IIEEC Report - Development of a Multi-hop LoRa Testbed

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Acronyms

3GPP 3rd Generation Partnership Project. 6

6LoWPAN IPv6 over Low Power Wireless Person Area Networks. 13

AES Advanced Encryption Standard. 8

API Application Programming Interface. 16

BPSF Binary Phase Shift Keying. 5

BW Bandwidth. 16

CDMA Code Division Multiple Access. 5, 6

CR Coding Rate. 10, 11, 16

CRC Cyclic Redundancy Check. 10, 11

CSS Chirp Spread Spectrum. 9

DAG Directed Acyclic Graph. 13

DAO DODAG Advertisement Object. 13

DBPSK Differential Binary Phase Shift Keying. 8

DIO DODAG Information Object. 13

DIS DODAG Information Solicitation. 13, 14

DL Downlink. 12

DODAG Destination Oriented Directed Acyclic Graph. 13

EC Extended Coverage. 7, 8

eDRX LTE Extended Discontinuous Reception. 7, 8

EGPRS Enhanced General Packet Radio Service. 7

eMTC Long Term Evolution enhacements for Machine Type Communications. 6–8

FEC Forward Error Check. 11

FSK Frequency Shift Keying. 11

GMSK Gaussian Minimum Shift Keying. 8

GPRS General Packet Radio Service. 7

GSM Global System for Mobile Communications. 7, 8

I2C (Inter-Integrated Circuit. 16

IETF Internet Engineering Task Force. 12

IoT Internet of Things. 2, 6, 7, 15

IP Internet Protocol. 5, 6

ISM Industrial Scientific Medical. 5, 8, 9

LAN Local Area Network. 9

LLN Low-power and Lossy Network. 12

LPWAN Low Power Wide Area Network. 4, 5, 8, 9

LTE Long Term Evolution. 6–8

MAC Medium Access Control. 13, 14

MCU Microcontroller. 15, 16

NB-IoT Narrow Band - Internet of Things. iii, 7, 8

OOK On-Off Keying. 9

P2P Peer to Peer. 8, 9

PER Packet Error Rate. 3

PN Pseudo Noise. 6, 9

PRB Physical Resource Block. 7

PSM Power Saving Mode. 7, 8

QAM Quadrature Amplitude Modulation. 8

QoS Quality of Service. 2, 12

QPSK Quadrature Phase Shift Keying. 8

RF Radio Frequency. 4, 9, 15

RPL Routing Protocol for Low power and Lossy Networks. 12–14

RPMA Random Phase Multiple Access. 5, 6, 9

RSSI Received Signal Strength Indicator. 3

SDK Software Development Kit. 16

SF Spreading Factor. 5, 6, 10, 11, 16

SIG Special Interest Group. 8

SNR Signal to Noise Ratio. 3

SPI Serial Peripheral Interface. 16

TDD Time Division Duplex. 8

UE User Equipment. 6, 7

UL Uplink. 12

UMTS Universal Mobile Telecommunication System. 6

UNB Ultra Narrow Band. 5, 8

usart Universal Synchronous Asynchronous Receiver Transmitter. 16

Chapter 1

Introduction

Each year millions of new users and devices connect to the Internet. The number of online devices had already passed the human population by 2012 and continues growth in billions every year [1]. What initially started as a way of individuals interacting within a global network to exchange data, evolved to connect barely any electronic device.
In an Internet of Things (IoT) system, devices collect data, transmit it usually using radio links to base stations, which relay it to an application server in the Internet. Data is stored in the Cloud and processed using machine learning and data mining techniques to retrieve useful information. This information may be used in several domain specific applications, which include smart home, education, market, industry, transportation, health and agriculture.
IoT devices collect their data through one or more connected sensors and are typical powered by a battery, which results in sending sample values periodically under a power constraint. This represents a much lower data rate requirement in comparison, for instance, with streaming video or voice applications. There were several needs: reduce complexity in the end-nodes in order to reduce cost, reduce available data rate to increase range and to develop methods to increase efficiency in power consumption. There are several enabling technologies for IoT which differ in power consumption, range, throughput, Quality of Service (QoS), scalability and cost. LoRa is one such technology operating in license-free sub-Ghz spectrum. The sub-Ghz spectrum has good propagation properties and longer range due to longer wavelength carriers than IEEE 802.11 or Bluetooth but it is limited in European Union to a duty cycle of 1% in 868-868.6 MHz and 0.1% in 868.7-869.2 MHz [2]. As all devices are under the same restrictions, gateways need to be carefully designed to make an efficient use of the spectrum.

1.1 Motivation

Gateways are complex and costly to maintain. They need to simultaneously listen in all channels and are constantly connected to the Internet. However, its density can be reduced through the use of simple relay nodes in a multi-hop scheme. This further allows to collect data from remote locations such as villages or rural areas with no accessible gateways and where it is not economically viable to deploy and maintain a gateway. For optimal performance, relay nodes shall have equally distributed load. Otherwise, if there is high intensity traffic and if all is being relayed through the same node, in the limit, it may run out of capacity and there is a high probability of losing messages.

In addition, if energy harvesting is used on relay nodes, costs of maintenance decrease and in case of electric failure, e.g. natural catastrophe, the nodes have the stored energy as backup.
Recalling the trend of growth in [1], it is of great importance to study what limits the duty cycle may impose in relay nodes as the number of connected devices grow.

Aspects of LoRa such as capacity, scalability, propagation and multi-hop have been initiated and explored in the most recent literature. Augustin et al. [3] proposed and tested a multi-hop protocol between LoRa nodes (analyzed in subsection 2.3.2) with a maximum of two hops in a challenging environment while assuming low traffic and low density of nodes. Adelantado et al. [4] suggests a multi-hop approach in future research, which would allow a decrease in transmitted power.

1.2 Objectives

The main objective of the present work is to design, implement and test a load and energy-aware routing protocol between LoRa transceivers. The protocol shall forward messages taking into consideration the following parameters of neighbor nodes that are closer to the gateway: occupancy, duty cycle limitations and stored energy. A test shall be elaborated with hardware to physical test the protocol and the technology under environmental conditions. The sequence of tasks is presented below.

- Start with analysis of the physical layer of LoRa and other technologies if possible and publicly available.
- Analyze the most suitable protocols, select the most appropriate or propose a variation and implement it.
- Study and identify LoRa field-tests in the most recent literature and propose a test environment of interest. Define the architecture of the physical LoRa network to test and select the required hardware to build the prototype.
- Test the protocol in the chosen testbed and gather data about Signal to Noise Ratio (SNR), Received Signal Strength Indicator (RSSI), Packet Error Rate (PER), congestion and energy consumption.

Chapter 2

Background

2.1 Low Power Wide Area Network

A Low Power Wide Area Network (LPWAN) is characterized by long range, low power consumption, low cost and low throughput End-nodes can be as far as dozens of kilometers, communicate up to dozens of kbits per second and with a battery lasting up to 10 years.

In a typical architecture, as represent in figure 2.1, end-nodes are usually battery powered devices with Radio Frequency (RF) modules which are placed in moving or static objects. Gateways are deployed several kilometers apart depending on range, node density and physical propagation environment. End-nodes communicate using their RF modules to a gateway which relays the information to an application server. A summary of the different technologies and their characteristics in illustrated in Table 2.1.

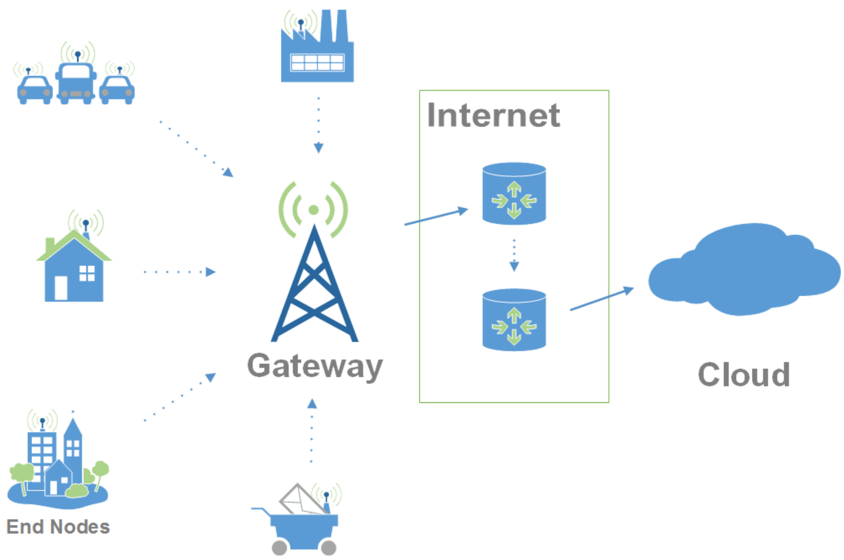


Figure 2.1: Typical architecture of a LPWAN.

Technologies	LoRa	SIGFOX	Weightless-N	Ingenu	LTE-M
Frequency	Sub-GHz ISM	Sub-GHz ISM	Sub-GHz ISM	2.4 GHz	LTE band
RF PHY	CSS and FSK	UNB	UNB	DSSS	LTE
Bandwidth	0.3 - 50 kbit/s	100 bits/s (EU)	100 bits/s	100 kB/day	1 Mbit/s

Table 2.1: Comparison between several technologies for LPWAN [5, 6].

2.1.1 Sigfox

Sigfox offers end-to-end LPWAN connectivity through a cellular style system in the Sub-GHz Industrial Scientific Medical (ISM) spectrum using proprietary technology. An end-device transmits to a base station using a Binary Phase Shift Keying (BPSF) modulation in an Ultra Narrow Band (UNB) subcarrier (100Hz). The base station then forwards the message to the backend servers through an Internet Protocol (IP)-based network. By concentrating the signal's energy in a very narrow band, Sigfox achieves low noise levels, high receiver sensitivity and high capacity of the network, at the cost of a maximum throughput of 100 bits/s. A maximum of 140 messages with a payload of 12 bytes are permitted on uplink and 8 messages with a payload of 8 bytes on downlink per device per day, in order to comply with the legal limitations of the license-free spectrum. Obviously, it is impossible to acknowledge every uplink message and without additional mechanisms the radio link would be unreliable. To improve the reliability, an end-device transmits the same message multiple times, typically three, over different frequency channels, adding redundancy in frequency and time, therefore increasing the probability of a base station receiving the message. In Europe there are 400 channels 100Hz wide between 868.180 and 868.220 MHz. An end-device chooses a random frequency channel in the previous interval and transmits, while on the network side, a base station scans all the available channels simultaneously for incoming messages.

2.1.2 Ingenu

Ingenu, former On-Ramp Wireless, operates at 2.4 Ghz ISM band with a patented technology for the physical medium access named Random Phase Multiple Access (RPMA). RPMA is a variant of Code Division Multiple Access (CDMA). CDMA spreads a signal over a bandwidth that is much broader than the one required to transmit that signal without spreading. Spreading is accomplished with a spreading code sequence, unique for each transmitter sharing the medium, which is XORed with each bit of the data signal. The result is usually referred as the chip sequence that is transmitted with at a given chip rate. At the receiver the incoming signal is correlated with the locally generated code sequence, which matches that used by the transmitter. Code sequences may vary in length according to the Spreading Factor (SF) ratio defined as in equation 2.1.

$$SF = \frac{Chip\ rate}{Data\ rate}\ . \tag{2.1}$$

SF indicates the length the code sequence per data bit. Logically, it derives that a greater SF increases the transmitted signals' resilience to interference and errors but inversely decreases the data rate. Codes must be carefully chosen to minimize mutual interference between signals from different transmitters. In synchronous CDMA, true orthogonal codes are used whereas asynchronous CDMA uses quasi-orthogonal Pseudo Noise (PN) codes for each transmitter. PN sequences aim to perform with an auto correlation with statistical properties of sampled white noise. That is, taken a sample and correlating it to itself at different points in time, the distribution is Gaussian with a mean equal to the DC component. Despite of appearing random in the channel, PN codes are deterministic with known period by both sender and receiver [7]. CDMA significantly mitigates the effects of broadband and narrowband interference and, if code sequences are well chosen, it can also mitigate inter-symbol interference.

RPMA uses PN sequences described previously in CDMA with the same purpose of spreading the signal but without unique PN codes per transmitter. Instead, a single PN sequence is used for all transmitters and, in order to distinguish transmissions, a phase is selected randomly. This phase selection sets the time offset, i.e. the time a sender must wait before transmitting in that time slot. Time slots are longer than in CDMA to compensate for the maximum possible time offset [8, 9]. Despite the large set of offsets, two or more transmitters may be given the same random offset and originate a collision, in which case it may not be possible to demodulate the two or more signals and a retransmission is attempted with another randomized offset [8]. For downlink, a base station uses CDMA to broadcast, assigning unique PN sequences per each end-device to isolate channels [8, 9].

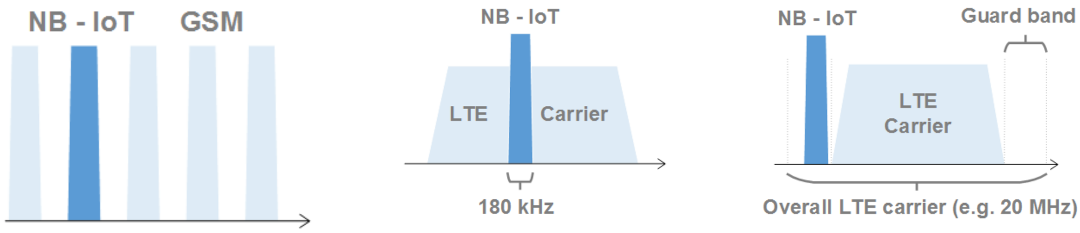
The 3rd Generation Partnership Project (3GPP) was initially created as a strategic association between groups of telecommunications to develop the specification for the next generation of mobile communications after the 3GPP. The standard should be globally applicable and support IP for wireless communications. The collaboration continued with the development of Universal Mobile Telecommunication System (UMTS) and most recently Long Term Evolution (LTE). With the growth of IoT and M2M market there was a need to address this market by taking advantage of the already deployed cellular network and infrastructure. Three standards were developed regarding the needs of IoT.

2.1.3 LTE Enhancements for Machine Type Communication

As being an upgrade in the mobile communications, LTE increased the capacity and simplified the network. It offers devices characteristics not suited for IoT context: high data rate, low latency in exchange of cost and power consumption. 3GPP defines various categories that establish maximum UL and DL data rates for different User Equipment (UE). Category 0 was introduced in release 12, reducing the peak data rate to ten percent of the first category and giving an option for half duplex. Furthermore, category M1, or Long Term Evolution enhacements for Machine Type Communications (eMTC), was introduced in the next release with even lower limits in bandwidth and data rate and, more importantly, two additional modes of operation for UEs. During normal LTE operation, UEs can be contacted by the base stations every 1.28 seconds which is called the paging cycle. The UE has to periodically wake up and check if there is queued traffic directed to him. If there is, it requests it, if not it enters sleep mode again. This obviously consumes power unnecessarily for cases where DL traffic is sporadic. LTE LTE Extended Discontinuous Reception (eDRX) addresses this by increasing the paging period to 10.24s and allowing the UE to announce to the base station the number of periods it will sleep until the next paging check. Moreover, the Power Saving Mode (PSM) allows the UE to announce that it will enter sleep mode indefinitely When it needs to transmits, it wakes up, transmits and remains idle right after in order to be reachable by DL traffic.

2.1.4 NarrowBand-IoT

NB-IoT standardization was completed in June 2016. It is a new air interface also integrated in LTE standard and, as eMTC, is described in release 13. LTE air interface uses Physical Resource Block (PRB) as the smallest chunk of transmitted data, each constituted by 12 subcarriers for a single time slot. There are three different deployment modes which differ on the spectrum region used to transmit - Stand Alone, In Band and Guard Band. A graphical representation of the three is provided in Figure 2.2.



(a) Stand Alone (b) In Band (c) Guard Band

Figure 2.2: Different deployment modes for NB-IoT

Stand-alone (Figure 2.2a) deployment utilizes a new bandwidth outside the bands used for LTE. In Band (Figure 2.2b), as the name implies, transmits in one PRB reserved for NB-IoT inside the LTE's spectrum, which allows for an improve in efficiency of frequency use and capacity of serving more UEs. Guard-band mode (Figure 2.2c) operates within the guard band of an LTE carrier. A single NB-IoT transmission can transmit in 1, 3, 6 or all the 12 PRB subcarriers. When end devices do not need maximum data rates or the number of connected devices to a base station is high, less bandwidth is allocated to each device which allows to multiplex them in frequency. As each LTE subcarrier is 15 kHz wide, using all the 12 subcarriers results in a maximum bandwidth of 180 kHz per device. [10].

2.1.5 Extended Coverage GSM

Extended Coverage (EC)-Global System for Mobile Communications (GSM), formerly EC-Enhanced General Packet Radio Service (EGPRS), is an evolution of EGPRS oriented for the IoT. It features low complexity and low power for end nodes and an extended coverage by 20 dB due to increase in sensitivity. An end node can use the General Packet Radio Service (GPRS)/EGPRS network in cells where EC operation is not available, taking advantage of higher data rates but less range and more power consumption. Energy efficient operation is achieved through relaxed mobility related requirements and optionally, similarly to LTE-eMTC, using eDRX and PSM. Paging monitoring is optimized and security framework is improved by both the network and the end node [11].

2.1.6 Weightless

The Weightless Special Interest Group (SIG), a non-profit global standards organization, developed three open LPWAN technologies both on licensed and unlicensed bands: N, P and W. Table 2.2 contains basic characteristics of the three and may give hints on the applications permitted by each one.

Parameters	Weightless-N	Weightless-P	Weightless-W
Directionality	1-way	2-way	2-way
Feature Set	Simple	Full	Extensive
Range	+5 km	+2 km	+5 km
Battery life	10 years	3-8 years	3-5 years
Terminal cost	Very low	Low	Low-medium
Network cost	Very low	Medium	Medium

Table 2.2: Relative comparison between Weightless standards [12].

Weightless-N utilizes a UNB technology on the sub-GHz ISM spectrum. It modulates the signal with a Differential Binary Phase Shift Keying (DBPSK). To reduce interference, frequency hopping is used. Encryption is provided via 128 bit Advanced Encryption Standard (AES) algorithm and mobility is supported.

Weightless-W uses unused portions of the spectrum allocated for analog TV - white spaces. In the regions where it is possible, Weightless-W transmits on these white spaces, where base stations query a database for used channels to select the free ones to transmit. The frequency range is between 470 MHz and 790 MHz. As the rules and regulations vary geographically this may be a constraint for Weightless-W to scale.

It uses several types modulation, from DBPSK to 16-Quadrature Amplitude Modulation (QAM) and a set of 1024 spreading codes allow trading-off between range and data rate to match the actual needs. As the spectrum is not guaranteed, uplink and downlink share the same frequency and transmit using Time Division Duplex (TDD).

Weightless-P is an improvement in reliability for the Weightless-N, allowing two-way communications and therefore acknowledgments. It uses Gaussian Minimum Shift Keying (GMSK) and off-set-Quadrature Phase Shift Keying (QPSK) modulation.

In the present section, LPWAN technologies with highest presence in the market and literature were covered. The following observations provide the link with the present work as well as hints on why LoRa was chosen.

NB-IoT, EC-GSM and LTE-eMTC have still not been fully launched. Nevertheless, NB-IoT, for instance, already has a module available for pre order (SARA-N2) [13]. Regarding Sigfox, Waspmote [14] is a Sigfox module that offers Peer to Peer (P2P) communication, which allows a multi-hop scheme. However,

the protocol used in the P2P communication does not employ the Sigfox modulation and is intended to form a Local Area Network (LAN) behind an end-node instead of extending the LPWAN. This end-node acts as a gateway between the LAN and nearby base stations.
Nano-S100 is a RF chip employing RPMA, which consumes more power than LoRa or Sigfox [6, 15, 16] mainly by operating at 2.4Ghz ISM (shorter wavelength). This region of the spectrum is limited in transmitted power but not in duty cycle. Therefore, if duty cycle proves to be a major limitation in achieving multi-hop with LoRa, Ingenu can be an alternative.

2.2 LoRa™Overview

LoRa™is the short for Long Range. It is a long-range wireless communication technology intended for battery powered applications where the battery lifetime and energy consumption is important. The term LoRa can refer to the physical layer LoRa™proprietary technology held by Semtech Corporation, or to the MAC layer protocol LoRaWAN promoted by the LoRa™Alliance. Figure 2.3 shows the architecture of a typical LoRaWAN system.

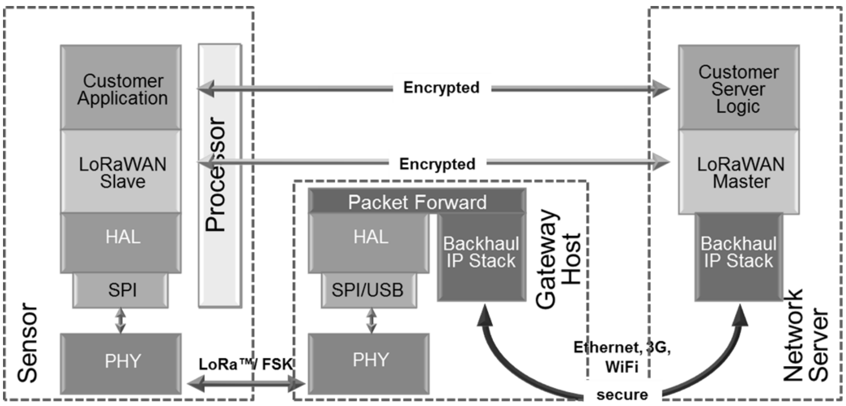


Figure 2.3: Architecture of a LoRaWAN network.

2.2.1 LoRa™

The LoRa™physical layer implements a derivative of Chirp Spread Spectrum (CSS) scheme. CSS was first developed in 1951 at Bell Telephone Laboratories as a classified work for the military radars. The work aimed to offer the same efficiency in range, resolution and speed of acquisition but without the high peak power of the traditional short pulse mechanism [17].

A chirp is a signal in which its frequency increases (up-chirp) or decreases (down-chirp) over time as observed in the sinusoidal linear chirp signal represented in Figure 2.4.

In CSS, each data bit is modulated with a single or a sequences of these chirps, e.g. On-Off Keying (OOK) - assigning an up-chirp to a logical 1 and no frequency variation to a logical 0 [18]. In the case of LoRa™, it employs its own LoRa™modulation. This constitutes an alternative to the spreading method described in subsection 2.1.2 without using PN sequences. Instead, transmissions are distinguished by

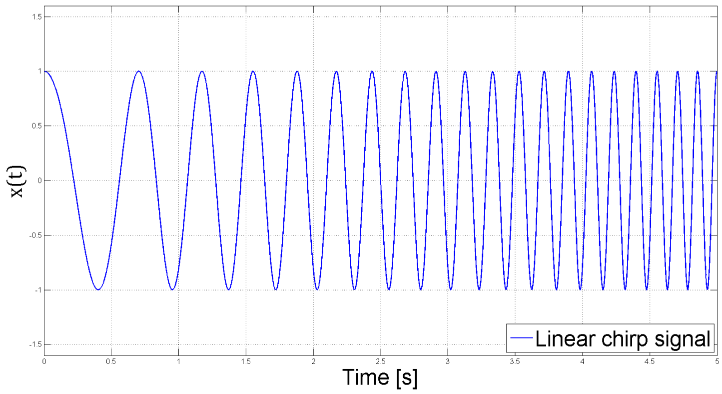


Figure 2.4: Representation of a simple sinusoidal linear up-chirp signal over time.

the time duration of each chirp reflected on the SF, i.e. higher SFs correspond to longer chirps and lower SFs to shorter chirps. Similarly to subsection 2.1.2, higher SFs increase resistance to natural interference, noise and jamming but decreases available bandwidth for data. According to [19], the definition of the SF for LoRa™is different from equation 2.1 of subsection 2.1.2, being $SF = \log_2(\frac{Chirp\ rate}{Symbol\ rate})$, which also means that every symbol is encoded in 2^{SF} chirps that cover the available bandwidth (BW) (one chirp per second per Hz). The duration of a symbol transmission, T_S, can therefore be expressed as in Equation 2.2.

$$T_S = \frac{2^{SF}}{BW} \tag{2.2}$$

Knowing that a symbol rate, R_S is the inverse of T_S, that symbol rate relates with the chip rate by $R_C = 2^{SF} \times R_S$ and that each symbol encodes SF bits, the expression for the useful bit rate comes:

$$R_B = SF \times \frac{1}{\frac{2^{SF}}{BW}}. \tag{2.3}$$

To improve robustness to errors, LoRa™adds redundancy by employing a Cyclic Redundancy Check (CRC) to perform forward error detection and correction. The measure of redundancy is the Coding Rate (CR) defined as the portion of the bit stream which corresponds to effective data, i.e. non-redundant. According to [19], the $Rate\ Code$ is defined as

$$Rate\ Code = \frac{4}{4 + CR}. \tag{2.4}$$

By applying the additional factor of equation 2.4 to equation 2.3, the data rate with all the factors into consideration is given in equation 2.5. Since in a LoRa™one can modify the BW, CR and SF, this expression comes at hand to calculate the available data rate to the above layers such as the application layer.

$$R_B = SF \times \frac{\frac{4}{4+CR}}{\frac{2^{SF}}{BW}} \tag{2.5}$$

The structure of a Lora packet, which can be explicit or implicit, is showed on figure 2.5 It comprises a configurable preamble for synchronization of the receiver, which is a sequence of symbols (chirps) ranging from 6 to 65535, an optional header that can provide information about the payload length, the Forward Error Check (FEC) CR and if CRC is present. Implicit mode exists to reduce overhead by eliminating the header field. This is useful in situations where both sides have prior information about the CR and the CRC or when these parameters are fixed and manually configured at both sides. Figure 2.5 allows one to notice where the previously mentioned SF and CR affect each part of the packet.

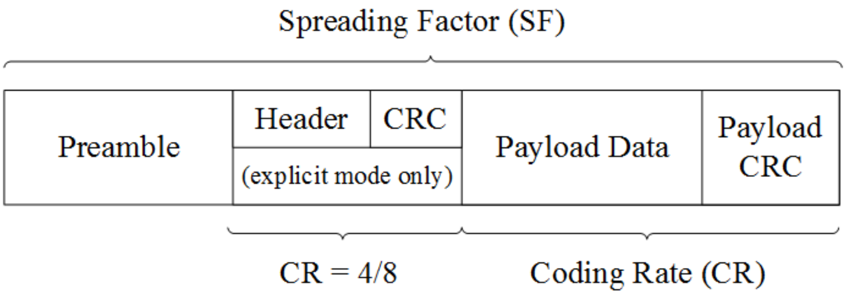
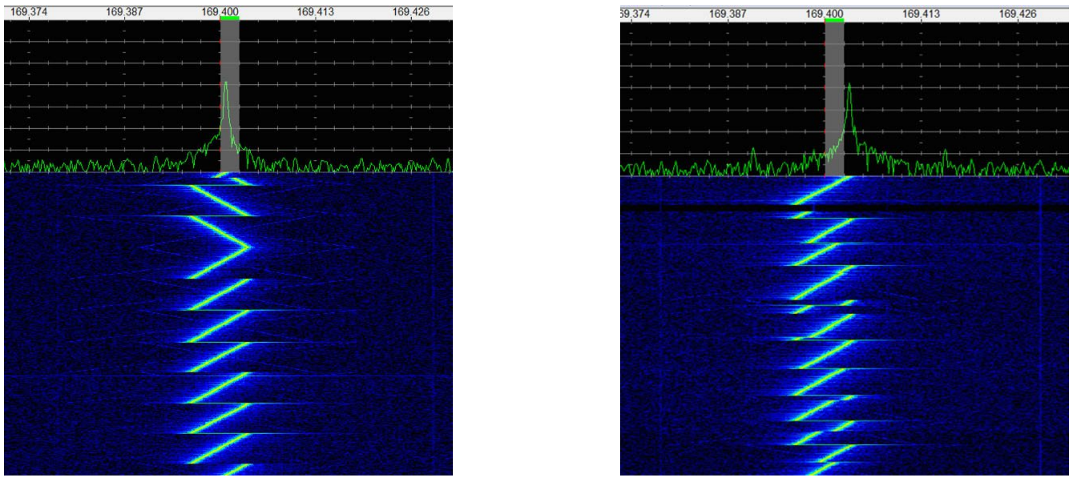


Figure 2.5: Structure of a LoRaTM packet [20].

Figure 2.6a represents the preamble of a LoRa™modulated signal as a sequence of symbols as chirps and 2.6b represents the following data symbols. Further information is provided about the configurable parameters and range of possible values in Chapter 3.



(a) Preamble symbols

(b) Data symbols

Figure 2.6: Representation in frequency in the horizontal axis and time in vertical axis of LoRa™signals [21].

2.2.2 LoRaWAN

LoRaWAN is a network protocol specified from the data link layer above. Typically, a LoRaWAN network consists of a star topology in which gateways relay messages between the end-devices and a Network Server. An end-device can reach one or more gateways using LoRa™or Frequency Shift Keying (FSK) modulation and through a pseudo-randomly chosen channel. As gateways are connected to the Internet, the message is delivered to the network server through IP [22].

Different end-devices and gateways can coexist under the same geographic area by differentiating communications in frequency and also in data rate virtual channels, as, due to spread spectrum, transmissions with different data rates do not interfere with each other. To address applications with different needs of power consumption, LoRaWAN specifies three classes of end-devices based on their listening time, all of which with bidirectional communication [22]:

- Class A - An end-device only listens for Downlink (DL) traffic during two scheduled time intervals after an Uplink (UL) transmission takes place. Schedule is accomplished in a random fashion. This type of end-devices is oriented for applications which mainly rely on UL transmissions and with the most severe power constraints. A DL message originated on the network server to a specific end-device will have to be queued on the gateway in order to wait for the next UL transmission of the desired end-device.

- Class B - An end-device will listen at scheduled times. A beacon is periodically sent by the gateway for synchronization. This allows an end-device to be reachable at certain intervals and removes the dependency of an UL transmission as in Class A.

- Class C - An end-device listens whenever it is not transmitting. This class offers the lowest latency for DL traffic at the cost of more power consumption.

The star topology of a LoRaWAN network is formed by a gateway on the center that handles all the end-devices connected to it through a single hop. LoRaWAN does not specify a peer-to-peer protocol other than going to from an end-node to the network server and from the network server to the destination peer end-node.
The present work targets a routing mechanism to delivery messages between end nodes and gateways with one or more relay nodes in between which use the same RF modules as the end-nodes. The next section provides an analysis on the best suited protocols.

2.3 Routing

Routing is the process of finding and selecting a path for messages from a source to a destination. If multiple paths are available, an algorithm responsible for the selective process takes into consideration one or several metrics, e.g. number of hops, latency, reliability, bandwidth, energy, QoS. In the present work, a routing protocol suited to energy constrained nodes is needed on intermediate nodes to relay messages from the end-devices to gateways.

2.3.1 Routing Protocol for Low-power and Lossy Networks (RPL)

Routing Protocol for Low power and Lossy Networks (RPL) is a proactive distance vector routing protocol specified by the Internet Engineering Task Force (IETF) for Low-power and Lossy Network (LLN). A LLN is formed by energy, processing power and memory constrained nodes, in which the links connecting them are bidirectional, lossy, low rate and possibly unstable. The traffic patterns may be point-to-point, point-to-multipoint or multipoint-to-point.

The protocol does not rely on an *a priori* knowledge of the network topology. Instead, RPL utilizes control messages between nodes that contain their distance to the root. This is accomplished in a distributed way in order to form the topology. The topology comprises a Directed Acyclic Graph (DAG) in which its root has no outgoing edges. The previous may be constituted by several Destination Oriented Directed Acyclic Graph (DODAG) in which every node has the same destination. A DODAG corresponds to an instance of RPL [23]. There is an instance for each different destination. The following control messages are used:

- DODAG Information Object (DIO) - Advertise an DODAG and its information to neighbor nodes. Message is sent downwards the root.
- DODAG Information Solicitation (DIS) - Request information about existent DODAGs to nearby nodes if no DIO message was received yet. Message is sent upwards the root.
- DODAG Advertisement Object (DAO) - Request permission to join the existent DODAG advertised.in a previous DIO message.
- DAO-ACK - Positive or negative response to the previous solicitation.

Altough RPL was designed for IPv6 over Low Power Wireless Person Area Networks (6LoWPAN), it can be implemented in a LoRa network. If one assume that the traffic in such network is usually oriented from the end-nodes towards the gateway, if one gateway is used, one RPL instance is enough.

2.3.2 LoRaBlink

LoRaBlink is multi-hop protocol for LoRa™transceivers proposed in Bor et al. to address multi-hop, low-energy, resilience and low-latency, which are not addressed in current LoRa protocols such as LoRaWAN. It combines Medium Access Control (MAC) and routing, using beacons for time synchronization and to communicate the distance in number of hops to the gateway or sink.

The first beacon is transmitted by the sink and then there is a flooding process in which each node propagates to its neighbors the number of hops it is away from the sink. As a time synchronization mechanism, a beacon indicates the start of an epoch. An epoch is constituted by N slots, in which the first N_B are beacon slots used to transmit hop distance beacons and N_D are data slots. N_B establishes the maximum number of hops. For instance, if a node received a beacon with a hop count of 4, it received in the 4th slot and will transmit (if this is the lowest value to date) its own hop count of 5 in the 5th slot.

A powering up node stays in listen mode until it receives a beacon. After a beacon is received, the node stores the information and waits for the next beacon slot within the same epoch to transmit its hop count to the neighbors. Concurrent transmission can occur if two nodes, namely, node 1 and node 2, transmit their beacon within the same time slot. If a third node is at range of both previous nodes, as LoRa transmissions are non-destructive, either the transmission from node 1 or 2 will, with high probability, be decoded by the third node (depending on time offset and perceived signal strength at the receiver [24]). For the implementation in [24], $N_B = 5$ and $N_D = 55$ were used with an epoch length of 5 minutes - 60 slots, each of 5 seconds. This gives each node time to receive, process and be ready to transmit in the next slot if needed. When a message with data is sent, all the neighbor nodes check its origin in terms of hop distance and if they are closer to the sink, they relay the message. Several transmissions may arrive at the gateway through different relaying paths, which introduces redundancy and therefore wasted power consumption. Some assumptions were considered by the author when developing the protocol, such as low density and low traffic volume of the network. Nonetheless, LoRaBlink is still a suitable option as a routing protocol for the present work.

LoraBlink was already tested in a LoRa network as described previously, whereas RPL is not documented to have been. Also, LoraBlink combines the MAC and routing with the result that advertisements with different hop counts are sent in different times, as well as data.
RPL is oriented for a convergence traffic pattern. Furthermore, if an end-node loses connectivity due to a failure in a relay node, it requests to other nearby relay nodes to join the network by issuing a DIS message.
None of the protocols should be discarded at the moment and a deeper search is needed to decide which protocol to use.

Chapter 3

Experimental Work

The main core of the thesis is to design, implement and test a routing protocol that is efficient in terms of load on relay nodes and energy on end-nodes. For this purpose, an experiment has to be set up in order to gather data to be analyzed. The network to test is formed by LoRa^{TM}nodes, distributed in a star topology. The center of each star is a gateway which is connected to end-nodes through none or several relay nodes, in which case it is a multi-hop network needing a suitable routing protocol. End-nodes will collect data from a sensor and, if a gateway is not reachable through a single hop, data will be sent to relay nodes and forwarded until it reaches a gateway. Uplink traffic exhibits a convergence pattern towards a gateway, selecting the relay nodes on the way which are less occupied, i.e. have less packets in their queues. Downlink traffic will exhibit a divergence pattern, outgoing from a gateway until it reaches the destination end-node. A candidate architecture for the physical LoRa network is illustrated in Figure 3.1. The circles with a white background correspond to end-nodes and grey background to relay nodes. The lines represent that two nodes are in RF range. Taking into consideration the scope of the present work, as all the network components after the gateway are IP-based they were not considered.

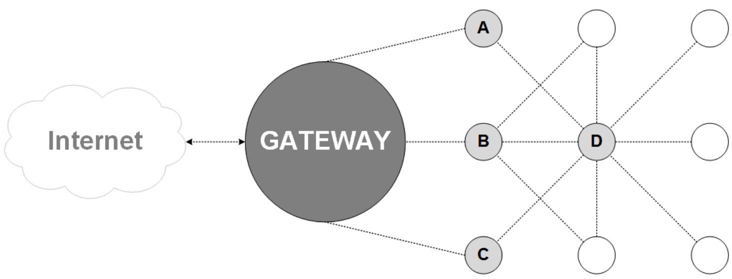
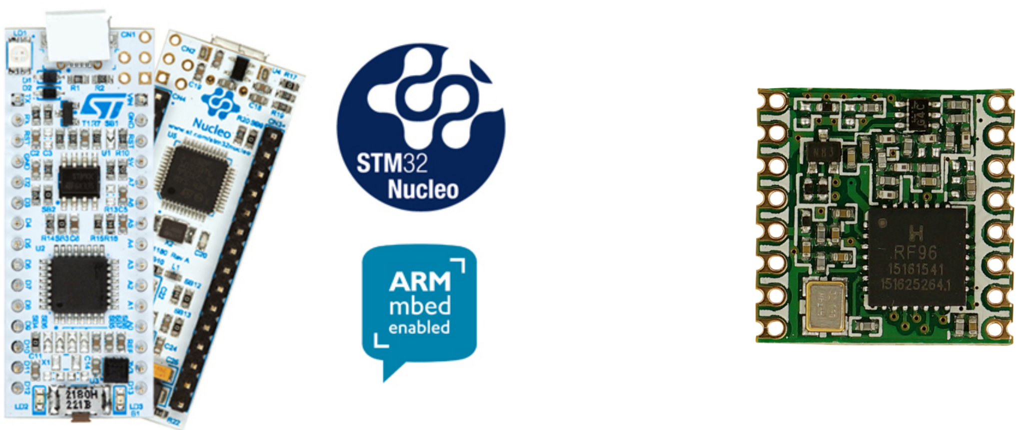


Figure 3.1: Candidate architecture of the physical LoRA network to be tested.

3.1 Description of the Testbed

The testbed will be conducted through a limited number of nodes between six and nine. Each node will have the components of a typical IoT end-node, which is a sensor or other way to generate meaningful values as data, a radio frequency module to send the data wirelessly to the network, a Microcontroller

(MCU) as a processing unit to run the routing algorithm and manage the communication between peripherals, and a power source, which will be a battery on the end-nodes and an electric plug on relay nodes.
The LoRa™radio module selected was the HopeRF RFM96 868/915Mhz RF Transceiver Module represented in Figure 3.2b, which will communicate with de MCU through Serial Peripheral Interface (SPI). There are several configurable parameters by modifying the module's registers such as the SF, CR and the Bandwidth (BW). Different operation modes are possible other and simple transmit and receive such as a low power and a mode to sense the medium on a given channel to detect a preamble. Further information can be found at [16].
There is a great variety of boards in the market with an integrated MCU that could address the need in terms of energy, memory, processing power and communication protocols on each node. The STM32L432KC board represented on Figure 3.2a, which includes an embedded ARM® 32-bit Cortex®-M4 CPU, was selected. The selection was based on its cheap cost, ultra low power operation modes, user-friendly Software Development Kit (SDK) and Application Programming Interface (API)s, compatibility with the shields for Arduino Nano and extent of open source code and libraries. As it needs a power supply between 1.71 V and 3.6 V, it can be powered by two AA Ni-MH rechargeable batteries (1.2V each) connected in series without an additional power converter. Communication with peripherals can be established through several simultaneous Universal Synchronous Asynchronous Receiver Transmitter (usart), SPI or (Inter-Integrated Circuit (I2C), which is more than enough to support the RFM96 module (SPI) and a sensor. Further information of the STM32L432KC is available in [25].



(a) STM32 Nucleo-32 board.

(b) HopeRF RFM96 LoRa™868/915Mhz RF Transceiver.

Figure 3.2: Candidate hardware components to be used in each node during the experiment.

3.2 Work Plan

The proposed work was divided into tasks, each comprising a multiple period of 7 days which was considered to be not too long nor too short and to give flexibility for adjustments. The work flow is to be executed according to the following work plan:

- February 15th 2017 - February 28th: Continue search for protocols that suit the application. Document them and choose or design the protocol to use. Establish metrics to measure in the experimental work.

- March 1st 2017 - March 15th: Implement the proposed solution in each node, set up the physical network and the testbed.

- March 16th 2017 - March 30th: Test the routing algorithm and obtain the first results under low traffic in relay nodes. Discuss the results, make adjustments if needed.

- March 31st 2017 - April 6th: Test the energy as metric.

- April 11st 2017 - April 15th: Time buffer to account for delays.

- April 16th 2017 - April 30th: Continue testing, increase the traffic from end-nodes to relay nodes. Document, organize and discuss results.

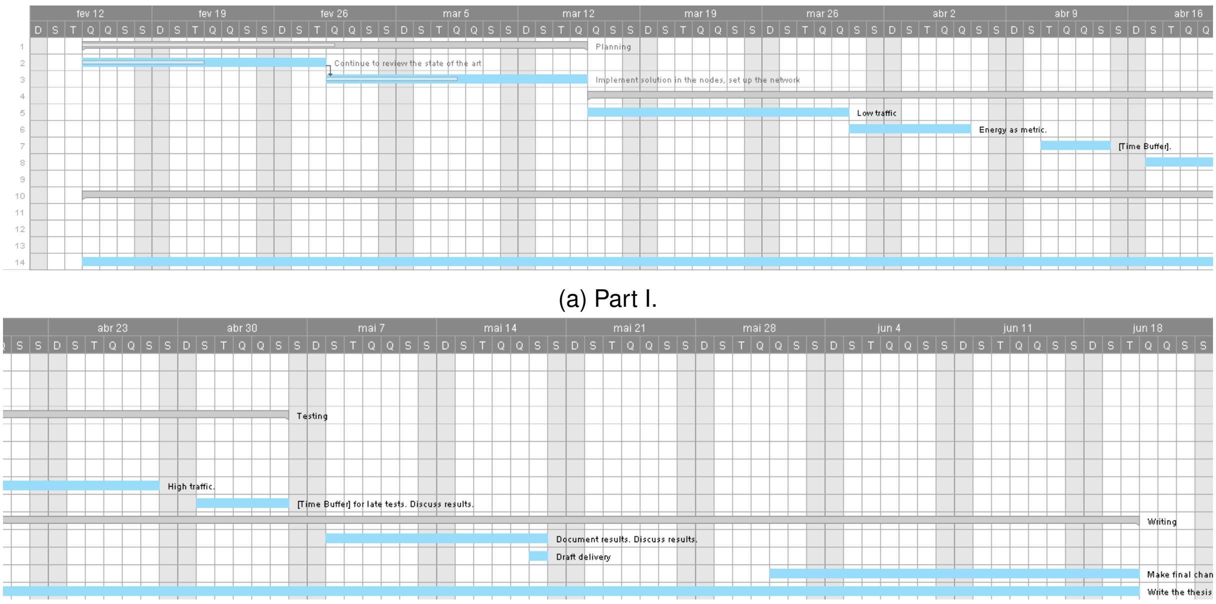
- May 1st 2017 - May 7th: Time buffer for late tests in case of delay.

- May 8st 2017 - May 21st: Finish writing and documenting. Submit a draft to the supervisors.

- June 1th 2017 - June 20th: Make changes according to supervisors' feedback.

- June 21st 2017 - Submit MSc thesis.

All the tasks above will occur in parallel with the writing of the thesis starting on February 15th 2017. The Gantt diagram corresponding to the thesis' schedule is shown in Figure 3.3. The dates may be slightly different from the bullets above due to the use of working days in the software used to generate the diagram.



(a) Part I.

(b) Part II.

Figure 3.3: Gantt diagram for the thesis' project.

Chapter 4

Conclusions

LoRa gives the flexibility to arrange different network topologies by deploying gateways and nodes. In terms of transmission, it provides long range, interference immunity, spread spectrum, low current consumption and allows three configurable parameters in the transceivers: coding rate, spreading factor and bandwidth.

All the technologies that operate in the license-free spectrum have duty-cycle legal limitations per node, which may be a barrier on the scalability of these solutions compared with those operating at the licensed spectrum. Routing has been used in LoRa under the assumption of low traffic. However, the relay nodes are under the same restrictions as the end-nodes. Therefore, higher traffic intensity increases congestions on relay nodes and duty cycle limitations may assume a more important role. Future work will attempt to provide useful data and findings on the limits of routing in LoRa nodes.

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