Coverage and Capacity Analysis of Sigfox, LoRa, GPRS, and NB-IoT

Vejlgaard, Benny; Lauridsen, Mads; Nguyen, Huan Cong; Kovács, István; Mogensen, Preben Elgaard; Sørensen, Mads

Published in:
2017 IEEE 85th Vehicular Technology Conference (VTC Spring)

DOI (link to publication from Publisher):
10.1109/VTCSpring.2017.8108666

Publication date:
2017

Document Version
Accepted author manuscript, peer reviewed version

Coverage and Capacity Analysis of Sigfox, LoRa, GPRS, and NB-IoT

Benny Vejlgaard[1], Mads Lauridsen[1], Huan Nguyen[1], István Z. Kovács[2], Preben Mogensen[1,2], Mads Sørensen[3]
[1]Dept. of Electronic Systems, Aalborg University, Denmark [2]Nokia Bell Labs, Aalborg [3] Telenor Danmark, Aalborg
ml@es.aau.dk

***Abstract*—In this paper the coverage and capacity of SigFox, LoRa, GPRS, and NB-IoT is compared using a real site deployment covering 8000 km^2 in Northern Denmark. Using the existing Telenor cellular site grid it is shown that the four technologies have more than 99 % outdoor coverage, while GPRS is challenged for indoor coverage. Furthermore, the study analyzes the capacity of the four technologies assuming a traffic growth from 1 to 10 IoT device per user. The conclusion is that the 95 %-tile uplink failure rate for outdoor users is below 5 % for all technologies. For indoor users only NB-IoT provides uplink and downlink connectivity with less than 5 % failure rate, while SigFox is able to provide an unacknowledged uplink data service with about 12 % failure rate. Both GPRS and LoRa struggle to provide sufficient indoor coverage and capacity.**

I. Introduction

According to Cisco the Internet of Things (IoT) may result in a combined increased revenue and lower costs of more than 14 trillion USD from 2013 to 2022 [1]. Therefore, numerous network technologies have been developed to provide wireless connectivity for the sensors and actuators that constitute the IoT. The technologies focus on providing scalability, extended coverage, low cost, and energy efficiency for the end user devices, which currently amount to 6-10 billion units [1], [2].

Some IoT devices will connect using local area networks such as WiFi and Bluetooth, but the market for wide area coverage is significant. Currently GSM, and its improvements GPRS and EDGE, is the main connectivity provider for wide area IoT [2]. However, operators are looking to replace the technology, which was standardized in the early 1990s [3], with 3G and LTE. Both GSM and LTE have been updated in recent 3GPP standardization releases to improve the aforementioned IoT-related key performance indicators (KPIs). The updates are Extended Coverage GSM, for GSM, and Narrowband-IoT (NB-IoT) for LTE, [2], [4]. The NB-IoT can be deployed in refarmed GSM carriers, but also in the guard band or in a single subcarrier of existing LTE deployments.

In addition to the cellular technologies there are also a number of Low-Power Wide-Area (LPWA) network technologies, which operate in the license free industrial, scientific, and medial (ISM) band. Long Range (LoRa) WAN [5] and SigFox [6] are probably the two most common IoT connectivity technologies, which benefit from access to this free spectrum.

The LPWA technologies are rather new, and while there are studies of their individual performance such as on LoRa [7], [8], on Sigfox [9], and on NB-IoT and its companion eMTC [10], to the best of the authors knowledge there is no academic

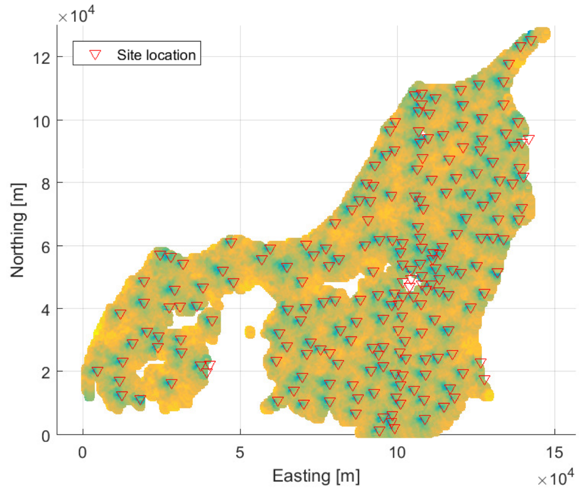

Fig. 1. Site deployment in Telenors sub GHz network covering 8000 km2.

work comparing the performance of LoRa, Sigfox, NB-IoT and GPRS. In recent work [11] we compared the coverage of the four technologies in a 8000 km^2 area, and in this paper our contribution is to build on the coverage results to model and analyze the probability of collisions and blocking, which corresponds to the overall system capacity.

The paper is based on simulated link loss between both urban and rural users and site locations, which are based on Telenor's sub 1 GHz cellular network grid in North Jutland, Denmark illustrated in Fig. 1. The link loss is compared with the link budget of each technology after which the achievable data rate and time on air is calculated. Using a simple traffic model the probability of uplink random access collisions and download blocking is then estimated.

The paper is structured as follows; Section II provides an overview of the four technologies followed by the system level modeling in section III. Next the results are presented in section IV and finally the conclusion is given in section V.

II. Technology Overview

In this section the four LPWA technologies are compared to facilitate the analysis of their performance in the following section. Table I summarizes the KPIs per technology.

As mentioned LoRa and Sigfox are deployed in license free ISM bands and this work targets a deployment in the European 868 MHz ISM band [12]. The band regulations specify two mechanisms for sharing the spectrum; duty cycle or listen

TABLE I
TECHNOLOGY OVERVIEW OF THE FOUR ANALYZED IOT SOLUTIONS; LORA, SIGFOX, NB-IOT, AND GPRS.

	LoRa		**Sigfox**		**NB-IoT release 13**		**GPRS**	
	UL	DL	UL	DL	UL	DL	UL	DL
Spectrum [MHz]	863-870	863-870	868.1-868.3	869.425-869.625	832-862	791-821	890-915	935-960
Tx power [dBm]	14	14-27	14	27	23	37	33	37
Modulation	Chirp spread spectrum		DBPSK	GFSK	GMSK	SC-FDMA	GMSK	GMSK
Bandwidth [kHz]	125	125	0.1	0.6	180	180	200	200
Max payload [bytes]	51	51	12	8	128	85	22	22
Scheduling	Uplink initiated (class A)		Uplink initiated		Network scheduled		Network scheduled	
MCL [dB]	154	152	158	161	164	164	144	152

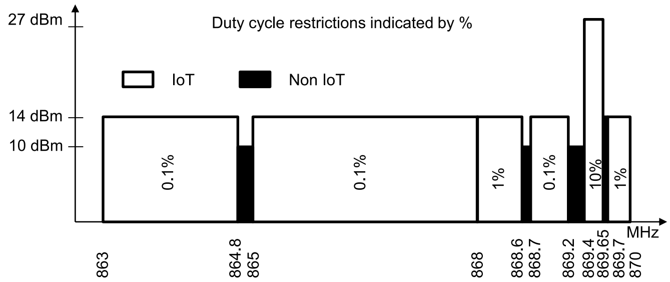

Fig. 2. 868 MHz EU ISM band power and duty cycle restrictions [12].

before talk. Both SigFox and LoRa use the duty cycle method, whose restrictions vary within the ISM band from 0.1 % to 10 % per hour as illustrated in Fig. 2. Furthermore, the maximum radiated power is between 10 and 27 dBm, depending on the specific subband. Note that external interference in the ISM band is not included in this study even though it has been shown to be present in urban areas [13].

A. Sigfox

SigFox [6] uses Ultra-Narrow Band (UNB) modulation with Differential Binary Phase-Shift Keying at 100 bps (DBPSK). In SigFox the device initiates a transmission by sending three uplink packages 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. The duty cycle restrictions of the utilized subband in the 868 MHz EU ISM band is 1 %. Therefore, a SigFox device may only transmit 36 seconds per hour. The time on air is 6 sec [14] per package and thus the maximum is 6 messages per hour with a payload of 4, 8, or 12 bytes.

B. LoRa

The LoRa solution consist of the LoRa physical layer specifications and the LoRaWAN network protocol [5], [15].

The LoRa physical layer uses chirp spread spectrum, with spreading factors from 6 to 12, and GFSK modulation to protect against in-band and out-band interference. LoRa can operate in the entire 868 MHz EU ISM band but has three mandatory channels; 868.10, 868.30, and 868.50 MHz.

Similar to Sigfox, GPRS, and NB-IoT the LoRaWAN protocol is based on a star protocol where each device communicates with a base station which relays the information to and from a central server via an IP based protocol. The LoRaWAN specification defines three device classes; a class A uplink transmission is followed by two downlink receive windows, a class B device opens extra receive windows at scheduled times, and class C have almost continuously open receive windows, which are only closed during transmission.

C. GPRS

The GPRS systems have been deployed for many years and serve as the reference for LPWA technology in many markets today. GPRS is the packet radio service built on top of GSM [3]. GPRS uses GMSK modulation and is frequency division multiplex divided into frames of 4.6 ms that are further divided into 8 timeslots. GPRS requires a frequency reuse scheme of up to 12 providing a fairly inefficient spectral density. GPRS and NB-IoT operate in the licensed bands and are therefore not restricted by duty cycle or listen before talk limitations.

D. NB-IoT release 13

The NB-IoT is an evolution of the LTE system and operates with a carrier bandwidth of 180 kHz [2], [4], [16]. The NB-IoT carrier can be deployed within an LTE carrier, in the LTE guard band, or as standalone. The subcarrier bandwidth for NB-IoT is 15 kHz, and each device is scheduled on one or more subcarriers in the uplink. Furthermore, uplink transmissions can be packed closer together by decreasing the subcarrier spacing to 3.75 kHz. For further information on NB-IoT performance refer to [10], [16].

III. SYSTEM LEVEL MODELING

In this section the system level modeling is described. The starting point is the simulation of link loss between end-user devices and base stations, which is estimated per technology.

The analyzed area is the North Jutland covering 8000 km^2 with 580.000 people [17]. The site locations are based on the commercially deployed Telenor 2G, 3G, and 4G network. Sites with less than 2 km inter-site distance and carrier frequencies above 1 GHz have been removed. The GPRS and NB-IoT simulations are made using the deployed sectorized antennas, while one omni-directional antenna per site is assumed for Sigfox and LoRa. The area is divided into a rural area and ten urban areas, which represent the ten largest cities, covering 147 km^2 and housing 242.000 people. The resulting urban area density is 1648 people/km^2, while it is 44 people/km^2 for the 7805 km^2 rural area. The rural area propagation is simulated using the Rural Macro Non-Line-of-Sight (NLOS) model, while the urban area relies on the Urban Macro NLOS model [18]. The area is divided into 100 m x100 m pixels to

TABLE II
SIMULATED TRAFFIC MODEL.

	Urban	Rural
Area	147 km^2	7805 km^2
People density	1648/ km^2	44/ km^2
IoT devices/person	1 growing to 10	
Uplink traffic	10 bytes/hour/IoT device	
Downlink traffic	a: DL acknowledge for UL data, b: unacknowledged	

ensure a feasible simulation runtime. For further details on the system level simulation, including shadow fading, terrain map, and antenna configuration refer to [11].

In the system level simulation tool all urban pixels are assumed to contain a user, while only the rural pixels that contain a postal address have a user (approximately 10 %). During the simulation the users are assumed to be outdoor, but in post-processing an outdoor-to-indoor penetration loss of 10, 20, or 30 dB is added. The 10 dB represent a location close to a window, 20 dB is the average indoor location, while 30 dB is for deep indoor locations e.g. in a basement.

The traffic model is based on assigning one IoT device to each user. According to [1], [2] the number of IoT devices increase significantly in the coming years and therefore the simulations include a scaling to ten IoT devices per user. The traffic per device is set to ten bytes per hour in uplink and uniformly distributed. The cellular technologies GPRS and NB-IoT automatically acknowledge any uplink data transmission, while LoRa and Sigfox may not always do this due to duty cycle limitations. The traffic model, described in Table II, captures this by including both a downlink acknowledgment for uplink data and unacknowledged uplink data.

The next step is to compare the simulated link loss with the Maximum Coupling Loss (MCL) of each technology, given in Table I. If the MCL is exceeded the device will be out of coverage. The covered devices will experience different uplink data rates and time on air depending on the link loss as illustrated in Fig. 3. The NB-IoT provides the best MCL of 164 dB, at the cost of long time on air, but also the highest data rate for good channel conditions [10]. Note GPRS is estimated to have a constant 0.5 s time on air for a 10 byte packet [19], while SigFox uses 2 s per message [14]. The LoRa [8] is simulated to be deployed using five 125 kHz channels in the 868 MHz EU ISM band with duty cycle of either 1 % or 10 %.

Having determined the data rate and time on air for each individual device per technology the probability of uplink collisions can be estimated. In this study the uplink collisions correspond to a random access failure. The GPRS and NB-IoT technologies are both scheduled systems and thus the performance depends on the blocking performance of the random access channel specified for each system. The GPRS random access channel blocking probability is calculated in [3]. The NB-IoT random access channel blocking probability depends on the link loss and is based on [16]. On the contrary, SigFox and LoRa are not scheduled systems. Instead the Sigfox and LoRa devices transmit their uplink packets at random time and in randomly selected channels. This approach is known as the pure Aloha access scheme. The probability

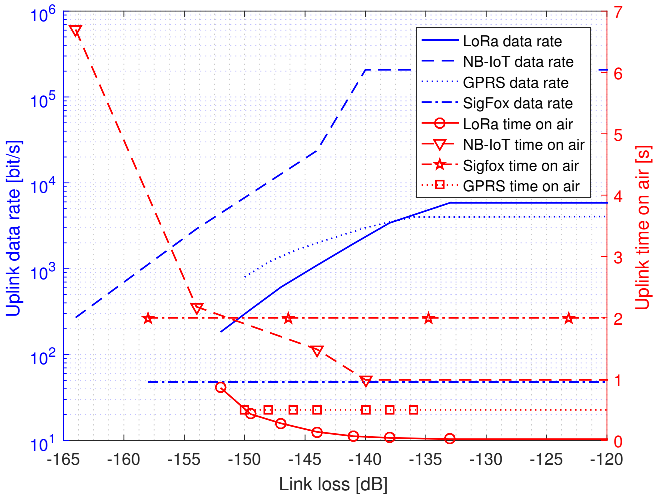

Fig. 3. Mapping curves for uplink data rate and uplink time on air as a function of link loss.

p of zero transmissions colliding with a device's own attempt and therefore resulting in a successful transmission is [20]:

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

where G is the average number of transmission attempts per time frame. The average number of transmissions is calculated using the time on air per device, the number of devices per site, and the number of transmission channels per technology. The transmissions in downlink are scheduled from each base station and therefore slotted Aloha access is used, meaning that the factor 2 is removed from eq. (1).

Sigfox transmits the same package in three attempts on random uplink channels and each attempt can either be received successful or not. Therefore, a Sigfox uplink package is modeled as a Bernoulli trial with a binomial distribution, where the probability of a single successful transmission using the Aloha scheme is p. The probability P, of receiving at least one Sigfox transmission without collisions, is thus modeled as a sequence of three Bernoulli trials:

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

where X is the total number of collision-free transmissions from a device and n is the number of trials.

IV. Results

In this section the results are presented. First, the simulated coverage results are introduced, after which the calculated collision and blocking probabilities are discussed.

A. Coverage

The coverage results, illustrated in the cumulative distribution function (CDF) in Fig. 4, show that all systems provide outdoor coverage with more than 99 % probability. Note that the figure contains results for both urban and rural pixels. For

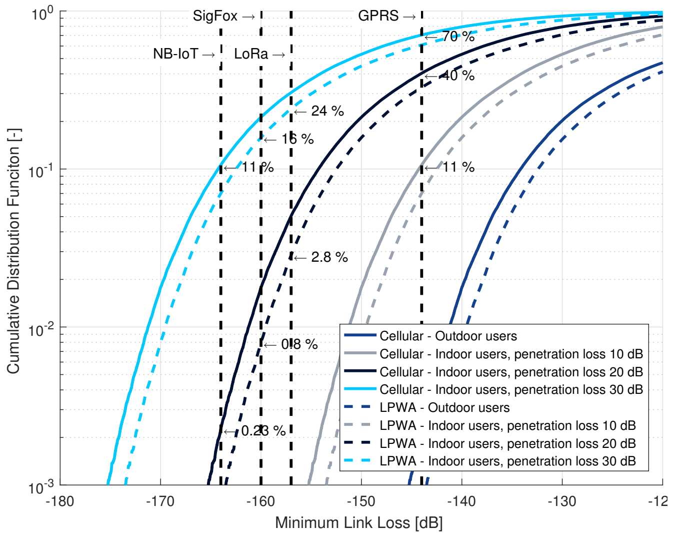

Fig. 4. Maximum coupling loss CDF for all locations in the analyzed area.

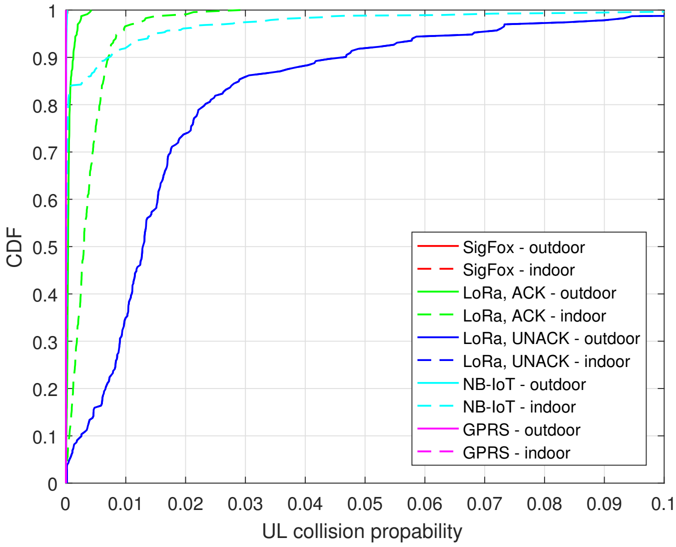

Fig. 5. CDF of the uplink collision probability due to random access failure.

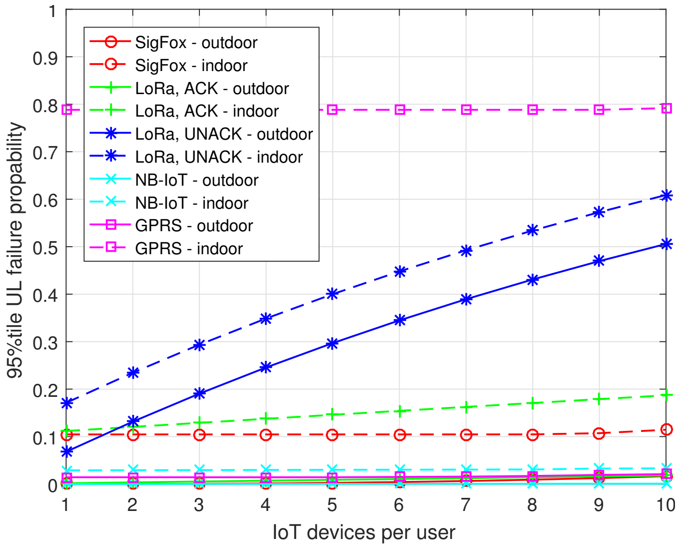

Fig. 6. 95 %-ile of the total uplink failure due to random access collisions and coverage limitations as a function of IoT devices per user.

a view on the individual areas refer to [11].

For indoor users experiencing 20 dB additional penetration loss the GPRS coverage is reduced to 60 %, while LoRa has 97 %, and SigFox and NB-IoT more than 99 % coverage. In the deep indoor case, with 30 dB additional penetration loss, GPRS only covers about 30 % of the users while Lora covers 76 %. SigFox and NB-IoT covers around 85 % and 90 % of the users, respectively.

Fig. 4 illustrates that there is a few dB difference between NB-IoT/GPRS and SigFox/LoRa in the link loss estimates. The reason is the use of sectorized, directional antennas and omni-directional antennas. The latter provide higher gain in the areas, which are covered by a sectorized antenna's side lobe. For further discussions on this topic refer to [11].

B. Collision & Failure Probabilities

Fig. 5 shows the uplink collision probability CDF, for one IoT device per user only. For LoRa and Sigfox the collisions occur when the devices transmit simultaneously using the Aloha scheme, while the GPRS and NB-IoT systems experience collisions, when the devices choose the same preamble in the random access procedure.

The LoRa unacknowledged configuration will transmit according to the worst link budget (using the highest spreading factor and the lowest data rate) since there is no feedback. The result is long time one air and a high collision rate. Since all devices use the same spreading factor and data rate the outdoor and indoor (20 dB penetration loss) curves overlap for this configuration. The acknowledged mode for LoRa experiences a similar problem with long time on air for the indoor deployment. About 15 % of the indoor NB-IoT devices are also estimated to have a non-zero collision probability. Finally, all GPRS and most outdoor devices, using the other technologies, experience less than 1 % uplink collision probability.

Combining the uplink collision probability with the coverage statistics results in the uplink failure probability. Fig. 6 shows the 95 %-ile uplink failure probabilities for the traffic growth from one to ten IoT device per user. First of all it is observed that indoor users (20 dB penetration loss) experience higher failure probabilities due to lack of coverage, and this is especially evident for GPRS, which has the worst coverage according to Fig. 4. However, GPRS has sufficient random access capacity and therefore the failure probability is not affected by the increasing number of devices.

When the users are outdoor LoRa supports five, Sigfox eight, and NB-IoT ten devices per user with less than 1 % combined failure rate, while GPRS devices have around 2 % failure rate mainly due to lack of coverage. The best performing indoor solution is NB-IoT, which provides less than 4 % failure rate for up to ten devices. Sigfox results in around 12 % failure with little dependency on the number of devices, while LoRa whether acknowledged or not has much higher failure rates, which also increase with the number of devices.

A similar study is performed for downlink, when the uplink traffic is acknowledged. However, while GPRS and NB-IoT are limited in uplink by the random access procedure, once the

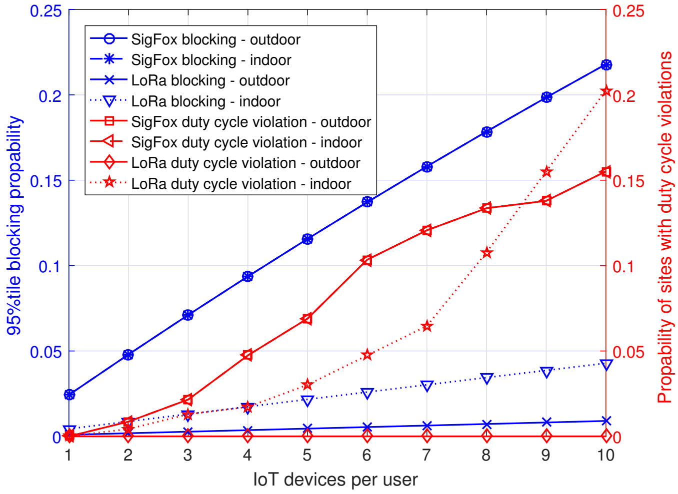

Fig. 7. 95 %-ile downlink blocking probability & probability of duty cycle violations as a function of the number of IoT devices per user.

uplink connection has been established the downlink blocking is not a limiting factor in this study. Therefore, the following results only include SigFox and LoRa downlink performance in terms of blocking probability and duty cycle violations.

Fig. 7 shows the 95 %-ile blocking probability for downlink (left y-axis) and the duty cycle violations (right y-axis). The blocking probability is calculated as the complement of the probability of error free transmission in eq. (1), while the duty cycle violation is based on the G in the same equation.

SigFox has a blocking probability of 2 % for one IoT device per user, and it increases to more than 20 % for ten IoT devices per user. Note that since Sigfox uses 3x2 s per transmission independent of link quality the outdoor and indoor curves are overlapping. The probability of having sites, which violate the duty cycle regulation of 10 % in the high-power Sigfox downlink band, see Table I and Fig. 2, is below 1 % for two IoT devices per user, but it approaches 15 % for ten devices.

Indoor LoRa users can use two IoT devices without exceeding 1 % error probability, while outdoor users can support ten devices with downlink acknowledgment with less than 1 % error probability and no duty cycle violations. For LoRa the duty cycle calculation is based on four channels with 1 % limit and one with 10 % limit. However, this is not sufficient for the indoor LoRa users, which exceeds 5 % probability of duty cycle violations for five devices per user.

V. Conclusion

This work analyzed the coverage and capacity for SigFox, LoRa, GPRS, and NB-IoT in a real deployment scenario covering 8000 km^2 in North Jutland, Denmark.

The four technologies provide better than 99 % outdoor coverage, based on Telenor's existing site locations. GPRS is unable to provide indoor coverage for 40 % of the users, while Sigfox, LoRa, and NB-IoT cover more than 95 % of the indoor users experiencing 20 dB penetration loss.

Sigfox provides very good outdoor and indoor uplink performance with a 95 %-tile failure probability of maximum 12 %. However, Sigfox is limited in downlink due to blocking and duty cycle violations of the 868 MHz ISM band.

LoRa can be operated in an unacknowledged mode, but since all devices will utilize the most robust communication settings the uplink collision probability is significant. When using acknowledged mode in downlink the uplink transmission settings can be adjusted and the performance improves. Nevertheless, LoRa does not match Sigfox in uplink performance, but it provides lower blocking probability and duty cycle violations in downlink, however also with worse coverage.

NB-IoT outperforms the other technologies, having an 95 %-tile uplink failure probability of less than 4 % even for ten devices. The reasons include the best coverage and the use of link adaptation, while a drawback is the longest time on air.

It remains to be studied how the technologies compare in terms of device cost and energy consumption, which are also key performance indicators for the Internet of Things.

Acknowledgment

The work is partly funded by the Danish National Advanced Technology Foundation.

References

[1] Cisco, "Embracing the Internet of Everything," White paper, 2013.
[2] Ericsson, "Cellular Networks for Massive IoT," White paper, 2016.
[3] T. Halonen, J. Melero, and J. Garcia, *GSM, GPRS and EDGE Performance: Evolution Toward 3G/UMTS*. Halsted Press, 2002.
[4] Nokia, "LTE-M Optimizing LTE for the Internet of Things," White paper, 2015.
[5] N. Sornin and M. Luis and T. Eirich and T. Kramp and O.Hersent, "LoRaWAN Specification," 1 2015. [Online]. Available: v1.0
[6] SigFox, Accessed Feb. 3 2017. [Online]. Available: https://www.sigfox.com/
[7] 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.
[8] 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
[9] G. Margelis, R. Piechocki, D. Kaleshi, and P. Thomas, "Low Throughput Networks for the IoT: Lessons learned from industrial implementations," in *IEEE World Forum on Internet of Things*, Dec 2015, pp. 181–186.
[10] 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.
[11] M. Lauridsen, H. Nguyen, B. Vejlgaard, I. Kovacs, P. Mogensen, and M. Sørensen, "Coverage comparison of GPRS, NB-IoT, LoRa, and SigFox in a 7800 km2 area," in *VTC Spring*. Accepted, 6 2017.
[12] 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.
[13] 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 *IEEE WCNC*, 3 2017.
[14] Libelium Comunicaciones Distribuidas, "Waspmote Sigfox Networking Guide," 1 2015. [Online]. Available: v4.1
[15] Semtech, "SX1272/3/6/7/8: LoRa Modem Designers Guide," AN1200.13, 7 2013.
[16] Rohde & Schwarz, "Narrowband Internet of Things," White paper, 2016.
[17] Wikipedia, "Region Nordjylland," Accessed Feb. 1 2017. [Online]. Available: https://en.wikipedia.org/wiki/North_Denmark_Region
[18] 3GPP, "Further advancements for E-UTRA physical layer aspects," TR 36.814 V9.0.0, 3 2010.
[19] X. Chen and D. Goodman, "Theoretical Analysis of GPRS Throughput and Delay," in *IEEE ICC*, 6 2004.
[20] N. Abramson, "The ALOHA System: Another Alternative for Computer Communications," in *AFIPS Fall*. ACM, 1970, pp. 281–285.