Analysis and Assessment of LoRaWAN

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***Abstract*—Low-Power Wide Area Network (LPWAN) supports long-range communication for hundreds to millions smart devices and enables new types of services in Internet of Things (IoT) context. Several wireless technologies have proposed; LoRa wireless technology is arguable the most adopted, and LoRaWAN is an open standard network stack based on LoRa modulation at the physical layer. That combination promises popular connectivity in outdoor applications, while maintaining simple network structures and managements. This work provides an in-depth analysis and assessment of LoRaWAN functional components: its capabilities (total traffic load, packet delivery quality) versus its efficiency (collision and frequency usage). The evaluation based on extensive simulation study has given the hints for scalability of network deployment as well.**

I. Introduction

Recently, Low Power Wide Area Networks (LPWANs) is specialized for interconnecting devices with low-bandwidth connectivity and focusing on range and power efficiency. It can be exploited as solutions for Internet of Things (IoT), or Machine-to-Machine (M2M) applications including smart city (smart metering, on-street lighting control) or smart agriculture (smart irrigation, precision cropping), etc..., the applications have been constrained by budgets and power issues. LPWAN can be used as a private network or an infrastructure, offered by a third party, allowing the service providers of IoT applications to deploy applications in large scale without investment on gateway technology. The key features of LPWAN are: up to 10 km communication between end devices and gateway, possibly 5-10 years of battery long lifetime, in the trade-off of less than 5Kbps of data rate. It has simple star network topologies lowering cost of network deployment and maintenance [1].

Among different wireless technology, LoRa technology is rising a star. With Chirp Spread Spectrum (CSS) modulation, in which a signal is modulated by chirp pulses, LoRa signal is improved in resilience and robustness against interference, Doppler's effect and multipath effect. LoRaWAN is an open standard network stack based on LoRa modulation at the physical layer. LoRaWAN features a raw maximum data rate of 27 Kbps (or 50 Kbps when using FSK modulation) [2], and claims that a single gateway can collect data from thousands of nodes deployed kilometers away. These capabilities have urged some solution providers and network operators, who have created a large motivation behind LoRaWAN to the point that it is sometimes considered as the connectivity enabler for any IoT use case.

The goal of this article is to analyse and assess the capabilities and efficiency of LoRaWAN. We provide the introduction of LPWAN and several technology candidates and summarize the related work on this topic in Section II. Section III describes the overview of LoRa radio technology and the LoRaWAN network stack in details and provides evaluation performance studies hereof. Extensive simulation study to assess the network capacity and discuss the scalability of network deployment is given in section V. Section VI gives the conclusion.

II. Background

A. Low Power Wide Area Network - LPWAN

LPWAN is not a new concept, however, it recently becomes a phenomenon since the Internet of Things grows drastically these days. LPWAN technology is perfectly suited for connecting devices that need to send small amounts of data over a long range, while maintaining long battery life, e.g. a parking garage sensor only needs to transmit several bits when a spot is free or occupied. The low power consumption of such a sensor device allows that task to be carried out with minimal battery draw and hardware cost. Moreover, LPWAN is great for applications of fixed devices but in high density connections, e.g. smart lighting controllers or distribution automation in smart grid. However, LPWAN technologies are not ideal for localization [1]. LPWAN is used when other wireless technology is not suitable – Bluetooth (or Low Energy Bluetooth), Wifi, Zigbee is unable to support long-range communication up to several kilometers, while cellular M2M is costly, largely consuming of energy and very expensive in terms of hardware and services provided.

Currently, several technologies and platforms, including Sigfox, LoRa, Weightless, Nwave, Ingenu, have been promoted in the scope of LPWAN. Most current LPWAN

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technologies use an unlicensed band, sub-GHz band, the 900 MHz ISM band (in the US) and the 868 MHz ISM band (in Europe), e.g LoRa, Sigfox use both, and the 2.4 GHz band, e.g. Ingenu. However, every country has different rules about using the sub-GHz spectrum, e.g. the 915 MHz band is available only in about a third of the world and some countries do not allow to use this band. Till now, there is no globally available band for LPWAN.

The receiver sensitivities in LPWAN is about -130 to -140 dBm, compared to -90 to -110 dBm in traditional wireless technology. It realizes the requirements of long range transmission but low power consumption. The enhancement is obtained by slowing the modulation rate, resulting in very low data rate, or using ultra narrow band signal [1].

In Sigfox, the long-range capabilities are accomplished as a result of very long and very slow messages [3]. Each end-device is able to send very small amounts of data (12 bytes) very slowly (100-600 bps) using BPSK (bandwidth of 100Hz) [1]. Sigfox also claims that each access point can handle up to a million end-devices, with a coverage area of 30-50 km in rural areas and 3-10 km in urban areas. Similar to Sigfox, Nwave8 runs off an ultra- narrow band (UNB) radio, which operates in sub-GHz ISM bands, however, its MAC-layer implementation is better [1].

Ingenu developed their solution in the 2.4 GHz band, using Random Phase Multiple Access (RPMA) [4]. Its main strength is the high data rate up to 624 Kbps for uplink transmission, and 156 Kbps for downlink transmission. However, the energy consumption is rather higher and the range is shorter (a range around 5-6 km) due to the high spectrum band used. Therefore, it is not well suited for battery-powered applications.

Together with Sigfox, LoRa radio technology is another candidate most adopted for LPWAN solutions. It leverages Chirp Spectrum Spreading to improve receiver sensitivities allowing a low data rate (0.3-50 Kbps, depending on various spreading factor and modulation scheme) and long communication range (2-5 km in urban areas and 15 km in suburban areas). It was developed and owned by Semtech [5]. Based on LoRa chip sets, several platforms have built up, e.g. Symphony Link of Link-labs [1], or open standard LoRa Wide Area Network (LoRaWAN) promoted by LoRa Alliance [2].

B. Existing work on LoRa network

To choose one technology/platform for IoT solution, insightful investigation of LoRa technology and LoRaWAN protocol should be performed. Several initial works have been summarized as follows. Aloys et.al. present the results of several field experiments to reconfirm the sensitivity and coverage of LoRa transceivers [6]. The field experiments of LoRa network performance in Padova city (Italy) results in the conclusion of the network coverage of about 1.2 km (urban environment) and the usage of 30 gateways to cover the city of Padova (of about 100 kilometer square) [7]. However, the resulted number of gateways has not accounted the traffic demand and the quality of service.

The existing work have analytically estimated the maximum throughput/capacity of end-device in a simplified network of a one end-device generating data, or evaluated the collision rate in a network of single channel [6, 8]. [9] presents the limitation of the regulations of using sub-GHz frequency band (duty-cycle less than 100%) on the capacity and network size. They have not implemented and analyzed the full function of MAC layer and especially the real scenario that the selection of channel and SF value for each transmission is random.

Ultimately, much of the value of a LPWAN technology is not only the underlying RF characteristics, the ability to create and maintain a network, and offer bi-directional data flow matters most for end users. The limitations or features of MAC implementation are very important to understand. In the following sections, the overview of LoRa wireless technology and the insightful investigation of LoRaWAN will be present and analysed.

III. Key Features of LoRa Wireless Technology

In LoRa, the Chirp Spread Spectrum (CSS) modulation, in which a signal is modulated by chirp pulses, helps to improve resilience and robustness against interference, Doppler's effect and multipath effect. With CSS, each LoRa symbol is coded by 2^{SF} chirps, in which SF is defined as the spreading factor, its value is among 7-12. The larger SF value, the longer a symbol transmission and the longer transmission range.

LoRa technology uses 3 typical bandwidth, 125 KHz, 250 KHz or 500 KHz at frequency band 868 MHz (Europe, Asia) and 915 MHz (the US) and 7.8-62.5 KHz at frequency band 433 MHz (Asia). According to the SF and bandwidth used, the data rate varies from 22 bps (BW= 7.8 KHz and SF= 12) to 27 Kbps (BW= 500 KHz and SF= 7). The SF and channel for each transmission can be chosen each time.

There is a trade-off between data rate and communication range. The higher the SF (i.e. the slower the transmission), the longer the communication range. LoRa signals having different chirp bandwidth are orthogonal: a LoRa receiver coded to receive signals at a determined bandwidth will only decode signals modulated with that, and other LoRa signals at different bandwidths, will appear to it as noise, even if their frequency spectrum overlaps that of the received signals [6].

A LoRa physical packet contains a preamble, a header, a payload of 51-222 bytes, and a field for Cyclic Redundancy Check (CRC). The maximum payload field is dependent on the value of SF used.

However, there is a key constraint for networks operating in unlicensed sub-GHz bands like LoRa networks: the maximum duty-cycle defined as the maximum percentage of time during which an end-device can occupy a channel is regulated by regional authorities. Therefore, the selection of the channel must implement pseudo-random channel hopping at each transmission and be compliant with the maximum duty-cycle. For example, the duty-cycle is 1% in EU 868 band, meaning the devices have to wait 100-times the duration of the last transmission before sending again in the same channel [5].

IV. THE LORAWAN PROTOCOL

LoRaWAN networks composed of end-device, gateway device and network server are organized in a star topology. End-devices send data to gateways over a single wireless hop and gateways relay messages to/from central network servers through a non-LoRaWAN network (e.g. IP over Cellular or Ethernet)[8]. Communication is bi-directional, although uplink communication from end devices to the network server is strongly favored.

LoRaWAN defines many MAC commands that allow customizing end-device parameters, e.g. control the data rate and output power used by end devices, change channel (or hopping sequence), update the duty cycle, change parameters of receiving window. End-device can use to check connectivity with gateway/server as well. In order to participate in a LoRaWAN network, an end-device must be activated, either by Over-The-Air Activation (OTAA) or by Activation By Personalization (ABP) [8].

LoRaWAN defines three types of devices (Class A, B and C) suitable for different type of applications [5]. Three classes can coexist in the same network and devices can switch from one class to another. However, there is not a specific message defined by LoRaWAN to inform the gateway about the class of a device and this is up to the application.

Class A devices use pure ALoHA mechanism to access the uplink medium. After sending a frame, a Class A device listens for a response during two downlink receive windows (RX1 and RX2) as shown in Fig. Each receive window is defined by an offset time and a data rate. The offset time can be configured over MAC commands, or setup at 1 second and 2 seconds, respectively. Data rate in RX1 is calculated as a function of the uplink data rate and the receive window offset, while the data rate in RX2 is fixed to the minimum, 0.3 kbps. RX2 is disabled when downlink traffic is received in RX1. Downlink traffic cannot be transmitted until a successful uplink transmission is decoded by the gateway.

Class B devices are designed for applications in need of additional downlink traffic. These end-devices are synchronized by periodic beacons sent by the gateway to allow the schedule of additional receive windows for downlink traffic without prior successful uplink transmissions. Obviously, a trade-off between downlink traffic and power consumption arises.

Class C devices always listen to the channel except when they are transmitting, therefore, the ACK message can be received immediately, however, the power consumption is rather high.

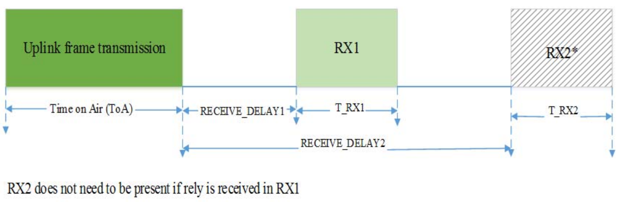


Fig 1. The operation of class A end-device

V. ANALYSIS AND ASSESSMENT OF LORAWAN

In this paper, we will analyze the network consisting of one gateway relaying data from hundreds to thousands of end-devices to the server. The general network consisting of several to many gateway would be considered as the superposition of several single gateway network. Although, the physical layer has a large influence on the capacity of devices/network, the operation of LoRaWAN has effect at some extent. The analysis and discussion of the performance of LoRaWAN are based on the results of simulation. Each transmission on the physical layer is characterized by a pair of channel and SF value which determines the Time on Air (ToA) of a packet. The crowd of traffic (uplink and downlink) based on the ToA of each transmitted packet are simulated and collisions occurring when ToAs of at least two packets on the same channel and SF value overlaps result in transmission failure. The MAC implementation follow the LoRaWAN specifications [5].

In this simulation, a network consists of a gateway and N end-devices which can transmit packets as soon as the channel limitations and the protocol allow, assuming that the transmission has not been affected by the position of end-device The network has 3 channels of 125 kHz and uses spreading factors from 7-12. Before each transmission of end-device, the channel and SF value used to code a LoRa packet is randomly selected from the possible ranges. Each packet includes 10 bytes of payload and 13 bytes of MAC header. The size of data payload in a packet is suitable for IoT monitoring applications, e.g. smart meter, and in the same order with the packets in Sigfox technology. According to EU 863-870MHz ISM Band, the duty-cycle is setup at 1%.

Each end-devices can store up to four packets in its queue before sending. The time to live (TTL) of a packet is 60s. After 60s, TTL expired and packet is cleared out of queue.

In confirmed transmission mode, end-device requires an ACK from the gateway. The packet exists in queue until it is successfully sent (the end-device receives an ACK) or its TTL is expired. The procedure of transmission consists of RX1 and RX2 window as depicted in Fig.1. In contrast, in unconfirmed transmission mode, end-device clears packets immediately after sending. In class C, the receive window is right after the uplink transmission, no waiting time is needed. The network performance in terms of the channel capacity usage and the collision rate are evaluated in the variation of traffic load defined as the rate of data that end-devices injected in the network. The effect of duty-cycle on data throughput and collision resolution is investigated as well.

A. Channel usage and collision rate

Using CSS modulation, two transmissions on the same frequency, but using different spreading factors, can be decoded simultaneously, hence, a logical channel between a gateway and an end-device is defined by a pair of frequency band and spreading factor. The total transmission capacity of a gateway in a LoRaWAN network is calculated as the sum of the capacities of all of the logical channels. In each 125-kHz frequency band, there are six possible spreading factors (from 7 to 12) and the corresponding data rate on each SF is specified in [5], which brings the nominal total capacity of a 125-kHz channel to 12,025 bps.

The channel capacity usage is computed as the ratio of the amount of successfully transferred data and the theoretical maximum amount of possibly transferred data which is the channel capacity multiplied by the investigated duration. When duty-cycle scheme is applied, the available time of a channel is scaled down by the allowed duty-cycle time. In this work, the duty-cycle is 1%.

Fig. 2 presents the channel usage, collision probability and successful packet delivery ratio in the variation of the traffic load from end-devices in three scenarios: network of class A devices in confirmed and unconfirmed mode, and class C devices. The operation of class B device is slightly different from the operation of class A device in periodically sending small beacon packets at specifically scheduled time, that could lower the downlink traffic latency, but does not affect much the channel usage. Therefore, we do not include the result in this paper.

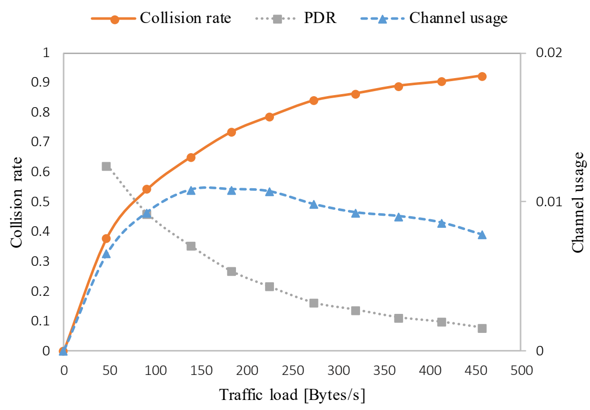
As depicted in Fig. 2a, when the traffic increases, the channel usage is going up. It reaches the maximum of about 1% when the traffic request is about 200 Bytes per second and later on, the more traffic request, and the lower channel efficiency. The reason is that the collision happens more often on the shared medium. It results in that the packet delivery ratio gradually decreases.

Compared to the class A confirmed mode, the unconfirmed mode is more efficient in terms of channel usage and packet delivery as well. In LoRa network used for IoT applications, the packet is rather small, and in the same order of the ACK packets. Therefore, using ACK scheme will create more collisions and degrades the overall performance.

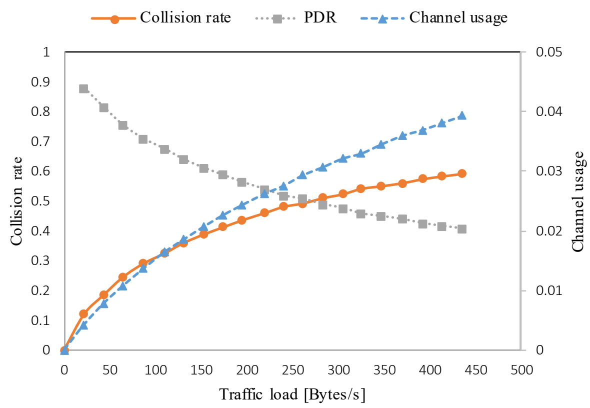
The class A unconfirmed mode is rather similar to the class C. The patterns of collision probability and channel usage variation are similar, and, the packet delivery ratio degrades rather identical

When the transmission time of two packets overlaps and they use the identical SF value, collision happens and the two packets are considered not reaching the gateway. The collision ratio also reflects the energy efficiency of the protocol.

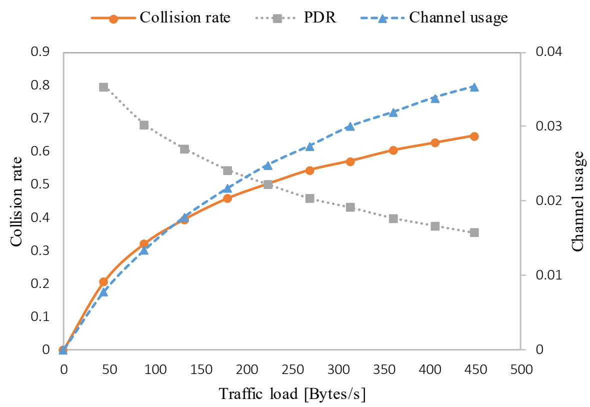
Specified in LoRaWAN, there is no “listen-before-talk” before any transmission from end-device or gateway, hence, the MAC mechanism in LoRaWAN is very similar to pure AloHa when considering in an independent network for each channel and for each SF [9]. However, in the pure AloHa, transmission time of all packet are same, while, in LoRaWAN, the packets are sent with different data rates, hence variable transmission time (because of varied SF value).



(a) Network of Class A devices in *confirmed* transmission mode



(b) Network of Class A in *unconfirmed* transmission mode



(c) Network of Class C devices

Fig.2. Channel usage, collision probability and succeeded packet delivery ratio in three different scenarios: network of class A devices require ACK and non-ACK and network of class C devices.

B. Duty-cycle

Since LoRaWAN is working on ISM free-licensed band which should be shared with numerous other applications, each area/region has a regulation of the possible usage of the wireless band. For example, the EU set up the ratio of usable frequency band (allowable time occupation) of 1%. Fig. 4 shows the evaluation of the influence of the duty-cycle scheme on the network performance. The duty-cycle is set up at different values of 1%, 10%, 20%, 50% and 100%. It shows that the collision happens more often when the usable time increases and when 100% frequency band can be used, then the collision is approximately 100%. Apart of the reservation of the shared frequency band for other applications, the duty-cycle mechanism is leveraged as a mean of collision control, note that only the intra-network interference is considered in the simulation. Network planning procedure should investigate inter-network interference caused by various other LoRa based applications in the same frequency band.

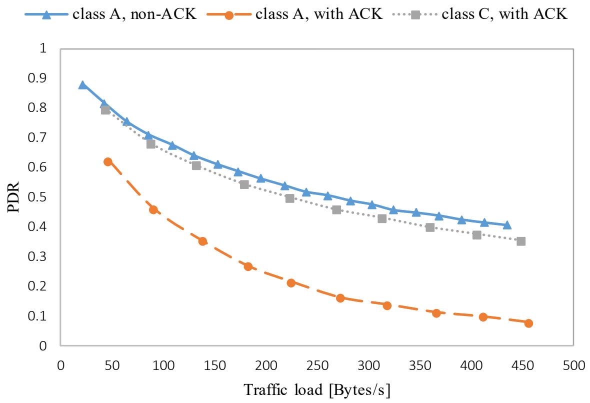


Fig.3. Comparison of packet delivery ratio among three operation classes

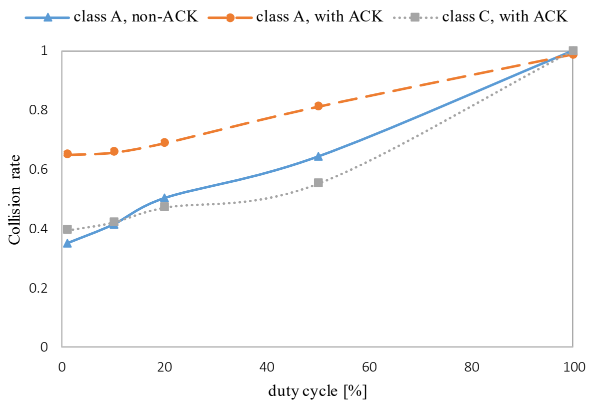


Fig. 4. Comparison of collision rate in the variation of duty cycle among three operation classes

C. Network size

The simulation is performed in the variation of traffic load, which accounts for the real data requests appears in the network, but does not depend on the network size, the number of end-devices. If the data rate of specified application is realized, the number of node in the coverage of a gateway (called a *cell*) can be derived in the chosen optimum condition of network (in terms of the channel usage, the packet delivery ratio related to the obtained data throughput). For example, referring to Fig.3, when end-devices are setup at class A with ACK, the obtained PDR is 60% if the total traffic load is 50 Bytes per second. Hence, given the required data rate is 100 messages of 23 Bytes (10 Bytes of payload and 13 Bytes of header) per 24h per end-device, an approximation of 1800 devices per cell can be served. Lowering the number of devices, the quality of service would be better. The PDR would be better (about 80%) as the devices operating in class A non-ACK or class C. However, the trade-off of using in class C is the energy consumption since end-devices will always listen on channels. In class A without ACK, there is no downlink communication for the gateway controlling the end-devices.

VI. Open Issues and Future Work

Through the analysis and evaluation above, we can draw some conclusions as follows:

1) Transmission at high spreading factor (SF 12 in current specification) would longer the transmission range and strengthen the interference resistance, however, the data rate is lower. This will decrease the throughput of each device, and reduce the obtained channel usage.

2) Duty-cycle scheme could help to reduce collision, hence, save the energy consumption, but, it lowers the channel capacity significantly.

3) LoRaWAN is extremely sensitive to the traffic load. Base on the average traffic request of each node, the optimal number of nodes per cell depends on the operation mode of devices and the trade-off of data delivery quality and energy consumption.

LoRaWAN uses the non-license ISM bands which are attracting more and more users and applications. These bands have finite capacity and the regulations of using these bands also limit the available time for each user. In the near future, when IoT applications are booming with millions of end-devices, it is guarantee that the capacity of this band is insufficient even LoRa is very resistant to interference. Moreover, it is perfectly legal for a malicious individual to emit random LoRa symbols, which will jam LoRa transmissions. The issues should be considered in the future work.

Currently, LoRaWAN uses pure AloHA and duty-cycle scheme to control medium access, however, the collision is still rather high and the energy efficiency has not been well investigated. Other mechanism like CSMA or TDMA should be investigated, especially in the context of specified applications.

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