Limitations of Current LP-WAN Systems

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***Abstract*— LP-WAN systems are important components of the IoT. They allow the exchange of small amount of data over long distances with relatively little energy and little infrastructure complexity. These important characteristics have led to great interest. They have also led to legitimate application and market dreams. As is often the case with new technologies, there are misunderstandings that can result in disappointments if the limitations of the technologies are not properly understood. In this work, we highlight some of those restrictions, looking especially (but not only) at aspects such as energy, throughput and determinism. We draw on our own practical experiences and measurements, as well as works done by other groups.**

Keywords—LPWAN; LoRa; Wireless; Sigfox; Throughput; Energy Harvesting;

I. INTRODUCTION AND MOTIVATION

The promises of communication anywhere and everywhere seem to be among the most attractive in the current information technology context. Objects should be fitted with appropriate low-cost and low-power technologies to allow them to communicate with servers and applications that generate or use the data. The benefits in term of quantities and revenues are staggering. Consequently, several communication protocols are vying to seize parts of that market. They are being marketed as most appropriate to empower objects with the needed resources. There is thankfully competition between the different technologies that seek to occupy the space.

Low-power Wide Area Network (LPWAN) systems should play an important role in allowing different kind of objects to communicate efficiently. There are now several protocols that address that need. Many of them use the unlicensed ISM band, which also helps keep costs low. Technologies such as NB-IoT are newer, use the licensed band and are not yet as widely established as LoRaWAN or Sigfox (we are in 2017). As usual, new and rapidly evolving systems also bring misunderstandings about what can or cannot really be achieved. These misunderstandings can lead to disappointments if the limitations of the technologies are not properly understood. Our purpose here is to shortly provide information helping to highlight some of those restrictions. We look especially at aspects such as energy, throughput and determinism, drawing on our own practical experiences and measurements, as well as works done by other groups. Conclusions from groups doing similar things are also reported. We concentrate on Sigfox and LoRa, because they are the most popular technologies at the moment.

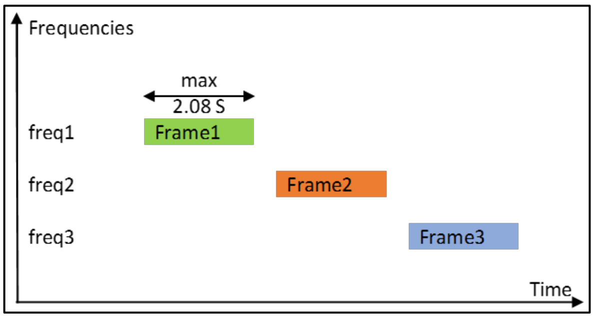
In what follows, we will briefly describe Sigfox and LoRa/LoRaWAN and then shortly address issues such as energy requirements, throughput and latency.

II. SHORT DESCRIPTION OF SIGFOX

Sigfox is one of the earliest LPWAN technologies. In Europe, it uses the 868MHz ISM band (192 kHz between 868.034 MHz and 868.226 MHz). There are adaptations for other countries, according to the local regulations. Fig.1 shows a basic structure of the system. Objects transmit information to the servers that will then process and make it available to applications and users. Most of the wireless communication is from objects equipped with Sigfox transceivers to the base stations (uplinks). Sigfox uses UNB technology (Ultra Narrow Band) for communication. The band is divided in very narrow channels, allowing energy to be concentrated in a small part of the spectrum. This helps improve the communication range. Uplinks are used to transfer data from objects to the servers, whereas downlinks go in the other direction. In France, the band is centred at 868.13 MHz for uplink, and 869.525 MHz for downlink [7,9,10].

Uplink

The modulation is BPSK (Binary phase-shift keying) for uplink messages, with a data rate of 100 bps and 100 Hz spectrum segment. Frames have a maximum payload of 12 bytes. At 100 bps, such a frame will require 2.08 seconds (payload and frame overhead). The same information is sent 3



times, each time on a different frequency, leading to a maximum on air time of 6.24 seconds. there is a frame overhead that is required for several purposes (identification, security, redundancy, …) [7].

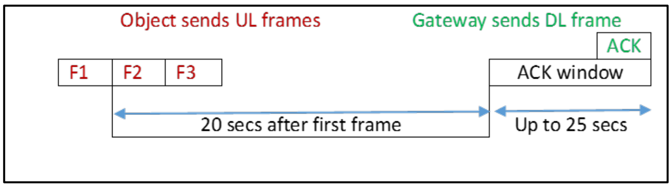
Structure of the Sigfox UL Frame					
Preamble	Frame Sync + Header	Device ID	Payload	Mess Auth Code	FCS
19 bits	29 bits	32 bits	0-96 bits=12 Bytes	16-40 bits	16 bits

Any base station in the range can receive the information and relay it to the servers. The base station monitors the whole band to decode messages sent by objects.

The central frequency accuracy is not relevant, provided there is no significant frequency drift within an uplink packet transmission.

Downlink

Sigfox (now) also allows messages to be sent from the application to the object. For downlink messages, the GFSK modulation is used, with a data rate of 600 bps and 600 Hz spectrum segment. Up to 4 downlink messages are allowed per day. Each downlink message has a maximum payload of 8 bytes (i.e. on top of the overhead) and is sent just once. 20 seconds after the transmission of the first frame, the object should go in receive mode. The window for reception from that point lasts at the most 25 seconds (average of 13 seconds according to Sigfox) [8].



If the first uplink frame is lost, there is still enough information in the other frames to allow the downlink to be sent at the right time.

The number of uplinks far outnumbers the number of downlinks. Several options are offered for the user, with the maximum number of uplinks and downlinks per day as shown in the table.

Ultra Narrow Band allows several channels to be used for communication, increasing the capacity. According to Sigfox, there is an average of 3 base stations that can receive the information. They also claim a capacity of up to 1 million IoT devices per base station.

Options offered by Sigfox		
Name	*Number of UL*	*Number of DL*
Platinum	101 to 140	4
Gold	51 to 100	2
Silver	3 to 50	1
One	1 to 2	0

The use of redundancy in different channels and at different times (uplink) leads to diversity in time, frequency and space. This increases the probability of getting the information through to at least one base station. A disadvantage is that the transmitter has to send the same information 3 times, thus increasing the energy consumption. Furthermore, the redundancy leads to a longer occupation of the medium by the same device (partly mitigated by the large number of channels).

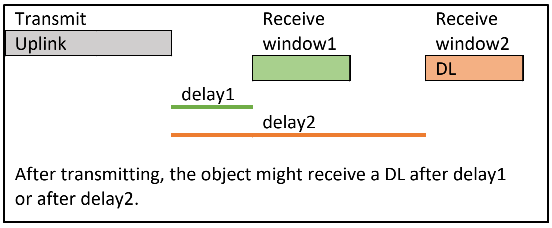
III. Short Description of LoRa/LoRaWAN

LoRa is a wireless modulation technology that can be used to build low-power long-range communication networks. It is a variation of CSS (Chirp Spread Spectrum) that spreads the signal on a larger band. It supports several baud rates but is generally seen as low bandwidth. Different spreading factors can be used to allow parallel communication links at different data rates. Nodes that are close to the gateway can communicate faster. Reducing the baud rate allows contact between nodes that are further apart. Thanks to the modulation it uses, LoRa has a good resistance to in-band and out-of-band interferences. It is also Doppler-shift resistant and presents a good immunity to multipath fading. These characteristics also make LoRa more suitable for use in moving objects. The link budget is 151 dB for SF12 (+14dBm, 125kHz).

LoRaWAN is a network layer that uses LoRa, with the following characteristics for Europe: maximum output power of +14dBm (25mW); bandwidth of 125KHz; 868MHz band.

The size of the frame varies. Tens of bytes can be accommodated. There is an overhead of 13 bytes or more. The real size depends on some communication parameters.

Bidirectional communication is possible. The duty-cycle of the band used should be respected (country regulations). There are more uplink messages than (there are allowed) downlink messages. Following the UL message, there are two windows



where a DL frame can be received. These receive time windows follow the UL frame after the predefined delay1 or delay2. In Europe, delay1 is 1 second and delay2 is 2 seconds. If a preamble is detected in the receive window, the receiver stays on until the whole DL frame is received. If the DL is sent in the first window, the receiver does not need to be active in the second window.

There are 3 classes or devices in LoRaWAN, which are described below.

Class A Unicast	Class B Unicast/multicast	Class C Unicast/Multicast
DL to object at predetermined positions after an UL	An extra receive slot is scheduled by server at ping slot (beacon used)	Object is always in receive mode when not transmitting
Lowest energy. Battery powered	Battery powered. More energy than class A	Mains power. Needs most energy
Object initiate coms. ALOHA-like	Server can initiate communication at ping slots	Server can initiate communication
High latency for server to object communication	Latency related to beacon	Lowest latency from server to object

Class A devices are functionally closer to Sigfox devices. They function in an asynchronous way. Class B nodes require a good time synchronisation between base stations. Class C devices are always in receive mode.

Several operators have installed the needed infrastructure for LoRaWAN and offer nationwide coverage. This is the case for Swisscom in Switzerland. Customers can chose from among the possibilities in the table below [6].

LPN Bundle Service per device	XS	S	M	L	XL	XXL
# of messages per day Uplink / Downlink	2 / 1	4 / 1	24 / 2	48 / 4	96 / 9	144 / 14

It can be seen that the number of UL frames per day greatly exceeds that of DL frames. For the XXL option, only 14 messages from 144 will have an ACK. That is 10%.

Since LoRa devices can work in parallel when using different Spreading Factors, ADR (Adaptive Rate Mechanism) can be used to inform a node that it may change the spreading factor while sending. A change to a lower SF (higher data rate) leads to shorter transmitting times, less energy consumption and increases the network capacity.

Contrary to Sigfox, LoRa allows the installation of private networks. This is a very important feature. A farmer could for instance build an own network "within the boundaries" of the property in order to keep track of animals.

Additional information can be found in the LoRaWAN specifications and datasheets of LoRa transceivers [12,13].

IV. ENERGY ISSUES

LPWAN systems have been acclaimed as low-power systems. It is however important to understand what that means. Systems such as LoRa or Sigfox trade time for distance. The lower the data rate, the greater the transmission range. Since transceivers consume more energy during transmission, longer messages inevitably have a greater impact on the power consumption. For example, a Sigfox radio working at 3V and sending a 12 bytes frame at 100 bps with 45mA will require 3 * 2.08s * 3V * 45mA = 842mJ (see annex for transceiver energy data).

We have measured the energy requirement of a typical LoRa message sent with SF12. It requires more than 200mJ (Fig. 7). The difference with Sigfox is in part due to the fact that Sigfox uses redundancy (3 messages) and a lower data rate. The embedded system might need more energy, depending on the different activities required before and after the transmission. For instance, for initialisation of registers, stabilisation of clocks, calibration, control of sensor or actuator associated to the application… etc.

Fig.7 shows energy measurements made with a LoRa system. The energy consumption is plotted in function of the spreading factor and the packet size. Considering only the delivered payload, LPWAN energy requirements are about 10 times lower than those of 2G systems, but still about 1000 times higher than those of WPAN [17]. The (long) duration of the frame means that energy components need to be adapted consequently.

Some parameters of a transceiver SoC used for Sigfox are given in Fig. 6. Using the current values at +14dBm and the maximum size of a frame, we estimated the battery lifetime for different scenarios. The voltage varied between 3V and 2V, following the depletion of the batteries. We used the Battery Life

Links per day	UL=144 DL=0	UL=48 DL=0	UL=24 DL=0	UL=12	UL=1	UL = 4 DL = 4 OOB = 4 RX= 25 S
2 Alkaline AAA batteries						
12 Bytes +14 dBm	105 d	310 d	1.62 y	3 y	14.5 / 7 y	3.4 y
12 Bytes 0 dBm	260 d	2 y	3.7 y	6.3 y	18 / 7 y	4.4 y
2 Alkaline AA batteries						
12 Bytes +14 dBm	235 d	1.85 y	3.55 y	6.2 y	21 / 7 y	6.8 y
12 Bytes 0 dBm	556 d	4.25 y	7.3 / 7 y	11.6 / 7 y	24 / 7 y	8.8 / 7 y
Simulations results for Sigfox radio. Estimations were made using the Silabs battery life simulator. Typical values from the datasheet were used. 7 years is the guarantee limit given by the battery manufacturer. The battery life is calculated for different scenarios of UL/DL/OOB						

Estimator of Silabs. Simulations show that a battery life above 5 years (with alkaline AA or AAA batteries) is only possible in situations where a small number of uplinks is needed. Increasing the size of the batteries or using other batteries is possible and comes with weight, size, costs consequences.

There is more room for LoRa, since the energy consumption is lower. However, the probability of losing the frame might be higher. Applications requiring low latency and a certain level of reliability in the communication can be implemented in class B and especially class C. This comes at the cost of more energy [18] and makes the use of batteries for several years more difficult (virtually impossible in class C).

V. THROUGHPUT ISSUES

Both LoRaWAN (class A) and Sigfox can be considered to implement access mechanisms close to pure ALOHA. Devices send data when they want to, providing that the duty-cycle and the restrictions of your operator (the number of times per day you are allowed to transmit) are respected. There is no central element that "synchronises" the communication. Since devices can transmit when they want, there are bound to be collisions. If 2 or more devices try to send at the same time (within the time needed for a frame to be transmitted), there will be collisions. The question of the efficiency in the use of the medium therefore arises. It can be summarised as follows: How many of the frames that are generated and sent get through (the rest are lost through collisions)? The more frames are sent on a specific communication channel, the higher the probability of having collisions. The more devices are active (installed), the higher the amount of attempts to send frames will be. It does not matter much if a collision occurs at the beginning or at the end or middle of the frame. The colliding frames are usually lost. It is well known that the efficiency of an ALOHA scheme is about 18% when the network is fully utilised.

Several research groups have looked into this question, especially for LoRaWAN. Some of the conclusions are reported below.

Mikhaylov et al. analysed "*the Capacity and Scalability of the LoRaWAN technology*" [14]. Their conclusions.

"*To sum up, one can see that LoRaWAN technology, like any other, has its own strengths and weaknesses. Among the former ones can be noted the high coverage and satisfactory scalability under low uplink traffic. The most critical drawbacks are low reliability, substantial delays and potentially poor performance in terms of downlink traffic. Based on our analysis, we suppose that LoRa can be effectively utilized for the moderately dense networks of very low traffic devices which do not impose strict latency or reliability requirements. Among the possible example use cases are, e.g., non-critical infrastructure or environment monitoring applications.*"

Adelantado et al. looked into the limits of LoRaWAN [15]. This is what they conclude.

"*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.*"

Augustin et al. built a testbed to experimentally study the network performance of LoRa. They concluded that [16]:

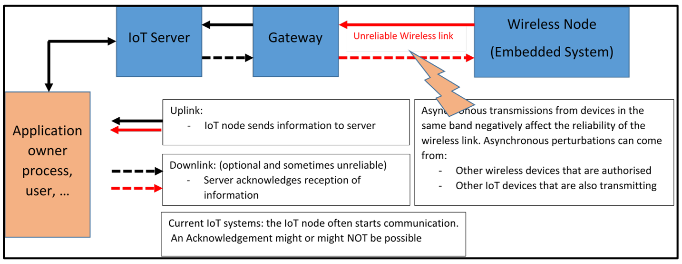
"*The results show that LoRa modulation, thanks to the chirp spread spectrum modulation and high receiver sensitivity, offers good resistance to interference. Field tests show that LoRa can offer satisfactory network coverage up to 3 km in a suburban area with dense residential dwellings. The spreading factor has significant impact on the network coverage, as does the data rate. LoRa is thus well suited to low-power, low-throughput and long-range networks. This paper has also shown that LoRaWAN is an LPWAN protocol very similar to ALOHA. Its performance thus degrades quickly when the load on the link increases.*"

VI. Interferences in the ISM Band

Systems that use the ISM band are in contention with other devices for the use of the transmission medium. Since the band is open to all, one should realistically expect uncontrolled activities that could lead to collisions. This is the case of the 868 MHz band that is used by LoRa and Sigfox (in Europe).

Using the unlicensed band saves some costs, but also has consequences. LPWAN technologies often target applications that should last for several years. So, the following questions are important. What are the possible interference sources in the course of the lifetime of the product? What are the consequences on the application? These points are worth thinking about. It is difficult to make predictions, since the band can be used by others. An application that works well at installation might become unreliable a few years later.

Some characteristics of the physical layers used in LoRa or in Sigfox certainly help mitigate some of these problems. The



enforcement of duty-cycle for every product in that band is also useful. However, there is still a factor of unpredictability and a potential for interferences that should be taken into account in certain application where reliability is key.

This is also highlighted in a study [2], from Vejlgaard et al. *"Interference Measurements in the European 868 MHz ISM Band with Focus on LoRa and SigFox"*. The contribution of their work was *"to measure the 868 MHz ISM band signal activity and power levels in Aalborg in five distinct locations; a shopping area, a business park, a hospital complex, an industrial area, and a residential area. The measurement analysis is specifically performed with focus on what the interference source may be and how the interference may affect LoRa and SigFox.*

Some of their conclusions are copied below.

"The measurement results have shown a very diverse utilization of the 868 MHz ISM band in Aalborg. In the shopping area and business park the general interference level is high and there is a number of devices, which transmit in the 868.0-868.6 MHz band with 22–33 % probability. This may be a significant issue, when considering a deployment of LoRa and/or SigFox to support the Internet of Things in downtown Aalborg, especially when taking into account the probability of collision due to transmissions from other SigFox and LoRa devices. However, the measurements have also showed that the hospital complex,

industrial area, and residential area have activity levels below 5 % within the band of interest. In addition, the potential downlink band 869.4-869.65 MHz is virtually unused except for the business park. This is a bit surprising since this bands allow for ERP of 0.5 W and 10 % duty cycle, and it should thus be a good candidate for long range or deep indoor transmissions."

Vejlgaard et al. intend to repeat the measurements, with equipment that is more appropriate. They also want to make sure that they are done nearer to gateways, in order to better match the uplink models of LoRa and Sigfox.

The small number of allowed downlinks hampers the use of acknowledgements to improve the reliability. Another obstacle is the fact that such ACK frames will use the same unreliable RF channels (sub-GHz unlicensed band).

VII. LATENCIES

There are different types of latencies. We will mention some of them in this section. We assume that the communication works in a reliable way.

Latency between an UL message and the requested DL frame. An object sends a message to the base station and requests a confirmation that the message has been received.

In the case of Sigfox, the DL frame window starts 20 seconds after the end of the first UL frame. The DL frame can be received in a window of 25 seconds + DL time. It means that the time between the message and the DL message varies between 20 and 45 seconds. See also reference [11].

In the case of LoRaWAN (class A) this is 2 seconds on top of the air time of the downlink frame.

Latency between an UL message and the time it is available for the application end point. An object sends a message. When will this message be available for the application?

In the case of Sigfox , there is a guarantee that "*98% of the messages are available as an output of the back-end (callback or API in less than 60 seconds.*" [11].

We do not have the values for LoRaWAN.

VIII. CONCLUSION

Research work done by several groups and by our own group show that there are important factors to be aware of before using some of the popular LPWAN technologies such as Sigfox and LoRaWAN. Those technologies fit well for very simple applications that are not too demanding on downlinks or reliability. In other cases, issues such as energy, reliability of the communication, throughput, energy, lifetime of the product need to be carefully considered.

ACKNOWLEDGMENTS

LoRa and Sigfox are registered trademarks of their respective owners.

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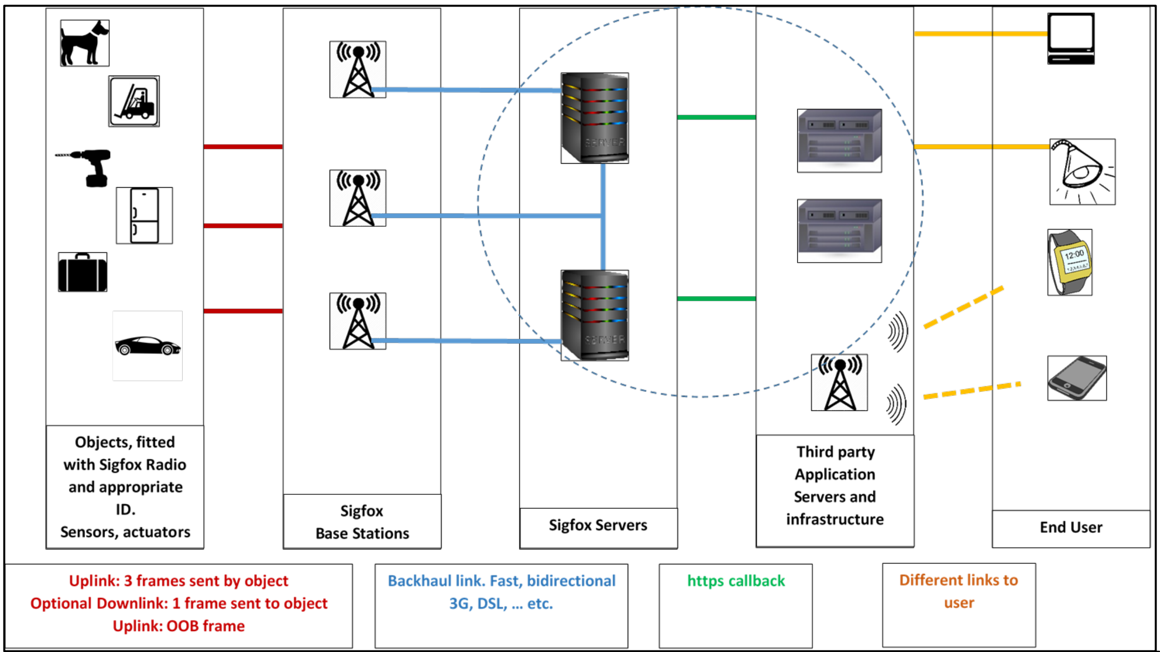


Fig.1. Components of a LPWAN IoT network (here with Sigfox).

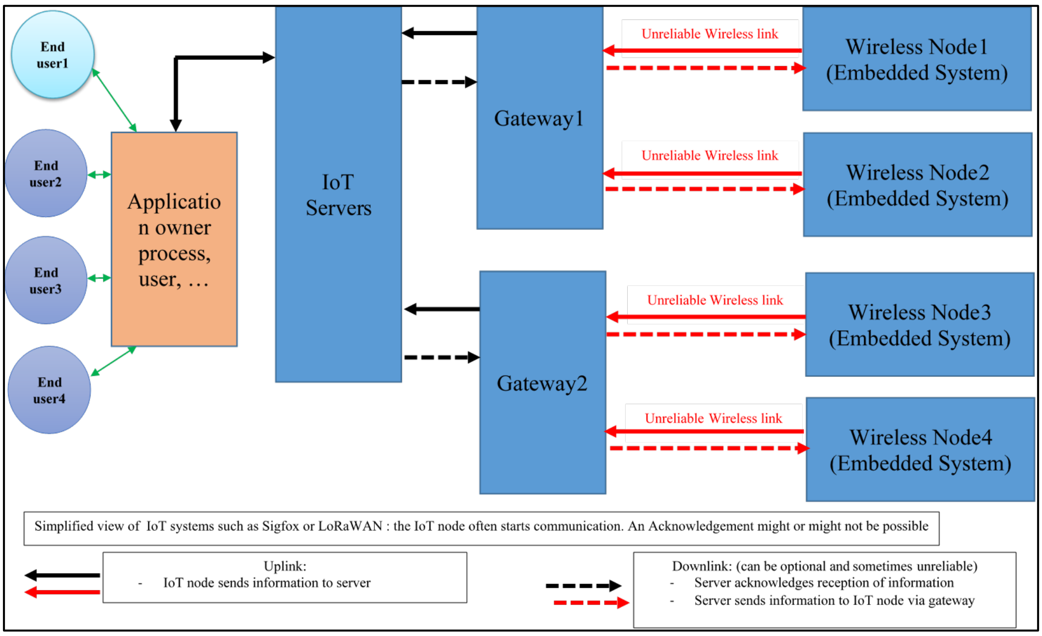


Fig.2. Simplified view of the network showing the wireless links as weak points

Radio Ctrl Field	Dest. Group Addr	Dest. Device Addr	Source Group Addr	Source Device Addr	Radio Stack Field	Payload: Sensor ID, Temperature, Humidity, Altitude and MCU restart flag
1 Byte	1 Byte	2 Bytes	1 Byte	2 Bytes	1 Byte	14 Bytes

Fig.3 Format of the transmitted LoRa frame

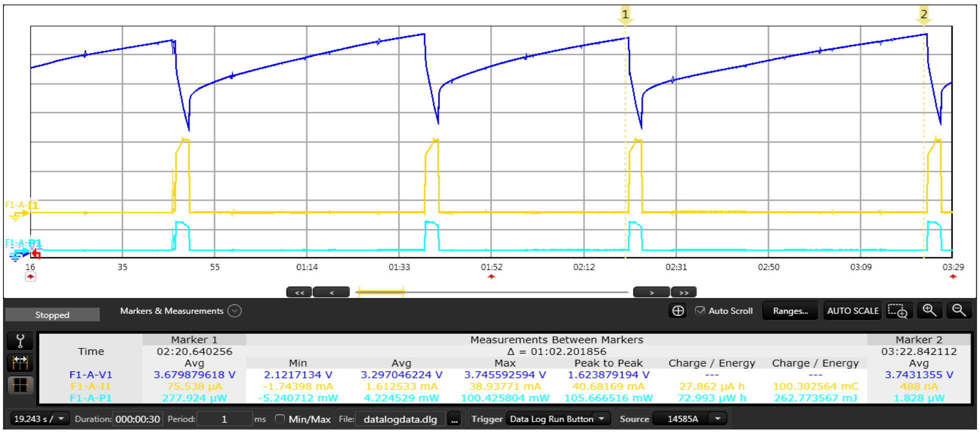


Fig.4 Example of power profile while transmitting data with a LoRa module. SF12 with +14 dBm. 262mJ needed. Storage voltage in blue. Current in yellow.

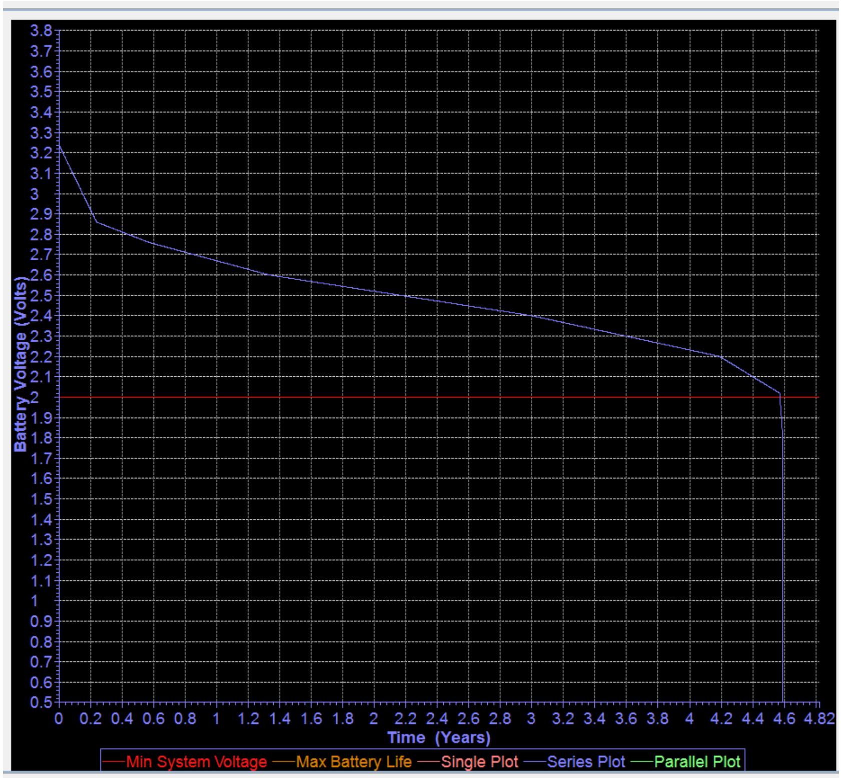


Fig.5 Battery lifetime of a Sigfox node, Transceiver of On Semi; output power 0dBm 4 activities per day with may payload; 6 secs UL + 1 DL+ 1 OoB frame; About 4.4 years between 3.3 volts and 2.1 volts (2 alkaline AAA batteries)

Example of a Sigfox RF transceiver: SoC AX−SIP−SFEU / AX−SIP−SFEU−API from On Semi
Reference: http://www.onsemi.com/pub/Collateral/AX-SFAZ-D.PDF

Current consumption:
Continuous radio RX−mode at 869.525 MHz: 14 mA
Continuous radio TX−mode at 868.130 MHz: 18 mA @ 0 dBm 45 mA @ 14 dBm
Deep sleep mode current is 100 nA (at room?)
Sleep mode current 1.3 uA

Receiver
- Carrier frequency 869.525 MHz
- Data rate 600 bps FSK
- Sensitivity −126 dBm @ 600 bps, 869.525 MHz, GFSK

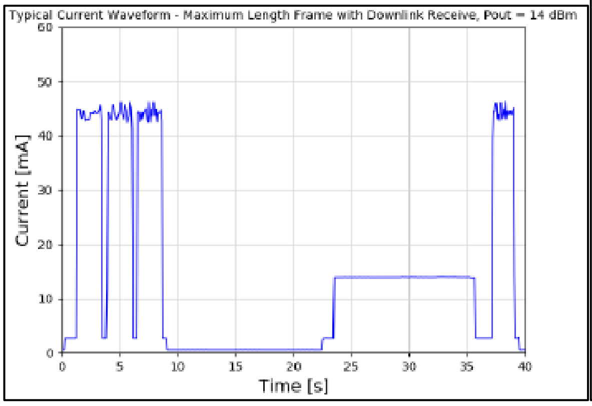
Transmitter:
- Carrier frequency 868.13 MHz
- Data−rate 100 bps PSK
- Maximum output power 14 dBm
- Power level programmable in 1 dBm steps

Typical charge estimations given by manufacturer at VDD=3V

Charge to send the longest possible Sigfox frame (12 byte), 14 dBm	0.30 C
Charge to send the longest possible Sigfox frame (12 byte) with downlink receive, 14 dBm	0.58 C
Charge to send a Sigfox out of band message, 14 dBm	0.26 C
Charge to send the longest possible Sigfox frame (12 byte), 0dBm	0.13 C
Charge to send the longest possible Sigfox frame (12 byte) with downlink receive, 0 dBm	0.35 C
Charge to send a Sigfox out of band message, 0 dBm	0.11 C

OOB messages, also called control messages, are transmitted periodically by devices. These transmissions are inherent to the Sigfox protocol stack. There exists two types of OOB messages: Status message and Downlink acknowledgement

Current profile and estimation of battery life: scenarios are from the manufacturer.



Battery Life Examples

Scenario 1:
- CR2032 coin cell battery
- One OOB frame transmitter per day at Pout = 0 dBm
- Device in Sleep
- Neglecting battery self−discharge

CR2032 capacity	225 mAh × 3600 s/h	810 C
Sleep charge per day	1.3 μA × 86400 s	0.11 C/day
OOB frame transmission		0.11 C/day
Total Charge consumption		0.22 C/day
Battery life		10 Years

Scenario 2:
- 2 AAA Alkaline batteries in series
- One OOB frame transmitter per day at Pout = 14 dBm
- Four maximum length frames with downlink receive per day at Pout = 14 dBm
- Device in Sleep
- Neglecting battery self−discharge

2 AAA alkaline capacity	1500 mAh × 3600 s/h	5400 C
Sleep charge per day	1.3 μA × 86400 s	0.11 C/day
OOB frame transmission		0.26 C/day
Frame transmission with downlink	4 × 0.58 C/day	2.32 C/day
Total Charge consumption		2.69 C/day
Battery life		5.5 Years

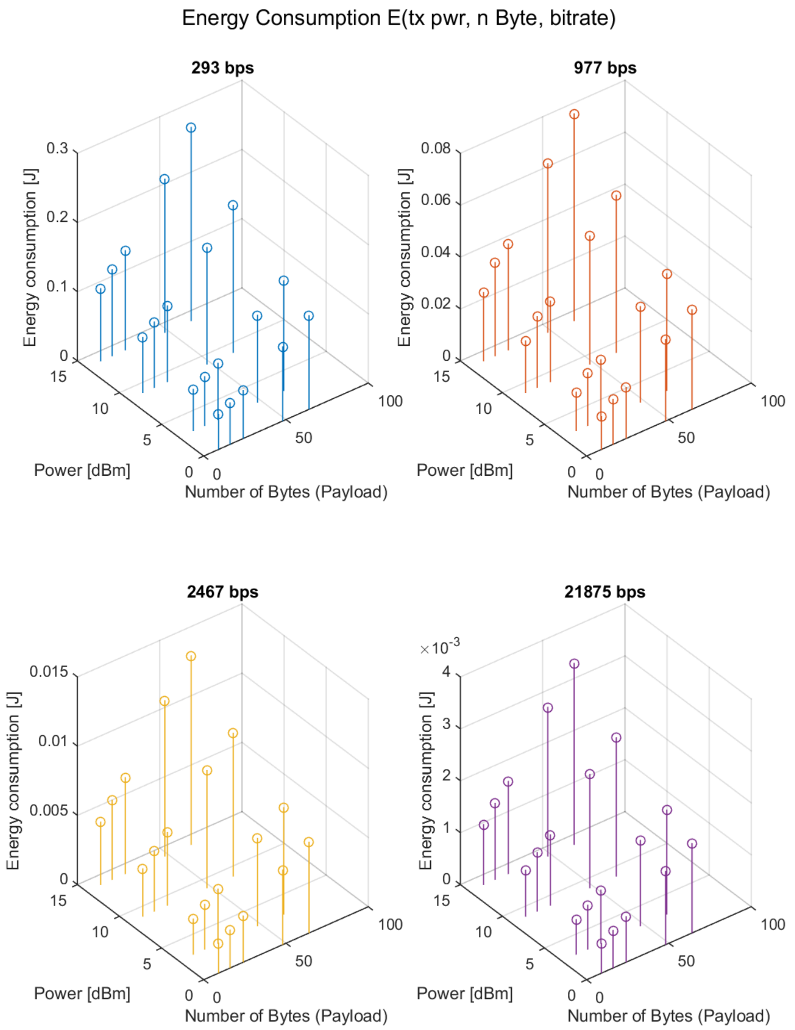


Fig.7 Energy consumption when sending frames of different sizes using LoRa at different baud rates.