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LoRa technology: MAC layer operations and Research issues

Chékra El Fehri *, Mohamed Kassab †, Slim Abdellatif ‡, Pascal Berthou ‡ and Abdelfettah Belghith §
*ENIS, Sfax University, Tunis, Tunisia, Email: chekraenisienne@gmail.com
†ISIM, University of Monastir, Monastir, Tunisia
‡CNRS, LAAS, F-31400 Toulouse, France
§College of Computer and Information Sciences, King Saud University, Saudia Arabia

***Abstract*—LoRaWAN is a wireless technology for Low Power Wide Area Network (LPWAN).**
Today, it is considered as one of the most serious alternatives for IoT thanks to its low cost, low power consumption equipments and its open business model. LoRaWAN specifications proposes interesting solutions regarding MAC layer operations to deliver the best communication performances to connected things.
Despite its crucial impact on the overall performances, few research consider the LoRaWAN MAC layer.
This paper presents LoRaWAN MAC layer operations and services based on LoRaWAN Alliance technical specifications. It provides a description of MAC layer operations and modes in a thorough manner. In addition, it proposes an overview of recent studies related to LoRaWAN performances and stands out the major challenges to be addressed in order to enhance the performances of data exchanges.

***Keywords*—IoT; LoRa; LoRaWAN; MAC layer; Medium access;**

I. Introduction

In today's world, with the expansion of the internet, the concept of the internet of things has known a huge revolution and the number of sensors connected over the world is increasing very fast. It is expected to reach about 20.4 billion by 2020 [1].
A great number of connected devices, with limited power autonomy, requires suitable network connectivity, with low data rate but highly scalable network architecture, and lower power consumption radio exchange.

Since the emergence of the IoT concept, several communication technologies are proposed to provide adequate services for IoT applications. In this context, the classical cellular technologies (2G, 3G and 4G) were the first solutions to provide long-range communications for IoT. However, these solutions are expensive and inadequate regarding energy consumption, which is not suitable for most IoT devices.
On another side, Low Power Wide Area Networks (LPWAN) are proposed as large-scale networks, with a low power consumption and low data rate specifically designed for IoT. In this context, several LPWAN technologies were proposed in the IoT market.
To begin with, Sigfox™ [2], the first LPWAN network launched in 2009. It is a private network based on a proprietary technology acting as a network provider for IoT applications. Then, Ingenu™ (formally On-Ramp wireless) [3], a service provider offering LPWAN via public and private IoT networks based on a proprietary technology (The Random Phase Multiple Access).
Last but not not least, LoRa™ [4], a wireless technology for deploying private or public LPWAN. This technology is using the radio modulation of LoRa™ based on chirp spread spectrum (CSS) [5]. MAC operations and network architecture are defined by the LoRaWAN™ specification [6], maintained by the LoRa Alliance. This latter is a consortium initiated by several industry leaders and service providers in order to standardize a LPWAN technology based on the radio modulation LoRa™ owned by Semtech Corporation. Since its appearance, LoRa Alliance specifies the use of LoRa™ radio modulation among the ISM band.
The interest for LoRa (the term we use in the rest of the paper to name the technology) is increasing among wireless communication and IoT research communities, as it is based on an open business model enabling anyone to deploy its own network, which is not the case of Sigfox™ and Ingenu™.
However, the main research interests were the study of the performances offered by LoRa radio modulation (data rate, energy consumption, etc.) as well as performance studies of simplistic medium access operations, which do not take into account the complex operations specified by LoRaWAN MAC layer.
For this reason, the aim of this paper is to provide a global vision of the technology based on the LoRaWAN specification. In addition, we propose an overview of the research work related to LoRa technology and we propose some open research issues based on our knowledge of LoRaWAN specification.
This paper is structured as follows. Section II, provides an overview of the network architecture and the physical layer. Section III, presents the MAC layer services. Section IV, details the MAC layer operations and modes. Then, section V presents recent research work focusing on LoRaWAN technology. Section VI, proposes a discussion on expected performances of LoRaWAN technology challenges and open issues that can be studied in this context. Section VII concludes this paper.

II. Network architecture and physical layer

Before detailing, the operating mode of a LoRaWAN network and understanding the different functions allowing a

good network behaviour, let's start with presenting the network architecture and the entities involved in the network operations.

In this context, the network architecture proposed by the LoRaWAN specification consists in a several number of end-devices communicating with one or many gateways in a star-of-stars topology, via single-hop connections. The gateway react as a bridge which relays in both directions and in a transparent way, messages between end-devices and a centralized intelligence called the NetServer.

The NetServer is connected to the gateway through a wired and/or wireless core network. It is responsible for data exchanges and network management. It manages redundant packets, configures parameters related to packet exchanges and checks security. It is a centralized intelligence which controls and manages all network transactions. In brief, all Mac operations that we will explain later are executed under his direction. Outside the LoRaWAN infrastructure, the net-Server is connected to another application server where IoT applications are deployed, that's how end-devices will be able to be connected to their IoT applications.

Fig1 shows the architecture of a LoRaWAN network with its different components.

In conformance to the recommendations of local or regional regulatory bodies proposed by ETSI, the LoRaWAN entities operate in unlicensed bands as following:

for instance, the 863-870MHz and EU433 MHz bands are used in Europe, while the US 902-928MHz band is in use in the United States and the CN779-787 MHz in China. Channel access restrictions are associated to these bands on a per device basis. In LoRaWAN, these restrictions are expressed as duty cycles, i.e. a maximum transmission time during which the channel resources can be busy (for example,Table I shows ETSI restriction applied to some of the European bands).

These bands are split into contiguous channels whose bandwidth are also dependent of local regulations but are in line with LoRa modulations (either: 125 KHz, 250 KHz or 500 KHz).

Referring to the LoRaWAN specification, the data transmission in a LoRaWAN system is executed on different channels. Indeed, before starting a new transmission, the end device picks up randomly among its set of allowed channels (limited by the standard to a maximum number of 16).

The set of allowed channels can be preconfigured prior to the end-device association to a LoRaWAN network and updated during the association. In fact, three mandatory default channels must be implemented in each end-device for data transmissions on a LoRaWAN network. Three other mandatory channels are used for supporting the communication between the Netserver and the end device during the join or association procedure. During, this latter procedure, the Netserver is potentially able to update the list of non-mandatory preconfigured data channels with an explicit list of at most five channels. Table I, presents the default mandatory channels as well as the join Request channel list configured in a LoRaWAN Network.

LoRa transmissions are based on the chirp spread spectrum modulation technique (CSS) [7], specified by Semtech [8]. It enables robust and effective Low power transmissions even in a noisy environment. The LoRa modulation is parameterized by a bandwidth (125 KHz, 250 KHz et 500 KHz), a spreading factor, and a coding rate. Each combination leads to a physical transmission rate (called Data Rate in LoRaWAN) and each device is allowed to choose and potentially adapt its physical transmission rate according to the quality of the wireless links to the gateways. Depending on the context, it either favors spectral efficiency and energy consumption by reducing its time on air thanks to a high physical transmission rate or it resorts to a more robust modulation in order to ensure a clear and correct transmission.

III. The MAC layer and Network operations

All Mac layer operations proceeded in a LoRaWAN system, respect specified physical configurations mentioned above.

For any operation or data transmission, there are two types of message that can be exchanged; Unconfirmed messages which request no response from the NetServer and confirmed messages for which the end-device request a response from the server. For confirmed messages, the end-device will open two receive windows "RX1" and "RX2" for the reception of downlink messages. These two receive windows are opened respectively "RxDelay1" and "Rxdelay2" after the end of Uplink data transmission

Before proceeding to any network operation or data transmission, an end-device must first join the network to be considered as an active entity.

All end-devices, regardless of their initial configurations, join the network in the same way. Joining the network is allowed via activating the end-device. This permits the end device to have a set of parameters which are necessary to operate in a LoRa network.

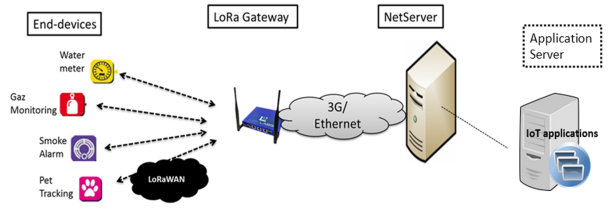


Fig. 1: LoRaWAN architecture

	Channel frequency (MHz)	Duty cycle
Default Channels	868.10	<1%
	868.30	
	868.50	
Join Request Channel List	864.10	<0.1%
	864.30	
	864.50	
	868.10	
	868.30	
	868.50	

TABLE I: Default and Join Request Frequency channel list

These parameters consist of: (1) the end-device Address "DevAddr" composed by two fields: the Network Identifier "NwkID" and the network address "NwkAddr", (2) the application Identifier "AppEUI" that identifies the end-device application provider, (3) the Network session key "NwkSKey" specific for the end-device and used both by the server and end-device to ensure data integrity, and (4) the Application Session Key "AppSKey" (an AES-128 key). In order to join the network, the end-device can be activated through two possibilities: Over-The-Air Activation and Activation by personalization.

A. Over-The-Air Activation

The end-device has to be personalized with an end-device identifier (DevEUI), an application identifier (AppEUI) and an AppKey. The end-device joins the network through a two-way handshake initiated by the end-device based on Join Request and Join Accept MAC message:

- Join Request: sent by the end-device to the NetServer to request joining the network. The message includes the AppEUI, the DevEUI and a random value DevNonce.
- Join Accept: sent by the netServer to the end-device. This message includes a random value AppNonce (used with the DevNonce, to generate the two session keys NwkSKey and AppSKey), the NetID, the DevAddr, configuration parameters for downlink messages DLSettings, the value for delays between transmission and reception RxDelays, and an optional channel list CFList.

The join procedure is presented in Fig2.

B. Activation by personalization

Activating an end-device by personalization consists in storing the two session keys "NwkSKey" and "AppSKey" in the end-device with the end-device address "DevAddr", so that the end-device join directly the network without the Join procedure.

After joining the network, an end-device is able to exchange data with the NetServer. LoRaWAN specification defines three classes of end-devices based on different data exchange behaviors. We describe the operating mode of end-devices according to these three classes in the following section.

IV. Data transmission

In the context of LoRaWAN systems, IoT applications can have different needs, regarding the data exchange, the energy autonomy and battery lifetime of the end device. That's why end-devices are pre-configured according to one of three classes (Class A, Class B or C) according to their needs.

There is no difference in how end-devices proceed to send their messages to the NetServer regardless of the class they belong to. The difference consists in, how and when end-devices receive Downlink messages.

Class A is the basic class implemented in every LoRa end-device. It is dedicated for devices with applications having low downlink data. It ensures low energy consumption and fits to low powered devices.

Class B, is an optional class useful for battery-powered end-devices used by applications requiring regular downlink exchanges like actuators. These end-devices have to support higher energy consumption than end-devices implementing only class A.

Finally, class C is also an optional class dedicated for fully powered end-devices that require continuous listening to the medium to receive downlink data.

A. Class A

According to class A, when an end-device has to send a message to the NetServer (an Uplink message), it chooses randomly a sending channel among the channels configured during the activation procedure. This message will be sent using an ALOHA-like channel access technique that takes into account duty cycle restrictions.

Once the Uplink transmission is finished, the end-device opens two short receive windows: RX1 and RX2 to listen to a downlink transmission from the NetServer as shown in Fig3. When an end-device sends a confirmed message, it waits for an acknowledgement during Receive Windows RX1. If nothing is received it stops listening until RX2. If nothing is received during RX2, it can retransmit the packet until it receives an acknowledgement or exceeds the maximum number of retransmissions. The recommended maximum number of retransmissions is 8. For every retransmission, the end-

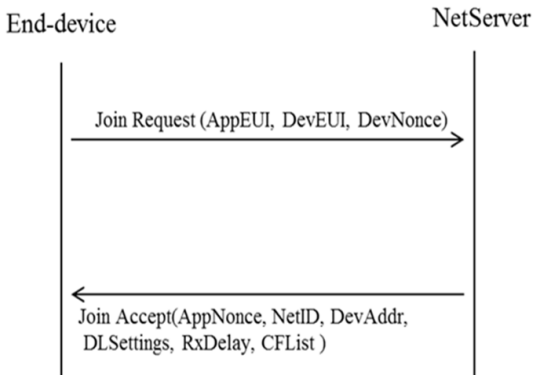


Fig. 2: Over-The-Air Activation Join Procedure

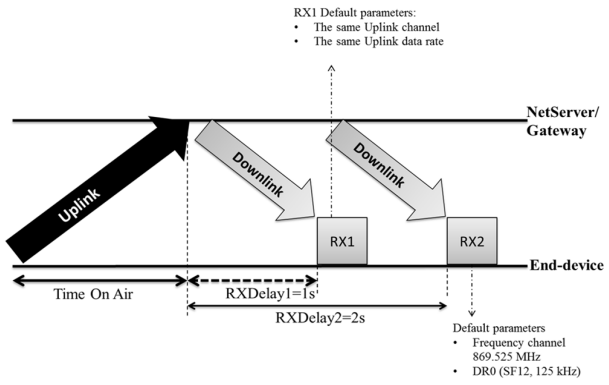


Fig. 3: The exchanging data messages procedure in class A

device chooses randomly a new channel. RX1 is opened RECEIVE_DELAY1 time period after the end of the uplink data transmission. RX1 is characterized by the use of the same channel as the uplink one. The data rate used during RX1 is a function of the Uplink data rate and the RX1DROffset field defined during the Join procedure. The default value of the data rate is the Uplink data rate.
RX2 is opened RECEIVE_DELAY2 time period after the end of the Uplink data transmission.
For the frequency band EU 863-870MHz, the default values of RECEIVE_DELAY1 and RECEIVE_DELAY2 are respectively 1s and 2s. The default parameters of RX2 are: 869.525 MHz for the channel, and DR0 (SF12, 125 kHz) for the data rate. These parameters are reconfigured using MAC commands.

B. Class B

In class B, the rational is to provide more receive windows for the downlink communications without changing the uplink communication management. Uplink transmissions in mode B are based on an ALOHA-like channel access as in mode A.
The general procedure relies on a periodic broadcast transmission of Beacon messages by the gateway. A downlink channel is timely divided into periods based on the beacon message periodicity. Each beacon period is divided in a set of slots that are distributed among end-devices as downlink reception opportunities.

An end-device joins the network as a class A entity. For reasons like, modification of the traffic type and improvement of battery condition, the end-device application layer can decide to switch to class B. In this context, referring to Fig4, the application layer asks the MAC Layer to search for a beacon message. The MAC layer searches for the beacon message either passively by listening successively to channels or actively by sending a "BeaconTimingReq" which triggers an answer from the NetServer with information on the next beacon timing and the associated channel (step 3). If a beacon is found, the MAC layer returns a BEACON_LOCKED. If not, a BEACON_NOT_FOUND is returned (step 2). In the former case, the application layer selects the ping slot data rate and periodicity and communicates them to the server (step 4). In the MAC Payload of uplink data frame, there is an "FCtrl" fields with a "class B" bit that has to be set to 1 once the end-device is switched to class B.

In class B, every end-device opens periodically ping slots to receive downlink messages. The gateway broadcast Beacon every "Beacon_period" time during a time interval "Beacon_reserved" defined only for the Beacon transmission.
The transmission of the Beacon is preceded by a "Beacon_guard" time interval where no ping slot can be placed in order to avoid collision between downlink and beacon transmission. Once the Beacon message is transmitted, a "Beacon_window" is opened where time is divided in ping Slots. The default value of a time ping slot is 30ms. For each Beacon_Period, time is divided in 212 ping slots indexed from 0 to 4095. The beacon timing is summarized in Fig5. At each Beacon period, an end-device and the NetServer establish a kind of contract in order to select the ping slots when the end-device must wake up to wait for a downlink. In fact, end-device and NetServer calculate a pseudo random parameter called "PingOffset". This parameter is unique for every end-device and it is based on its DevAddr and Beacon Time. Once the "PingOffset" is defined, it will be used to calculate all ping slot index and their starting times when end-device must wake up to wait for a downlink. End-device can transmit only when it is not listening for a downlink. The server knows that at these times this end-device is listening to the medium. Downlink channel parameters for class B are specific to EU863-870 band. The downlink messages are transmitted over 869.525 MHz frequency channel which can be modified via a MAC command. The transmission of the Beacon message is characterized by the following parameters: DR3 (SF9, BW 125 kHz), Coding rate = 4/5.

C. Class C

Class C is defined for applications requiring more time for downlink transmission and using end-devices with sufficient power. Class C implements the same receive windows of the class A. However, end-devices are listening continuously during the second receive window RX2. After an Uplink transmission, the end-device opens directly a short receive window RX2 during the RECEIVE_DELAY1 and before opening the RX1 window. The end-device opens then the RX1 receive window. When the RECEIVE_DELAY2 expires, the end-device reopens the RX2 until the next uplink transmission. RX1 and RX2 have the same parameters as defined in class A.

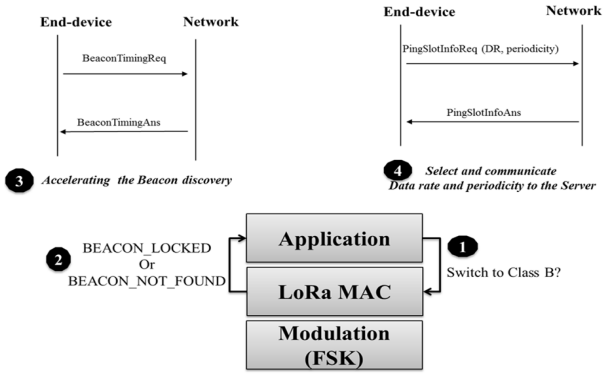


Fig. 4: Switching from class A to class B

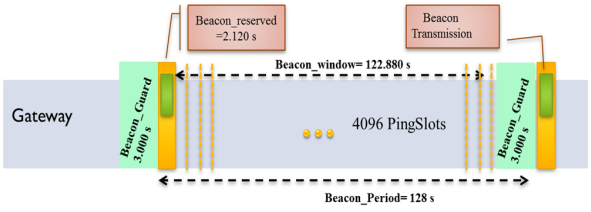


Fig. 5: class B - Beacon Timing

Fig6 presents how messages are exchanged in class C. End-devices implementing class C consume more energy than other end-devices, because they are continuously listening to the medium.

V. LoRa in the literature

In order to evaluate the LoRa technology performances, and to ensure that it is a good choice for IoT end-device connectivity, several research works have been dedicated to evaluate its performance and to identify the domains where LoRa can be used.

These works can be split into two categories. In the first category, researchers have been interested to the evaluation of performances offered by the technology. In the second category, researches have proposed proof of concept through actual deployments and platforms to evaluate the usability of LoRa for specific application domains and use cases.

Several studies based on network simulation and/or analytical modeling, have evaluated different LoRa features related to the physical layer and the medium access performances. In this context, there has been interest in the receiver sensitivity and network coverage [9]. Other features concern the LoRaWAN end-device performance and the scalability of the LoRaWAN network [10]. The problem of scalability was also treated in other works [11], [12]. In the context of scalability and the network capacity, other works have studied problems that limits the network capacity [9], [13]. In other researches, the interference between multiple LoRa networks and its impact on the network quality was also studied, and some solutions have been proposed [14], [12].

The Receiver sensitivity in [9] was evaluated by measuring and comparing specified RSSI (Received Signal Strength Indication) to observed RSSI for different Spreading Factor and results showing that the decrease of the RSSI has no relation with the increase of the Spreading Factors due to the additional shadowing causing by the indoor location of the gateway. Moreover, they concluded that the coverage of the network can be improved with selecting a higher Spreading Factor which can be increased by the end-device. In the context of the end-device performance, the study in [10] has evaluated the end-device performance in term of several metrics based on different physical layer parameters, like the maximum and the minimum throughput for one end-device, the time on air for the longest and the shortest uplink and downlink Frame for different data rates under the ISM EU868-870 band. They

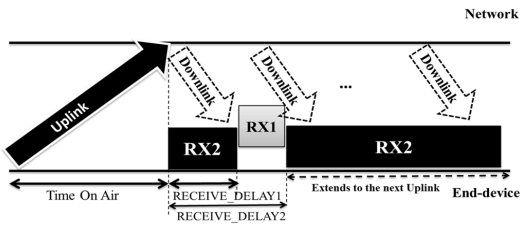


Fig. 6: The exchanging data messages procedure in class C

also evaluated the capacity of a LoRaWAN cell in term of the number of end-devices operating with a pure ALOHA access for one case, and under perfect synchronization for another case. Their evaluation was established for different applications and with different network configurations. They studied the end-devices distribution with optimal number and pure ALOHA access, in term of different scenarios of generated packets and different data rate configurations. In another way, in term of scalability in[11], they made use of both simulation and experiments to show that in the context of the current deployment of LoRaWAN, the scalability of the network is limited by factors like duty cycle, the subdivision of the sub-band and the number of transmitters. However, it can be improved with dynamic selection transmission parameters. Using multiple sinks can also boost the network scalability.

Added to this, different problematics limiting the network capacity have been identified. Ferran Adelantado *et al.* in [13] have studied the network quality in term of packet transmission for a variable number of end-devices. Results show that network capacity is limited by collisions, which increase with the number of end-devices. They proved also by a mathematical modelisation that the duty-cycle limits the size of the network.

In the same context, an evaluation of LoRa technology scalability have been performed based on simulation. the scenario considers a LoRa network using three channels, conecting 100 end-devices, with 500 000 packets sent for each data point [9]. Results have shown that the channel load has a serious impact in the successful reception of packets. With a link load of 0.48, around 60% of the packets transmitted are dropped due to collisions.

The LoRaWAN capacity was also evaluated when multiple LoRaWAN networks interfere. In [14], simulations proved that interference between LoRaWAN networks has a serious impact in network quality. In fact, the high number of interfering networks decreases the network's quality in term of the Data Extraction Rate parameter. The authors proposed to use directional antennae and multiple base stations in order to improve the network quality under interference.

Most of the previous evaluations were confirmed with experimental use cases and in the context of IoT applications. The following will describe the experiments results.

In [15], an environment composed by one end-device sending periodically 4 bytes of data, one network server and one gateway, was tested. The author's evaluations touch parameters like the throughput, and the rate of packet loss/packet error... Among their conclusions, a good selection of a right data rate configuration is needed to reduce collisions and packet loss.

In the context of a monitoring of troughs water level system developed with the LoRaWAN network [16], the authors evaluated the impact of distance between end-device and gateway elevation in the data transmission quality. They conclude that the quality of data transmission decreases with a high difference between node and Hub elevation.

In another context, Petajajarvi *et al.* have studied the indoor performance of LoRa based on real measurements and prove

that the LoRaWAN technology is suitable for health and wellbeing monitoring applications [17]. According to their experimental environment and configuration, a high percentage of packets generated were successfully received by the gateway.

To resume, the LoRaWAN researches have been interested in different evaluations concerning, the physical layer, and the data transmission quality qualified by different parameters like distance between gateways and end-devices, throughput, duty cycle, data rate and payload size. More over, the data transmission quality was evaluated in term of channel access method and its impact in the data exchange performance. In the following part, we will deal with one of the important factors caused by the randomly nature of the channel access mode in the LoRaWAN system: Collisions.

VI. Data exchange performances and open issues

In a LoRaWAN network, collisions are an embarrassing enemy preventing the good performance of the network behaviour.

Studies conducted in this field, have only considered the evaluation of the class A implementation in a LoRaWAN system. It was proved that the randomly Aloha channel access mode leads to a considerable collision rate which increases the percentage of packet loss in the network [9]. Furthermore, this situation will be more complicated when confirmed messages are exchanged between entities. It is clear in this case, that downlink messages have a negative impact in the network in term of collisions number and packet loss rate. At this stage, regarding the previous study, the question is whether classes B and C may be the required solution for collisions problem. Referring to the LoRaWAN specification, the modes B and C just provide a more structured way for downlink message reception. The channel access mode for Uplink transmission causing collisions problem, do not change. So, we can conclude that even in a LoRaWAN system implementing class B and C, collisions and packet loss issues will persist. Moreover, these latter do not have have a huge impact in networks with limited area[13]. Collisions is a disturbing factor for large scale networks.

As an attempt to improve this situation, some directions was mentioned in the litterature;

One of the ideas was to explore new channel hopping methods sequences which must be able to respect the network requirements [13]. Even if it seems to be a good solution, this can make sens only for a limited area network. In a large scale LoRaWAN, there is a great chance that the chosen channel is already busy, and consequently collisions would occur.

Also the possibility of defining the Time Division Multiple Access method over LoRaWAN was considered as a direction that can improve the channel access mode, instead of the randomly Aloha method[13]. In this case, it is necessary to specify how time slots must be distributed between the network entities. It must be done according to trafic type and IoT applications needs.

Besides, it is worthy to mention that providing a good solution for reducing collisions increased in an extended LoRa network, must be preceded by a deep study that consider all the network requirements, IoT applications needs, and different types of traffic. The duty-cycle constraints must also be taken into account. Also the co-existence of more than one trafic type, can have a negative effect on the performance of the channel access mode. So, defining a performed way able to respect the needs of different traffic types in the same network, couldn't be a simple mission.

Finally, we resume that several studies have analysed and validated the problem of collisions as a critical factor reducing the network performance. In return, no solution had been evaluated to resolve this problem and to enhance data transmission quality. This thematic is an interesting direction for research contributing to a better LoRaWAN quality.

VII. Conclusion

In this paper, we have proposed an overview of Lora technology while focusing a comprehensive description of MAC layer operations as defined by LoRaWAN specifications. In addition, we have proposed a review of recent expiremental and theorical studies related to LoRa. We have combined our knwolodge about LoRaWAN MAC layer operations and valuable evaluation results to give an preview of global data exchange performances of LoRa and future ressearch directions that can be conducted to optimize the use of LoRa;

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