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

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Abstract—In this paper the coverage and capacity of SigFox, LoRa, GPRS, and NB-IoT is compared using a real site deployment covering 8000 km2 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 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 km2 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
cies. The base station will successfully receive the package even uplink packages in sequence on three random carrier frequencies.

LoRaWAN specification defines three device classes; a class to and from a central server via an IP based protocol. The protocol is based on a star protocol where each device communicates with a base station which relays the information.

mandatory channels; 868.10, 868.30, and 868.50 MHz.

In SigFox the device initiates a transmission by sending three Differential Binary Phase-Shift Keying at 100 bps (DBPSK). A uplink transmission is followed by two downlink receive transmissions can be packed closer together by decreasing the 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].

A. Sigfox

SigFox [6] uses Ultra-Narrow Band (UNB) modulation with DBPSK. In SigFox the device initiates a transmission by sending three uplink packages in sequence on three random carrier frequencies. The base station will successfully 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 km² 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 km² and housing 242.000 people. The resulting urban area density is 1648 people/km², while it is 44 people/km² for the 7805 km² 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 x 100 m pixels to

### Table I: Technology overview of the four analyzed IoT solutions: LoRa, Sigfox, NB-IoT, and GPRS.

<table>
<thead>
<tr>
<th></th>
<th>LoRa</th>
<th>Sigfox</th>
<th>NB-IoT release 13</th>
<th>GPRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx power [dBm]</td>
<td>14</td>
<td>14-27</td>
<td>27</td>
<td>23</td>
</tr>
<tr>
<td>Modulation</td>
<td>Chirp spread spectrum</td>
<td>DBPSK</td>
<td>GFSK</td>
<td>GSMK</td>
</tr>
<tr>
<td>Bandwidth [kHz]</td>
<td>125</td>
<td>125</td>
<td>0.1</td>
<td>6</td>
</tr>
<tr>
<td>Max payload [bytes]</td>
<td>51</td>
<td>51</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>Scheduling</td>
<td>Uplink initiated (class A)</td>
<td>Uplink initiated</td>
<td>Network scheduled</td>
<td>Network scheduled</td>
</tr>
<tr>
<td>MCL [dB]</td>
<td>154</td>
<td>152</td>
<td>158</td>
<td>161</td>
</tr>
</tbody>
</table>

![Fig. 2. 868 MHz EU ISM band power and duty cycle restrictions [12].](image-url)
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 transmis-
sion, 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
of zero transmissions colliding with a device’s own attempt
and therefore resulting in a successful transmission is [20]:

\[ p = e^{-2G} \]  

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 re-
ceived 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:

\[
P(X > 0) = P(X = 1) + P(X = 2) + P(X = 3) = 1 - P(X = 0) = 1 - \binom{n}{X} p^X (1 - p)^{n-X}
\]

\[= 1 - \binom{3}{0} p^0 (1 - p)^3 - 0 \]  

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 distribu-
tion 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

<table>
<thead>
<tr>
<th>Area</th>
<th>Urban</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>People density</td>
<td>1648/ km²</td>
<td>44/ km²</td>
</tr>
<tr>
<td>IoT devices/person</td>
<td>1 growing to 10</td>
<td></td>
</tr>
<tr>
<td>Downlink traffic</td>
<td>a: DL acknowledge for UL data, b: unacknowledged</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table II</th>
<th>SIMULATED TRAFFIC MODEL</th>
</tr>
</thead>
<tbody>
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<td>IoT devices/person</td>
<td>1 growing to 10</td>
</tr>
<tr>
<td>Uplink traffic</td>
<td>10 bytes/hour/IoT device</td>
</tr>
<tr>
<td>Downlink traffic</td>
<td>a: DL acknowledge for UL data, b: unacknowledged</td>
</tr>
</tbody>
</table>

\[
Uplink data rate [bit/s]\\n\begin{array}{llll}
\hline
\hline
\text{GPRS} & 1 & 10 & 20 & 30 \\
\text{Sigfox} & 1 & 10 & 20 & 30 \\
\text{LoRa} & 1 & 10 & 20 & 30 \\
\text{NB-IoT} & 1 & 10 & 20 & 30 \\
\hline
\end{array}
\]

\[
\begin{array}{llll}
\text{Uplink time on air [s]}\\
\hline
\hline
\text{GPRS} & 0.5 & 0.5 & 0.5 & 0.5 \\
\text{Sigfox} & 2 & 2 & 2 & 2 \\
\text{LoRa} & 2 & 2 & 2 & 2 \\
\text{NB-IoT} & 2 & 2 & 2 & 2 \\
\hline
\end{array}
\]

Fig. 3. Mapping curves for uplink data rate and uplink time on air as a function of link loss.
growth from one to ten IoT device per user. First of all it is
verage statistics results in the uplink failure probabilit y. Fig. 6
experience less than 1 % uplink collision probability. GPRS and most outdoor devices, using the other technologies ,
estimated to have a non-zero collision probability. Finally, all
deployment. About 15 % of the indoor NB-IoT devices are also
a similar problem with long time on air for the indoor
configuration. The acknowledged mode for LoRa experiences
and indoor (20 dB penetration loss) curves overlap for this
devices use the same spreading factor and data rate the outdo or
factor and the lowest data rate) since there is no feedback. T he
random access procedure.
Collisions, when the devices choose the same preamble in the
oha scheme, while the GPRS and NB-IoT systems experience
occur when the devices transmit simultaneously using the Al-
Traffic is acknowledged. However, while GPRS and NB-IoT
rates, which also increase with the number of devices.
LoRa whether acknowledged or not has much higher failure
failure with little dependency on the number of devices, whi le
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 perfor-
moving 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

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4}
\caption{Fig. 4. Maximum coupling loss CDF for all locations in the analyzed area.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5}
\caption{Fig. 5. CDF of the uplink collision probability due to random access failure.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6}
\caption{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.}
\end{figure}
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. 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 %-ile 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.

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