LoRa: A Low-Power Wide-Area Network for the Internet of Things

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Seminar Report: Current Trends in Wireless Communications

Abstract

The Internet of Things (IoT) field is fast growing and already reaching and impacting the industry and consumer market. One of the main necessity for an IoT device is the network capability - a wireless network. As the requirements for wireless IoT networks are different and poses new challenges, a new class of wireless network was developed: the Low-Power Wide Area Networks (LPWANs). The offered data rate is significantly less compared to traditional networks, like cellular or WiFi, as LPWANs focus on a lower power consumption while maintaining a long range.

LoRa will be presented as an example for a LPWAN. The technical details and the protocol stack will be discussed. The focus is set towards the requirements, how they can be achieved and which compromises have to be made. Additionally, LoRa will be critical evaluated and the scalability will be discussed, as scalability is an important factor for the IoT.

Lastly, LoRa will be compared to two other technologies in the LPWANs group and the differences will be summarised.

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I. INTRODUCTION

Something which can be considered the third wave of Information Technology (after the Internet and Mobile Communications) is here: the Internet of Things (IoT). The IoT describes a network of objects which are connected to a network and can exchange data amongst other things, for example sensors. Currently there is an enormous growth of IoT devices, as they become less expensive and have a wide variation of applications, such as security, voice assistance, agriculture and more [1]. An essential part of IoT devices is the interconnection. A technology is needed to either interconnect the devices or connect them to a network - this can be a local one, or the Internet. Wired connections are not suited for the IoT, as IoT devices come in huge quantities and a wired connection is not flexible. Therefore, a lot of the current IoT devices for the consumer market, such as home automatisation, use existing technologies, like WiFi and Bluetooth because they have reached nearly all households.

However, there is a wide range of IoT applications and each IoT application has its own requirements. Accordingly IoT applications have different demands for the wireless network. IoT applications which are deployed outside to measure a wide variety of data, also need to be networked to share their data and be part of the IoT. WiFi, Bluetooth and even new emerging technologies like ZigBee, which is specially designed for the IoT, do not offer a long-range, as they are designed for local household networks. Traditional cellular technologies, like 2G, 3G and 4G, cover wider areas and allow the deployment in the open field, but this also comes at a cost: a service provider is needed which operates the cellular network [2].

Another constraint for IoT devices which are flexibly deployed in the open field are power constraints. As no power outlets are available, those device often run battery powered. This makes the usage of existing cellular technologies less appropriate because their power requirements are high, as they feature a complex design to offer reliability, but also enormous data rates. Anyhow, IoT devices often do not need a high data rate, especially not the same data rate, as a modern smartphone user nowadays requires. Smartphones today are used for video streaming or other data intensive applications.

Therefore a new range of protocols and technologies have emerged which fulfil the above mentioned requirements: low-cost, long-range while maintaining low-power consumption: the **LPWANs**.

This seminar report will first describe the requirements of LPWANs, introduce LoRa and discuss the technical details of LoRa. Furthermore LoRa will be evaluated and the scalability will be discussed. Lastly, LoRa will be compared to two other existing LPWAN technologies: NB-IoT and Sigfox.

II. LOW-POWER WIDE-AREA NETWORKS

Some people refer to LPWAN as the WiFi of IoT. WiFi has and had an enormous impact on consumer networking and is the de facto standard for wireless local area networking nowadays [3].

Figure 1 gives an overview of current wireless communication technologies and sorts them by the available data rate and the physical range. Current wireless technologies in the group of the *short range* are limited in their range, as most of them focus on device-to-device communication. The data rates differ in this group, but none of them focuses mainly on a high data rate. While WiFi and cellular technologies extend the range and also the data rate. Technologies in this group are used for modern general purpose communication, such as consumer computers and smartphones. However, this comes at the cost of more complex architecture and an increased power consumption.

IoT devices are not designed for general purpose computing - their application is specialised. This usually concludes, that there is no need for high data rates. To fill the gap and offer a networking solution which offers long-range, while maintaining low-power consumption and consequently offers a low data rate: LPWANs technologies were introduced.

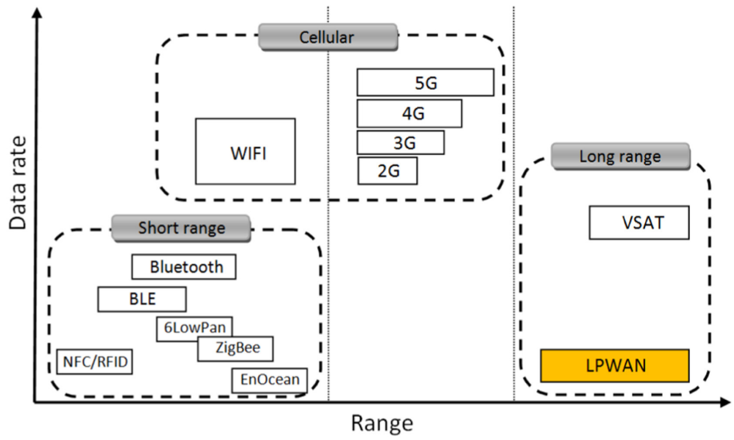

Fig. 1. Comparison of the range and the available data rate of different radio communication technologies (taken from [2])

According to [3], LPWANs focus on the following features:

- **Long-range:** Usage of gateways which cover a wide physical area. Compared to WiFi not every user needs to set up his own network, gateways of network operators can be used.
- **Low-data rate:** In a lot of IoT applications there is no need for high-speed data transfer, as often only sensor data gets transmitted. Therefore a low data rate is a consequence of long-range and low-power.
- **Low-power:** As IoT devices are usually deployed in the open field or in dynamic environments, they run on battery power. Therefore low-power consumption is one of the main requirements in LPWANs.
- **Limit activity level:** To further enhance the low-power consumption.
- **Cheap hardware:** IoT devices work together in networks and therefore come in huge quantities. Enabling cheap hardware costs is an important factor to lower the acquisition costs.
- **Localisation:** IoT applications and sensors can be embedded on moving objects, such as animals or vehicles. Therefore localisation allows to further decrease the cost, as a GPS module can be omitted.

As the listed requirements differ drastically to existing wireless solutions, the group of LPWANs was created and different protocols have emerged. In the following Section III, an example for an existing LPWAN technology will be introduced: **LoRa**.

III. LoRa Overview

LoRa is a LPWAN technology and the topic of this seminar report. LoRa is an abbreviation of Long-Range. It enables end-devices to power efficiently transmit and receive data at a low data rate.

LoRa was first developed in France by the start-up Cycleo in 2009. In 2012 it was purchased by the US semiconductor company Semtech. LoRa was standardised in 2015 by the founded non-profit LoRa Alliance [4].

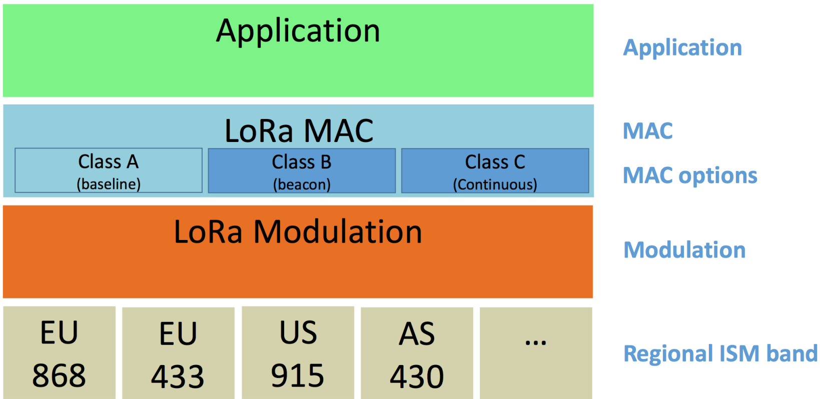

Fig. 2. LoRa Overview (taken from [5])

Figure 2 gives an overview of the LoRa technology. In the following Sections IV and V, the two layers of LoRa will be introduced. The report first discusses and introduces the basic network architecture behind LoRa.

A. *LoRa Network Architecture and Components*

A LoRa network consists of three network entities: the **end-devices**, **gateways** and a **network service**, as seen in Figure 3.

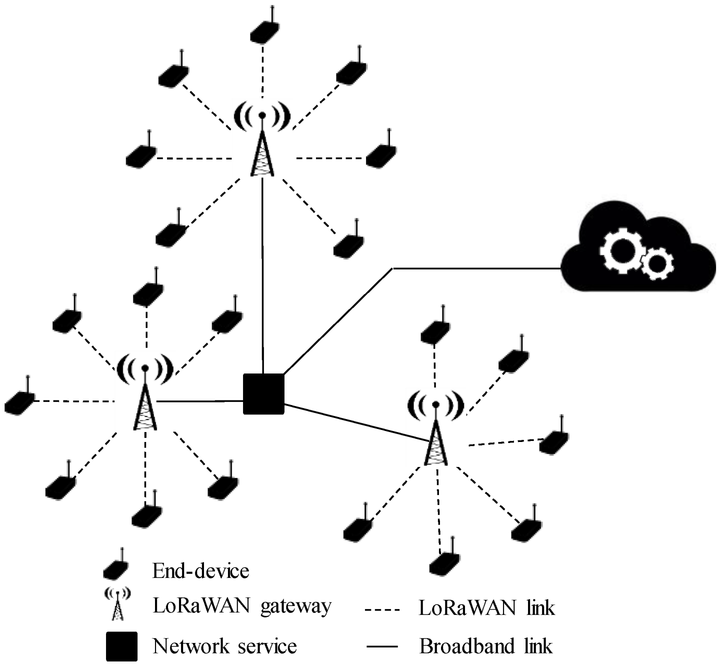

Fig. 3. LoRa star-of-stars topology (taken from [6])

The end-devices or end-nodes are the IoT devices. This can be an IoT device out of the wide variety of IoT applications. End-devices use the LoRa technology to communicate with the gateway. This is a single hop communication. Therefore the network topology of the end-devices and gateways is described as a *star of stars network* [6].

The gateway is an entity which does not belong to the group of IoT devices. It is connected to a power source and networked via traditional cellular technologies or wired via Ethernet which allows higher data throughput. The end-devices and gateway link is bidirectional, but due to power constraints on the end-devices, three different classes exist which enable three different receive mechanisms. They will be covered in Subsection V-A. The gateway supplies a certain area with coverage. There it acts as link-relay or protocol-convert which forwards the LoRa frames. The received LoRa message is simply forwarded by the gateway to the network service using traditional networking methods.

Messages transmitted by LoRa end-devices can be received by multiple gateways within their range, as the end-devices are not associated to a single gateway. This redundant reception improves the overall success rate. The gateways do not detect duplicate messages, this function is limited to the network server in the background. Therefore no handover mechanism is implemented. End-devices make use of the omnidirectional propagation and do not need a handover mechanism which assigns a specific gateway to a specific node [2]. Consequently, devices are not associated to a gateway, they are associated to a network server. This property can also be exploited for locating end-devices. With triangulation, end-devices can be located when base station have an accurate time synchronisation [2].

These gateways can either be private or public gateways. A LoRa network operator can deny the forwarding of end-device messages when the devices are unknown [1]. The community *The Things Network*[1] is an example for a public network [7].

As the gateways only forward the messages and do not process it, the data processing is up to the network server. The network server describes a typical server using existing and traditional technologies. Usually existing infrastructure, like cloud services, is used. The server is responsible for processing the data and all other implementations, for example storing the data in a database or triggering complex scenarios. This architecture of leaving the data processing to known infrastructure enables an easy implementation of LoRa into existing technologies and setups. Devices can be connected using traditional technologies, but also via LoRa. The data will be processed on the same server which allows a broad deployment.

An overview of the components of LoRa was given. In the next section, the details of the technology and the different layers to achieve the mentioned features will be covered.

IV. LoRa PHY

The physical layer of LoRa is proprietary technology which is not completely open accessible. At the moment Semtech is the only supplier for the radio chip, but the LoRa-Alliance has announced that additional microcontroller suppliers have intentions of manufacturing LoRa radio chips [4].

Some properties are found in the LoRa Specifications [5], while more detailed insights were found by the authors of [8] using reverse engineering. Using Software-defined radios (SDRs) the authors decoded the modulation technique and decoded the LoRa signal. An open-source implementation for GNURadio `gr-lora` was created.

LoRa operates in the sub 1 GHz ISM bands: 433-, 863-, or 915 MHz. The exact band depends on the region as they are different by each regulating government. The usage of a sub 1 GHz band is one of the factors which enable the coverage of a wide physical area. In Europe the 863 MHz ISM band is often used, using 3 channels of 125 kHz each. 3 channels

[1]The things network has more than 32.000 individuals participating in the project. The Netherlands and Berlin for example are already completely covered by LoRa gateways.

are used because LoRa uses a pseudo-random channel hopping to decrease the chance of collision [5].

As ISM bands are used, LoRa has to obey the regulations. In Europe the channels of the 863 MHz ISM band are usually restricted to a duty cycle of 1% or even 0.1%. When transmitting a frame for 1 ms, the next transmission has to wait 100 ms or 1,000 ms. The implications of the duty cycle will be covered in the LoRaWAN Section V and the Evaluation Section VII-A. The usage of ISM bands is a common theme in LPWAN technologies. The acquisition of frequency spectrum is cost intensive and this would limit the deployment and execution of gateways to network operators [9].

Therefore the frequency spectrum is chosen with long-range and low-cost in mind. To further enhance those requirements and enable low power consumption a specific modulation technique is used: Chirp Spread Spectrum (CSS)

A. *Chirp Spread Spectrum (CSS)*

Chirp Spread Spectrum (CSS) was originally designed and developed in the 1940s by the military for long communication distances. A chirp is a linear variation of the frequency in time. This linearity results, that frequency offsets are equivalent to timing offsets. Therefore they can be easily eliminated at the decoder. Additionally this also results in an immunity to the Doppler effect [9]. According to [9], an offset of up to 20% can be tolerated without impacting the encoding performance. This also results in a reduced cost of the transceiver devices, as the timing accuracy does not need to be perfect and cheap oscillators can be used. In Figure 4 a part of a LoRa frame is plotted with the linear frequency variation over the time. The preamble introduces an incoming LoRa frame.

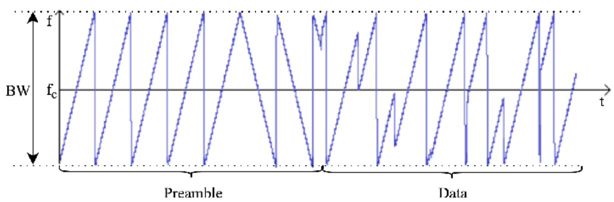

Fig. 4. Frequency over Time of a LoRa frame (taken from [9])

Some parameters can be customised to adjust the tradeoff between data rate and physical range: Bandwidth (BW), Spreading Factor (SF) and the Code Rate (CR). These parameters determine the available data rate, but also the robustness to interference, hence the range. LoRa PHY implements three available bandwidths to chose from: 125-, 250- and 500 kHz. The bandwidth sets the chirp rate: one chirp per second per Hertz of bandwidth. The spreading factor is an implementation of Code Division Multiple Access (CDMA) and therefore encodes the data for multiple communications. It separates the signals using orthogonal unique spreading factors. LoRa PHY implements six spreading factors (from SF7 to SF12). The higher the SF the longer the communication range, but a high SF results in a smaller data rate. The CR is introduced to enable error correction: $CR = \frac{4}{4+n}$ with $n = 1, 2, 3, 4$ [2], [8], [9].

Accordingly the bit rate can be calculated the following:

$$R_b = SF \times \frac{BW}{2^{SF}} \times CR \frac{bits}{second}$$

While this does not take the regulations of the MAC layer or the duty cycle of the ISM bands into consideration. A realistic evaluation is conducted in Section VII.

To enable a dynamic usage, an Adaptive Data Rate (ADR) is implemented. This adjusts the spreading factor based on a given Signal-to-noise ratio (SNR) limit. Consequently, LoRaPHY can achieve a sensitivity of up to -138 dBm [2].

Concluded, it can be said that CSS is a special modulation technique which improves the resilience and robustness against interference. The modulation technique focuses on robustness and simplicity, hence reduces the costs and enables a long range.

V. LoRaWAN

The LoRaWAN is the implementation of the second and third layer of the OSI model: data link layer and network layer. In contrast to the physical layer, this layer is an open standard which technical details are described in [5]. It is developed and maintained by the LoRa Alliance. Some details and the components of LoRaWAN were already covered in Section III.

This protocol was designed with long time intervals between messages in mind - usually hours, sometimes even days. Therefore certain non-traditional technologies were used because high frequent transmissions was not one of the design constraints. The choices were made to maintain the most important features, as low-cost and long-range [9].

The medium access is controlled in an Aloha like manner. When there is data to send, the end-device sends the data. If a collision is detected, the end-device will backoff and transmit later. A critical discussion about this MAC scheme will be conducted in Section VII-A.

LoRa has no mesh function or device-to-device communication. A device-to-device communication needs to detour via the networking service. There are two reason for this: First, device-to-device communication is only likely in specific IoT applications. A lot of IoT devices usually only measure and forward the data. Choices and controlling are passed to the network server, as this one has the complete overview. Second, mesh networking and device-to-device communication would create an additional overhead, as they need more complex routing and MAC algorithms. Especially the routing mechanism and receiving window needs to be adjusted which would increase the overall complexity, especially the power consumption.

As mentioned before, LoRaWAN offers a bidirectional communication. This is common for wireless consumer networks, but not all existing LPWANs offer bidirectional communication, due to the increased power consumption. To enable bidirectional communication while maintaining low-power consumption, LoRa groups end-devices into 3 different classes [5].

A. Classes

Listening for incoming data requires power as the receiver constantly listens and processes the incoming signals. In LoRa networks end-devices are distinguished into thee classes to enable a tradeoff between power consumption and latency. This is represented in Figure 5.

1) **Class A**: Class A end-devices only listen for incoming downlink transmission shortly after their own uplink transmission. Each uplink transmission is followed by two downlink receive windows. Therefore Class A end-devices have the highest available latency, but consume the least amount of power due to those harsh listening constraints.
2) **Class B** (beacon): Class B end-devices listen for incoming transmission at scheduled receive slots. To enable the scheduling of the receive slots, Class B end-devices receive a beacon from the gateway to enable time synchronisation.
3) **Class C** (continuous): Class C end-devices have a continuous receive window. This enables small latency but with increased and the highest power consumption.

Summarised the division in classes allows the developer to choose a class which fits the needs of its application or the need of an individual end-device [11]. To be compliant with the LoRa Alliance, the device needs at least to support Class A. Class B and C are optional [5].

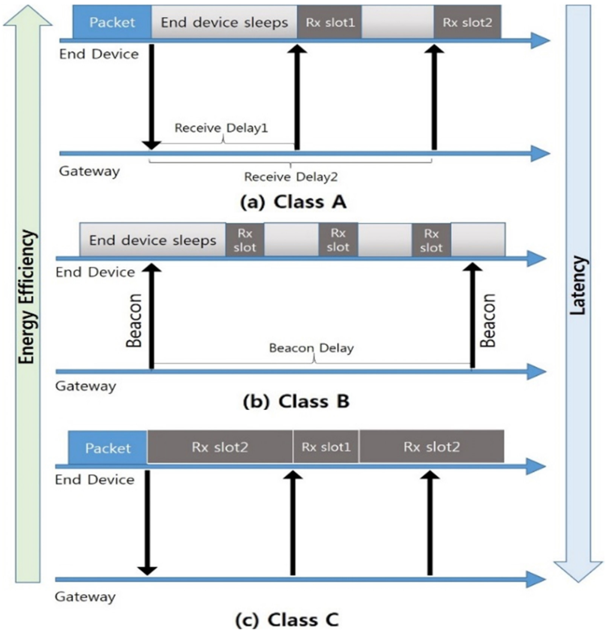

Fig. 5. LoRa Classes (taken from [10])

B. Message Format

As LoRaWAN includes its own two layers, also the message format is designed with the LPWANs requirements in mind. In Figure 6 the physical frame of LoRa is presented. Each LoRa message contains a preamble, an optional header and the payload which can be secured with a cyclic redundancy check (CRC).

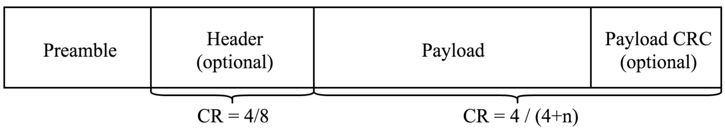

Fig. 6. LoRa PHY Frame (taken from [9])

The components of the PHY payload are displayed in Figure 7. The following list will explain the most important components and their function [5], [9].

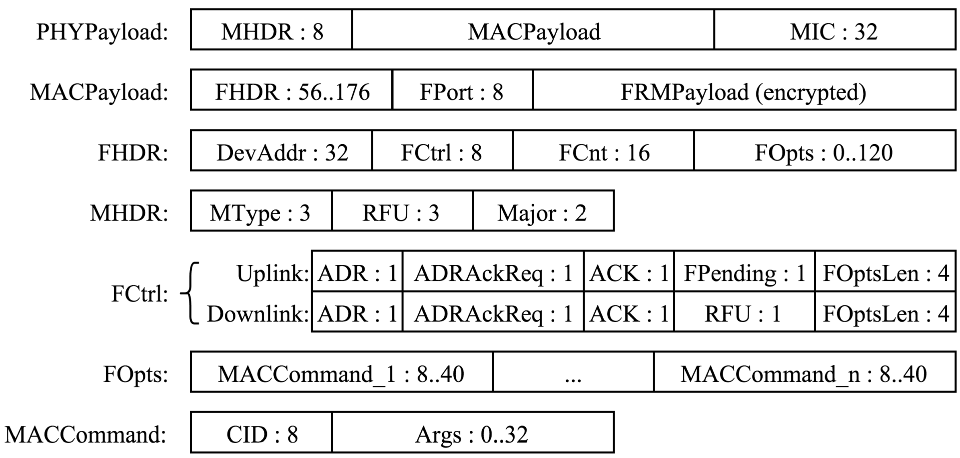

Fig. 7. LoRa MAC Frame (taken from [9])

- `MHDR`: MAC Header

  - `MType`: Message type: Uplink or downlink, confirmed or unconfirmed. If unconfirmed no need for ACKs.
  - `Major`: LoraWAN Version
- `MACPayload`
  - `FHDR`
    - `DevAddr`: 32bit address of the device - this is a unique identifier.
    - `FCtrl`: Frame control
      - `ADR and ADRAckReq`: Control the data rate adaption.
      - `ACK`: Acknowledges the last received frame.
      - `Fcnt`: Frame counter
      - `FPending`: Indicates additional data to send. This is handy in Class A, so the device sends and therefore opens another receive slot as soon as possible.
    - `Fcnt`: Frame counter
    - `FOpts`: MAC Commands - can be piggybacked on data message.
  - `FPort`: Multiplexing port field. If it equals 0 then only MAC commands payload.
  - `FRMPayload`: Encrypted payload using AES-128.
- `MIC`: Cryptographic integrity code computed over `MHDR, FHDR, Fport` and the encrypted `FRMPayload`

Compared to other protocols the LoRa MAC frame is a small frame which focuses on reducing the overall size while only maintaining the most important fields. For example, there is no destination address in the header of the MAC layer, as LoRa messages do not have a recipient because end-devices are not associated to gateways [5].

C. Security

To maintain integrity LoRaWAN implements two layers of cryptography. The 128-bit AES application session key `APPSKey` is shared between the end-device and the network server. This secures that the gateway operator cannot decode the payload of the message. The network session key `NwkSKey` is used for the validation of the message between the end-device and the network server [5] [9].

The details of the security mechanism are explained in a security whitepaper provided by the LoRa Alliance [12].

VI. Example Application

LoRa is commonly used in applications which are categorized under the term *smart city*. The company Libelium developed a smart parking sensor which uses LoRa. The device is mounted on the parking spot and features a waterproof case. It uses a dual detection system to detect a parked car. LoRa is used for wireless communication, that a network server can be notified about the current parking situation. This allows citizens to find parking spots easier and the city management to monitor and analyse car traffic. It is advertised with up to 10+ years of battery lifetime. However, this depends on the discussed parameters [13].

LoRa is a good wireless network solution for this application because it allows a power efficient usage and enables therefore the long battery lifetime. Additionally this application only sends minimum amounts of data which is well suited for LoRa.

Parameter	Value
TX Power	14 dBm (25 mW)
Frequency	868.1 MHz
RX gateway antenna gain	6 dBd
RX antenna polarisation	Vertical
RX antenna polar pattern	Omnidirectional
TX Device height above ground	2.5 m
RX sensitivity	-138 dBm to -123 dBm
RX antenna height above sea level	470 m
Terrain model	buildings/trees/ground etc.

TABLE I
LPWA COVERAGE ESTIMATION TABLE PARAMETERS (TAKEN FROM [1])

VII. LoRa Evaluation

In this Section, some theoretical, but also practical evaluations on LoRa will be presented. In [1] a theoretical analysis of the range and coverage of LoRa was conducted. The parameters from Table I were used. These parameters are all within the range of the European regulations and the RX sensitivity is realistic for LoRa devices using a high spreading factor. In this evaluation a theoretical gateway is installed at a height of $470\ m$ (on Three Rock mountain in Dublin). In the simulation, using the parameters from Table I, a core coverage area of $1380\ km^2$, which could be extended to $3800\ km^2$, was served. This theoretical model gives an overview about the coverage area of a LoRa gateway when it is deployed at an optimal location in a sub-rural area [1].

In [11] an indoor experiment was conducted. The network setup only included the minimum mandatory devices, one network server, one end-device and one gateway. The distance is ranging from $50\ cm$ to $60\ m$ on different floor levels. The authors evaluated LoRa in a building and tried to measure the impact by walls and floors. They concluded that due to the physical details of LoRa, the walls and floors do not have a huge impact. During a communication with the basement, the link quality was degraded. This was the only time, as the ground was thicker as usual, because the basement is used as a sparking space [11].

Concluded, LoRa's physical and MAC layer create a robust wireless network which is more robust to interference than traditional cellular technologies. Consequently, the range is extended and the number of necessary gateways is reduced.

A. Medium Access Control (MAC) & Duty Cycle Limitations

Figure 8 from [9] displays the capacity usage and collision rate depending on the load for one logical channel. As seen, the theoretical behaviour of LoraWAN is nearly similar to pure ALOHA. Once the channel load surpasses more than 50%, the capacity usage decreases dramatically.

However, this simulation does not apply to LoRa in practical. There a two additional factors which introduce an artificial MAC: random channel selection and the duty cycle regulations. LoRa always choses a random channel out of 3 available channels [5]. This decreases the collision rate dramatically.

As pointed out before, the usage of ISM bands is regulated by a duty cycle. The most common duty cycle in Europe is 1% - this reduces the transmission time significantly. The maximum transmission time with a duty cycle of 1% is 36 seconds per hour. Therefore, lots of devices are necessary to achieve a high channel load. In Figure 9 the random channel selection and duty cycle are taken into consideration. Using a low spreading factor also increases the resilience to collision. The simulation in Figure 9 used a bandwidth of 125 kH, six different

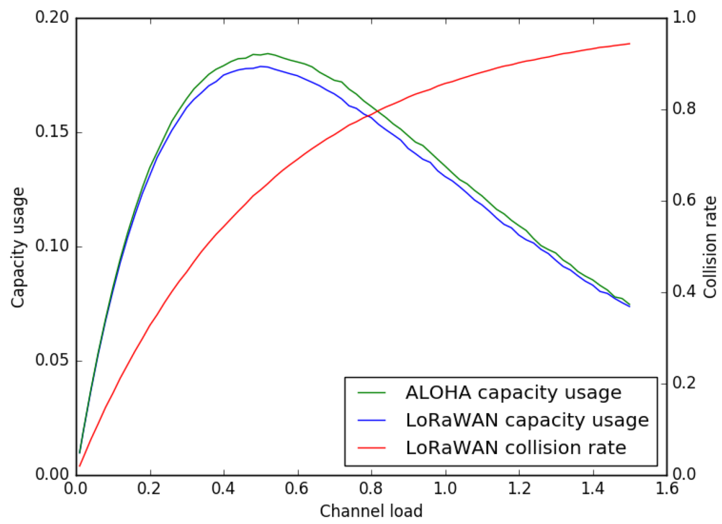

Fig. 8. Simulation of link capacity usage and packet collision rate for LoRa (taken from [9])

SF and 3 three channels, therefore a total of 16 logical channels. For ~1,000 devices per gateway the average throughput is ~6 times higher for LoRa than for pure Aloha [14].

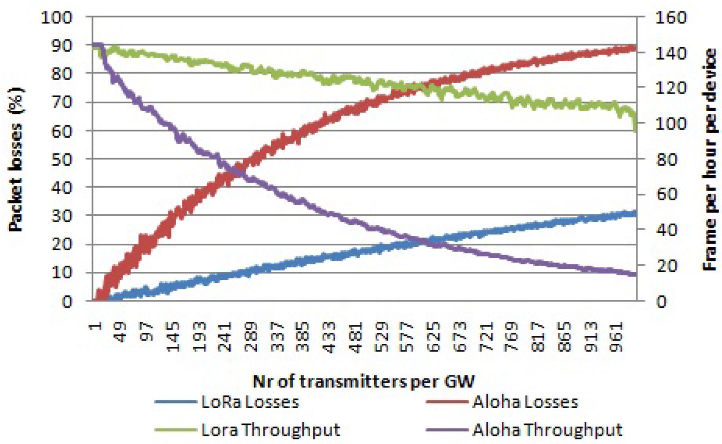

Fig. 9. Comparison between LoRa and pure Aloha in terms of percentage of packets lost and average throughput per device. Multiple channels, multiple SFs and payload size of 20 bytes (taken from [14])

Nonetheless, it should be considered that the presented scenarios are based on a very frequent transmission of data from end-devices - as frequent as the regulations allow. As stated before a lot of IoT applications require less than one message per day, so the scalability increases even more. Some examples for applications and the scalability for a duty cycle of less than 1% is presented in Figure II [14].

The authors of [14] conclude, that a single gateway could only support the *Traffic lights* application which is considered to have a total of 152 devices, but theoretically supported with up to 1,200 devices with the network losses not surpassing a 10% loss. For the *Home appliances* scenario only 8.45% could be served because a total of 1,7 million nodes are assumed. Compared to the traffic lights application, the message period is way smaller. Theoretically up to 150,000 home appliance devices could be supported by one gateway.

Therefore using a MAC protocol based on pure Aloha might seem like an obvious bad choice, but compared to other networking protocols, LoRa introduces multiple artificial MACs, like spreading factors, channel hopping and the duty cycle regulations. Aloha still is an easy to implement protocol which does not require the device to listen before transmitting - an

Applications	Transaction Mesage Period (s)	Payload Size (bytes)	Highest SF	No. of Nodes in 7 km Radius Cell in New York	No. of Nodes for Total Network Losses <10%	% of Nodes Served in One 7 km Radius Cell in New York
Home Security	600	20	12	591,773	~1400	0.24
Home appliances	86,400	8	12	1,775,319[1]	~150,000	8.45
Roadway signs	30.03	1	10	9340[2]	~650	6.95[2]
Traffic lights	59.88	1	11	152[3]	~1200	100[3]
Credit machine	120.48	24	12	32,049	~280	0.87

[1] average of 3 devices per house
[2] area reduced to 5.2 km, due to lower maximal SF
[3] area reduced to 5.5 km, due to lower maximal SF

TABLE II
LoRaWAN scalability for different IoT applications (taken from [14])

important property for the power efficiency. In the future a different protocol might be needed when the ISM band gets more crowded and the IoT market continues growing in the total number of devices. Displayed in Table II and Figure 9, the capabilities of a gateway is limited in the number of supported devices. A more complex MAC protocol might become necessary, especially when retransmitting a message surpasses the energy costs, than implementing a new MAC protocol which for example listens before transmitting.

VIII. COMPARISON OF LPWANS

LoRa is one example of a wireless networking technology which fits in the group of LPWANs. With the enormous increase of interest in the topic of IoT, other LPWANs technologies haven emerged. The following subsections will present two additional LPWANs and give a short overview of their differences.

A. Sigfox

Sigfox is a LPWAN technology, but also the operating company and therefore one of the network providers. It uses the unlicensed ISM bands, like LoRa does. A Binary phase-shift keying (BPSK) modulations in an ultra-narrow band of 100 Hz is used. This results in a maximum data rate of only 100 bps. The payload length is limited to 12 bytes. Each message is transmitted multiple times over different frequency channels to increases the resilience and the success rate. In the initial release Sigfox only supported uplink communication, but uplink communication was later integrated [2].

B. NB-IoT

Narrowband-IoT is developed by 3GPP which is a collaboration between groups of telecommunication standard associations. NB-IoT operates in the licensed LTE spectrum and uses a narrowband of 200 kHz. It is focused on indoor usage and low cost while maintaining a high connection density and lower power usage. It is based on the LTE protocol stack which is reduced to the minimum. Features like carrier aggregation, dual connectivity and measurements to monitor the channel quality are omitted. A transport layer is not part of NB-IoT, therefore conventional protocols, like TCP/IP, are used. A data rate of up to 200kbps for the downlink and up to 20 kbps uplink can be achieved, while the maximum payload size is 1600 bytes. OFDM modulation is used for downlink operation, SC-FDMA (Single Carrier Frequency Division Multiple Access) for uplink [10].

C. Comparison of LoRa, Sigfox and NB-IoT

In [2] the author lists the technical details of LoRa, Sigfox and NB-IoT. The following Table III is based on this and extended with further details.

The authors in [10] suggest that LoRa is better suited for IoT industry applications, like smart agriculture and logistics tracking. While NB-IoT, due to the higher data rate, better QoS and latency performance, might be better suited for personal IoT applications which are limited to one device per individual, like wearables or kids monitoring.

The three LPWANs are compared in terms of different IoT requirements in Figure 10. This figure therefore summaries Table III. LoRa enables a low cost deployment, as the gateways and end-devices are cheap to produce. However, in terms of latency and QoS the other LPWANs offer better technologies.

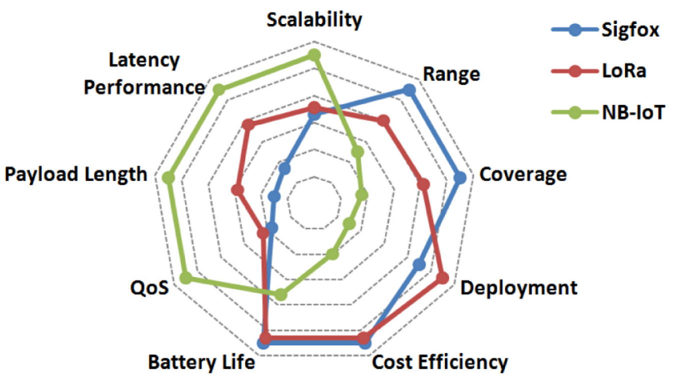

Fig. 10. Comparison of LoRa, Sigfox and NB-IoT in different IoT factors (taken from [2])

	LoRa	Sigfox	NB-IoT
Frequency	Unlicensed ISM bands	Unlicensed ISM bands	Licensed LTE frequencies
Modulation	Chirp Spread Spectrum (CSS)	BPSK	QPSK
Bandwidth	125 kHz & 250 kHz	100 Hz	200 kHz
Maximum data rate	50 kbps	100 bps	200 kbps
Bidirectional	Yes, half-duplex	Limited, half-duplex	Yes, half-duplex
Maximum payload	243 bytes	UL: 12 bytes, DL: 8 bytes	1600 bytes
Interference robustness	very high	very high	low
Encryption	AES-128bit	No	LTE encryption
Adaptive data rate	Yes	No	No
Handover	not associated to a single station	not associated to a single station	associated to a single station
Localisation	Yes possible via TDOA	Yes via RSSI	No
Private network	Yes	No	No
Sensitivity	-137 dBm	-129 dbM	*unknown*
Peak current	32 mA	49 mA [15]	120-300 mA
Sleep current	$1\,\mu\mathrm{m}$	$1.3\,\mu\mathrm{m}$	$5\,\mu\mathrm{m}$
Cost of gateway	100€ per gateway	4,000€ per base station	15,000€ per base station
Cost of end-device radio module	3 to 5€	less than 2€	more than 20€
Standardisation	LoRa-Alliance	Sigfox company collaborating with other companies	3GPP
Open Standard	Yes, partly	No	No

TABLE III
LORA, SIGFOX AND NB-IOT COMPARISON (TAKEN AND EXTENDED FROM [2])

IX. CONCLUSIONS

This seminar report has summarised the LPWAN protocol LoRa and discussed its technical details.

LoRa's PHY and MAC layer were specifically designed w.r.t. LPWAN requirements - low-power consumption, long-range and simple low-overhead implementation in some protocols. LoRa is already used in the industry and consumer market. The adaption is growing - regarding to [16] by 2022, LoRa will make up two-thirds of the LPWAN market. This is based on current trends, especially in Asia. One of the driving factors are the partly open source standards. NB-IoT and Sigfox are both proprietary implementations. Especially community projects like The Things Network [7] greatly promote LoRa, as it enables hobbyists and makers to deploy and join open gateways. Additionally Open Source and low costs plays a huge role in those communities. This is only possible, due to the usage of the ISM bands, otherwise individuals would not be allowed to deploy their own gateway.

The authors of [8] made the efforts of reverse engineering the LoRa physical layer. This increased the accessibility and an open source GNU Radio implementation was released. In the future this might play a role, as it might motivate the LoRa Alliance to open source their whole protocol stack. After all, this depends on a lot of economical factors - the first step for the LoRa Alliance is to attract more chip manufactures and therefore open the market.

Although LoRa has some shortcomings, most of them were conscious choices to reduce the overhead. This was pointed out in Section VII-A. LoRa performs well because of artificial MAC layers, such as the duty cycle, SF and the random channel hopping. More than 1000 devices can be served at a duty cycle of 1%. Using less frequent transmissions, even more devices can be supported by a single gateway. In the future performance might decrease, as the interest in LoRa and the unlicensed frequency bands, gain more attention due to the enormous growth in the IoT market, especially in the LoRa market.

Multiple LPWAN technologies exist on the market, some of them operate in unlicensed, some in licensed spectrums. Each solutions has its benefits and there is no *one solutions fits it all*. The usage depends on the applications. Therefore when designing an IoT device the requirements determine the network protocol. LoRa is the preferred LPWAN solution when cost efficiency and an open protocol stack is preferred, while compromises can be made regarding the latency and the Quality of Service (QoS).

X. Abbreviations

IoT	Internet of Things
LPWAN	Low-Power Wide Area Network
LoRa	Long-Range (*but also the technology itself*)
SDR	Software-defined radio
PHY	physical layer
CSS	Chirp Spread Spectrum
BW	Bandwidth
SF	Spreading Factor
CR	Code Rate
ADR	Adaptive Data Rate
SNR	Signal-to-noise ratio
CDMA	Code Division Multiple Access
CRC	cyclic redundancy check
BPSK	Binary phase-shift keying
UL	Uplink
DL	Downlink
TDOA	Time Difference of Arrival
QoS	Quality of Service

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