Understanding the limits of LoRaWAN

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Abstract

The quick proliferation of LPWAN networks, being LoRaWAN one of the most adopted, raised the interest of the industry, network operators and facilitated the development of novel services based on large scale and simple network structures. LoRaWAN brings the desired ubiquitous connectivity to enable most of the outdoor IoT applications and its growth and quick adoption are real proofs of that. Yet the technology has some limitations that need to be understood in order to avoid over-use of the technology. In this article we aim to provide an impartial overview of what are the limitations of such technology, and in a comprehensive manner bring use case examples to show where the limits are.

I. Introduction

With the raise of Low Power Wide Area Technologies (LPWAN) [1], [2], network operators are starting to deploy horizontal M2M solutions to cover a wide set of large scale verticals. Those include smart city applications, smart metering, on-street lighting control and agriculture monitoring, among others. LPWAN technologies combine low data rates and robust modulation techniques to achieve large coverage, enabling the construction of simple star network topologies [3]. This simple approach eases network deployment and simplifies network maintenance, thus enabling plug and play applications. While the benefits of these technologies are known and someone can consider them the key enablers of real large scale IoT deployments, some of their limitations are still not well understood [4], [5]. In this article we aim to provide an impartial overview of the limitations of LoRaWAN [6], one of the most successful technologies in the LPWAN space. LoRaWAN is a network stack solution that exploits a robust wide band modulation referred as LoRa. LoRaWAN brings connectivity at raw data rates below 27 kbps and enables thousands of nodes to be connected to a single gateway in the range of kilometers. This interesting capabilities have raised the attention of industries and network operators, presenting it as the connectivity enabler for any use case [7]. In this article we aim to provide a comprehensive analysis of what are the capabilities and limitations of LoRaWAN, in order clarify what are their possibilities and scope and to avoid over-use of the technology in scenarios where it does not fit. In the next section we present a short description of the technical insights of LoRaWAN. Section III then analyzes the network capacity and scale limitations of the technology. Section IV aims to provide example use cases that can be met with the LoRaWAN technology, leading to the Section V presenting the open research challenges to improve the operation of LPWAN networks in general and LoRaWAN in particular. Finally Section VI concludes the article.

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II. Short description of LoRaWAN

LoRa is a robust modulation technique for long range, low data rate and low power wireless communications developed by Cycleo, a French company which was later acquired by Semtech, that is used in LoRaWAN networks. LoRaWAN networks are typically organized in a star-of-stars topology in which gateways relay messages between end-devices and a central network server in the back-end. Gateways are connected to the network server via IP links while end-devices use single-hop LoRaWAN communication to one or many gateways. All communication is generally bi-directional, although uplink communication from end-devices to the network server are strongly favored[6].

Communication between end-devices and gateways is spread out among different frequency channels and so-called spreading factors (SF), which are defined as the logarithmic ratio between the symbol rate (R_s) and the chip rate (R_c), i.e. $SF = \log_2{(R_c/R_s)}$ Accordingly, selecting a spreading factor is a trade-off between communication range and data rate. Thanks to the orthogonal nature of the set of codes used to spread the signals, spreading factors enable simultaneous non-interfering communications between devices. Depending on the spreading factor in use, LoRaWAN data rates range from 0.3 kbps to 27 kbps for a 125 kHz bandwidth. To maximize both battery life of end-devices and overall network capacity, the LoRaWAN network infrastructure manages the data rate and RF output for each end-device individually by means of an ADR (Adaptive Data Rate) scheme. End-devices can transmit on any channel available at any time using any available data rate, being restricted by the mandatory need to implement pseudo-random channel hopping at each transmission and to comply with the maximum transmit duty-cycle (e.g., in EU 868 1% for end-devices and in the US limited by a dwell time relative to the sub-band of 400 ms; for gateways this is a 10% depending on the sub-band).

The LoRaWAN PHY uses a robust Chirp Spread Spectrum (CSS) modulation. It defines 6 spreading factors (SF), from SF=7 to SF=12, that ensure orthogonal transmissions at different data rates. Packets contain a preamble (typically with 8 symbols), a header (only mandatory in explicit mode), the payload (whose maximum size varies from 51 to 222 bytes based on the SF) and a Cyclic Redundancy Check (CRC) field (with configurations that provide a coding rate from 4/5 to 4/8). Typical bandwidth (BW) values are 125, 250 and 500 kHz in the HF ISM 868 and 915 MHz band, while they are 7.8, 10.4, 15.6, 20.8, 31.2, 41.7 and 62.5 kHz in the LF 160 and 480 MHz bands. The raw data rate varies according to the SF and the bandwidth and ranges between 22 bit/s (BW = 7.8 kHz and SF = 12) to 27 kbit/s (BW = 500 kHz and SF = 7) [2]. In addition, frequency hopping is exploited at each transmission in order to mitigate external interference [8].

At the medium access sub-layer, LoRaWAN supports three different types of devices according to their functionality. Class A devices use pure ALOHA access for the uplink, followed by two short downlink receive windows at predefined intervals. It is important to remark that in Class A devices downlink is only guaranteed after a successful transmission and depends on the application uplink rate. Class B devices are synchronized using periodic beacons sent by the gateway to allow the schedule of additional downlink transmissions. Finally, Class C devices are always listening to the channel except when they transmit. Although the three classes are defined in the specifications [7], only class A must be implemented in all end-devices.

III. Capacity and Network Size Limitations

In this section we aim to bring an impartial analysis of the capabilities of a LoRaWAN network. We study the network scale with respect to data rate, duty-cycle regulations, etc.

A. Network size limited by duty cycle

Although the performance of LoRaWAN is mainly determined by the PHY/MAC overviewed in Section II, it is also influenced by regional regulations that define restrictions on the operation in ISM bands [9], [10]. In particular, the duty cycle, defined as the percentage of time during which the channel can be occupied, arises (from regulation) as a key limiting factor for the traffic served by LoRaWAN. In that sense, the time required to transmit a packet in a sub-band, known as time on air (T_a), must be followed by a minimum off-period (T_s) during which the channel is unavailable for the device, i.e. $T_s = T_a(\frac{1}{d} - 1)$, where d is the duty cycle. For instance, a 1% duty cycle is translated into a maximum transmission time of 36 sec/hour in each sub-band for each end-device. Or equivalently, a maximum number of transmitted packets equal to $M = 3600/(T_a + T_s)$ packets per hour and node. Given the PHY of LoRaWAN, Figure 1 shows the Time on Air for a packet when the coding rate is 4/5 and the bandwidth is 125 kHz.

After selecting the SF and the channel, end-devices access the medium with the Aloha method. Although Listen Before Talk is not precluded and can be implemented, only Aloha access is mandatory. Therefore, and in order to roughly analyze the capacity of a LoRaWAN network, we assume the 'pure' Aloha medium access. Two key aspects must be noted:

- For a number of end-devices equal to N and a number of channels n, the pseudo-random channel hoping results in a uniform distribution of the N end-devices over the n channels.
- For a given channel, the simultaneous transmission of two end-devices only causes a collision if they both select the same SF.

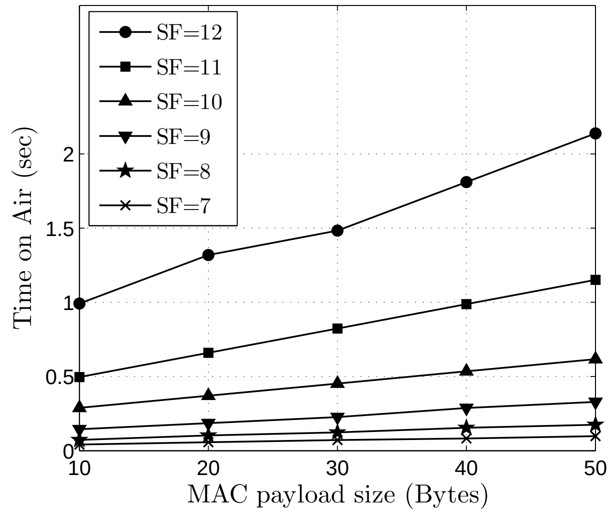

Fig. 1. Time on Air of LoRaWAN with code rate 4/5 and a 125 kHz bandwidth.

Based on this, the throughput (in packets/hour or packets/sec) can be approximated by the superposition of a set of independent Aloha-type access networks characterized by the number of channels and the SFs. Therefore, the number of packets received per second is given by,

$$S = \sum_{i \in F} N p_i \lambda_i e^{-2 p_i N T_{a_i} \lambda_i / n} \tag{1}$$

where $F = \{i = 7 \ldots 12\}$ is the set of SFs, p_i is the probability that an end-device uses the SF i, λ_i is the packet rate of the users with SF i, and T_{a_i} is the time on air with SF i. Although all end-devices are assumed to have the same packet generation rate (λ), the real transmitted packet rate never exceeds the duty cycle, and therefore, $\lambda_i = \min(\lambda, d/T_{a_i})$. The performance of the LoRaWAN network is thus dependent on both the duty cycle and the intrinsic collisions of the Aloha-based access. Furthermore, the time on air is also a fucntion of the SF, and the highest SFs (i.e. the lowest bit rates) are also the most likely to be selected. For instance, in a simple scenario, with end-devices distributed uniformly within a round-shaped area centred at the gateway, if the the path loss is calculated with the Okumura-Hata model for urban cells, the probability that an end-device uses a SF i would be $p_{12} = 0.28$, $p_{11} = 0.20$, $p_{10} = 0.14$, $p_9 = 0.10$, $p_8 = 0.08$ and $p_7 = 0.19$ (note that sensitivity varies among different SFs).

If all end-devices transmit packets at the maximum packet rate (the SF specific duty cycle rate, i.e. $\lambda_i = d/T_{a_i}$), the number of packets successfully received at the gateway decreases as shown in Figure 2, where a network with $n = 3$ channels has been analyzed. The number of received packets drops due to the effect of collisions in Aloha-based schemes.

As aforementioned, the throughput of the LoRaWAN network depends both on the duty cycle and on the probability of collisions. In Figure 3 the number of packets successfuly transmitted per hour and node is shown for deployments with $N = \{500, 1000, 5000, 10000\}$ end-devices and $n = 3$

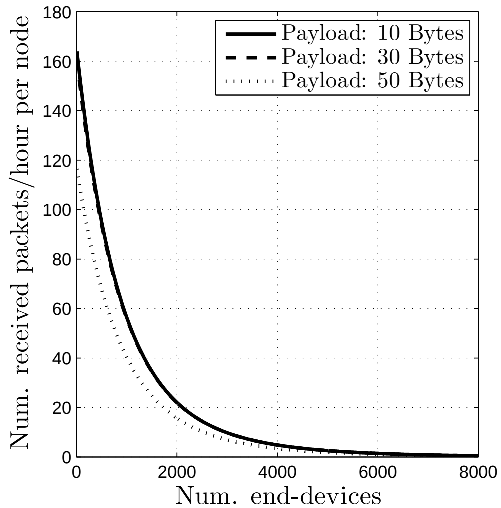

Fig. 2. Number of packets received per hour when end devices attempt transmission at $\lambda = d/T_{a_i}$ with coding rate 4/5 and $n = 3$ channels of 125 kHz bandwidth.

channels. For low λ values (in packets/hour), the throughput is limited by collisions; for high values, the duty cycle prevents end-devices from increasing the packet transmission rate and stabilizes the thoughput. Interestingly, for deployments with a "small" number of end-devices, the duty cycle constrain limits the maximum throughput.

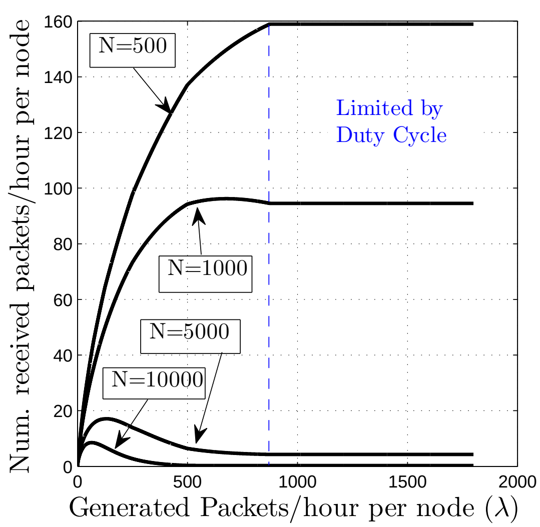

Fig. 3. Number of 10 Bytes payload packets received per hour and node for $N = \{500, 1000, 5000, 10000\}$ end-devices and $n = 3$ channels as a function of the nodes' packet generation.

Table I summarizes the maximum achievable throughput per node and the probability of successful transmission for a set of different deployments. It is obvious that the maximum throughput falls as the deployment incorporates more nodes. However, note that deployments with $N = 500$ end-devices, the probability of successful transmission is basically higher than the same probability for denser deployments.

B. Reliability and Densification drain Network Capacity

In LoRaWAN reliability of transmissions is achieved through the acknowledgment of frames in the downlink. For class A end-devices, the acknowledgment can be transmitted in one of the two available receiving windows; for class B end-devices it is transmitted in one of the two receiving windows or in an additional time-synchronized window; and it can be also transmitted at any time for class C end-devices.

In LoRaWAN the capacity of the network is reduced not only due to the transmission of ACK frames in the downlink, but also due to the off-period associated to the Time on Air of the ACK transmission (note that gateways have also to comply with the duty cycle regulation). Therefore, the design of the network and the applications that run on it must minimize the number of acknowledged frames to avoid the capacity drain. This side-effect questions the feasibility of deploying ultra-reliable services over large-scale LoRaWAN networks.

At this point of development of the technology, LoRaWAN faces deployment trends that can result in future inefficiencies. Specifically, LoRaWAN networks are being deployed following the cellular network model, that is, network operators provide connectivity as a service. This model is making gateways to become base stations covering large areas. In turn, application developers use the connectivity service provided by network operators to extract data from their end-devices using the common infrastructure. As LoRaWAN coverage areas are being progressively populated by different vendor applications that share the same infrastructure, new challenges are posed to coordinate the different applications. Therefore, this model, i.e. the cellular network operator, requires techniques to ensure fair spectrum sharing between application nodes, as the congestion grows with scale despite of the existing regulations.

IV. Use Cases

Several application use cases are considered in order to analyze the suitability of LoRaWAN and complement the understanding of the advantages and limitations of the technology when applied to different types of data transmission patterns, latency requirements, scale and geographic dispersion among others.

A. Real Time monitoring

Industrial automation, critical infrastructure monitoring and actuation require some sort of real time operation. Real time is understood in general by low latency, and bounded jitter and depends on the specific application. LoRaWAN technology cannot claim to be a candidate solution for industrial automation, considering for example that industrial control loops may require response times around 1 ms to 100 ms and that, even for small packets of 10 Bytes, the time on air with SF=7 is around 40 ms. As presented in the previous section, due to the MAC nature of LoRaWAN, deterministic operation cannot be guaranteed despite of application specific periodicity as Aloha access is subject to contention which impacts network jitter. Despite of that, small LoRaWAN networks can deliver proper service to applications that require, for instance, sampling data

TABLE I
MAXIMUM THROUGHPUT AND PROBABILITY OF SUCCESSFUL TRANSMISSION FOR DIFFERENT DEPLOYMENTS (WITH n=3 CHANNELS AND 1% DUTY CYCLE)

	$N = 500$			$N = 1000$			$N = 5000$			$N = 10000$		
Payload (Bytes)	10	30	50	10	30	50	10	30	50	10	30	50
Max. throughput per node (Packets/hour)	159	94	68	96	57	41	17	10	7	8.5	5.5	3.5
Max. throughput per node (Bytes/hour)	1590	2820	3400	960	1710	2050	170	300	350	85	165	175
λ of the max. throughput (Packets/hour)	874	500	370	650	390	287	135	74	53	65	37	26.5
Prob. of successful transmission (%)	18.19	18.80	18.38	14.77	14.62	14.29	12.59	13.51	13.21	13.08	14.86	13.21

every second. To do that, two main design considerations should be taken into account:

- The spreading factor should be as small as possible to limit both the time on air and the off-period derived from the maximum duty cycle regulation. In other words, the gateway must be close enough to the end-devices.
- The number of channels must be carefully designed and must be enough to i) minimize the probability of collisions (tightly coupled with the number of end-devices) and ii) offer quick alternative channels for nodes to retransmit collided packets to diminish the impact of the duty cycle.

However, despite the two aforementioned aspects to be considered during the design process, latency will not be deterministic.

B. Metering

The LoRa Alliance is working on standard encapsulation profiles for popular M2M and metering protocols. Keeping an existing application layer allows to keep intact most of the firmware and ecosystem, facilitating migration to LPWAN. These protocols include Wireless M-Bus for water or gas metering, KNX for building automation, and ModBus for industrial automation. It is important to understand that those scenarios range from time sensitive operation to best effort monitoring. Therefore, it is key to identify in such a diverse eco-system what the requirements of each application are and if LoRaWAN is the appropriate technology to address them.

C. Smart City applications

LoRaWAN has shown key success stories with smart lighting, smart parking and smart waste collection due to their scale and the nature of the data generated by those applications. These encompass periodic messaging with certain delay tolerance. For example, smart parking applications report the status of the parking spots upon a change is detected [11]. Parking events are slow and therefore network signaling is limited to few tens of messages per day. Analogously smart waste collections systems and smart lighting actuate or report information in response to a measure with large variation periods. Although latency and jitter are not major issues in these applications, in some of them the triggering factor is simultaneous for a huge number of end-devices. For instance, sunset and down trigger the lighting elements around the whole city, thereby causing an avalanche of messages. LoRaWAN is an appropriate technology for this use case since it handles the wide coverage area and the significant number of users at the expense of increasing number of collisions, latency and jitter.

V. OPEN RESEARCH CHALLENGES

The effect of the duty cycle stated in Section III compromises the actual capacity of large-scale deployments. This has been initially addressed by TheThingsNetwork [12], an interesting global, open, crowd-sourced initiative to create an Internet of Things data network over LoRaWAN technology. The proposed solution defines an access policy, known as the TTN Fair Access Policy, that limits the Time on Air of each end-device to a maximum of 30 sec per day. This policy is simple to implement and guarantees pre-defined end-device requirements for a large-scale network (more than 1000 end-devices per gateway). However, it fails to provide the network with enough flexibility to adapt to environment and network conditions (i.e. link budget of each end-device, number of end-devices, number of gateways, etc), as well as to applications with tight latency or capacity requirements.

At this stage, the optimization of the capacity of the LoRaWAN network, as well as the possibility to perform traffic slicing for guaranteeing specific requirements in a service basis, remain as open research issues. From the authors' point of view, the research community will have to address the following open research challenges during the next years:

- Explore new channel hoping methods to enhance the pseudo-random methods currently implemented in LoRaWAN (e.g. pre-defined and adaptive hopping sequences).
- Transform LoRaWAN into a Time Division Multiple Access (TDMA) network (completely or partially) and implement centralized scheduling algorithms to reduce the number of collisions and provide a solution for deterministic traffic.
- Explore the reduction of the transmission power together with the enabling of multi-hop solutions (from single-hop communications to two-hops communications when required) to boost the usage of small SF values while maintaining the coverage area.
- Analyze the impact of dense networks of LoRaWAN gateways in scenarios with limited number of channels, and devise coordination mechanisms between gateways from the same or different operators to limit interference and collisions.

VI. CONCLUSIONS

This article is aimed to clarify the scope of LoRaWAN by exploring the limits of the technology and matching them to application use cases. In the low power M2M fragmented connectivity space there is not a single solution for all the possible connectivity needs and LoRaWAN is not an exception. A LoRaWAN gateway, covering a range of tens of kilometers and able to serve up to thousands of end-devices, must be carefully dimensioned to meet the requirements of each use case. Thus, the combination of the number of end-devices, the selected SFs and the number of channels will determine if the LoRaWAN Aloha based access and the maximum duty cycle regulation fit each use case. For instance, we have seen that deterministic monitoring and real time operation cannot be guaranteed with current LoRaWAN state of the art.

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