On the Limits of LoRaWAN Channel Access

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***Abstract*—The rising tide of the Internet of Things has brought to the surface numerous low-power, long-range and low-bitrate wireless network technologies. One of them, LoRaWAN, is being intensely popularized as a solution for sensor networks, however, its potential and limitations are unclear, because there is still neither accurate study nor massive LoRaWAN deployment. This paper surveys and analyzes LoRaWAN operation, focusing on performance evaluation of its channel access as the most crucial component for massive machine type communication. We reveal and point out weaknesses of the LoRaWAN specification and propose solutions to improve LoRaWAN performance.**

Keywords—LoRa, LoRaWAN, LPWAN, Channel Access, Performance Evaluation

I. INTRODUCTION

To catch the Internet of Things wave, many companies develop new applications and services which need a tremendous number of low-power devices to be interconnected. The lack of communication technologies applicable for such scenarios attracted much interest from world-wide standardization bodies — such as 3GPP or IEEE Standard Committee — as well as small and medium-sized enterprises (SMEs). While the first ones try to develop common technologies which can be used in a vast range of scenarios, e.g. NB-IoT [1] and WiFi HaLow [2], SMEs focus on rapid development of niche technologies to master the emerging market before telecommunication leaders. Among such niche technologies are Sigfox [3] and LoRa/LoRaWAN[1]. Both Sigfox and LoRa are proprietary technologies. However, Semtech, the developer of LoRa, has published a specification for LoRaWAN [4], opening the door for deep independent performance evaluation.

Since LoRaWAN specification [4] has been published in 2015, only few papers study its performance. Specifically, [5]–[7] briefly introduce LoRa, mainly focusing on its applications and PHY and paying small attention to the Medium Access Control (MAC) protocol. Some test-bed and simulation results in a scenario with low number of devices are presented in [8]. Authors of [9] use the classical ALOHA-like approach to evaluate LoRaWAN performance in a scenario with high number of devices, however no simulation/test-bed validation is provided. In this paper, we show that such an approach is inapplicable and manifold overestimates the network capacity. So we evaluate performance of a LoRaWAN network under much more realistic conditions.

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[1]LoRa refers to the Physical (PHY) layer, while LoRaWAN defines the whole cross-layer (MAC and PHY) communication protocol.

The rest of the paper is organized as follows. Section II gives briefly introduces the LoRa and LoRaWAN technologies, focusing on their features, critical for multiple access, their weaknesses, and unclear spots of the specification. Section III

describes the scenario in which we evaluate the performance of a dense LoRaWAN network. In Section IV, we present and analyze simulation results. Section V concludes the paper.

II. LORAWAN

A. Network Architecture

A typical LoRaWAN network consists of end-devices (sensors or actuators, also called *motes*), gateways and a server which collects and analyzes information mined by the motes. The network topology is a "star of stars", which means that groups of motes are connected to gateways via LoRa wireless links while the gateways are connected to a remote server via IP network (see Fig. 1). The server can be located in a cloud.

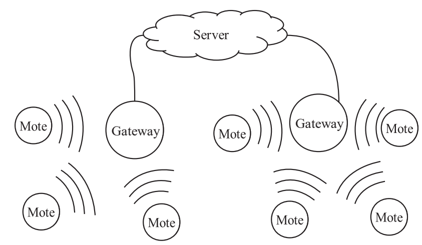

Figure 1. Topology of a LoRaWAN network

LoRaWAN motes are divided into three classes.

Class A supports the basic LoRaWAN functionality, obligatory for all devices. Class A enables bi-directional communication which is organized as follows. For uplink transmission, the devices use unslotted random access, similar to ALOHA. Downlink transmission can be done only during dedicated time intervals called receive windows, which follow successful uplink transmissions. If network load is low, Class A provides the lowest energy-consumption for the motes, but even in this case has long delays in downlink. *Class B* implements bidirectional communication with scheduled downlink receive slots. The dissemination of schedule information is performed via beacons sent by the gateway. *Class C* devices listen to the channel continuously, thus providing the lowest downlink latency, but requiring extremely high power consumption.

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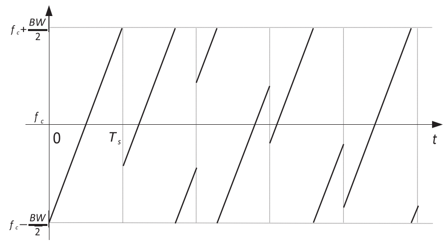

Figure 2. Evolution of signal frequency with time for a LoRa transmitter

In this paper, we study operation of Class A LoRaWAN devices.

B. LoRa Modulation

LoRaWAN motes communicate with gateways using LoRa technology. This technology is based on a modulation scheme that is an adaptation of Chirp-Spread Spectrum (CSS) modulation [10]. Initially designed in 1940's for radars, CSS is widely used in military and secure communications due to its relatively low transmission power requirements and inherent robustness from channel degradation effects such as multipath, fading, Doppler and in-band jamming interferers [11].

In LoRa each symbol can be presented as a sinusoidal signal, the frequency of which cyclically changes within window BW around the central frequency f_c. Specifically, the frequency starts with some value, then increases until maximum $f_c + \frac{BW}{2}$, then drops to the minimum $f_c - \frac{BW}{2}$ and continues growth until reaching the initial value (see Fig. 2). The number of possible initial values is 2^{SF}, where spreading factor SF defines the number of transmitted bits in a symbol.

Because of forward error correction coding, the number of information bits is less, and the bit rate equals

$$R_b = \frac{SF}{T_s} CR = \frac{SF \times BW}{2^{SF}} CR,$$

where CR is the rate of the forward error correction code that can be $\frac{4}{5}$, $\frac{4}{6}$, $\frac{4}{7}$ or $\frac{4}{8}$, and T_s is the symbol duration that depends on both spreading factor and bandwidth as follows:

$$T_s = \frac{2^{SF}}{BW}.$$

Thus, three parameters — BW, SF and CR — determine the bit rate of a point-to-point LoRa link. Higher SF values result in lower bit rate, but at the same time, higher sensitivity. For example, according to [12], in a 125kHz channel a Semtech SX1276 LoRa device can receive a transmission at −125dBm when SF = 7, but when SF = 12 the sensitivity is −137dBm. For the code rate of $\frac{4}{5}$, the bit rate is 293 bps and 5468 bps for SF = 12 and SF= 7, respectively.

A remarkable feature of such a modulation and coding scheme is that a LoRa device can correctly receive two overlapping transmissions with different spreading factors in the same channel. Moreover, the vendor claims that even in case of two simultaneous transmissions with the same spreading factor, a device can correctly receive the most powerful one, provided that the difference in signal power is higher than 3dB.

The set of available data rates depends on regional specifications. Table I lists possible data rates for European EU 863-880 MHz ISM (Industrial, Scientific and Medical) band.

Table I. DATA RATES IN EU 863-780 MHZ ISM BAND

#	Spreading factor	Channel width, kHz	Code rate	PHY bit rate, bps	RF sensitivity, dBm
0	12	125	4/6	250	-137
1	11	125	4/6	440	-136
2	10	125	4/5	980	-134
3	9	125	4/5	1760	-131
4	8	125	4/5	3125	-128
5	7	125	4/5	5470	-125
6	7	250	4/5	11000	-122

C. Frame Format

Let us study how LoRa modulation is used for data transmission. Since LoRaWAN is designed for low-power low-rate communication, using heavy TCP/IP is hardly advisable. Thus LoRaWAN is a lightweight protocol which can be directly used by sensor and actuator applications to communicate with the gateway. For that, let us consider the frame structure.

At the PHY layer, a LoRaWAN frame (see Fig. 3) starts with a preamble. Apart from the synchronization function, the preamble defines the packet modulation scheme, being modulated with the same spreading factor as the rest of the packet. Typically, the preamble duration is 12.25 T_s.

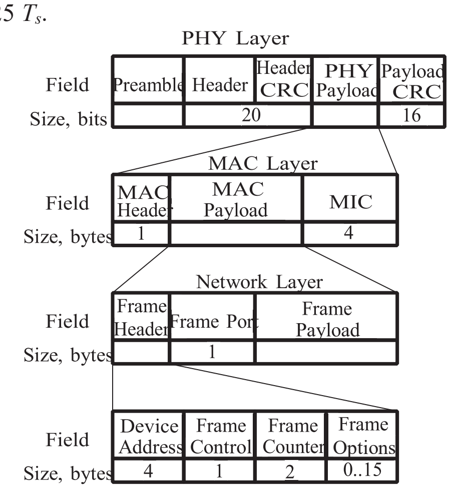

Figure 3. LoRaWAN Frame Format

The preamble is followed by a PHY Header and a Header CRC that together are 20-bits long and are encoded with the most reliable code rate of $\frac{4}{8}$, while the rest of the frame is encoded with the code rate specified in the PHY Header. The PHY header also contains such information as payload length and whether the Payload 16-bit CRC is present in the frame. Specifically, in a LoRaWAN network, only uplink frames contain payload CRC.

According to Semthech [13], the number n of symbols needed to transmit the PHY payload and the PHY header is

$$8 + \max\left(\left\lceil \frac{8PL - 4SF + 28 + 1[CRCispresent]16}{CR(SF - 2DE)} \right\rceil, 0\right),$$

where PL is the payload length in bytes, and DE is 1 if low data rate optimization is enabled and 0 otherwise. Low data rate optimization is an option that can be enabled in LoRa transmitters to improve the robustness of transmission to variations in frequency. LoRa datasheets do not provide the explanation of this optimization, but state that it is mandated with symbol duration greater than 16ms, e.g., for SF = 11 and SF = 12 in 125kHz band. As one can see, this feature increases the number of symbols needed to transmit a frame. So the duration of the frame is $T_{frame} = (n + 12.25)T_s$.

Let us describe the content of the PHY Payload field. Onebyte MAC header defines protocol version and message type, i.e., whether it is a data or a management frame, whether it is transmitted in uplink or downlink, whether it shall be acknowledged. MAC Header can also notify that this is a vendor specific message.

MAC header is followed by Frame Header which contains the following information.

- *Device address* which contains two parts. The first 8 bits identify the network, other bits are assigned dynamically during joining the network and identify the device in a network.
- *1 byte of network control information*, such as whether to use the data rate specified by the gateway for uplink transmission, whether this message acknowledges the reception of the previous message, whether the gateway has more data for the mote.
- *Sequence number*.
- *Frame options*, which can contain commands used to change data rate, transmission power, validate connection, etc.
- *Frame Port* contains a value which allows distinguishing several flows between a gateway and a mote (e.g., in case of several applications running at the mote). If it equals 0, the Frame Payload contains MAC commands instead of user data. Note that in a frame either Frame Payload or Frame Options is used to encapsulate MAC commands.

MIC is used as a digital signature of the message.

The total size of the PHY payload equals 13+FP+$FOpts$, bytes, where FP is the size of Frame Payload and $FOpts$ is the size of Frame Options field. As the result, even if a LoRaWAN device wants to transmit an empty frame to acknowledge another frame, it has to include 13 bytes of payload in it. This leads to significant overhead, for example, if devices transmit at the lower data rate in EU 863-780 MHz ISM band, the duration of an acknowledgement is almost 1 second (and the maximum frame duration is approximately 2.4s)!

D. Channel Access

A LoRaWAN network operates in several frequency channels that are determined by the gateway configuration. The number of allocated channels depends on regional restrictions and the network options. Some channels are reserved for data transmission (hereafter called *main channels*), one channel (hereafter called *downlink* channel) is reserved for gateway's responses for frames, and some channels are used by motes to transmit join requests to the gateway. LoRaWAN class A devices access the channel as follows.

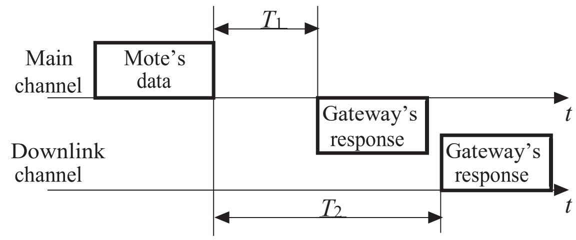

Figure 4. LoRaWAN Channel Access

When a mote has some data for transmission, it randomly selects one of the main channels and transmits a frame to the gateway in unslotted ALOHA mode [14], i.e., without synchronization and carrier sense. After the transmission, the mote opens two short receive windows (i.e., turns on its receiver for a time interval)— the first one in the channel used for uplink transmission and the second one in the downlink channel, during which it expects to receive the response (i.e. a frame with the raised ACK flag, if the uplink transmission requires an acknowledgment, and/or some piggybacked downlink data, if any, from the gateway), see Fig. 4). The first receive window is opened T_1 seconds after the end of uplink transmission while the second one is opened 1 second later. Such a scheme is used for the following reason. LoRaWAN motes are battery supplied and additional retries increase power consumption. With such limitation, it is worth to consume more channel time and to waste gateway energy on additional downlink transmissions rather than to make the mote do additional data transmission if the downlink frame is damaged by an uplink transmission or random noise. A mote does not open the second receive window if it successfully receives a frame during the first receive window.

The specification does not determine the receive window duration, however it should be long enough to enable receiver to effectively detect a downlink preamble. The value of T_1 is configurable and by default equals 1s.

As one can see, a gateway can transmit data to a LoRaWAN class A mote only as a response to the mote's frame during the receive windows. If a gateway needs to transmit data with size greater than a single frame, it raises the Pending bit in the Frame Control field to inform the mote that the mote needs to send a frame in uplink (which can be empty, if the mote has no pending data) to start the next downlink transmission, since the downlink transmission can be only initiated by the mote. Thus, Class A cannot guarantee a limited delay for downlink messages, therefore Class B or C should be used in case of delay-sensitive applications.

LoRaWAN supports both confirmed and unconfirmed data messages. If a mote sends a confirmed data message, the gateway should respond the mote with a frame with a raised ACK flag during the receive windows. If a gateway sends a confirmed data message to the mote, the mote transmits an acknowledgment at its own discretion.

When a mote does not receive an acknowledgment to a confirmed message, it retransmits it. The retransmission is made in a randomly chosen channel at least ACK

TIMEOUT seconds after the second receive window. The specification does not define a strict mechanism to select the delay before retransmission, however, the recommended behaviour is to set ACK TIMEOUT to a random delay between 1 and 3 seconds. The retransmissions can be made at a lower data rate, the specification recommends to select the rate DR_r for attempt r as follows:

$$DR_r = \max\left(DR_0 - \left\lfloor \frac{r}{2} \right\rfloor, 0\right),$$

The recommended retry limit is 8, exceeding which the frame is discarded and the MAC layer notifies the application layer about the transmission error.

E. Rate Control

In LoRaWAN networks, motes can individually use any of possible data rates from a regional-specific set. The data rates are defined by a combination of bandwidth and spreading factor and are enumerated in ascending bit-rate order, number zero being the slowest and the most robust data rate. The network can use an adaptive data rate control mechanism that enables the network to control data rate of end devices through the appropriate MAC commands. However, the specification does not describe the mechanism exactly, and it is still an open question, which measurements should be taken into account when deciding that a device should switch from one data rate to another [15]. The data rate used to transmit the downlink data depends on the uplink data rate and on the configurable network parameter $RX1DROffset$. If an uplink frame is transmitted with data rate number DR_{up}, the downlink frame is transmitted with data rate

$$DR_{down} = \max(DR_{up} - RX1DROffset, 0).$$

Possible values for $RX1DROffset$ vary for different regions. In EU 863-870 MHz ISM band, this parameter is chosen in the range from 0 to 5. The data rate for the second answer is configurable, fixed and does not depend on the uplink data rate. The default behaviour for EU 863-870 MHz ISM band is to use the lowest data rate in a separate 125kHz channel.

F. Duty Cycle

Several regional regulations introduce the duty cycle limitation, according to which a device may not use a frequency band for a period of time after transmitting in this band. If the transmission time lasts *TimeOnAir* and the duty cycle equals *DutyCycle*, then the channel is unavailable for

$$T_{off} = \frac{TimeOnAir}{DutyCycle} - TimeOnAir.$$

For example, if a device transmits a 1s long frame and dutycycle equals 1%, then the band is unavailable for 99s. This statement conflicts with the retry policy described in Section II-D, and we do not consider it in Section IV.

G. Open Issues

From the previous sections it is obvious that the specification raises many issues which significantly affect network performance. Let us summarize the most important of them.

The first issue is related to whether the gateway should listen to the channel during the interval between frame reception and transmission of a response. If the gateway should listen to the channel, the standard does not specify the behavior of the gateway, when it is going to transmit a response and the channel appears to be busy with some transmission. A possible solution is to cancel a pending transmission in the main channel because it can create a collision at the mote, and to transmit the response only in the downlink channel. Another solution is to choose such a data rate for the response, that allows to avoid two overlapping transmissions at the same data rate.

A similar issue arises when two frames are transmitted in overlapping time intervals in different channels (or in the same channel with different spreading factors). If the gateway has only one downlink channel, it cannot transmit responses to both frames during the corresponding second receive windows, because these responses should be transmitted with the minimal (the same) data rate.

The third issue is the retransmission policy. The recommended behavior for retransmissions is to select a random delay between 1 and 3 seconds. However, the duration of a frame and of an acknowledgment can be more than 1 second, resulting in a high probability of repeated collision with a frame or with an acknowledgment. The usage of multiple channels for frame transmission improves the situation, virtually increasing the interval for random delay selection, but this interval is still fixed, which limits the network scalability. It could be better to use the binary exponential backoff procedure, similar to the one used in the Wi-Fi protocol.

The fourth issue is the policy to select the data rate for retransmissions. On one hand, decreasing the data rate we improve the reliability of transmission. On the other hand, if devices reduce the data rate for retransmissions they can all end at the lowest data rate which greatly increases the collision probability.

The mentioned issues are especially important in a highly loaded networks however they are typically omitted by LoRaWAN developers and operators on their deployment sites with small number of devices and low traffic. However, the further growth of IoT popularity will increase both the number of devices and the number of networks of different operators working in the same area in unlicensed spectrum, therefore such issues should not be neglected.

III. SCENARIO

To evaluate performance of the LoRaWAN protocol, we consider the following scenario. The network consists of N motes connected to a gateway. They operate in 3 main channels and one downlink channel, all the channels being 125kHz wide, which is a typical EU configuration. The devices use data rates from 0 (SF = 12) to 5 (SF = 7), set by the gateway during the network initialization according to the signal power from the sensors.

As in [9], we consider the following probabilities for a mote to transmit using a specific data rate: $p_0 = 0.28$, $p_1 = 0.2$, $p_2 = 0.14$, $p_3 = 0.1$, $p_4 = 0.08$ and $p_5 = 0.2$, which corresponds to a case, when end-devices are distributed uniformly in a circular area around the gateway and the path loss is described by the Okumura-Hata model. We consider that a collision occurs if at least two transmissions at the same data rate overlap in time.

All motes transmit frames with 64-byte PHY payload (51-byte Frame Payload) which corresponds to the biggest payload that can fit a frame at the lowest data rate. The frames are transmitted in acknowledged mode, the acknowledgment frames carry no frame payload. We consider a situation, when the mote has no queue, i.e. if two messages are generated, it transmits the most recent one. The messages are generated according to Poisson distribution, i.e. with an exponentiallydistributed inter-arrival time.

The goal of the research is to study how transmission reliability depends on the number of motes and the load, i.e. the number of packets that are generated at the motes, and to find the network capacity.

IV. Results and Discussion

In contrast to the previous works (e.g. [9]) we pay attention to the packet error rate (PER) and packet loss ratio (PLR) rather than to the maximal goodput that the network can transmit. Packet error rate is the probability that a packet transmission is unsuccessful. Packet loss ratio is the probability that a generated packet is not delivered either because the retry limit is reached or a packet was dropped because of a new packet arrival. Fig. 5 shows the obtained simulation results for various values of network load and number *N* of motes. It also present results obtained with a mathematical model for infinite number of nodes, which we do not describe in the paper because of space limitation.

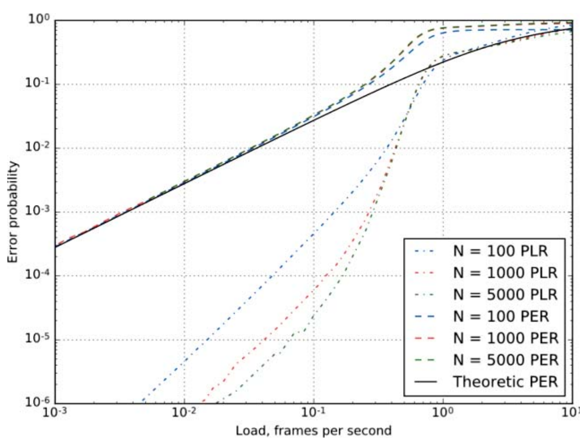

Figure 5. PER and PLR vs network load

For load less than 0.1 packet per second, the packet loss ratio is negligibly small (less than 0.001) and we can state that the communication is rather reliable. Note that to achieve such a low load in a network with 100 motes, on average each mote shall generate a packet more rarely than once per 20 minutes. If $N = 5000$, on average each mote shall generate a packet more rarely than 2 packets per day.

When the load increases, both PER and PLR significantly increase for two reasons. First the collision resolution approach used in LoRaWAN is inefficient with a high number of motes and leads to collision avalanche. The only way to stop this avalanche is joint usage of finite retry limit and small queue size (in our simulation it is 1). The second reason is that the packets arrive in a non-empty queue, resulting in packet drops.

Note that the developed mathematical model can be used to calculate PER if the load is low, and PLR if the load is high.

V. Conclusion

In the paper we have analyzed the LoRaWAN technology and its performance in a network with a high number of motes. We found that even with 3 main channels and 6 data rates
(i.e. 18 virtual transmission channels), the network capacity is about 0.1 51-byte (Frame Payload) messages per second. For example, this capacity corresponds to the traffic generated in a network with 5000 motes, each of which generates 2 messages per day. It limits the possibility to use LoRaWAN technology in many scenarios of smart city.

A possible solution for this problem is to increase the density of LoRaWAN gateways. However it can lead to the inter-network interference. An accurate interference-aware performance evaluation of a LoRaWAN network in such a scenario will be done in future works.

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