log Normal Shadowing Model [11,12]. This model is described by Eq. (11):

$$L_{pd}(d) = \overline{L_{pd}(d_0)} + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \qquad (11)$$

$L_{pd}(d)$ in dB is the path loss at the distance d , $\overline{L_{pd}(d_0)}$ in dB, is the model path loss at the reference distance d_0 ,in meters. γ is the path loss exponent $X_\sigma \sim N(0,\sigma^2)$ is the normal distribution to model *shadowing* phenomena. σ^2 is the variance of the *shadowing* in dB^2 .These parameters were parameterized according to [12] for sub-urban areas . $d_0 = 100$ m, $\overline{L_{pd}(d_0)} = 128{,}95$ dB, γ =2.32 and $\sigma = 7.08$ dB.

B. Bit Error Rate

To model the LoRa modulation it was used the probability of errors express by Eq.12:

$$P_{e,css} = Q\left(\frac{\log_{12}(SF)}{\sqrt{2}} * \frac{E_b}{N_0}\right) \quad (12)$$

, where SF is the Spreading factor , E_b is the energy per bit and N_0 is the noise power spectral density[13].

V. Simulation Setup

To evaluate the LoRaWAN and the IEEE 802.15.4 a scenario was created in the OMNeT++ simulator. This scenario was based on a low-voltage power grid in Batalha, Portugal[X]. Since IEEE 802.15.4 transmission range is lower that the transmission range of LoRaWAN, a static routing to perform a multi-hop transmission was added. The gateway receives all packets from the devices. The scenario created for IEEE 802.15.4 is displayed in Figure 4 . The host [0] sends its packet to the host [1], which forwards it to the host [2]. The host[2] forwards to the host [3], which forwards to the host [4], etc. This routing was done so that all packets are delivered to the gateway.

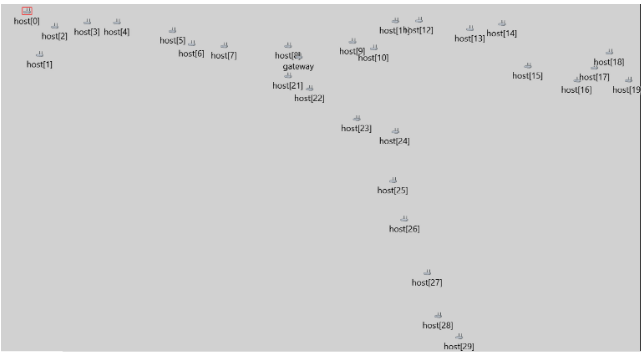

Figure 4: Simulation´s scenario based on a low voltage grid in Batalha.

VI. Simulation Results

According to the Batalha scenario [7], the data was gathered every 15 minutes. This data gives some information about a phase of the Low voltage feeder. In each phase the following information was gathered:

- Reactive Power, through a double-long-signed data type.
- Apparent Power, through a double-long-signed data type.
- Medium voltage through a long unsigned data type.
- Current through a long-unsigned data type.
- Cabinet temperature through a double-long-signed data type.

If we assume that a double-long-signed has a size of 64 bits and the long-unsigned has a size of 32 bits, we have in total 256 bits of payload. It should be noted that three phases are measured in the sensor. For each POST from the Constrained Application Protocol (CoAP), a 32-bit header, 2-bytes token and a 1-byte Start Frame Delimiter (SFD), we can estimate number of bits needed, by Eq (13):

$$Request_{bits} = 3 * sensor_{bits} + token_{bits} + header_{bits} + SFD_{bits} = 824\ bits \quad (13)$$

After each POST an answer is given. If an answer has 2-bytes token and a 32-bit header, we can estimate the number of bits needed by Eq (14):

$$Response_{\ bits} = token_{bits} + header_{bits} = 40\ bits \quad (14)$$

A. LoRaWAN Result

According to Eq. (13) and Eq. (14) we conclude that these number of bits are the payload of the LoRaWAN downlink and uplink messages, respectively.

Three simulations were performed to test the LoRaWAN scenario in Figure 4.

Based on a 15-minute generation interval, LoRaWAN was tested in the simulator for the scenario of Figure 4. Devices were sent to send the first packet within the first 200 seconds. Three simulations were done to test the scenario. The simulation was run for 5000 seconds. Devices send packets every 15 minutes.

A 22 dBm transmission power was set. The payload code rate to 4/5. In Tables 4-1, 4-2 and 4-3, some statistics for the gateway were taken.

B. IEEE 802.15.4

According to Eq.(13) and Eq. (14) we conclude that this number of bits is the payload of the IEEE 802.15.4 downlink and uplink messages, respectively. Three simulations were performed to test the IEEE 802.15.4 scenario in Figure 4.

A 22 dBm transmission power was set. An exponential back-off was used. This means that the time slot is chosen according to the BE parameter and that the time slot will be chosen between 0 and 2^{BE}. In this simulation, BE can have a minimum value of 3 and a maximum of 5. A 0.32 ms time slot was configured. The maximum number of retransmissions of the same packet, before the packet is dropped, was set to 3. To respect the duty-cycle an inter frame space (IFS) based on the message length was configured. The devices send interval parameter was set to 15 minutes. A simulation time of 5000 seconds was set.

VII. Simulation results

A. LoRaWAN

Tabel IV shows some results about the end-to-end delay, number of bytes received and Throughput. Tabel V shows that it wasn’t detected any collisions during the simulation. Tabel VI shows the percentage of packet lost.

TABEL IV. MEAN END-TO-END DELAY, BYTES RECEIVED AND THROUGHPUT FOR A LORAWAN NETWORK WITH 3 CHANNELS.

	Mean end-to-end delay [s]	**Bytes received [B]**	**Throughput [bit/s]**
Simulation 1	0,335	13451	21,52
Simulation 2	0,321	12318	19,71
Simulation 3	0,320	12318	19,54
Standart desviation	0,00839	685,80	1,10

TABEL V. COLLISIONS FOR A LORAWAN NETWORK WITH 3 CHANNELS.

	Mean end-to-end delay [s]	**Bytes received [B]**	**Throughput [bit/s]**
Simulation 1	0,592	17992	28,78
Simulation 2	0,586	17992	28,78
Simulation 3	0,598	17992	28,78
Standart desviation	0,006	0	0

TABEL VI. LOST PACKETS FOR A LORAWAN NETWORK WITH 3 CHANNELS.

	Packets sent by the device's application	**Packets received by the gateway's application**	**Lost packets [%]**
Simulation 1	184	184	0
Simulation 2	170	170	0
Simulation 3	166	166	0
Standart desviation	184	184	0

$$E_b = = \frac{P_{trasnmission}}{R_{b_{SF=8}}} = 50{,}69\ \mu J/bit \qquad (15)$$

According to the number of packets sent by the devices, message length, transmission power and a SF equal to 8, we can estimate the amount of energy consumed per bit thought Eq. (15) :

$$E_{consumption} = 0{,}1584 * 0{,}35 = 55{,}44\ mJ \qquad (16)$$

In each transmission with SF equal to 8, with a code rate of 4/5 and a LoRa packet that takes 0.35 seconds to transmit, we can calculate the amount of energy consumed by Eq. (16):

Figure 5 shows the end-to-end delay histogram of a simulation 2.

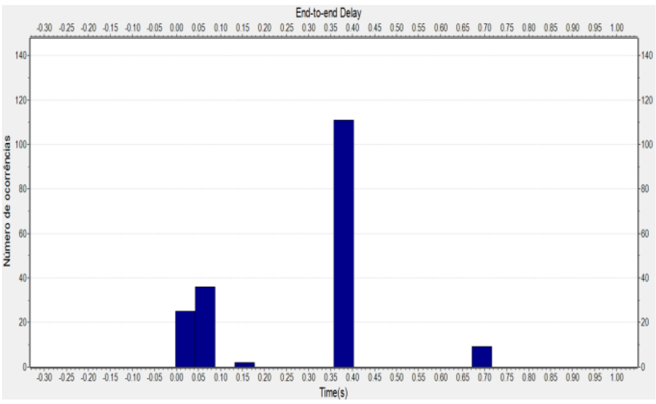

Figure 5: End-to-end delay for a LoRaWAN Network – taken from OMNeT++.

B. IEEE 802.15.4

Tabel VII shows some results about the end-to-end delay, number of bytes received and Throughput. Tabel VII shows the percentage of packet lost.

TABEL VII. MEAN END-TO-END DELAY, BYTES RECEIVED AND THROUGHPUT FOR AN IEEE802.15.4 NETWORK.

	Collisions per packet received
Simulation 1	0
Simulation 2	0
Simulation 3	0

TABEL VIII. LOST PACKETS FOR AN IEEE 802.15.4 NETWORK.

	Packets sent by the device's application	**Packets received by the gateway's application**	**Lost packets [%]**
Simulation 1	174	174	0
Simulation 2	174	174	0
Simulation 3	174	174	0
Standart desviation	174	174	0

According to the number of packets sent by the devices, message length and transmission power, we can estimate the amount of energy consumed per bit thought Eq. (17) :

$$E_b = \frac{P_{trasnmission}}{R_b} = \frac{0{,}1584}{24000} = 6{,}6\ \mu J/bit \qquad (17)$$

In a multi-hop scenario, the number of transmissions is high . This fact increases the amount of energy consumption. Each transmission takes about 0.034 seconds to transmit. Therefore, by Eq (18) we can calculate the amount of energy spent:

$$E_{consumption} = 0{,}1584 * 0{,}034 = 5{,}4\ mJ \qquad (18)$$

For a 10-hop packet this spends 54 mj.
The highest end-to-enddelay detected was 2,1 seconds.

C. Models Comparation

Regarding the scenario of a low voltage grid with 30 devices in Batalha, both solutions allow similar network throughputs at the application level. The number of collisions in IEEE 802.15.4 and LoRaWAN is insignificant because of the high devices' send interval. Collisions in IEEE 802.15.4 are avoided due to the CSMA / CA mechanism, especially for nodes closer to the gateway. In IEEE 802.15.4 there are only collisions due to the hidden terminal problem. This problem is mitigated due low network traffic, so the probability of collision is small. Concerning the number of packets lost (application) the value is zero. This happens because there are packets' retransmissions.

In LoRaWAN the absence of collisions is due to the existence of more than one channel (in this case 3 channels). LoRaWAN has no CSMA / CA mechanism. Devices send packets whenever they have information to be sent

(ALOHA). They only need to fulfil the duty-cycle restriction. As transmissions take more time to be received, packet collisions are more likely to happen. The presence of 3 different channels reduces this probability. Regarding the mean end-to-end delay between packets sent among the two applications, LoRaWAN has a lower value than the IEEE 802.15.4 solution. Despite having a lower bit rate, 3125 b / s (SF = 8) compared to the 24000 b / s of IEEE 802.15.4, there is only one hop distance to the gateway. It should be noted that in IEEE 802.15.4 the highest end-to-end delay detected was 2.1 seconds. This packet was sent by a host that needs to take 11 hops until it reaches the gateway. In larger networks and with the same send interval, the IEEE 802.15.4 end-to-end delay would increase even more. This happens because the packets need to be process in the devices before they can be sent again. LoRaWAN is not a multi-hop technology, so it doesn't have this problem. In relation to the packets lost in the LoRaWAN scenario, these are due to the high value of the PER given by Eq. (11) and the high fading of 7.02 dB. In terms of energy per bit, LoRaWAN has a higher value. It should be noted that in IEEE 802.15.4 the energy consumption is lower than in LoRaWAN. This is due to the small number of packets sent by the devices and the number of hops until the gateway is relatively low. For IEEE 802.15.4 scenarios where hops are higher than 11, LoRaWAN transmission has lower energy consumption. More devices imply that the energy consumption is higher, since the device consumes energy thought its several components, and not only through the packet transmission. For this reason, LoRaWAN can consume less energy than IEEE 802.15.4 and employs more energy per bit in the packets ´s transmission.

The IEEE 802.15.4 network throughput is considerably higher, despite the number of packets lost and high latency.

In relation to LoRaWAN, the increase in the number of channels allowed the reduction of the number of collisions, which allowed that no transmission was made with SF to 9. Thus, with smaller SF a small increase of the binary rate was possible. It is noteworthy that with a number of 6 channels, each with duty cycle of 0.1%, it was possible to further reduce the packet sending interval.

VIII. CONCLUSION

Given a 15-minute send interval, both technologies have similar throughput (application level).

Regarding the power per bit of the LoRa modulation, it has higher values than the BPSK of IEEE 802.15.4, which allows a longer transmission´s range. If IEEE 802.15.4 has most of its devices at a distance greater than 11 gateway hops, LoRaWAN is the best solution for the low power grid when a lower energy consumption is required. One advantage of LoRaWAN is that it doesn't have as much equipment as in IEEE 802.15.4 solutions, neither does it requires high throughputs. The end-to-end delay in LoRaWAN is also a bit smaller.

In case of scenario with lower devices' send interval, LoRaWAN allows better results than IEEE 802.15.4. This is due to the existence of more than 1 channel in LoRaWAN. The CSMA / CA in IEEE 802.15.4 becomes less efficient. This is due to the hidden terminal problem.

ACKNOWLEDGMENT *(Heading 5)*

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