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Interference Impact on Coverage and Capacity for Low Power Wide Area IoT Networks

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***Abstract*—In this paper we analyze and discuss the coverage and capacity of Sigfox and LoRaWAN in a large scale urban environments covering 150 km^2 in Northern Denmark.**

First, the study measures and analyzes interference in the European 868 MHz license free industrial, scientific, and medical band, creating a model for the interference. The measured interference in downtown Aalborg has an occurrence rate of 22 % and a generalized extreme value distributed power level.

Next, the study compares the coverage of the two Internet of Things network solutions using the existing Telenor cellular site grid both with and without interference from the measured external sources. The study concludes that without interference, both LoRaWAN and Sigfox provides very good indoor coverage of more than 99 %. Furthermore, Sigfox and LoRaWAN can provide uplink and downlink failure rates of less than 1 % for the 95 percentile of the devices for all cells without external interference. Adding the external interference results in an outdoor coverage of 90-95 % and indoor coverage of 50-80 %. Finally, the uplink and downlink 95 percentile failure rate increases significantly to 50 % for LoRaWAN and exceeds 60 % for Sigfox.

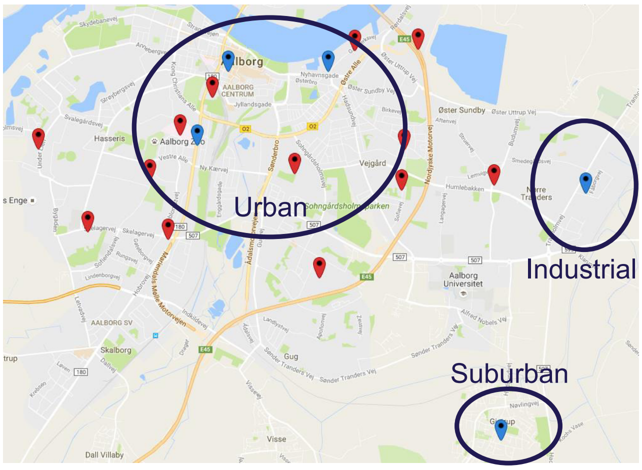

Fig. 1. Measurement locations for interference in the ISM band. Blue dot: measurement point, red dot: cellular site location.

I. Introduction

Low power wide area (LPWA) networks represent an evolution of networks targeted for the Internet of Things (IoT), which offers connectivity to various sensors and actuators. Unlike traditional mobile broadband networks these networks do not focus on offering high data rates and low latency, but rather on scalability, extended coverage, low cost, and energy efficiency for end user devices.

According to Cisco [1] there are already approximately 20 billion connected devices, and the estimate for 2020 is more than 50 billion connected devices. Not all devices are connected to a LPWA network but rather to local area networks such as Wi-Fi and Bluetooth low energy. However, the potential of LPWA networks is still very significant.

Today in most parts of the world, the main connectivity platform for IoT is the existing GSM/GPRS with its good coverage and low cost devices. An alternative solution to GSM/GPRS is the narrowband IoT (NB-IoT) network based on LTE standard. NB-IoT has been specified under 3GPP Rel. 13 [2] with the aim to offer IoT connectivity in a 200 kHz spectrum (on a single physical resource block) within the LTE system [2]. Besides cellular networks, IoT networks are also being deployed in the license free industrial, scientific, and medical (ISM) bands. Two of the most common IoT connectivity technologies being deployed in the ISM band are Long Range (LoRa) WAN [3] and Sigfox [4]. LoRaWAN is based on proprietary spread spectrum techniques and Gaussian frequency shift keying. Sigfox is an ultra-narrowband technology using differential binary phase-shift keying (DBPSK) with 100 Hz channel only. The license free ISM band can be used by anyone, but will have to deal with both internal and external interference, contrary to the licensed cellular spectrum utilized by e.g. GPRS and NB-IoT.

Since LPWA networks for IoT and their technologies are rather new they have not received much attention from the academic community yet. There are only a few papers available, and while they provide insight in the individual technologies they do not analyze the impact from external interference sources. Examples include the analysis of the basic performance of LoRa [5], [6], and NB-IoT [7].

The contribution of this paper is to analyze the coverage and capacity for Sigfox and LoRaWAN under the influence of external interference in the EU ISM band at 868.0-868.6 MHz. The analysis is based on the technologies' link budget, a new measurement-based interference model [8], the technologies' time on air, and a probabilistic modeling of the random access capacity and potential collisions.

To quantify the level of interference in the 868.0-868.6 MHz ISM band we carried out a measurement campaign in suburban, industrial, harbor, and downtown urban areas [8]. The measurements were made in Aalborg, Denmark at the loca-

TABLE I
TECHNOLOGY OVERVIEW.

	LoRa	Sigfox	
	UL & DL	UL	DL
Spectrum [MHz]	863-870	868.1-868.3	869.425-869.625
Tx power [dBm]	14-27	14	27
Modulation	Chirp spread spectrum	DBPSK	GFSK
Bandwidth [kHz]	125	0.1	0.6
Max payload [bytes]	51	12	8
Scheduling	Uplink initiated	Uplink initiated	

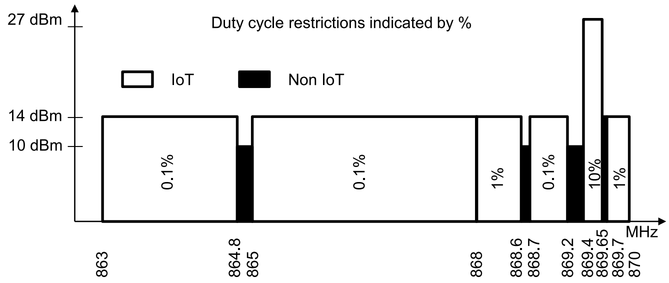

Fig. 2. 868 MHz EU ISM band power and duty cycle restrictions [9].

tions identified in Fig. 1. When evaluating the coverage and capacity of Sigfox and LoRaWAN LPWA networks Telenor's sub 1 GHz cellular grid in Northern Denmark was used as a realistic reference for site locations. The average intersite distance is ≤ 2 km and the sites are shown in Fig. 1.

The paper is structured as follows: In the next section the EU ISM band regulations and the two LPWA network technologies are analyzed, while the system level modeling and interference measurements are presented in section III. Next, the results are given in section IV followed by the conclusions in section V.

II. TECHNOLOGY OVERVIEW

This paper compares the coverage and capacity of Sigfox and LoRaWAN LPWA networks for IoT. Both communication systems are designed for and deployed in the ISM sub 1 GHz band. Different world regions provide different frequency bands for ISM and this paper addresses a deployment in the license free European 868 MHz band [9]. In this section the spectrum usage restrictions and the key properties of Sigfox and LoRaWAN are reviewed. Selected LPWA network properties are summarized in Table I.

The 868 MHz EU ISM band enables two basic mechanisms for sharing the spectrum; duty cycle restrictions or listen before talk (LBT). Both Sigfox and LoRaWAN use the duty cycle restrictions for access in the EU ISM band. Therefore, LBT access is not addressed in this paper. The duty cycle restriction varies within the ISM band from 0.1 % to 10 %, where the latter is only available for the 250 kHz band in 869.4-869.65 MHz, as illustrated in Fig. 2. Certain parts of the ISM band is pre-allocated to specific use cases such as alarms and voice systems, which are limited to a maximum radiated power of 10 dBm. The remaining parts of the ISM band allow a maximum radiated power of 14 dBm, while the aforementioned 250 kHz band may use 27 dBm [9].

A. Sigfox

The Sigfox network [4] is relying on Ultra-Narrow Band (UNB) modulation using DBPSK at 100 bps. Sigfox is based on a simple access scheme where the device initiates a transmission by sending three uplink packages, containing the same data, in sequence on three random carrier frequencies. The base station will successful receive the package even if two of the transmissions are lost due to e.g. collision with other devices or interference from other systems using the same frequency. Sigfox uses 868.1-868.3 MHz for uplink with a maximum radiated power of 14 dBm under the EU ISM band regulations [9].

The duty cycle of this frequency band is maximum 1 %, allowing the Sigfox device to transmit only 36 seconds every hour. With a time on air of 2 s per transmission that is 6 s in total for a single Sigfox package, this allows maximum 6 messages per hour with a payload of 4, 8, or 12 bytes [10].

Sigfox was initially designed without a downlink channel, but it has been added in the recent Sigfox standards [4]. The downlink channel uses Gaussian Frequency-Shift Keying (GFSK) with 600 bps in the frequency band 869.425-869.625 MHz. This ISM band allows a maximum radiated power of 27 dBm and a duty cycle of 10 % or 360 seconds per hour. The downlink payload is always 8 bytes and, depending on the Sigfox subscription, up to 4 downlink messages per day are allowed.

B. LoRaWAN

The LoRa LPWA solution consist of two major components, the LoRa physical layer specifications and the LoRaWAN which is the network protocol.

The LoRa physical layer is based on chirp spread spectrum with GFSK modulation and high bandwidth-time product (BT>1) to protect against in-band and out-band interference. LoRa provides 6 different spreading factors from 6 to 12. This enables multiplexing of different devices without causing performance degradations and reducing time on air. LoRa can operate in the entire EU ISM band but has three mandatory channels at 868.1, 868.3, and 868.5 MHz. The maximum LoRaWAN payload depends on the spreading factor and for the best protected channels it is limited to 51 bytes.

Both the Sigfox and LoRaWAN LPWA networks are based on a typical star protocol where each device communicates with a base station that relays the information to and from a central server via an IP based protocol. Each end user device can transmit any time, and the LoRaWAN devices using any data rate unless instructed otherwise by the base station. Finally, each end device needs to track the time spent for each transmission to observe the local spectrum regulations.

TABLE II
LINK BUDGET FOR SIGFOX AND LORAWAN.

Technology	**LoRa**		**Sigfox**	
UL/DL	UL	DL	UL	DL
Transmitter				
(1) Tx power [dbm]	14	14	14	27
Receiver				
(2) Thermal noise density [dBm/Hz]	-174	-174	-174	-174
(3) Receiver noise figure [dB]	3	5	3	5
(4) Occupied channel bandwidth [kHz]	125	125	0.1	0.6
(5) Effective noise power =(2) + (3)+(4)+10log((4)) [dBm]	-120	-118	-151	-141
(6) Required SINR [dB]	-20	-20	7	7
(7) Receiver sensitivity = (5)+(6) [dBm]	-140	-138	-144	-134
(8) MCL = (1)-(7) [dB]	**154**	**152**	**158**	**161**

III. SYSTEM LEVEL MODELING AND MEASUREMENTS

The analysis is based on a system level modeling where commercial site locations and a digital height map are implemented in a simulation tool to estimate the coupling loss between end user devices and base stations. The simulation method is aligned with the work described in [7]. Using the simulated coupling loss it is then determined whether the devices are in coverage or not based on the link budget, described in the following subsection. Next the time on air per device is calculated, based on the coupling loss, and finally the random access capacity is estimated based on the probability of the number of concurrent active devices. In the interference scenario the coverage is recalculated using the interference model, after which the time on air and the random access capacity estimates are also updated.

The analyzed area is the urban part of Northern Denmark covering 10 cities; in total 150 km^2 with 242.000 inhabitants [11]. The site locations are based on Telenor's commercially deployed cellular network. All 2G, 3G, and 4G sites with sub 1 GHz carriers are used to simulate the Sigfox and LoRaWAN networks, but on the contrary to the cellular deployment all sites only have one omni directional antenna. The simulated area is divided into 100m x 100m pixels with an average density of 16 people per pixel that is 1600 people per km^2.

The applied channel model is the Urban Macro NLOS model [12]. Furthermore, shadow fading with a log normal distribution of 6 dB is added to the simulated path loss [12].

The traffic model assumes 1 IoT device per person, that is the IoT spatial density follows the people density. The traffic per device is modeled as uplink originated traffic of 10 bytes/hour with an uniformly distributed transmission time. Therefore, one Sigfox or LoRa message is sufficient to transfer the payload.

A. Maximum Coupling Loss (MCL)

The next step in the system level evaluation is to compare the simulated coupling loss with the technologies' maximum coupling loss (MCL) to determine whether the devices are covered. The MCL is shown in Table II based on [13].

B. Time on air

The time on air is constant for Sigfox, which uses 2 s per message [10]. LoRaWAN uses link adaptation and thus the time on air varies from 22 ms to 860 ms depending on the coupling loss [14]. The LoRaWAN is deployed using the three mandatory channels with 125 kHz bandwidth in the 868.0-868.6 MHz EU ISM band with duty cycle of 1 % [9].

C. Random access capacity

Sigfox and LoRaWAN are not scheduled systems, but rather transmits the uplink packets in a random time and channel. This contention-based method is known as the pure Aloha access scheme [15]. The probability p of having zero transmission attempts from other devices coincide with a device's own transmission, and thus resulting in a successful transmission in the pure Aloha access method is:

$$p = e^{-2 \cdot G} \tag{1}$$

where G is the mean number of transmission attempts per time frame according to a Poisson distribution. In the simulations the mean number of transmissions per hour is based on the time on air per device, the number of devices per specific site, and the number of channels per technology. Note that slotted Aloha access is used in downlink because the transmissions from a single base station are scheduled.

As mentioned earlier, Sigfox transmits the same package in three attempts on random and independent uplink channels. Each attempt can either be received successful or not. Thus the reception of a Sigfox uplink package can be modeled as a Bernoulli trial with a binomial distribution. The probability P, of receiving at least one of three Sigfox transmissions correctly, is therefore modeled as a sequence of three Bernoulli trials:

$$\begin{aligned} P\left(X>0\right) &= P\left(X=1\right)+P\left(X=2\right)+P\left(X=3\right) \\ &= 1-P\left(X=0\right) = 1-\binom{n}{X} p^{X}\left(1-p\right)^{n-X} \\ &= 1-\binom{3}{0} p^{0}\left(1-p\right)^{3-0} \end{aligned} \tag{2}$$

where the probability of a successful transmission using the Aloha scheme is p, defined in Eq. 1, X is the total number of successful transmissions from the specific device and n is the number of trials, which is three for Sigfox.

D. Interference

The license free ISM band allows many different types of devices to access the spectrum as long as they obey the regulations [9]. Therefore the level of interference between the different radio access technologies may be significant and thus harmful to successful operation of e.g. LoRaWAN and Sigfox. To study this issue, interference measurements have been carried out in Aalborg, Denmark in the five locations identified in Fig. 1, which include suburban, industrial, harbor, and downtown urban areas. The measurements were made in a stationary position for 2 hours at each location during normal

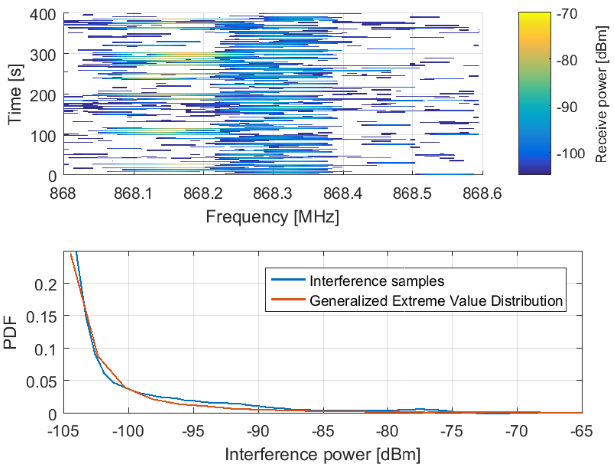

Fig. 3. Interference measurement result and modeling of the mandatory LoRaWAN and Sigfox band (868.0-868.6 MHz).

working hours and covering the 863-870 MHz ISM frequency band. The measurements were made with a Rohde & Schwarz TSMW radio network scanner [16] using a resolution of 7 kHz by 200 ms per sample. Each sample is referred to as an interference unit in the following. For further details on the measurement campaign refer to [8].

The measurement in urban Aalborg in the mandatory LoRaWAN and Sigfox 868.0-868.6 MHz frequency band shows that interference occurs frequently and with high power as illustrated in the top plot of Fig. 3. Interference units (7 kHz by 200 ms samples) stronger than -105 dBm occur in 22 % of all samples and with a maximum recorded interference power level of approximately -65 dBm. In order to include the interference in the coverage and capacity estimates the interference is modeled with a uniformly random occurrence rate of 22 %. When an interference sample is generated its power level is modeled by a generalized extreme value distribution [17] as illustrated in the lower plot of Fig. 3.

The impact on receiver performance will be different from LoRaWAN and Sigfox as the systems apply different mechanisms to combat the interference. As mentioned earlier, LoRaWAN utilizes a spread spectrum technique to spread the interference in the received band and minimize its impact. Sigfox on the other hand transmits each data package in uplink three times on different frequencies to maximize the probability of receiving at least one packet successful. However, for both systems, the impact on the signal to interference + noise ratio (SINR) can be modeled as:

$$S_{\mathrm{Rx}} = \frac{S_{\mathrm{Tx}} - L}{N + I} \tag{3}$$

where S_{RX} is the received SINR [dB], S_{Tx} is the transmitted power [dBm], L is the coupling loss [dB], N is the effective noise power from Table II [dBm] and I is the modeled interference [dBm]. Note the SINR model of Eq. 3 applies to both uplink and downlink.

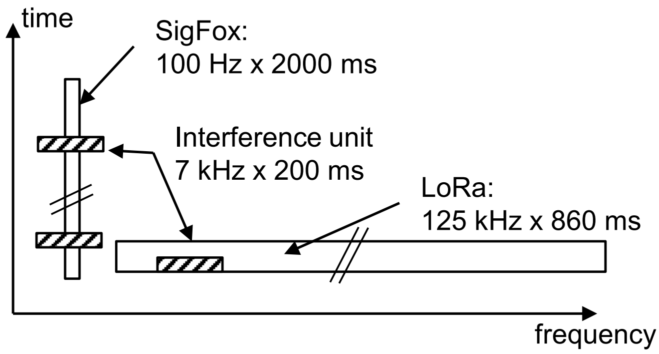

Fig. 4. Interference model and scaling of Sigfox and LoRaWAN systems. Note that most LoRa messages are shorter than 200 ms.

The measured interference unit (7 kHz by 200 ms) is wider in frequency than a Sigfox burst and significantly shorter in time as illustrated in Fig. 4. Therefore, multiple interference units, following each other in the time domain, may impact a Sigfox transmission. Likewise, the LoRaWAN burst is significantly wider in frequency and thus multiple interference units, parallel to each other in the frequency domain, may impact a LoRaWAN transmission as illustrated in Fig. 4.

The probability of interference $P\left(i > 0\right)$ is modeled with a binomial distribution, similarly to Eq. (2), where i is the number of interference units within the Sigfox or LoRa signal. The probability of interference is determined as the complement of the probability of all Bernoulli trials not resulting in interference $\left(P\left(i = 0\right)\right)$. The number of trials is based on the relationship between the interference unit and the time-frequency domain allocation of Sigfox and LoRaWAN transmissions:

$$P_{\mathrm{LoRa}}\left(i > 0\right) = 1 - \binom{\frac{125\,\mathrm{kHz}}{7\,\mathrm{kHz}}}{0} p_i^0 \left(1 - p_i\right)^{\frac{125\,\mathrm{kHz}}{7\,\mathrm{kHz}} - 0} \tag{4}$$

$$P_{\mathrm{Sigfox}}\left(i > 0\right) = 1 - \binom{\frac{2\,\mathrm{s}}{200\,\mathrm{ms}}}{0} p_i^0 \left(1 - p_i\right)^{\frac{2\,\mathrm{s}}{200\,\mathrm{ms}} - 0} \tag{5}$$

where the probability p_i is the occurrence rate of the interference unit (22 %). In most cases the LoRaWAN signal is shorter than the 200 ms interference unit and therefore the time domain probability is not included in the number of trials in Eq. (4). Similarly the Sigfox signal is much narrower than the 7 kHz interference unit and thus not included in the number of trials in Eq. (5).

If interference occurs the interference power I [dBm], applied in Eq. (3) and based on the generalized extreme value distribution in Fig. 3, is scaled according to the ratio between the interference unit and the radio signal as follows:

$$I_{\mathrm{LoRaWAN}} = I_{\mathrm{gev}} + 10 \cdot \log_{10}\left(p_i \cdot \frac{125\,\mathrm{kHz}}{7\,\mathrm{kHz}} \cdot ISF\right) \tag{6}$$

$$I_{\mathrm{Sigfox}} = I_{\mathrm{gev}} + 10 \cdot \log_{10}\left(\frac{100\,\mathrm{Hz}}{7\,\mathrm{kHz}}\right) \tag{7}$$

where I_{gev} is the base interference power level [dBm], drawn randomly from the generalized extreme value distribution

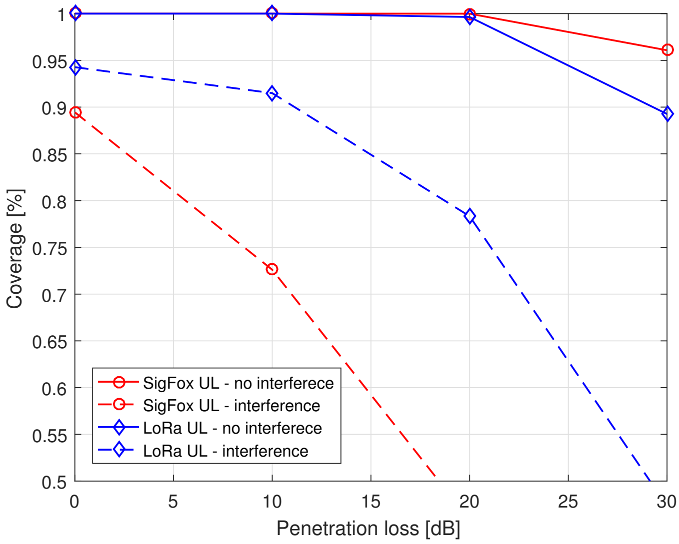

Fig. 5. Uplink coverage relative to penetration loss with and without interference.

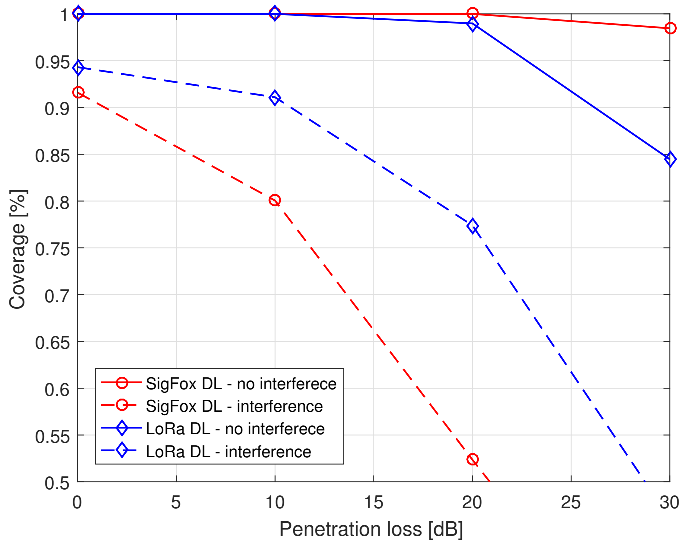

Fig. 6. Downlink coverage relative to penetration loss with and without interference.

in Fig. 3, and ISF is the interference spreading factor of LoRaWAN, which is $7\,\mathrm{kHz}/125\,\mathrm{kHz}$ because the interference unit's power is spread across the LoRaWAN signal. Furthermore, the LoRaWAN interference is scaled with the average number of interference units: $0.22 \cdot 125\,\mathrm{kHz}/7\,\mathrm{kHz} = 3.93$ to include the possibility of having more than one interferer during the transmission. The Sigfox interference is calculated for uplink (100 Hz signal) and the average number of interference units is not included, because it is assumed that a collision with just one interference unit will result in a failed transmission provided that the SINR is less than the requirement of Table II. In downlink the 600 Hz wide Sigfox signal would change the scaling accordingly.

IV. Results

In this section the simulation results are presented. They are based on the path loss estimates for the urban areas of Northern Denmark, combined with the MCL and time on air of Sigfox and LoRaWAN. The path loss calculations are made for outdoor positions, but additional losses of 10, 20 and 30 dB are added to account for outdoor-to-indoor penetration losses in buildings [7]. Finally, the modeled interference is included to determine the impact on coverage and capacity,

A. Coverage

The estimated Sigfox and LoRaWAN uplink coverage in the urban areas of Northern Denmark is illustrated in Fig. 5. Both technologies provide more than 99 % coverage for up to 20 dB indoor penetration loss when interference is not included as illustrated with the solid lines. For deep indoor coverage (penetration loss of 30 dB) Sigfox provides 96 % coverage and LoRaWAN 90 % coverage under ideal conditions without interference. Including the interference from external sources, as modeled in the previous section, reduces the coverage area as shown with dashed lines in Fig. 5. Sigfox only covers 90 % of the outdoor area while LoRaWAN provides 95 % coverage. According to the modeling Sigfox is more sensitive to interference than LoRaWAN as LoRaWAN uses spread spectrum techniques. Even though Sigfox transmits three times on random frequencies each Sigfox message is likely to collide with interference units during the transmission. For indoor coverage (20 dB penetration loss), the impact from interference is even worse as the link budget is reduced and LoRaWAN has 78 % coverage and Sigfox less than 50 % coverage.

Fig. 6 shows the coverage of Sigfox and LoRaWAN in downlink. The observations are similar to those made for uplink in Fig. 5, but Sigfox performs slightly better in downlink due to the higher transmit power of the base station (27 dBm vs 14 dBm according to Table II).

B. Capacity

The uplink failure rate is shown in Fig. 7 for both LoRaWAN and Sigfox. Without interference (solid lines) both Sigfox and LoRaWAN are able to provide one 10 byte message every hour per devices for both indoor (20 dB indoor penetration loss) and outdoor locations with 95 percentile uplink failure (combination of collision and lack of coverage) less than 1 %.

Including the external interference (dashed lines) the LoRaWAN outdoor devices have a 95 percentile uplink failure of about 7 % while Sigfox has an uplink failure rate of 17 %. For the indoor deployment LoRaWAN has 95 percentile uplink failure rate of 50 % while Sigfox has an uplink failure rate of more than 60 %.

Fig. 8 shows the capacity of Sigfox and LoRaWAN in downlink. Generally, the downlink failure rate is similar to uplink in Fig. 7, but again Sigfox performs slightly better in downlink due to the higher transmit power.

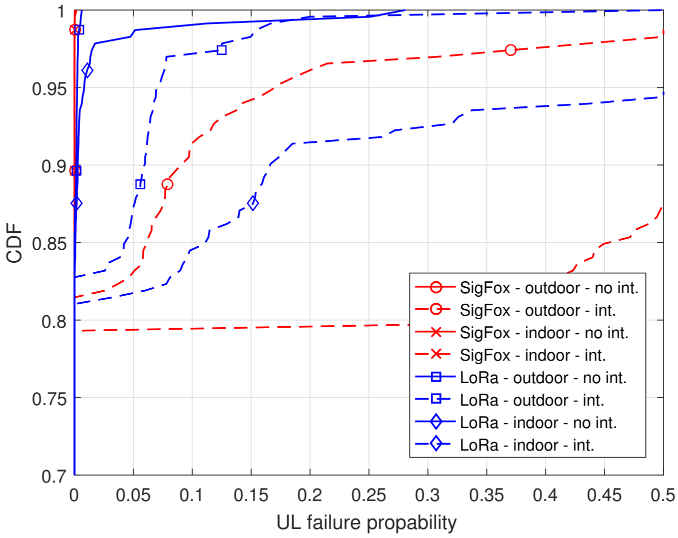

Fig. 7. CDF of the total uplink failure from random access collision and coverage limitations. The penetration loss is 20 dB for indoor devices.

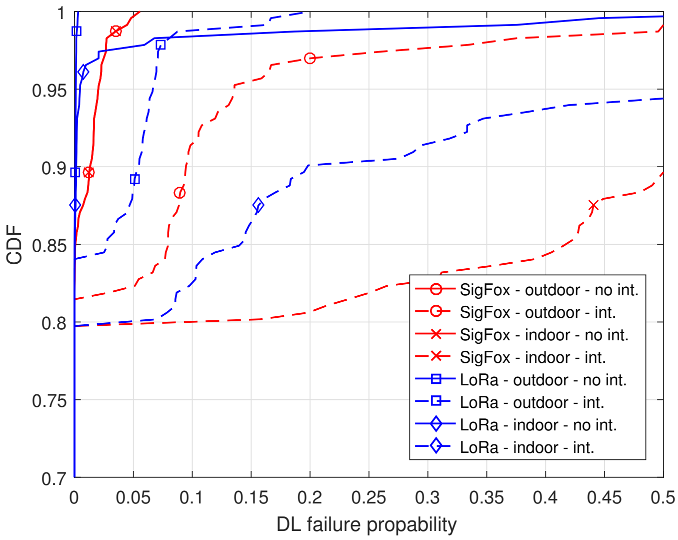

Fig. 8. CDF of the total downlink failure from blocking and coverage limitations. The penetration loss is 20 dB for indoor devices.

V. Conclusion

This paper analyses coverage and capacity for Sigfox and LoRaWAN in a deployment scenario, based on real operator site locations, covering 150 km^2 of urban areas in Northern Denmark. Both LoRaWAN and Sigfox show very good performance, in the initial interference-free scenario, with indoor coverage of more than 99 %. Furthermore, both Sigfox and LoRaWAN can provide 95 percentile uplink and downlink failure rates of less than 1 % for all cells, when each device transmits 10 bytes/hour.

The interference level in the 868.0-868.6 MHz EU ISM band, utilized by Sigfox and LoRaWAN, is measured in downtown Aalborg. Interference powers stronger than -105 dBm occur with a probability of 22 % and the power level is fitted to the generalized extreme value distribution. Adding the measured and modeled external interference to the simulations results in an outdoor coverage reduction of up to 10 % points and an indoor coverage reduction of 20-50 % points. The indoor uplink and downlink 95 percentile failure rates increase significantly under interference, exceeding 60 % for Sigfox in both uplink and downlink. LoRaWAN provides a failure rate of about 50 % for both uplink and downlink indoor devices.

The level of interference in the 868 MHz EU ISM band is expected to grow with the deployment of several wireless IoT solutions not limited to Sigfox and LoRaWAN. Therefore, it will be difficult to provide reliable and predictable communication, with wide area coverage and capacity, in the 868 MHz EU ISM band due to the frequent and significant level of external interference.

Based on this study further work is needed for uplink and downlink interference mitigation in urban areas.

Acknowledgment

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References

[1] Cisco, “Embracing the Internet of Everything,” White paper, 2016.

[2] Nokia, “LTE-M Optimizing LTE for the Internet of Things,” White paper, 2015.

[3] N. Sornin and M. Luis and T. Eirich and T. Kramp and O.Hersent, “LoRaWAN Specification,” 1 2015. [Online]. Available: v1.0

[4] SigFox, Accessed Jan. 4 2017. [Online]. Available: https://www.sigfox.com/

[5] K. Mikhaylov, J. Petaejaejaervi, and T. Haenninen, “Analysis of Capacity and Scalability of the LoRa Low Power Wide Area Network Technology,” in *European Wireless*, May 2016, pp. 1–6.

[6] F. Adelantado, X. Vilajosana, P. Tuset-Peiró, B. Martínez, and J. Melià, “Understanding the limits of LoRaWAN,” *CoRR*, vol. abs/1607.08011, 2016. [Online]. Available: http://arxiv.org/abs/1607.08011

[7] M. Lauridsen, I. Kovacs, P. Mogensen, M. Sørensen, and S. Holst, “Coverage and Capacity Analysis of LTE-M and NB-IoT in a Rural Area,” in *VTC Fall*, 9 2016.

[8] M. Lauridsen, B. Vejlgaard, I. Kovacs, H. Nguyen, and P. Mogensen, “Interference Measurements in the European 868 MHz ISM Band with Focus on LoRa and SigFox,” in *Wireless Communications and Networking Conference*, 3 2017.

[9] ETSI, “Electromagnetic compatibility and Radio spectrum Matters; Short Range Devices; Radio equipment to be used in the 25 MHz to 1 000 MHz frequency range with power levels ranging up to 500 mW; Part 1,” ETSI EN 300 220-1 V2.4.1, 1 2012.

[10] Libelium Comunicaciones Distribuidas, “Waspmote Sigfox Networking Guide,” 1 2015. [Online]. Available: v4.1

[11] Wikipedia, “Region Nordjylland,” Accessed Jan. 4 2017. [Online]. Available: https://en.wikipedia.org/wiki/North_Denmark_Region

[12] 3GPP, “Further advancements for E-UTRA physical layer aspects,” TR 36.814 V9.0.0, 3 2010.

[13] ——, “Cellular system support for ultra-low complexity and low throughput Internet of Things,” TR 45.820 V13.1.0, 11 2015.

[14] Semtech, “SX1272/3/6/7/8: LoRa Modem Designers Guide,” AN1200.13, 7 2013.

[15] N. Abramson, “The ALOHA System: Another Alternative for Computer Communications,” in *Proceedings of the November 1970, Fall Joint Computer Conference*, ser. AFIPS ’70 (Fall). ACM, 1970, pp. 281–285.

[16] Rohde & Schwarz, “TSMW Universal Radio Network Analyzer,” Product brochure v.14.00, 5 2016.

[17] S. Klugman, H. Panjer, and G. Willmot, “Extreme value distributions,” in *Loss Models: Further Topics*. Wiley Series in Probability and Statistics, 2013.