BACHELOR DEGREE THESIS

TFG TITLE: Theoretical and experimental analysis of NB-IoT technology

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**Overview**

This project aims at analyzing the NB-IoT technology both in a theoretical and practical manner. Its performance has been assessed from three different and complementary viewpoints: theoretical analysis, creation of a simulator with the corresponding simulations and measurements with a NB-IoT device in a real network deployment.

The theoretical calculations have been performed under different NB-IoT configurations, with different levels of data protection / redundancy. The worst case allows very deep coverage conditions but it does negatively impact on transmission times. For short data packets throughput levels are acceptable. On the other hand, large packets of 1 Mbyte show unacceptable transmission times of more than 12 days for the worst case scenario.

A simulator of NB-IoT has been designed to compare the simulations with the theoretical cases and to allow the user to simulate any downlink or uplink scenario configuring all the possible parameters allowed by NB-IoT. Results reveal that the initial point of the downlink transmission in the system frame affect the total transmission time, which means that average theoretical calculations may show an approximation error. In the uplink, resource allocation algorithms should smartly consider NPRACH opportunities occupation to minimize transmission delays, which can be very large for certain configurations.

Finally, using Vodafone’s NB-IoT network, some uplink data transmissions have been performed and analyzed with different data packet length for an intermediate coverage and a bad coverage case. The results have revealed a high variability in the transmission times and the way of transmitting the packet even with similar coverage levels. The real scenario has been reproduced in the simulator and the results have been compared with the real measurements.
Resumen

Este proyecto tiene como objetivo analizar la tecnología NB-IoT de una manera teórica y práctica. Su desempeño ha sido evaluado desde tres puntos de vista diferentes y complementarios: análisis teórico, creación de un simulador con las simulaciones correspondientes y mediciones con un dispositivo NB-IoT en una implementación de red real.

Los cálculos teóricos se han realizado bajo diferentes configuraciones NB-IoT, con diferentes niveles de protección / redundancia de datos. El peor de los casos permite condiciones de cobertura muy profundas, pero tiene un impacto negativo en los tiempos de transmisión. Para paquetes de datos cortos, los niveles de rendimiento son aceptables. Por otro lado, los paquetes grandes de 1 Mbyte muestran tiempos de transmisión inaceptables de más de 12 días para el peor de los casos.

Se ha diseñado un simulador de NB-IoT para comparar las simulaciones con los casos teóricos y permitir al usuario simular cualquier escenario de enlace descendente o de enlace ascendente configurando todos los parámetros posibles permitidos por NB-IoT. Los resultados revelan que el punto inicial de la transmisión del enlace descendente en la trama del sistema afecta el tiempo total de transmisión, lo que significa que los cálculos teóricos promedio pueden mostrar un error de aproximación. En el enlace ascendente, los algoritmos de asignación de recursos deben considerar inteligentemente la ocupación de oportunidades de NPRACH para minimizar los retrasos en la transmisión, que pueden ser muy grandes para ciertas configuraciones.

Finalmente, utilizando la red NB-IoT de Vodafone, se han realizado y analizado algunas transmisiones de datos de enlace ascendente con diferentes paquetes de datos para una cobertura intermedia y un caso de mala cobertura. Los resultados han revelado una gran variabilidad en los tiempos de transmisión y en la forma de transmitir el paquete incluso con niveles de cobertura similares. El escenario real se ha reproducido en el simulador y los resultados se han comparado con las mediciones reales.

Título: Análisis teórico y experimental de la tecnología NB-IoT

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I would like to thank all my family, my girlfriend and my friends the support shown during all these months. Especially thanks to my project director Mario Garcia Lozano who supported me greatly and was always willing to help me.
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INTRODUCTION

The term Low Power Wide Area Networks (LPWAN) refers to wireless wide area network solutions that are mainly designed to interconnect low-bandwidth, battery-powered devices with low bit rates but very long ranges. Since the beginning of 2015, LPWANs have experienced an important expansion in the form of many different standards and proprietary technology solutions.

Two of the most important LPWANs are Sigfox [1] and LoRaWAN [2], which operate over industrial, scientific and medical (ISM) bands. On the other hand, the 3rd Generation Partnership Project (3GPP), responsible for the development of classic mobile communications standards such as the Global System for Mobile Communications (GSM) and the Long Term Evolution (LTE), has introduced new LPWAN flavors operating over licensed bands. In particular, the 3GPP started a study known as Cellular System Support for Ultra-low Complexity and Low Throughput Internet of Things (CSS-ULC-LT-IoT) [3] in 2015. This study had the aim to improve coverage, battery lifetime and a reduction in the User Equipment (UE) complexity. As a consequence, the 3GPP Release 13 introduced two new improvements to GSM and LTE and a brand new standard.

From GSM, the 3GPP proposed the Enhanced Coverage - Global System for Mobile Communications - Internet of Things (EC-GSM-IoT) and from LTE, Long Term Evolution for Machines (LTE-M). These new set of specifications meet the proposed objectives but the new standard, denoted as Narrowband Internet of Things (NB-IoT), pushes them even more. NB-IoT increases the attainable ranges and power consumption reduction by using very narrow bandwidths. This feature also allows a massive deployment of devices under the umbrella of the same base station (access point to the core network).

The objective of this project is to provide a comprehensive study of NB-IoT. A holistic approach has been followed and, after a brief background on the standard in chapter 1, it has been analyzed by means of:

- **Theoretical analysis** about its performance in chapter 2. Detailed calculations of throughput and transmission time have been done for the best and worst possible scenarios in order to see the limits of the technology.

- NB-IoT is a system with a very large number of parameters that directly impact on the quality of service. Hence, the work was completed in chapter 3 with the development of a simulator that allows to configure all the parameters that affect the physical layer and medium access layer. This is a valuable tool to evaluate and compare different configurations and analyze its pros and cons.

- Finally, the third stage of the work comprises the configuration and measurements of a real NB-IoT device over Vodafone’s network, presented in chapter 4. An important number of measurements have been performed for different coverage levels and packet sizes.
CHAPTER 1. NARROWBAND INTERNET OF THINGS (NB-IoT)

1.1. Introduction

This chapter will describe the design principles for NB-IoT and thus how it achieves the basic features required by the 3GPP. The signals and channels will be analyzed and some management procedures will be explained, both in idle and connected mode.

The NB-IoT system is supported in a bandwidth of 180 kHz for uplink (UL) and downlink (DL). Due to that fact, NB-IoT can be deployed inside an empty GSM carrier as well as inside an LTE carrier. NB-IoT is part of the 3GPP LTE specifications and shares some features with LTE like its frequency and time numerology, the downlink Orthogonal Frequency-Division Multiple Access (OFDMA), the uplink Single-Carrier Frequency-Division Multiple Access (SC-FDMA), channel coding, interleaving, rate matching and most of higher layer procedures. As those components are already defined in the LTE standard, the NB-IoT standardization process is reduced and a fast and smooth transition to the market is ensured. The current LTE networks just need a software upgrade to support NB-IoT.

1.2. Design Principles for NB-IoT

NB-IoT is a different flavor of LTE, but unlike LTE-M, it allows very narrow bandwidth allocations which contribute to increase the system capacity. Indeed, NB-IoT has been designed to support a massive number of devices in the context of Machine-Type Communications. It is expected that in the following years, more than 5 billion devices will be connected through NB-IoT. The system also goes one step ahead in power consumption reduction and it allows deeper coverage conditions than LTE-M. The narrow band also allows several deployment options with easy LTE and GSM coexistence.

The following sections introduce the radio design principles that allow achieving the features and benefits indicated before:

- Low cost and reduced device complexity.
- Coverage improvement / Extended coverage
- Battery lifetime enhancement.
- Deployment flexibility
1.2.1. **Low Cost and Device Complexity**

Half duplex operation is used, this means that a duplexer is not needed at the user device and a single antenna may be used. This also means that there is no uplink transmission diversity nor downlink reception diversity. The device is composed by one transmitting antenna and one receiving antenna. Therefore, there is no transmission nor reception diversity, reducing the complexity of the device. In addition, the device just has to support the half-duplex mode.

The (optional) use of uplink single tone signals modulated with rotated $\pi/2$-BPSK, leads to a close to 0 dB Peak to Average Power Ratio (PAPR). This improves the efficiency of the Power Amplifier (PA) and reduces the necessity of using more expensive PAs. In addition, the maximum transmission power is just 20 or 23 dBm, depending on the UE class, and this allows to use on-chip PAs, also resulting in a cheaper device.

1.2.2. **Coverage Improvement / Extended Coverage**

The NB-IoT coverage improvement has been compared to General Packet Radio Service (GPRS), estimating a maximum allowed path loss of extra +20 dB. In particular the Maximum Coupling Loss (MCL) for NB-IoT is estimated in 164 dB. The MCL is calculated from the evolved Node B (eNodeB) antenna to the device antenna (Figure 1.1).

![MCL Scheme](image)

**Figure 1.1** MCL Scheme

To achieve this coverage improvement, it must be noted that the reduced bandwidth (being as small as 3.75 kHz in the uplink) leads to more sensitive devices, reaching values around -138 dBm in the eNodeB.

In addition, coverage can be further enhanced by repeating the transmission several times to increase the energy per bit and thus the probability of bit
reception. The number of repetitions and allocated radio resources depend on the UE received signal strength and the Coverage Enhancement Level (CEL) configured at the eNodeB. Up to three CELs can be used and they are referred to the GPRS MCL (144 dB): CEL0 (normal coverage class) +0 dB, CEL1 (robust coverage class) +10 dB, CEL2 (extreme coverage class) +20 dB.

1.2.3. **Battery Lifetime Enhancement**

Most Internet of Things (IoT) applications require the transmission of infrequent small data packets. Then, most of the UE power consumption does not come from the connected state but from the idle one. The NB-IoT Release 13 has two main power saving mechanisms for such state, the extended Discontinuous Reception (eDRX) and the Power Saving Mode (PSM) (Figure 1.2).

While the device is in idle mode, it must monitor whether it has downlink incoming data. In order to save battery, mobile devices implement Discontinuous Reception (DRX) and just wake up periodically to monitor the corresponding control channel. The LTE DRX has a maximum periodicity of 2.56 s. This value has been extended in NB-IoT eDRX to a maximum of ~175 minutes, thus allowing to increase battery savings even more. DRX can also be used in connected mode and NB-IoT also extends it from 2.56 s to up to 10.24 s.

The other technique to save battery is the PSM. During this mode, the device goes into a deep sleep state. The UE just keeps the oscillator running to keep the time reference and be able to wake up periodically. The device is still registered to the network but it is not reachable and does not monitor any paging message. The PSM time is implicitly defined by two timers: The duration of the idle phase (timer T3324), up to ~3 hours, and the Tracking Area Update (TAU) timer (T3412) after which, the UE must indicate its current area to the core network. The duration of the PSM cycle can be up to ~413 days.
1.2.4. Support of Massive Devices per Cell

NB-IoT supports a high number of devices inside an NB-IoT carrier thanks to the efficient spectral transmission scheme in the uplink for devices in the extreme coverage situations. In order to understand this, let’s recall the capacity of a channel under additive white Gaussian noise conditions. This is given by the Shannon-Hartley theorem:

\[ C = W \log_2 \left( 1 + \frac{S}{N_0 W} \right) \]  

(1.1)

Where C is the channel capacity (bits/s), S is the received desired signal power, \( N_0 \) is the noise power spectral density and W the noise bandwidth. When an extreme coverage case happens:

\[ \frac{S}{N_0 W} \ll 1 \]  

(1.2)

Now, since the \( \ln (1+x) \approx x \), for \( x \ll 1 \), it can be seen that the bandwidth dependency disappears. Thus, under very low Signal-to-Noise-power Ratio (SNR) regime, the channel capacity is mostly determined by the ratio of S and \( N_0 \) and does not scale with the bandwidth allocation:

\[ C = \frac{S}{N_0} \log_2(e) \]  

(1.3)

Under these circumstances, waveforms of small bandwidths are more spectrally efficient to serve devices in bad coverage (see chapter 7.1.2.4 in [4]). NB-IoT allows to allocate a bandwidth of 3.75 kHz to devices in situation of extreme coverage, whereas the devices in situation of good coverage will be allocated with up to 180 kHz. It is noticeable that the minimum allocable bandwidth in GPRS is 200 kHz, and 180 kHz in LTE.

Thanks to that variable allocation in the uplink, an efficient use of the spectrum is done and a higher number of devices can be allocated.

1.2.5. Deployment Flexibility

NB-IoT supports different modes of deployment, in-band, guard-band and stand-alone. In the first two cases, NB-IoT is transmitted inside the existing LTE networks. The in-band deployment is done by changing an LTE Physical Resource Block (PRB) for an NB-IoT PRB, since both occupy 180 kHz. The guard-band deployment is done by using the guard-band of LTE. Figure 1.3 shows both cases, for the second case, the guard band between two LTE signals has been used to place NB-IoT.
Theoretical and experimental analysis of NB-IoT technology

On the other hand, a typical case of stand-alone deployment is inside a GSM radio channel, which has an available spectrum of 200 kHz (Figure 1.4). This allows a progressive refarming of the IoT services currently running under GPRS into NB-IoT. Based on the coexistence requirements in [5], it is recommended that guard-bands of 100 kHz are left, thus using two GSM radio channels in practice. This is due to the necessity of NB-IoT to fit the GSM spectral mask and avoid adjacent channel interference.

1.3. Physical Layer

This section is mainly focused in the design of both uplink and downlink NB-IoT channels in order to understand the physical layer, how the transmissions work and which is the main function of each channel and signals.

1.3.1. Downlink Physical Channel and Signals

The temporary structure in NB-IoT follows a frame structure (Figure 1.5). One frame has a duration of 10 ms and it is composed by 10 subframes (1 ms each subframe). At the same time, one subframe is divided into two time slots (0.5 ms each one). The time slot definition is kept from LTE. In NB-IoT the minimum resource unit for the DL occupies 1 subframe. Each subframe contains 14 Orthogonal Frequency Division Multiplexing (OFDM) symbols (Figure 1.6). The structure in frequency occupies at least one PRB, which means 180 kHz. In case it occupies more than one PRB, one of them would be the anchor or primary. The DL has 12 subcarriers spaced 15 kHz.
Unlike LTE, the downlink physical layer signals and upper layer channels are mostly multiplexed in time.

Signals are generated at the physical layer and allow synchronization and channel estimation functions. Three signals are used:

- Narrowband Primary Synchronization Signal (NPSS)
- Narrowband Secondary Synchronization Signal (NSSS).
- Narrowband Reference Signal (NRS),

On the other hand, channels carry information coming from higher layers. Three DL channels are defined:

- Narrowband Physical Broadcast Channel Narrowband (NPBCH).
- Narrowband Physical Downlink Control Channel (NPDCCH)
- Narrowband Physical Downlink Shared Channel (NPDSCH).
1.3.1.1. **Synchronization signals**

They are transmitted by the eNodeB and allow the device to get synchronized:

- **NPSS** is used by the devices for initial time and frequency acquisition. It is transmitted in subframe number 5, using its last 11 OFDM symbols.

- **NSSS** is used for the full downlink synchronization obtaining the physical Narrowband Cell ID (NCellID). It is transmitted in the subframe number 9 of every odd frame (every 20 ms), also using the last 11 OFDM symbols.

1.3.1.2. **NRS**

The NRS is used to provide phase reference for the demodulation of the downlink channels. The average received power of NRS constitutes the Reference Signal Received Power (RSRP) and it is a metric used to evaluate the channel quality.

NRSs do not use all the PRB bandwidth. They are time and frequency multiplexed with the rest of signals and channels, using 8 subcarriers per subframe and antenna port at the eNodeB. So, if the eNodeB uses transmission diversity with 2 antennas, 16 subcarriers are occupied by NRSs.

1.3.1.3. **NPBCH**

The NPBCH carries the Master Information Block (MIB). The MIB contains a set of high level information like additional timing information, the operation mode (in-band, guard band or standalone) and scheduling information about additional information blocks. The NPBCH is transmitted in subframe number 0 and a complete MIB takes 640 ms to be fully transmitted.

**Figure 1.7** shows two complete NB-IoT frames with all the previous signals/channels for a guard-band or stand-alone deployment. In case this PRB was allocated in-band, within an LTE signal, there would be some subcarriers forbidden to be used for compatibility issues with LTE.

1.3.1.4. **NPDCCH**

The NPDCCH carries the Downlink Control Information (DCI) which, depending on its functionality, has three different formats:

- DCI Format N0 (23 bits) contains the information related to uplink scheduling grants. This basically means the radio resources that have been allocated for the UE to transmit and their physical features, e.g. modulation and coding scheme.

- DCI Format N1 (23 bits) is used for downlink scheduling information.

- DCI Format N2 (15 bits) is used to search for a UE having new incoming DL data (paging) or to warn UEs about a system information update.
The NPDCCH can be transmitted in any subframe and its bandwidth may be 90 or 180 kHz (half or complete PRB). However, for the sake of brevity, for further information on the organization of the NPDCCH into one or two control channels elements, the reader is referred to the ANNEX 1.

As previously indicated, repetitions can be used to improve the likelihood of correct decoding. The number of repetitions for NPDCCH can be any number $2^n$ with $n = 1, 2...11$. In particular, the possible set of values depends on $R_{\text{max}}$, a signaled parameter that depends on the coverage quality as shown in Table 1.1.

**Figure 1.7** Stand-alone / Guard-band even frame (top) and odd frame (bottom)
Table 1.1 R values for a given $R_{\text{max}}$

<table>
<thead>
<tr>
<th>$R_{\text{max}}$</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>$\geq 8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>$\frac{R_{\text{max}}}{8}$</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>$\frac{R_{\text{max}}}{4}$</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td>$\frac{R_{\text{max}}}{2}$</td>
</tr>
</tbody>
</table>

When 2048 repetitions are used for devices under extreme deep coverage, the DL channel is blocked by them for a long time. For this reason, a transmission gap is added to allow time opportunities for other devices that have better coverage transmissions and do not need long times to receive their data.

1.3.1.5. NPDSCH

The NPDSCH is the signal used for data and system information transmission. The data that comes from the upper layers, is divided into one or more Transport Blocks (TBSs) at the Medium Access Control (MAC) layer that are then transmitted by the physical layer.

The NPDSCH occupies the complete 180 kHz bandwidth and, in time, it can take any number of subframes in the set $\{1, 2, 3, 4, 5, 6, 8, 10\}$ multiplied by the number of repetitions that are used for redundancy issues. The number of repetitions can be $\{1, 2, 4, 8, 16, 32, 64, 128, 192, 256, 384, 512, 768, 1024, 1536, 2048\}$.

Table 1.2 shows the combinations of NPDSCH Transport Block Size (TBS) and number of NPDSCH subframes. It must be noted that each row (mostly) share the same code rate, so the number of subframes is chosen depending on the number of bits to be transmitted, with a maximum of 680 bits. Then, the code rate increases (redundancy decreases) with the row number (TBS size index). So, depending on the UE coverage conditions, one or another row is chosen. The worse the coverage is, the lower the TBS index should be and thus, a higher number of subframes is required to transmit the same amount of bits. These are net bits, before attaching a 24-bit Cyclic Redundancy Check (CRC) and applying the corresponding channel coding.

The subframes in the in-band deployment have less REs available for NPDSCH due to the occupation of existing signaling of LTE. Hence, the TBS index 11 and 12 are not used (see chapter 7.2.4.6 in [4]).

The DL peak data rate at MAC level can be obtained with the maximum number of bits per TB at the highest possible TBS index (TBS index 12, 680 bits transmitted in 3 subframes). This gives a peak data rate at MAC level of 226.67 kbps, for stand-alone and guard-band deployments. For in-band deployments, the maximum TBS index recommended is 10 and selecting 680 bits over 4 subframes gives a peak data rate of 170 kbps. There are 152 free OFDM subcarriers per subframe for guard-band and stand-alone deployments. Hence, given the use of QPSK modulation, the peak data rate at physical layer is 304 kbps.
Table 1.2 NPDSCH TBSs

<table>
<thead>
<tr>
<th>TB Size Index</th>
<th>Number of Subframes ($N_{SF}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td>1</td>
<td>24</td>
</tr>
<tr>
<td>2</td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>56</td>
</tr>
<tr>
<td>5</td>
<td>72</td>
</tr>
<tr>
<td>6</td>
<td>88</td>
</tr>
<tr>
<td>7</td>
<td>104</td>
</tr>
<tr>
<td>8</td>
<td>120</td>
</tr>
<tr>
<td>9</td>
<td>136</td>
</tr>
<tr>
<td>10</td>
<td>144</td>
</tr>
<tr>
<td>11</td>
<td>176</td>
</tr>
<tr>
<td>12</td>
<td>208</td>
</tr>
<tr>
<td>3</td>
<td>56</td>
</tr>
<tr>
<td>4</td>
<td>88</td>
</tr>
<tr>
<td>5</td>
<td>144</td>
</tr>
<tr>
<td>6</td>
<td>208</td>
</tr>
<tr>
<td>7</td>
<td>256</td>
</tr>
<tr>
<td>8</td>
<td>328</td>
</tr>
<tr>
<td>9</td>
<td>392</td>
</tr>
<tr>
<td>10</td>
<td>456</td>
</tr>
<tr>
<td>11</td>
<td>512</td>
</tr>
<tr>
<td>12</td>
<td>590</td>
</tr>
</tbody>
</table>

1.3.2. Uplink Physical Channels

The uplink channel is composed of two basic channels. The Narrowband Physical Random Access Channel (NPRACH) used by the device to access to the network and request for radio resources to transmit its data and the Narrowband Physical Uplink Shared Channel (NPUSCH) used to transmit uplink data itself and acknowledgement for downlink data. Unlike LTE, there is no specific control channel in the uplink at the physical level.

1.3.2.1. NPRACH

The NPRACH transmits a random access preamble, which is the first step of the random access procedure for the UEs to establish new connections. The preamble is a set of 4 symbol groups that perform frequency hopping. In frequency, each symbol group occupies 3.75 kHz. In time, there are two possible formats depending on the Cyclic Prefix (CP) used by the OFDM signal:

- **Format 0**: The CP length is 66.67 µs for a cell radius up to 10 km. One symbol group takes 1.4 ms, so the complete preamble is 5.6 ms.

- **Format 1**: The CP length is 266.67 µs for a cell radius up to 35 km. The symbol group length is 1.6 ms and the preamble is 6.4 ms.

The hopping sequence uses a band of 12 tones indexed from 0 to 11. Table 1.3 summarizes the different deterministic patterns that can be applied for each preamble. The numbers ±1 and ±6 indicate the number of tones in each frequency hop. An example is shown in Figure 1.8.
Table 1.3 Deterministic hopping patterns for NPRACH preamble

<table>
<thead>
<tr>
<th>Index of tone in 1st symbol group</th>
<th>Pattern (num. of tones up or down)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0, 2, 4</td>
<td>{+1, +6, -1}</td>
</tr>
<tr>
<td>1, 3, 5</td>
<td>{-1, +6, +1}</td>
</tr>
<tr>
<td>6, 8, 10</td>
<td>{+1, -6, -1}</td>
</tr>
<tr>
<td>7, 9, 11</td>
<td>{-1, -6, +1}</td>
</tr>
</tbody>
</table>

Figure 1.8 Deterministic hopping pattern (11, {-1, -6, +1})

In order to serve different coverage classes, the network can configure up to three NPRACH configurations, which are signaled by the eNodeB in the form of RSRP thresholds (Figure 1.9). Some important configurable parameters are:

- Starting time of the NPRACH resource.
- Periodicity of NPRACH resource: 40 ms, 80 ms, 160 ms, 240 ms, 320 ms, 640 ms, 1280 ms or 2560 ms.
- Number for repetitions: $2^n$ where $n = 0, 1...7$.
- Number of subcarriers: 12, 24, 36 or 48.
- Subcarrier offset: 0, 12, 24, 36, 2, 18 or 34.

Figure 1.9 NPRACH Configurations vs Threshold
1.3.2.2. NPUSCH

The NPUSCH has two different formats. NPUSCH Format 1 (NPUSCH F1) which is used for carrying uplink data and NPUSCH Format 2 (NPUSCH F2) for acknowledgments of downlink data. Both formats support a number of repetitions going from 1 to 128 in steps of 2

The NPUSCH F1 can be transmitted with different bandwidths and different time lengths. The maximum TBS is 1000 bits (slightly longer than the DL data channel, the NPDSCH) and the minimum one is 16 bits. These values are valid for devices defined in the release 13 (category CAT-N1). The possible TBs with the corresponding number of subframes are indicated in Table 1.4.

### Table 1.4 NPUSCH F1 TBSs

<table>
<thead>
<tr>
<th>TB Size Index</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>16</td>
<td>32</td>
<td>56</td>
<td>88</td>
<td>120</td>
<td>152</td>
<td>208</td>
<td>256</td>
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<tr>
<td>1</td>
<td>24</td>
<td>56</td>
<td>88</td>
<td>144</td>
<td>176</td>
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<td>256</td>
<td>344</td>
</tr>
<tr>
<td>2</td>
<td>32</td>
<td>72</td>
<td>144</td>
<td>176</td>
<td>208</td>
<td>256</td>
<td>328</td>
<td>424</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>104</td>
<td>176</td>
<td>208</td>
<td>256</td>
<td>328</td>
<td>440</td>
<td>568</td>
</tr>
<tr>
<td>4</td>
<td>56</td>
<td>120</td>
<td>208</td>
<td>256</td>
<td>328</td>
<td>408</td>
<td>552</td>
<td>696</td>
</tr>
<tr>
<td>5</td>
<td>72</td>
<td>144</td>
<td>224</td>
<td>328</td>
<td>424</td>
<td>504</td>
<td>680</td>
<td>872</td>
</tr>
<tr>
<td>6</td>
<td>88</td>
<td>176</td>
<td>256</td>
<td>392</td>
<td>504</td>
<td>600</td>
<td>808</td>
<td>1000</td>
</tr>
<tr>
<td>7</td>
<td>104</td>
<td>224</td>
<td>328</td>
<td>472</td>
<td>584</td>
<td>712</td>
<td>1000</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>120</td>
<td>256</td>
<td>392</td>
<td>536</td>
<td>680</td>
<td>808</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>136</td>
<td>296</td>
<td>456</td>
<td>616</td>
<td>776</td>
<td>936</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>144</td>
<td>328</td>
<td>504</td>
<td>680</td>
<td>872</td>
<td>1000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>176</td>
<td>376</td>
<td>584</td>
<td>776</td>
<td>1000</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>208</td>
<td>440</td>
<td>680</td>
<td>1000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

As it happens with the NPDSCH, the lower TBS indexes should be used for scenarios with bad coverage and the higher ones with scenarios with the best coverage. Note that two modulations are possible in the uplink ($\pi/4$-QPSK and $\pi/2$-BPSK), so the row now indicates the specific modulation and coding scheme, and not just the coding rate as it happened in the downlink.

NPUSCH F1 accepts 15 kHz multi-tone and single-tone transmission and 3.75 kHz single-tone transmission. On the other hand, NPUSCH F2 only supports single-tone transmissions for 3.75 and 15 kHz. Table 1.5 summarizes the different minimum time Resource Unit (RU) lengths for NPUSCH depending on the bandwidth allocation and its format. Note that, whenever the bandwidth is halved in the multi-tone cases, the time duration is doubled so the total available subcarriers is kept invariant. It is important to recall that downlink data transmissions are always 180 kHz, so the minimum allocable time was always 1 ms (1 subframe).
Theoretical and experimental analysis of NB-IoT technology

Table 1.5 RU lengths for NPUSCH

<table>
<thead>
<tr>
<th>NPUSCH format</th>
<th>Scheduled bandwidth (kHz)</th>
<th>Number of slots per time resource unit</th>
<th>Length of the time resource unit (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Format 1</td>
<td>180</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>3.75</td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td>Format 2</td>
<td>15</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3.75</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>

The devices under deep coverage may need a high number of repetitions in order to be able to decode correctly the information. First it may seem that this would cause a block in the radio resources that may be used by other devices. This is not true because the uplink transmission in these cases is made with single carrier transmissions and this allows the other devices to use the radio resources.

The UL peak data rate at MAC level, can be obtained with the maximum number of bits per TB at the highest possible TBS index (TBS index 12, 1000 bits over 4 RU). To obtain the maximum data rate, the shortest RU has to be selected which is 1 ms (12 subcarriers of 15 kHz allocation). This gives a peak data rate at MAC level of 250 kbps. Considering the same RU which is the equivalent to one subframe, there are 168 OFDM symbols available per subframe, which results in a physical peak data rate of 336 kbps.

However, another problem arises due to long transmission times. Low-cost oscillators can overheat and cause a phase drift which would require a resynchronization with the DL reference signals. Hence, for NPUSCH transmissions, a 40 ms gap must be introduced every 256 ms of continuous transmission. For NPRACH, it is a little different and the 40 ms gap is introduced every 64 preambles, recall that one preamble can take 5.6 or 6.4 ms.

1.4. Idle Mode Procedures

This section will describe the idle mode procedures that are performed when the device is registered in the network but cannot transmit nor receive data. That is to say, the UE has not an active radio resource control (RRC) session. The UE needs to perform the random access procedure to switch to connected mode. In fact, this is one of the procedures explained in this section along with the cell selection and the paging.

1.4.1. Cell Selection

The main purpose of cell selection is to identify, synchronize to, and determine the suitability of an NB-IoT cell. First of all, the device starts a frequency and time synchronization, once this is completed, the device acquires the MIB.
When the device selects a suitable cell to camp on, it needs to acquire a full set of System Information (SI) messages. A summary of the System Information Blocks (SIBs) for NB-IoT is defined in Table 1.6.

### Table 1.6 System Information Blocks

<table>
<thead>
<tr>
<th>System Information Block</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIB1-NB</td>
<td>It contains information relevant for the UE to evaluate if it is allowed to access the cell. It also indicates the scheduling information to find and decode the rest of the SIBs.</td>
</tr>
<tr>
<td>SIB2-NB</td>
<td>Radio resource configuration information</td>
</tr>
<tr>
<td>SIB3-NB</td>
<td>Cell re-selection information for intra-frequency, inter-frequency</td>
</tr>
<tr>
<td>SIB4-NB</td>
<td>Neighboring cell related information relevant for intra-frequency and cell re-selection</td>
</tr>
<tr>
<td>SIB5-NB</td>
<td>Neighboring cell related information relevant for inter-frequency cell re-selection</td>
</tr>
<tr>
<td>SIB14-NB</td>
<td>Access barring parameters</td>
</tr>
<tr>
<td>SIB16-NB</td>
<td>Information related to GPS time and Coordinated Universal Time (UTC)</td>
</tr>
</tbody>
</table>

The device monitors the RSRP to decide whether a re-selection of a new cell is required. The RSRP threshold may be different for the intra-frequency and the inter-frequency case. The device ranks the cells and selects the highest ranked cell which is suitable to camp on it.

For NB-IoT is valid to talk about micro mobility. The devices can move within a few kilometers if the devices do not have to change of cell. In NB-IoT, there is no handover and thus the device has to go to idle state before re-selecting another cell. Due to that fact, a device would take much more time than in LTE to select another cell and the connection is lost during the re-selection cell procedure.

### 1.4.2. Random Access Procedure

The random access procedure is initiated by the device and it is used to initiate a connection with the eNodeB either for transmitting or receiving data. A random access procedure is illustrated in Figure 1.10.

When the device has synchronized with the network, it sends a NPRACH preamble based on the configurations defined in the eNodeB and signaled by its SIB2-NB. Note that different configurations are possible to account for different coverage levels. The UE will use the one corresponding to its RSRP.
If the eNodeB detects the preamble sent by the device, it sends back a Random Access Response (RAR), also known as message 2. This is indeed to physical layer transmission. First, the eNodeB sends the NPDCCH for the RAR scheduling, and the RAR itself is sent using an NPDSCH. All downlink transmissions will follow this approach: NPDCCH + NPDSCH. The message 2 contains information about the Timing Advance (TA) and the radio resources that the device should use for message 3. At this point, the eNodeB already knows if the device can transmit using multi-tone. Message 3 sent by NPUSCH F1, includes the scheduling request and information of the device like the identity, the buffer status report and power headroom thus the eNodeB will schedule a more appropriate power and scheduling allocation. Finally, message 4 (as outlined, composed of the pair NPDCCH + NPDSCH) transmits a connection setup / resume message to complete the transition to the connected state. Finally, the device sends an acknowledgement through NPUSCH F2, also scheduled in the NPDDCH for message 4. Finally, the user sends an NPUSCH F1 with the connection setup or resume complete that may contain the UL data.

### 1.4.3. Paging

Whereas the NPRACH procedure is the first step to establish an uplink connection, the paging procedure happens first for downlink ones. The paging procedure searches for the UE by distributing a search message within a set of cells denoted as tracking area list. Whenever a UE moves and enters into a tracking area that is not in its list, it should send an update message (TAU, tracking area update) so that the system knows where to look for it.
Of course this means that the UE needs to monitor paging messages and reply back by means of a random access procedure over the NPRACH. However, as it was previously explained, the UE performs DRX. Thus, during the idle mode, it goes to sleep mode and just wakes up periodically to detect the paging events (NPDCCH with DCI Format N2) addressed to the device. The eNodeB is aware of the UE DRX cycle and it would only send the paging message accordingly.

The frequency with which the device monitors the paging has implications on the device battery lifetime. Thus as previously explained, NB-IoT includes extended DRX modes and a power saving mode.

1.5. Connected Mode Procedures

Once the device is in connected mode, it is ready to send or receive data to/from the eNodeB. Under this state, the most important procedure is the scheduling of UL and DL data, which defines the complete format and timing of the signal to be transmitted. An open loop power control is also applied.

The NB-IoT Release 13 allows low-complexity device implementation and adopts the following scheduling principles:

- A device only needs to support one Automatic Repeat re-Quest (ARQ) process in the DL and another one in the UL. The ARQ process is a protocol used to control errors in data transmissions. To control the correct reception of the packet, an ACK is sent in case the packet is correctly received and a NACK if the packet is not correctly received. Hence, in NB-IoT the next packet cannot be sent until the ACK is received.

- The time for the device to switch between transmission and reception modes must be long enough to support the half-duplex operation and required UE time to switch from DL to UL and vice versa.

1.5.1. Uplink Scheduling

The UL scheduling information is carried by the downlink control channel by using the so called DCI Format N0. Table 1.7 lists the different parameters that can be configured and their possible configurations. It can be seen that the number of possibilities is huge, there are many ways of transmitting a piece of data.

It is important to highlight the fact that not all the allocations are possible in frequency. We can observe, that if the uplink signal is multi-toned and composed of 3 sub-carriers, the allocation should start in the subcarrier 0, 3, 6 or 9 of the 12 subcarriers possible in the 180 kHz bandwidth (subcarriers spaced 15 kHz).

The time between the last subframe used to transmit the scheduling allocation and the first subframe to transmit the data itself (NPUSCH) must be at least 8 ms. This time allows the device to decode the control information, change from the reception mode to the transmission mode and prepare the UL transmission. This gap is called NPUSCH scheduling delay and it can be 8, 16, 32 or 64 ms.
Table 1.7 DCI Format N0 for NPUSCH Format 1 scheduling

<table>
<thead>
<tr>
<th>Information</th>
<th>Size [bits]</th>
<th>Possible Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flag for format N0/N1</td>
<td>1</td>
<td>DCI N0 or DCI N1</td>
</tr>
<tr>
<td>Subcarrier indication (NPUSCH F1)</td>
<td>6</td>
<td>Allocation based on subcarrier index</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.75 kHz spacing: 0,1 ( \ldots ) 47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 kHz spacing:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 1 tone: 0,1 ( \ldots ) 11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 3 tones: {0,1,2}, {3,4,5}, {6,7,8}, {9,10,11}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 6 tones: {0,1} ( \ldots ) 5, {6,7} ( \ldots ) 11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 12 tones: {0,1} ( \ldots ) 11</td>
</tr>
<tr>
<td>Scheduling delay</td>
<td>2</td>
<td>8, 16, 32, 48</td>
</tr>
<tr>
<td>DCI subframe repetition</td>
<td>2</td>
<td>The R values in Table 1.1</td>
</tr>
<tr>
<td>Number of RUs</td>
<td>3</td>
<td>1, 2, 3, 4, 5, 6, 8, 8 or 10</td>
</tr>
<tr>
<td>NPUSCH Repetitions</td>
<td>3</td>
<td>1, 2, 4, 8, 16, 32, 64, or 128</td>
</tr>
<tr>
<td>Modulation and Coding Scheme</td>
<td>4</td>
<td>0, 1, \ldots \ or 12</td>
</tr>
<tr>
<td>Redundancy version</td>
<td>1</td>
<td>Version 0 or 2</td>
</tr>
<tr>
<td>New data indicator (NDI)</td>
<td>1</td>
<td>1 for new TB or 0 for same TB</td>
</tr>
</tbody>
</table>

The second gap is introduced after the data transmission has finished. The gap is a minimum of 3 ms and allows the device to change from transmission to reception mode and get ready to monitor the downlink control message again. Recall that the control channel NPDCCH will carry the corresponding N/ACK. Due to the fact that just one ARQ process is supported, it just refers to the last TB.

An example is shown in Figure 1.11. The NPDCCH (in the picture, C, for control) is transmitted with two repetitions and schedules an NPUSCH transmission of 6 ms. The NPUSCH scheduling delay and the gap from NPUSCH are both in their minimum values.

![Figure 1.11 Uplink scheduling example](image-url)
1.5.2. Downlink Scheduling

The DCI Format N1 is the responsible of the NPDSCH scheduling. The DL scheduling also requires some gaps similar to the UL Scheduling. Table 1.8 explains the different parameters and possible configuration for each of them. This control message, not only indicates the scheduling information for the user device to decode the data from the eNodeB, but also it schedules the information for the ACK resource (NPUSCH F2) that it must use afterwards.

Table 1.8 DCI Format N1 for NPDSCH scheduling

<table>
<thead>
<tr>
<th>Information</th>
<th>Size [bits]</th>
<th>Possible Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flag for format N0/N1</td>
<td>1</td>
<td>DCI N0 or DCI N1</td>
</tr>
<tr>
<td>NPDCCH order indication</td>
<td>1</td>
<td>DCI used for NPDSCH scheduling or NPDCCH order</td>
</tr>
<tr>
<td>Additional time offset for NPDSCH (the minimum gap is 4 ms)</td>
<td>3</td>
<td>( R_{\text{max}} &lt; 128 ): 0, 4, 8, 12, 16, 32, 64, or 128 (ms)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R_{\text{max}} \geq 128 ): 0, 16, 32, 64, 128, 256, 512, or 1024 (ms)</td>
</tr>
<tr>
<td>DCI subframe repetition</td>
<td>2</td>
<td>The ( R ) values in Table 1.1</td>
</tr>
<tr>
<td>Number of NPDSCH subframes per repetition</td>
<td>3</td>
<td>1, 2, 3, 4, 5, 6, 8 or 10</td>
</tr>
<tr>
<td>NPDSCH Repetitions</td>
<td>4</td>
<td>1, 2, 4, 8, 16, 32, 64, 128, 192, 256, 384, 512, 768, 1024, 1536 or 2048</td>
</tr>
<tr>
<td>Modulation and Coding Scheme</td>
<td>4</td>
<td>0, 1, … or 12</td>
</tr>
<tr>
<td>New data indicator (NDI)</td>
<td>1</td>
<td>1 for new TB or 0 for same TB</td>
</tr>
<tr>
<td>ARQ-ACK resource</td>
<td>4</td>
<td>15 kHz subcarrier spacing:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Time offset value: 13, 15, 17 or 18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Subcarrier index: 0, 1, 2 or 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.75 kHz subcarrier spacing:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Time offset value: 13 or 17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Subcarrier index: 38, 39, 40, 41, 42, 43, 44 or 45</td>
</tr>
</tbody>
</table>

A gap of at least 4 ms is introduced between the last DCI subframe and the first scheduled NPDSCH. Recall that at least 8 ms were left for the UL case. This difference is due to the fact that there is no need to change from reception to transmission between the DCI and the NPDSCH transmission. Both control and data transmission happen in the DL direction.
There is a field that carries the information on how the ACK should be sent over a subsequent NPUSCH F2. Two modes are available using single-toned signals of 15 kHz or 3.75 kHz bandwidth. The minimum gap between the end of the data reception (NPDSCH) and the start of the ACK transmission (NPUSCH F2) is 12 ms. This allows the device to decode the NPDSCH, change from reception to transmission mode and prepare the NPUSCH F2.

An example is shown in Figure 1.12. There is a DL transmission of control information composed of two NPDCCH repetitions, data in the NPDSCH is also transmitted with two repetitions. Finally, the ACK is sent over an NPUSCH F2 of 8 ms. The NPDSCH scheduling delay is the minimum gap of 4 ms and the ACK happens 12 ms after the data is received. Finally, the gap to start the monitoring of a new NPDCCH is at its minimum value, which is 3 ms.

![Figure 1.12 Downlink scheduling example](image-url)
CHAPTER 2. NB-IoT ANALYTICAL PERFORMANCE EVALUATION

2.1. Introduction

Once the characteristics of NB-IoT have been explained, the study and evaluation of the system will be performed from three different viewpoints: analytical, simulation and measurements. This chapter is devoted to calculations about the expected quality of service of NB-IoT under different scenarios, worst and best cases. Parameters such as total transmission time and data rate will be computed and results will be discussed.

For the downlink, the calculations will be performed over a 20 bytes short message that may contain an order to reconfigure a parameter of the device plus the new value. Additionally, calculations will be done for a 1 Mbyte packet, which can be a firmware update for the device. The case of the firmware update may be problematic since the network is mainly intended for small data transmission. The feasibility of this action will be assessed.

For the uplink, the calculations will be performed over an 8 bytes message, which would be more than enough for most sensor reports.

2.2. Assumptions

All the calculations performed in the following sections assume that:

- All the calculations are done considering in-band deployment. 164 dB of MCL corresponds to the worst case scenario, this means that the maximum redundancy is needed in terms of channel coding and repetitions. On the other hand, the 144 dB MCL corresponds to the best case scenario, meaning that no repetitions are needed and the code rate can be the highest possible in NB-IoT.

- There is just one device transmitting or receiving at the same time.

- It is assumed that transmission of system information blocks (broadcast messages) do not interfere with the data transmission. In case the operator overloads the system with many SIBs, the computed data rates would be reduced by a percentage of time devoted to such messages in average.

- The SINR is assumed to be good enough so that the Block Error Rate (BLER) is negligible for the coding and repetition scheme used in each case. Otherwise, the transmission time would lengthen accordingly.

- Regarding the scheduling timings that were explained in the previous chapter:
- The scheduling delay between the control message that allocates uplink radio resources and the uplink data message itself (NPUSCH F1) is 8 ms.
- The additional time offset indicated by the control message that allocates downlink radio resources is 0 ms. This means that the gap between the control message NPDCCH and the downlink data (NPDSCH) is the mandatory minimum gap of 4 ms + 0 ms = 4 ms.
- It is considered a 12 ms gap between the NPDSCH that contains the downlink message and the required ACK (NPUSCH F2).
- After an uplink transmission, the next search space for new control channels is 3 ms.

- The application data needs to be protected with some headers. Table 2.1 contains the headers that have been assumed for all the OSI layers.

- The application level is the Constrained Application Protocol (CoAP) which is a specialized web transfer protocol for constrained networks in the Internet of Things and it is designed for Machine-to-Machine applications.
- For the transport level, User Data Protocol (UDP) is used with its minimum header.
- The network layer protocol is the Internet Protocol version 4 (IPv4).
- The data link layer in cellular networks is divided into three protocols, Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC) and MAC. Note that PDCP performs robust header compression, thus a reduction is applied to the IP and UDP headers giving a 1B header for both IP and UDP [6].

**Table 2.1 NB-IoT headers proposition**

<table>
<thead>
<tr>
<th>Type</th>
<th>Size [bytes]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoAP</td>
<td>4</td>
</tr>
<tr>
<td>UDP</td>
<td>8</td>
</tr>
<tr>
<td>IPv4</td>
<td>20</td>
</tr>
<tr>
<td>PDCP</td>
<td>5</td>
</tr>
<tr>
<td>RLC</td>
<td>2</td>
</tr>
<tr>
<td>MAC</td>
<td>2</td>
</tr>
<tr>
<td>Total (with PDCP reduction)</td>
<td>14</td>
</tr>
</tbody>
</table>

In Section 1.3.1 the signals for the downlink channel were presented. Considering all the signals and their periodicity, it is possible to define a downlink signaling cycle of 20 ms (Figure 2.1)
Figure 2.1 Downlink signaling cycle

Every 20 ms just 15 ms, 15 subframes, can be used for NPDSCH or NPDCCH. When the calculations are performed, this fact has to be considered. Most documents on NB-IoT calculations just multiply the number of required subframes by 4/3 (=20/15). For example, when one subframe (1 ms) of NPDSCH or NPDCCH has to be transmitted, it is considered that it will take 1 ms × 4/3 = 1.33 ms on average. This is the approach that has been followed in subsequent calculations in this chapter.

However, it is important to note that the previous calculation has a slight error. The frame structure of NB-IoT, with periodic NPBCCHs and synchronization signals, means that a 1 ms transmission can potentially take 1, 2 or 3 ms. When the transmission time “collides” with a NPBCCH or NPSS (4 in 20 subframes), it will have to wait until the next available subframe and thus, the transmission will take 2 ms. Also, if the transmission should be done where there is a NSSS signal (1 in 20 subframes), the transmission will last 3 ms. This is because after the 20th subframe, which has the NSSS the subframe, there is an NPBCCH. For the rest of the cases (15 in 20 subframes), the transmission may happen right away and so it just takes 1 ms. If we compute the time considering this behaviour we have that the average time to transmit 1 subframe is:

\[
t = 1 \text{ ms} \times \frac{15}{20} + 2 \text{ ms} \times \frac{4}{20} + 3 \text{ ms} \times \frac{1}{20} = 1.3 \text{ ms}
\]  

Note the slight difference between 1.33 and 1.3 ms. This is a 2.5 % of error in the first approach.

2.3. Downlink

For DL calculations, just the “raw” data transmission process is computed. This means that the device is assumed to have accessed the cell already, so the random access procedure has already happened.

2.3.1. 20 bytes report

The first calculation will be done considering an application data of 20 bytes that may contain an order to reconfigure a parameter of the device plus the new value. First of all, it will be performed under the worst case scenario (extreme deep
coverage situation) with the highest redundancy values allowed by NB-IoT specifications.

- MCL: 164 dB
- NPDSCH repetitions: 2048
- NPDCCH maximum repetitions: 2048
- NPDCCH repetitions: 2048
- NPUSCH F2: 8 ms RU with 128 repetitions, 1024 ms

From Section 2.2 the headers size without considering the MAC one is 12 bytes, then the packet size is 32 bytes. The situation of extreme deep coverage requires the lowest TBS index available (Section 1.3.1.5). From Table 1.2 the TBS index selected is 0. The higher TBS value for the selected TBS index is 256 bits and it is not enough for transporting the total 272 bits at the RLC level. The RLC will divide the packets to fit them in the TBS.

From the 256 bits of TBS there are only 240 bits (16 bits are reserved for MAC header) available for data payload, thus:

\[
\text{MAC packets} = \left\lceil \frac{256 \text{ bits}}{240 \text{ bits}} \right\rceil = 2 \text{ packets} \quad (2.2)
\]

Therefore, 2 packets will be necessary to send the application data. There are two transmission possibilities:

- Static TBS for each complete transmission: The transmission is done with one packet of 256 bits (240 bits of data + 16 bits of MAC header) and another packet of 256 bits (16 bits of data + 16 bits of MAC header + 224 bits of padding). This solution consists in adding padding to the small packet in order to not change the TBS.

- Dynamic TBS for each complete transmission: The transmission is done with one packet of 256 bits (240 bits of data + 16 bits of MAC header) and another packet of 32 bits (16 bits of data + 16 bits of MAC header).

The adopted possibility is the second one, and so two TBS are managed:

- TB size index: 0, TBS: 256 bits, Number of subframes: 10
- TB size index: 0, TBS: 32 bits, Number of subframes: 2

The time it takes to send the NPDSCH is:

\[
T_{\text{NPDSCH}} = (10 \text{ subframes} + 2 \text{ subframes}) \times 2048 \text{ rep} \times \\
\times 1 \text{ ms} \times \frac{20 \text{ ms}}{15 \text{ ms}} = 32.768 \text{ s} \quad (2.3)
\]
Now it has to be added the time that takes to transmit the NPDCCH which carries the control information of the DL scheduling. Considering the number of repetitions and the fact that the DCI Format N1 occupies 1 subframe, the time is:

\[ T_{\text{NPDCCH}} = 1 \text{ ms} \times 2048 \text{ rep} \times \frac{20 \text{ ms}}{15 \text{ ms}} = 2.73 \text{ s} \quad (2.4) \]

As there are two packets, the eNodeB sends two DCI Format N1 messages, one for each TB. In order to finish the calculation of the transmission time, the transmission gaps mentioned in Section 2.2 have to be added as well as the NPUSCH F2 message that will carry the corresponding N/ACK. Hence, the total transmission time is:

\[
T_{\text{TX}} = T_{\text{NPDSCH}} + 2 \times T_{\text{NPDCCH}} + 2 \times 4 \text{ ms} + \\
+ 2 \times 12 \text{ ms} + 3 \text{ ms} + 2 \times 1024 \text{ ms} = 40.313 \text{ s} \quad (2.5)
\]

Then the data rate can be computed as:

\[
r = \frac{160 \text{ bits}}{40.313 \text{ s}} = 3.97 \text{ bps} \quad (2.6)
\]

This data rate is very low when compared to the speed that a user can experience in a classic mobile network, but it must be kept in mind that the bandwidth is just 180 kHz and information is highly protected by using 2 bits per symbol, very low code rate and many repetitions. This protection is required since the coverage conditions are bad. On the other hand, such deep coverage conditions would not be possible in such networks.

Let’s now relax the coverage situation and compute the transmission time and effective data rate for the best case, meaning with the lowest values for repetitions allowed by NB-IoT specifications. The conditions are:

- MCL ≤ 144 dB
- NPDSCH repetitions: 1
- NPDCCH maximum repetitions: 1
- NPDCCH repetitions: 1
- NPUSCH F2: 2 ms RU with 1 repetition, 2 ms

The packet size remains 32 bytes at the RLC level. Now, thanks to the better coverage conditions, the TBS index selected has the highest possible channel coding rate, in particular number 10 in Table 1.2. Having a look at the possible TBS values, the smallest one being able to accommodate 256 bits of data + 16 bits of MAC header is 328 bits and using 2 subframes. This means that 56 bits of padding are added to fill the TBS. Following the same approach as in the previous section, it is concluded that:

\[
T_{\text{NPDSCH}} = 2 \text{ subframes} \times 1 \text{ rep} \times 1 \text{ ms} \times \frac{20 \text{ ms}}{15 \text{ ms}} = 2.6 \text{ ms} \quad (2.7)
\]
The theoretical and experimental analysis of NB-IoT technology

\[ T_{\text{NPDCCH}} = 1 \text{ ms} \times 1 \text{ rep} \times \frac{20 \text{ ms}}{15 \text{ ms}} = 1.3 \text{ ms} \tag{2.8} \]

\[ T_{\text{TX}} = T_{\text{NPDSCH}} + T_{\text{NPDCCH}} + 4 \text{ ms} + 12 \text{ ms} + 2 \text{ ms} = 22 \text{ ms} \tag{2.9} \]

Then, the data rate is:

\[ r = \frac{160 \text{ bits}}{22 \text{ ms}} = 7.27 \text{ kbps} \tag{2.10} \]

The peak data rate at MAC level for in-band deployments is 170 kbps. However, for the best case scenario, the effective data rate is 7.27 kbps. This difference is caused by the transmission of the NPDCCH, the gaps between transmissions and the delays that the downlink signaling generates that are included in the calculation. Recall that the 170 kbps are at MAC level and the obtained 7.27 kbps are at application level. The headers from the upper layers also affect to the throughput. In addition, although the selected TBS Index is the highest possible for in-band deployment, the TB is not the highest possible. This is caused because the data fits into a lower TB within the same TBS Index.

The worst coverage case scenario has an effective data rate of 3.97 bps. This low data rate is caused for the previous reasons plus the high level of redundancy and the high protection of the data which allocates less bits per subframe and thus reduces the peak data rate. Figure 2.2 shows a chart with the summary of the transmission times for NPDCCH, NPDSCH, the total transmission time and the throughput.

![Figure 2.2 Transmission time summary](image)

The transmission time difference between the worst case scenario and the best one is of 40.29 seconds. It can be noted that the configuration chosen by the scheduler has a huge impact on the transmission time. For this reason, it is very important that the eNodeB has a good estimation of the coverage conditions and can adapt with the minimum redundancy that guarantees a correct reception.
2.3.2. 1 Mbyte Firmware Update

NB-IoT is mainly designed for small data packet transmissions that are delay tolerant in general. Despite that fact, it may be necessary to send a firmware update to a device through NB-IoT. This section will cover that case, in particular for an app data of 1 Mbyte. It is assumed that 1 Mbyte is $10^6$ bytes.

The considered Maximum Transport Unit (MTU) for the IP layer will be 1500 bytes, which is a typical value. 20 bytes of IP header, 8 bytes of UDP header and 4 bytes of CoAP header have to be reserved. This leaves a space of 1468 bytes for application data inside the IP packet. Therefore, the number of necessary IP packets is:

$$\frac{10^6 \text{ bytes}}{1468 \text{ bytes}} = 681.199 \text{ IP packets} \quad (2.11)$$

In particular, there will be 681 packets of 1500 bytes and 1 packet of 324 bytes (292 bytes of data and CoAP, UDP, IP headers). These 682 packets arrive to the PDCP that applies a compression of the IP/UDP headers from 28 bytes to 1 byte. PDCP adds a header of 5 bytes and RLC 2 bytes. This means there are 681 packets of 1480 bytes and 1 packet of 304 bytes at the RLC layer.

Again, as for the best case scenario in the previous section, the TBS index selected is 10. There is no TBS able of fit a packet of 1480 bytes neither of 304 bytes. Thus, the maximum TBS is initially chosen: 680 bits in 4 subframes. The TBS has to contain the data and the MAC header (16 bits) so just 664 bits of data per packet are available. The first 1480 bytes require:

$$\frac{1480 \text{ bytes} \times 8 \text{ bits/bytes}}{664 \text{ bits}} = 17.83 \text{ MAC packets} \quad (2.12)$$

This means 17 packets plus 552 bits that also need a maximum TBS. Similarly, the RLC packet of 304 bytes is transmitted in 3 packets with maximum TBS and an extra TBS that can be smaller: 504 bits in 3 subframes (TB size index 10). To sum up, these are the packets that the eNodeB is going to transmit:

- 12,261 packets with TB size index: 10, TBS: 680 bits and transmitted in 4 subframes.
- 1 packet with TB size index: 10, TBS: 504 bits and transmitted in 3 subframes.

Now, the transmission time for the NPDSCH is:

$$T_{NPDSCH} = (12.261 \text{ packets} \times 4 \text{ subframes} + 1 \text{ packet} \times 3 \text{ subframes}) \times \frac{1 \text{ ms}}{1 \text{ rep}} \times \frac{20 \text{ ms}}{15 \text{ ms}} = 65.396 \text{ s} \quad (2.13)$$
The time it takes to transmit the NPDCCH is:

\[ T_{NPDCCH} = 1 \text{ ms} \times 1 \text{ rep} \times \frac{20 \text{ ms}}{15 \text{ ms}} = 1.3 \text{ ms} \]  

(2.14)

Finally, the calculation of the total transmission time can be done. This is the time between the scheduling information (DCI Format N1) and the reception of the N/ACK (NPUSCH F2) corresponding to the last packet. All the transmission gaps are considered and an NPUSCH F2 of 2 ms is applied:

\[ T_{TX} = T_{NPDSCH} + 12.262 \times T_{NPDCCH} + 12.262 \times 4 \text{ ms} + 12.262 \times 12 \text{ ms} + \\
+ 12.261 \times 3 \text{ ms} + 12.262 \times 2 \text{ ms} = 339.24 \text{ s} = 5 \text{ min 39 s} \]  

(2.15)

The data rate then:

\[ r = \frac{10^6 \text{ B}}{339.24 \text{ s}} = 23.58 \text{ kbps} \]  

(2.16)

The effective data rate is now higher than the best case of the 20 bytes packet. When the 20 bytes packet was transmitted using 2 subframes and 328 bits, just 160 bits were application level data, the TB was not being used to the maximum. Since the packet is much bigger now, there are several transmissions using the maximum data rate for in-band deployments (TBS index 10 and 680 bits in 4 subframes) with 664 bits of application data (16 bits are reserved for MAC header), the maximum possible. Thanks to that, the data rate increases achieving 23.58 kbps.

Even though, 23.58 kbps is a rather low data rate, a firmware update is expected to be a rare event. It is important to note that the DL channel would be collapsed just for one device during 5 min unless extra PRBs are used for NB-IoT. Another solution is introducing transmission gaps in the DL to give space for other devices to transmit, but this would increase the total transmission even more.

It is also important to note that this time is an upper bound since good coverage conditions are assumed. If the calculations are repeated for the deep coverage case, the data rate would be just 7.62 bps, which yields a total transmission time of more than 12 days. The calculations are pretty similar to the previous ones and can be found in ANNEX 2. This seems a prohibitive download time, so firmware downloads could be reserved just for UEs having good coverage conditions. In Figure 2.3 a chart with the summary of the transmission times for NPDCCH, NPDSCH, the total transmission time and the throughput is available.
2.4. Uplink

For UL calculations, it will be assumed that the UE needs to send a scheduling request and so a random access procedure is needed. The UL calculations are thus performed considering the UL NPRACH opportunities. Just one calculation will be performed over an 8 bytes report for the best and worst case scenario. The same headers as the DL case are used.

2.4.1. 8 bytes report

The calculation of the data rate and the time that is going to take to send a report of 8 bytes from the device to the eNodeB for the worst case scenario (extreme deep coverage) has the configuration:

- MCL: 164 dB
- NPUSCH F1 repetitions: 128
- NPUSCH F2: 3.75 kHz subcarrier index 38, time offset value 13 and 128 repetitions with a RU of 8 ms.
- NPRACH repetitions: 128
- NPDCCH maximum repetitions: 2048
- NPDCCH repetitions: 2048
- NPRACH Format 1: 6.4 ms
- NPRACH CE 2

The situation of extreme deep coverage requires the lowest TBS index available (Section 1.3.2.2). From Table 1.4, the TB size index selected is 0. Doing similar calculations as in the DL, we conclude that the device will send a unique packet of 208 bits + 24 bits (CRC) over 8 RU. The basic time unit in the uplink is the RU and not the subframe as it was in the DL. The RU size scales with the bandwidth used. In particular, the transmission of NPUSCH Format 1 can be done using 3.75 kHz or 15 kHz subcarrier spacing. The different RU are shown in Table 2.2.
Table 2.2 Uplink resource unit summary – NPUSCH Format 1

<table>
<thead>
<tr>
<th>Δf</th>
<th>Resource Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Num. Subcarriers</td>
</tr>
<tr>
<td>3.75 kHz</td>
<td>1</td>
</tr>
<tr>
<td>15 kHz</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>12</td>
</tr>
</tbody>
</table>

The calculation of the NPUSCH transmission time depending on the RU length is:

\[ T_{\text{NPUSCH}} = 8 \text{ RU} \times \text{RU length} \times 128 \text{ reps} \quad (2.17) \]

Therefore, depending on the number of subcarriers used by the UE, the RU will take longer. Table 2.3 shows the total transmission time of the NPUSCH containing the 8 bytes of data that the device sent.

Table 2.3 NPUSCH total transmission time

<table>
<thead>
<tr>
<th>Δf</th>
<th>Resource Unit</th>
<th>Tx time (without RA procedure)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Num. Subcarriers</td>
<td>Num. Slots</td>
</tr>
<tr>
<td>3.75 kHz</td>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td>15 kHz</td>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>2</td>
</tr>
</tbody>
</table>

In the following, it is assumed that the shaded case in the table has been chosen. Since just 1 subcarrier is used, it is assumed that first one in the PRB is allocated by the control channel. From the table, raw data transmission time can be obtained, but the control channel and the access procedure need to be added too. In particular, the time it takes to transmit the scheduling information in the corresponding downlink control channel (DCI Format N0 in NPDCCH) is:

\[ T_{\text{NPDCCH}} = 1 \text{ ms} \times 2048 \text{ rep} \times \frac{20 \text{ ms}}{15 \text{ ms}} = 2.73 \text{ s} \quad (2.18) \]

Regarding the time it takes to access the system, the explanation of the RA was done in Section 1.4.2. It was revealed the complexity of the RA procedure and the many configurations it has. It will be shown how certain configurations may affect the attainable throughput in a very negative manner.

The NPRACH message is going to be transmitted considering preamble 1 which allows the longest coverage radius, up to 40 km. The preamble 1 has a TTI of
6.4 ms that has to be transmitted with 128 repetitions. Three different NPRACH access opportunities are defined and the UE will choose one or the other based on its coverage level. They are described next and plotted in Figure 2.4:

- **NPRACH CE 0**: This corresponds to UEs under good or average coverage conditions. For this reason, the NPRACH does not need too much redundancy and it occupies very few subframes. Hence, a short periodicity is chosen so that UEs do not experience a long latency due to the delay to get access to the network. This configuration is represented in blue color. In particular, the opportunities occupy the upper 24 subcarriers (3.75 kHz). Two preamble repetitions are used, meaning $2 \times 6.4 \text{ ms} = 12.8 \text{ ms}$, thus taking 13 subframes. The periodicity is 40 ms.

- **NPRACH CE 2**: This would be the other extreme case, deep coverage conditions. In this case, a lot of redundancy is required to maximize the likelihood of correct reception. This means very long NPRACH transmissions and the corresponding occupation and blockage of its subcarriers for other users. As a consequence, the periodicity will be configured much longer and UEs will have a larger average access delay. The opportunities for the devices under CE 2 level occupy 12 subcarriers (3.75 kHz) from the 13th to the 24th, represented in red. The preamble is repeated 128 times yielding 820 complete subframes. It can be noticed the transmission gap every 64 NPRACH preambles. Remember the gap is introduced to allow the resynchronization with DL reference signals in low-cost oscillators. The periodicity is 1280 ms.

- **NPRACH CE 1**: Finally, this is the case of UEs under bad coverage conditions but not as extreme as in CE 2. The opportunities occupy 24 subcarriers (3.75 kHz) from the 1st to the 24th, in green color. The same periodicity as in CE 2 has been chosen (1280 subframes) so that it does not collide with NPRACH CE 2. Considering that 16 preamble repetitions are used, 103 subframes are occupied every 1280 subframes, much less than in CE 2. On the other hand, it is important to notice that since data is scheduled on the 1st subcarrier, the device might have interruptions by this NPRACH. Then, the device can only use 1177 ms out of 1280 ms (NPRACH CE 1 occupation is 8.04 %). The time for the data transmission is updated accordingly:

$$T'_{NPUSCH} = 32.768 \text{ s} \times \frac{1280 \text{ ms}}{1177 \text{ ms}} = 35.636 \text{ s} \quad (2.19)$$

Similarly to the NPRACH, 40 ms gaps are needed between blocks of 256 ms. Thus the average transmission time is:

$$T_{NPUSCH} = 35.636 \text{ s} + \left\lfloor \frac{35.636 \text{ s}}{0.256 \text{ s}} \right\rfloor \times 40 \text{ ms} = 41.2 \text{ s} \quad (2.20)$$
Now that the whole RA procedure has been characterized, the calculation of the time it takes to make the whole RA procedure can be performed. The RA procedure requires an exchange of messages between the device and the network so that access is granted. Such messages were explained in Figure 1.10 and they use the normal pair of control plus data channels. These are very brief messages so they occupy 1 subframe in the DL and 1 RU in the UL. Maximum redundancy (2048 repetitions) is used in this example.

The message 1 is the transmission of the NPRACH preamble itself. We assume the device selects NPRACH CE 2, therefore, from Figure 2.4:

$$T_{msg1} = 820 \text{ ms} + 40 \text{ ms} = 860 \text{ ms} \quad (2.21)$$

Then for the control and data channels devoted to message 2 in DL, the average transmission time would be $T_{msg2}$, scheduling delays will be added when computing the total time:

$$T_{msg2} = (1 \text{ ms} \times 2048 \text{ rep} + 1 \text{ ms} \times 2048 \text{ rep}) \times \frac{20 \text{ ms}}{15 \text{ ms}} = 5.462 \text{ s} \quad (2.22)$$

The message 3 is an uplink transmission, so it takes 1 RU, meaning 32 ms in this example. It is necessary to consider the time occupied by NPRACH opportunities:

$$T_{msg3} = 32 \text{ ms} \times \frac{1280 \text{ ms}}{1177 \text{ ms}} = 34.8 \text{ ms} \quad (2.23)$$

The message 4 is again an NPDCCH followed by the NPDSCH, so the time is the same as in message 2, 5.462 s.

After message 4, the last step is its acknowledgement, a single tone signal (3.75 kHz) carrying NPUSCH F2. The RU is 8 ms and it is repeated 128 times. In this case, it is allocated in the upper subcarrier so that NPRACH occupations have a lower impact. Here, the percentage of time that NPRACH leaves free is 67.5% and 40 ms gaps are also needed between blocks of 256 ms.
\[ T_{NPUSCH\ F2} = 8\text{ ms} \times 128\text{ reps} \times \frac{40\text{ ms}}{27\text{ ms}} = 1517.03\text{ ms} \tag{2.24} \]

\[ T_{NPUSCH\ F2} = 1517.03\text{ ms} + 40\text{ ms} \times \left\lfloor \frac{1517.03\text{ ms}}{256\text{ ms}} \right\rfloor = 1717.03\text{ ms} \tag{2.25} \]

The total time of the RA procedure can be calculated as the sum of all the messages and gaps/scheduling delays:

\[ T_{RA} = T_{msg1} + T_{msg2} + 4\text{ ms} + 12\text{ ms} + T_{msg3} + 3\text{ ms} + T_{msg4} + 4\text{ ms} + 12\text{ ms} + T_{NPUSCH\ F2} = 13.571\text{ s} \tag{2.26} \]

The total transmission time for the report of 8 bytes considering all the gaps is:

\[ T_{TX} = T_{RA} + 3\text{ ms} + T_{NPUSCH} + 2 \times T_{NPDCCH} + 8\text{ ms} + 3\text{ ms} = 60.24\text{ s} \tag{2.27} \]

Finally, the uplink data rate can be calculated as:

\[ r = \frac{8\text{ bytes} \times 8\text{ bits/bytes}}{59.8\text{ s}} = 1.07\text{ bps} \tag{2.28} \]

From these result we can observe that the worst uplink case provides a data rate that is seven times lower than the downlink. Deep coverage conditions are possible but just transmitting 1 bit every second, so it is clear that the system is intended for very short messages. For example, with a report every 24 h, there is no problem on receiving the 8 bytes report in 1 min from certain devices.

Application developers should be very well aware of this capacity and try to compress information as much as possible. Differential encoding of sensor data might be a good approach too. Nevertheless, it is important to remark that this is the lowest bound for the data rate. Devices that do not need the extra redundancy/protection would just need 139.98 ms (rate of 457.2 bps) which means a not noticeable delay for most applications. The calculations for this second case are rather similar and can be found in ANNEX 3. They follow the same steps as before but updating the channel configurations accordingly.

The peak data rate at physical layer for UL transmissions is 250 kbps for 1 ms RU length and 7.81 kbps for 32 ms RU length. There is a huge difference between the obtained data rates and the promised peak data rates at MAC level. The obtained data rates, include the time it takes to perform the random access procedure and the necessary gaps during the transmission reducing the data rate. As it happened with the DL calculations, the upper layer headers also affect to the throughput. In Figure 2.5 a chart with the summary of the transmission times for the random access, NPDCCH, NPUSCH F1, the total transmission time and the throughput is available.
Figure 2.5 Transmission time summary
CHAPTER 3. NB-IoT PERFORMANCE ANALYSIS SIMULATOR

3.1. Introduction

From the theoretical explanation of NB-IoT it was learned that the system has a lot of parameters to be tuned. There are several tradeoffs as for example:

- Short NPRACH cycles imply faster access to the network (lower latency) but longer transmission times.

- Providing connectivity to UEs in deep coverage conditions implies using a high number of repetitions for each packet, but it also implies very long transmission times and thus an increase in the system load and a reduction in the maximum number of devices that can be served.

- If the eNodeB is installed in an area without deep coverage conditions, more relaxed configurations can be used. So, the network would require a per eNodeB optimization, meaning different performance as well.

- Multi tone allocations are shorter in time but increase the PAPR and noise power, so they would not suit UEs far from the eNodeB.

- Long scheduling delays relax a lot the timing requirements on UEs but do impact negatively the transmission time.

- Scheduling allocations should be careful done and adapted to the set of UEs to be served so that NPRACH interruptions are minimized.

Chapter 2 provided some examples of transmission time and associated rate for best and worst cases in UL and DL, however there is a need to evaluate the performance of the system under any possible configuration. For this reason, a simulator of the NB-IoT technology has been developed. This will allow to evaluate the performance of different cases and analyze the impact of the parameters more easily.

The app was designed using App Designer, a functionality given by Matlab introduced in 2016 release. The application receives the name of NB-IoT Performance Analyzer and was written in Matlab R2018.

The code has been organized in three different parts that correspond to the three main tabs of the GUI: DL data rate, NPRACH configuration and UL data rate. The following sections explain in detail the purpose of each tab, which are its configurable parameters and some results extracted with the simulator.
3.2. Downlink Data Rate

3.2.1. Purpose

This is the first tab that is shown on the screen when the app is opened (Figure 3.1). The main goal of this section is to see a temporal representation of the downlink and the uplink for downlink transmissions.

It is important to recall that DL allocations occupy all the PRB, for this reason there is no purpose in including the frequency occupation analysis. Notice that this is extended for the corresponding UL N/ACK (NPUSCH F2), which the user can analyze in full detail in the corresponding UL tab.

Due to the fact that NB-IoT just supports half-duplex transmissions, whenever NPUSCH F2 coincides with DL signaling, both are represented but it must be understood that the UE is just transmitting and not decoding the signaling message.

Figure 3.1 DL Data Rate Tab

3.2.2. Configurable Parameters

There are several parameters to configure the system. The first one is a drop down list called “Scenario” and allows to switch between the best case scenario and the worst case one. This allows having this extreme configurations very quickly. Selecting one or another will change the rest of the parameters to match the scenario chosen. Nevertheless, all the parameters can be adjusted one by one as well.

The following parameter is “NPDCCH Max Rep” which is a drop down list of the selectable maximum repetition value for NPDCCH.

Next, there are two drop down lists with the NPDSCH and NPDCCH repetitions with the selectable values 1, 2, 4, 8, 16, 32, 64, 128, 192, 256, 384, 512, 768,
1024, 1536, 2048 and 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048 respectively. Remember that the selectable values for “NPDCCH repetitions” change depending on the “NPDCCH maximum repetition” value according to Table 1.1.

Regarding the NPUSCH F2, even though the length of the NPUSCH F2 depends on the number of repetitions and subcarrier spacing (3.75 kHz or 15 kHz), the DL tab just provides the final time value. The drop down list contains all the possible values generated by the combinations of repetitions and subcarrier spacing. In addition, there is another drop down list containing the “NPUSCH F2 Offset” which also depends on the subcarrier spacing but allows to select all the possible values. For informative purposes, the selected value informs the user if the value is valid for both or just 15 kHz subcarrier spacing. As previously indicated, the user is able to analyze the frequency aspects of NPUSCH F2 in the UL tab.

Then, another drop down list carries the information of the TB size index used in the system. All values ranging from 0 to 12 are available. Recall that TB size index 11 and 12 are not recommended for in-band deployments (see chapter 7.2.4.6 in [4]).

As it has been explained in Section 2.2 the downlink basic signals have a repetitive frame structure of 20 ms. The initial position drop down list has values ranging from 0 to 19 to select in which millisecond of this 20 ms structure the user wants to start and evaluate the downlink transmission. The presence of different common signals may increase the transmission time as previously explained.

“NPDSCH Additional Offset” is a drop down list that allows to extend the minimum gap of 4 ms between the NPDCCH and the NPDSCH. The possible values are 0, 4, 8, 12, 16, 32, 64, 128, 256, 512 and 1024 ms. The set of values change depending on the NPDCCH maximum repetition value according to Table 1.8.

The “Application Data” field carries how many bytes of data the user wants to send and it has available values ranging from 1 byte to 1 Mbyte. From here, the app is able to compute the TBS (bits) and number of subframes per repetition and the value is presented.

Finally, when the “Calculate” button is pushed, a graph and some numeric results are shown in the screen.

The graph shows a matrix of two by the number of milliseconds that the transmission lasts where each number represents a signal or a hole of 1 ms (1 subframe). A color code is used and a legend is displayed below the graph to help the user to understand which color represents each signal. The matrix is filled following the rules of NB-IoT so it is a simulation of what would occur in a real system. Then, it is easy to see that the results will not be the same as the ones calculated theoretically and that is the reason why the system also displays a field called approximation error that displays the percentage of error over the real transmission time.
The approximated transmission time and data rate are results that came from the methodology used in the theoretical calculations from the chapter 2 and then considering the 4/3 approximation that has been discussed in the same chapter. On the other hand, real transmission time and data rate are results that came directly from the displayed graph. A comparison on the results obtained from the simulator with respect to the theoretical calculations is shown in Table 3.1.

<table>
<thead>
<tr>
<th></th>
<th>Theoretical</th>
<th>Simulated</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 bytes</td>
<td>22 ms</td>
<td>21 ms</td>
<td>4.76</td>
</tr>
<tr>
<td>1 Mbyte</td>
<td>339.24 s</td>
<td>326.983 s</td>
<td>3.75</td>
</tr>
<tr>
<td>20 bytes</td>
<td>40.313 s</td>
<td>40.31 s</td>
<td>0.007</td>
</tr>
<tr>
<td>1 Mbyte</td>
<td>1049287.489 s</td>
<td>1049281.413 s</td>
<td>0.00057</td>
</tr>
</tbody>
</table>

It is remarkable that the committed error is higher when the redundancy is low. The error generated by the use of 4/3 approximation affects more to transmissions of a short number of subframes. During a given period of time X, with less redundancy more TB are transmitted and thus more times the error may be produced, however it may occur that just one transmission with high redundancy is produced in the same time and just one time the error is produced.

In order to see clearer the graph, using two edit fields, the user can select the range of milliseconds that wants to see in the graph. Clicking the button Zoom will perform a zoom between the selected values. When the user clicks Reset, the whole transmission is displayed.

3.2.3. Results

Thanks to the downlink tab, some interesting plots can be obtained in order to see the impact of the starting transmission point, or how different can be the transmission time calculated using the theoretical formulas with respect to the simulator.

3.2.3.1. Starting Transmission Point

Due to the fact that there is a downlink signaling cycle that lasts 20 ms (Figure 2.1), the point where the eNodeB initiates the downlink transmission may affect to the total transmission time. A simulation with the 20 different starting points going from 0 ms to 19 ms over a different packet sizes and the best case scenario are presented in Figure 3.2.
Figure 3.2 Extra time for best case scenario

The Y-axis shows the additional time with respect to the lowest transmission time achieved with the different initial positions. The extra time with respect to the lowest time is generated by the allocation of the NPDCCHs and NPDSCHs that may match with DL signaling. When the packet size increases the maximum delay does it too. The necessary number of subframes increases with the data size and there may be more potential collisions and thus more delay.

The same simulation was performed but considering the worst case scenario Figure 3.3. Note that the line corresponding to the 50 bytes data packet where is superposed with the 200 bytes line. Now it is more probable to have delays higher than 2 ms contrary to what happened in the best case. The tendency of higher delays for larger packet sizes it is kept with the best case.

Figure 3.3 Extra time for worst case scenario
3.2.3.2. **Theoretical Approximation Error**

Using the NB-IoT Performance Analyzer, the error committed by the classic transmission time approximation (explained in Section 2.2) is done. Recall that it is often assumed that just 15 ms in 20 ms are usable and the starting time effect is omitted. This starting time does have an impact on both control and data channels that generates an error in the theoretical calculations represented in Figure 3.4.

\[
\begin{align*}
\text{Figure 3.4} & \quad \text{Approximation error for best case scenario. Each line represents each possible starting point.} \\
\end{align*}
\]

The plot shows the 20 possible allocations within the 20 ms downlink signaling cycle, for different data packets ranging from 50 bytes to 1 Mbyte. The Y-axis displays the approximation error, 5% means that the theoretical calculation of the total transmission time was a 5% larger than the simulated one. Hence, each line represents the approximation error for 1 of the 20 possible starting points. The error is in fact a consequence of the extra time introduced by broadcast and synchronization signals, as seen in the previous section. It is interesting to see that when the size of the packet increases, starting around 10 Kbytes, the approximation error converges into 3.75%.

\[
\begin{align*}
\text{Figure 3.5} & \quad \text{shows the worst case scenario. Again, each line represents the approximation error for different packet sizes for a given position inside the downlink signaling cycle.} \\
\end{align*}
\]
The approximation error is calculated with respect to the theoretical calculation for packet size going from 50 bytes to 1 Mbyte. As it happens with the approximation error for best case scenario, around the 10 Kbytes packet size, the error converges, but this time to $1.08 \times 10^{-3}$ %. Compared to the best case scenario, the error is much smaller and it is almost 0% for big packet sizes. As it has been mentioned previously, when the redundancy increases, the downlink transmissions, both data and scheduling information, are more likely to last more than one downlink signaling cycle. Hence, for a given period of time, the lower the redundancy, the higher the number of different transmissions in which an error can occur. In that case, with the maximum redundancy (2048 repetitions) the 4/3 approximation is correct during a large period of time.

### 3.3. NPRACH Configuration

This is the second tab of the application (Figure 3.6) and its goal is to prepare a random access channel configuration and see the different possibilities allowed by NB-IoT. The selected configuration will be used for the uplink tab.

#### 3.3.1. Configurable Parameters

As it has been explained in the Section 1.3.2.1 all the parameters may be declared for up to three CE levels.

The first parameter that must be configured is the number of repetitions per preamble attempt. The possible values are 1, 2, 4, 8, 16, 32, 64, and 128 repetitions. At the beginning, just the CE 0 is enabled because the CE 1 options will change depending on the value chosen in the CE 0. As more repetitions means more protection for users with worse MCL, the app will not allow the user to select less repetition than the previous CE level.
Theoretical and experimental analysis of NB-IoT technology

The number of selected subcarriers for the preambles of the different CE levels can be 12, 24, 36 and 48. The user also has to configure the “Subcarrier offset” for every CE level and the different possible values are 0, 12, 24, 36, 2, 18 and 34. The periodicity of the preamble for the different CE levels can be configured with 40, 80, 160, 240, 320, 640, 1280 and 2560 ms. The last parameter is the “Preamble basic TTI” which can be 5.6 ms or 6.4 ms.

The user should be cautious when selecting the different configurations because it may appear collision between the different NPRACH opportunities of the different CE levels.

The app also gives the possibility of loading two different configurations predefined. Button load preset 1 generates the configuration of Figure 3.7 whereas the button load preset 2 generates the configuration of Figure 3.8. The preset 2 configuration is the one that is used to perform the uplink calculations in chapter 2 and 3 (the preamble TTI is 5.6 ms for best case and 6.4 ms for worst case).
Once all the parameters are configured, the user can click the generate button which will generate a matrix of 48 by 2560 that represents the 48 possible subcarriers of 3.75 kHz and the 2560 milliseconds which is the maximum periodicity allowed by NB-IoT for a preamble attempt. The matrix is represented in a graph following a color code explained below the graph. Now, the user is ready to go to the uplink data rate tab.

### 3.3.2. Results

The NPRACH Configuration may affect to the performance of the UL channel. It is important to find a balance between the number of repetitions, periodicity, number of subcarriers and subcarrier offset in order to be able to cover all the possible users in the different CE levels. Aggressive configurations to support a lot of users in deep coverage may result in some subcarriers with a low number of subframes available for NPUSCH transmissions. Figure 3.9 shows the percentage of free subframes over each subcarrier for 5 different NPRACH Configurations. The different NPRACH configurations are available in Figure 3.10. The configuration number two is a configuration focused on deployments where it may be a huge number of devices in deep coverage conditions. For deployments where the number of devices under deep coverage conditions is similar to those in bad coverage conditions the configuration 1 may be optimal. With the configuration number 3, the objective is to give 12 subcarriers free of NPRACH opportunities and just to be used for uplink data transmission. The users under deep coverage conditions would have low latency to access the network. Configuration number 4 is another variant for balanced deployments whereas the configuration number 5 is an example of what it may be an incorrect configuration.

![Figure 3.9 Percentage of NPUSCH opportunity](image)

There are too aggressive configurations like the number 5. It will allow a lot of devices with very bad coverage to access to the system fast but at the same time, it will collapse the system just giving a 37% of available time to send uplink data.
Figure 3.10 NPRACH Configurations 1 to 5. Configuration 1 is preset 1 and configuration 2 is preset 2 in the app.
As it has been explained before it may be an incorrect configuration. On the other hand, there are configurations like the number 1 and number 4 that are more balanced and are ideal for scenarios where most of the devices are in good coverage. In all the subcarriers there are from 73% to 93% of free subframes.

### 3.4. Uplink Data Rate

#### 3.4.1. Purpose

This is the third tab of the application (Figure 3.11). The main goal of this section is to characterize the UL data transmission of a packet smaller than 1 Kbyte considering the NPRACH configuration of the second tab. Now, unlike the downlink data rate tab, the NPUSCH F2 can be allocated in different subcarriers according to the valid NB-IoT configuration parameters. Therefore, frequency information is also included in the graphical representation that the app provides.

![Figure 3.11 UL data rate tab](image)

#### 3.4.2. Configurable Parameters

The first parameter is the same one as in the DL data rate and it is a drop down list called Scenario that does the same action, selecting one or another will change the rest of the parameters to match the conditions of the worst or the best case.

There are several parameters that can be configured with respect to the NPUSCH F1. The first one is a list where the user can select the number of “NPUSCH F1 repetitions” configured that can be 1, 2, 4, 8, 16, 32, 64 and 128. Next, there is a table with the 5 ways of configuring an NPUSCH F1 RU (Table 2.2). Clicking on any cell will select a RU length for the NPUSCH F1 which will be displayed in a label called “NPUSCH F1 RU Length”. The last one is another selectable list called “NPUSCH F1 Subcarrier/s” and it allows to select the subcarrier/s where the NPUSCH F1 is going to be allocated. The displayed values depend on the selected RU configuration (subcarrier spacing and number of subcarriers).
The users can select the “NPDCCH Max Repetitions”, “NPDCCH Repetitions”, “NPDSCH Repetitions” and “NPDSCH Additional Offset” configuration through a given list of values and work in the same way that were explained for the downlink tab in Section 3.2.2.

The user can select the “CE Level” for the NPRACH using a drop down list with the values 0, 1 and 2.

Regarding the NPUSCH F2 parameters, the “NPUSCH F2 Mode” allows the user to select between the 15 kHz and 3.75 kHz subcarrier spacing. Another list called “NPUSCH F2 Repetitions” allows the user to select the following repetition values: 1, 2, 4, 8, 16, 32, 64 and 128.

The “NPUSCH F2 Offset” gives the option to select the gap between the last downlink data transmission (NPDSCH) and the correspondent N/ACK signaled through an NPUSCH F2. When the “NPUSCH F2 mode” selected is 15 kHz, the selectable values are 13, 15, 17 and 18, otherwise 13 and 17 are available. The user, has also the possibility to select the “NPUSCH F2 Subcarrier” thus the subcarriers where the N/ACK are going to be allocated. Those values vary depending on the “NPUSCH F2 mode”, 1, 2, 3 and 4 when 15 kHz subcarrier spacing is selected and 39, 40, 41, 42, 43, 44, 45 or 46 when 3.75 kHz subcarrier spacing is selected. Two labels that help the user to understand what is happening with the NPUSCH F2: “NPUSCH F2 RU Length” which is 2 ms or 8 ms depending on the subcarrier spacing selected and “NPUSCH F2 Duration” which shows the total duration of the NPUSCH F2.

The “TB Size Index” drop down list, TBS label and RU per repetition label do the same function and work the same way as in the downlink data rate tab in Section 3.2.2.

Finally, the “Application Data” field indicates the number of data bytes to be sent in a range from 1 byte to 1 Kbyte.

Once the “Calculate” button is pushed, uplink results corresponding to the frame configuration, transmission time and data rate are computed and displayed. This is done in a similar manner as in the DL with the exception that now frequency information is also provided in the graph.

Simulation results can be compared with the theoretical transmission times, which allows us to estimate the error of common estimations. A comparison on the results obtained from the simulator with respect to the theoretical calculations is shown in Table 3.2.

**Table 3.2** Theoretical vs simulated transmission times

<table>
<thead>
<tr>
<th></th>
<th>Theoretical</th>
<th>Simulated</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 bytes Best Case</td>
<td>139.98 ms</td>
<td>197 ms</td>
</tr>
<tr>
<td>8 bytes Worst Case</td>
<td>60.24 s</td>
<td>60.929 s</td>
</tr>
</tbody>
</table>
It can be seen that for the best case, the simulated time is larger than the theoretical, exactly a 40.73% larger. When the theoretical calculation is performed, the time it takes to transmit the uplink data is multiplied by the periodicity of the NPRACH opportunities of the selected subcarrier (subcarrier 1) and divided by the free transmission time in the same subcarrier. This calculation increases the NPUSCH transmissions in this subcarriers by a few ms. When the simulation is performed the RA procedure starts at the beginning of the periodic NPRACH opportunities and the NPUSCH transmission has to wait until the opportunity for devices under CE Level 1 are finished, this increases the length of the transmission. The same thing happens for the worst case scenario but for the first uplink transmission.

3.4.3. Results

Different tests have been done to evaluate how the UL performance changes for different RU sizes and subcarrier allocations. For the best case scenario, the NPRACH configuration is the preset 2 with 5.6 ms of preamble TTI and for worst case scenario the preset 2 with 6.4 ms of preamble TTI (Figure 3.8).

For the sake of clarity, the table having the different UL transmission modes is presented again:

<table>
<thead>
<tr>
<th>Table 3.3 RU lengths for NPUSCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPUSCH format</td>
</tr>
<tr>
<td>Format 1</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Format 2</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

In Figure 3.12 there is an example of uplink transmission with 32 ms RU length, the X-axis represents the time and the Y-axis the subcarrier number (3.75 kHz subcarrier spacing). The yellow rectangle represents an NPUSCH F1 data transmission. Hence, for any allocation in the subcarrier between the number 24 and 48 the transmission time will be the same.

Figure 3.13 and Figure 3.14 show the required transmission time for the different NPUSCH F1 possibilities and allocating different subcarriers for the best case scenario and an 8 bytes transmission. The X-axis represents the different possible RU whereas the Y-axis represents the total transmission time in milliseconds. Inside each bar, there are the possible allocations for NPUSCH F1 where the result is the same one.
The NPUSCH F2 tone is sent using 15 kHz subcarrier spacing and the results are common if the 1\text{st}, 2\text{nd} or 3\text{rd} subcarrier are selected (Figure 3.13) but different if the selected subcarrier is the 4\text{th} (Figure 3.14). The different times are caused by the position of the selected subcarrier/s with respect to the NPRACH opportunities. This is not random and will depend on how the opportunities are configured.

At the beginning, it may seem strange to have an uplink N/ACK through an NPUSCH F2 in an UL transmission. This is caused because the last message of the random access procedure is an ACK and has to be signaled through an NPUSCH F2.
The first remarkable similarity between the two plots, is that for a set of configurations (transmission times of 859, 855, 492 and 857 ms) the position of the ACK for the random access (NPUSCH F2) does not vary the transmission time and the throughput. When the transmission of UL data coincides with the opportunities placed on subcarriers from 12 to 24, the position of the NPUSCH F2 does not affect. Placing the NPUSCH F2 in subcarrier 4 (still with 15 kHz subcarrier spacing) does not increase the time as it can be observed in Figure 3.15, where NPUSCH F1 is represented in yellow and NPUSCH F2 in pink.

The rest of transmission times have been increased because the position of the NPUSCH F2 affects to the total time as it can be appreciated in Figure 3.16 where NPUSCH F1 is represented in yellow and NPUSCH F2 in pink.
Something as simple as an ACK to finish the random access procedure can change a lot the throughput depending on its frequency allocation. For the first bar of both plots (32 ms RU length and any subcarrier from 1 to 12) the throughput is reduced from 280.7 bps to 120.3 bps if the single tone NPUSCH F2 is allocated in the subcarrier number 4. The throughput has been at least halved for all those cases.

At the same time, the influence of the bandwidth allocated for the UL data transmission (NPUSCH F1) is noticeable when it coincides with the bandwidth where the CE 2 random access opportunities are located. Recall that CE 2 opportunities are intended for UEs in the worst coverage conditions of the cell.

For the worst case scenario, the transmission of the ACK is performed with a single tone transmission of 3.75 kHz subcarrier spacing that. In Figure 3.17 the transmission times can be observed, in that case the position of the NPUSCH F2 does not affect. This is caused because for any of the possible allocations (subcarrier 39 to 46) the NPRACH interruptions are the same (Figure 3.13)

For the worst case scenario, there is a slight downward trend in the transmission time when the RU decreases (and allocated bandwidth increases). The noticeable peak that can be observed in the second bar happens due to the high redundancy used, large RU length and the allocation of subframes colliding with access opportunities more often. The transmission time is 2.5 times larger than the next longest.

One again, the redundancy can affect too much to the throughput (Table 3.4). To transmit 8 bytes with the highest possible redundancy (2048 repetitions) the maximum throughput is 2.79 bps, it is shown again that the technology is thought for low data transmissions and separated along the time. With the lowest redundancy possible the times are shorter and the maximum achievable throughput is 0.566 kbps.
Figure 3.17 Worst case scenario NPUSCH F2 3.75 kHz

Table 3.4 Throughput and transmission times summary

<table>
<thead>
<tr>
<th></th>
<th>Max. transmission time</th>
<th>Min. transmission time</th>
<th>Max. throughput</th>
<th>Min. throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Best Case</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NPUSCH F2</td>
<td>15 kHz (any subcarrier from 1 to 3)</td>
<td>883 ms</td>
<td>112 ms</td>
<td>571.42 bps</td>
</tr>
<tr>
<td><strong>Worst Case</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NPUSCH F2</td>
<td>3.75 kHz (any subcarrier from 39 to 46)</td>
<td>153.61 s</td>
<td>22.94 s</td>
<td>0.42 bps</td>
</tr>
</tbody>
</table>

There are several factors that affect the throughput in NB-IoT systems. During this section, it has been evaluated under the same NPRACH configuration. However, it has been observed that a slight change in the configuration of one of the CE levels, may drastically change the system performance. The network planner has to choose a balanced configuration to allow all the devices to access to the network. It is necessary to be cautious also with the format of the N/ACK (NPUSCH F2) and its allocation because it may increase the transmission time and reduce the throughput.
Future interesting tests should include different random access configurations to compare which one is better or gives the maximum throughput. This part of the simulator may be also upgraded to accommodate multiple devices transmitting at the same time to check how concurrent transmissions would eventually affect each other’s throughput.
CHAPTER 4. MEASUREMENTS OVER REAL NETWORK

4.1. Introduction

This chapter is a last step for the global evaluation of the NB-IoT technology. In this case, the study is done with real measurements by performing data transmissions over Vodafone’s network that will be analyzed. The Vodafone’s network will be introduced. The user equipment used will be explained as well as the scenario.

4.2. Test Scenario

During this section, the different tools used during the tests will be explained. The user equipment that was used and the network provider.

4.2.1. User Equipment

The hardware used to perform all the tests is the SODAQ SARA AFF R410M [7] (Figure 4.1). It is a developer’s board in the standard Arduino form factor. It has a 32 bits microcontroller, accelerometer, GPS and the NB-IoT module itself. The main features of the board are in Table 4.1.

![Figure 4.1 SODAQ SARA AFF R410M](image)
Table 4.1 SODAQ SARA AFF R410M Features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcontroller</td>
<td>ATSAMD21J18, 32-Bit ARM Cortex M0+</td>
</tr>
<tr>
<td>Compatibility</td>
<td>Arduino M0 Compatible</td>
</tr>
<tr>
<td>Size</td>
<td>Arduino Uno formfactor, 53.4 x 68.6 mm</td>
</tr>
<tr>
<td>Operating Voltage</td>
<td>3.3 V</td>
</tr>
<tr>
<td>I/O Pins</td>
<td>23</td>
</tr>
<tr>
<td>Analog Output Pin</td>
<td>10-bit DAC</td>
</tr>
<tr>
<td>DC Current per I/O pin</td>
<td>7 mA</td>
</tr>
<tr>
<td>Flash Memory</td>
<td>256 Kbytes</td>
</tr>
<tr>
<td>SRAM</td>
<td>32 Kbytes</td>
</tr>
<tr>
<td>EEPROM</td>
<td>Up to 16 Kbytes by emulation</td>
</tr>
<tr>
<td>Clock Speed</td>
<td>48 MHz</td>
</tr>
<tr>
<td>Power</td>
<td>5V USB power and/or 3.7 LiPo battery</td>
</tr>
<tr>
<td>Charging</td>
<td>Solar charge controller, up to 500mA charge current</td>
</tr>
<tr>
<td>NB-IoT</td>
<td>uBlox SARA N2XX, R4XX Series</td>
</tr>
<tr>
<td>GPS</td>
<td>uBlox SAM M8Q</td>
</tr>
<tr>
<td>Accelerometer/Magneteto</td>
<td>LSM303AGR</td>
</tr>
<tr>
<td>USB</td>
<td>MicroUSB Port</td>
</tr>
</tbody>
</table>

The NB-IoT module is the uBlox SARA-410M-02B [8]. The protocol stack is based on the 3GPP Release 13, thus it is an LTE Cat NB1 device. The power class number is 3, meaning a maximum transmission power of 23 dBm.

In order to control the module, AT commands are sent through the serial port, which is emulated through an USB cable. In the module’s firmware an AT command interpreter has been placed. The software used to send the AT commands is “m-center” provided by uBlox and free of charge (available in [https://www.u-blox.com/en/product/m-center](https://www.u-blox.com/en/product/m-center)).

The first time that the NB-IoT SIM card is introduced to the module, the AT commands shown in Table 4.2 have to be applied.

Table 4.2 Initial Configuration

<table>
<thead>
<tr>
<th>AT Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT+URAT=8</td>
<td>The command is used to select the radio access technology to be used by the module and the number 8 indicates that it is LTE Cat.NB1.</td>
</tr>
<tr>
<td>AT+CMEE=2</td>
<td>The result code of errors is enabled and verbose format is used.</td>
</tr>
<tr>
<td>AT+CGDCONT=1,&quot;IP&quot;,&quot;ep.inetd.gdsp&quot;</td>
<td>The command configures APN provided by Vodafone.</td>
</tr>
<tr>
<td>AT+CFUN=1</td>
<td>The command sets the module functionality to full functionality. For example AT+CFUN=4 would set the device in airplane mode.</td>
</tr>
</tbody>
</table>
Once these commands are configured, the module is ready to operate under NB-IoT technology, now it needs to connect to a network and start the transmission of data. The AT commands to perform these operations are in Table 4.3. For extra information of the commands and a full list of commands see [9].

Table 4.3 Transmission Configuration

<table>
<thead>
<tr>
<th>AT Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT+COPS=1,2,&quot;21401&quot;</td>
<td>The command is used to select the operator. The number 1 is used to select the manual mode, the 2 indicates that the operator will be indicated by number and the 21401 is the operator number of Vodafone NB-IoT in Spain.</td>
</tr>
<tr>
<td>AT+CEREG=2</td>
<td>This command is to see the EPS network registration status. When the selected CEREG is 2, it indicates that the command AT+CEREG? Will return the network registration and location information.</td>
</tr>
<tr>
<td>AT+CEREG?</td>
<td>The command will return the network registration and location information and it will display the mode, status of the registration, the tracking area update code and the cell id.</td>
</tr>
<tr>
<td>AT+USOCR=17</td>
<td>The command is used to create a socket, in the case of the transmissions in this project, it is done using the UDP protocol indicated by the number 17.</td>
</tr>
<tr>
<td>AT+USOST=0,&quot;147.83.118.42&quot;,3000,4,&quot;Data&quot;</td>
<td>The command is used to send UDP data. The first value which is 0 is the socket number (opened with the previous command), the second value is the remote IP. The third one indicates the remote port, the following one is the number of bytes that are going to be transmitted. Finally, the last one indicates the characters that are going to be sent.</td>
</tr>
<tr>
<td>AT+CSQ?</td>
<td>It is sent to know the signal quality. The command returns values going from 1 to 31 that are mapped into the Received Signal Strength Indicator (RSSI) from -111 dBm to -51 dBm. The RSSI represents the total power captured in a certain band including the useful signal, noise and interferences.</td>
</tr>
</tbody>
</table>
4.2.2. Scenario

The coverage at the laboratory where the tests were performed was but a shield box (Figure 4.2) was used to increase attenuation and emulate different coverage levels. It is remarkable that NB-IoT coverage was possible even inside the box, so indeed the system allows connectivity under very bad coverage conditions.

The module is connected to a laptop where the m-center program is opened to send the AT commands. In order to see when the module is awakened and consuming current, the data and power cables inside the USB cable are spliced with another cable connected to a current sensor and then to the oscilloscope. This is the way used to monitor when the device is checking for incoming paging messages and also to differentiate between idle or connected mode. Different power consumption levels will indicate the different situations.

At the same time, the module has an antenna which is used for transmitting and receiving data. So, data uplink data transmissions are also captured by using another antenna connected to a second channel of the oscilloscope.

The laptop and the digital oscilloscope are connected through Ethernet allowing to take snapshots of the oscilloscope directly from the laptop.

![Figure 4.2 Test scenario](image)

4.2.3. Network Provider

To perform the different tests over NB-IoT, the network carrier used is Vodafone Spain. The network carries the data using IP directly to the customer server using either UDP or TCP transport protocol. The nature of NB-IoT which is strongly message oriented drives to the prioritization of the UDP protocol. In case TCP is used, its timers must be tuned to account for the high latencies of the technology.
Vodafone is supporting NB-IoT in the 800 MHz frequency band. At that band, Vodafone operates LTE and owns several spectrum chunks, for the case of NB-IoT the guard band of a 10 MHz LTE signal is used. In particular, from 801-811 MHz for downlink and 842-852 MHz for uplink.

Figure 4.3 is a screenshot of an RF analyzer. The figure shows the RF signals from 800 to 802 MHz. Thanks to the max hold function it can be identified the end of an Orange LTE signal downlink that ends at 800.5 MHz (and leaves 500 kHz of guard band). On the right the LTE signal for Vodafone starts in 801.5 MHz. Finally, from 801.15 to 801.33 MHz the NB-IoT signal can be clearly identified, just in the middle of the 500 kHz guard band of Vodafone.

![RF Analyzer - 800 to 802 MHz](image)

The packet data network connections over NB-IoT can remain in place with an IP address still assigned to the device even when the device is asleep. Even though the possibility of buffering the messages until device is detected to be awake, the Evaluation Pack does not include Vodafone Messaging Service which is the service that provides this option. As a consequence, the network will discard the packets send to the device when is asleep.

To avoid IP fragmentation, the maximum packet size is 1280 bytes. Some of the previously presented theoretical and simulated calculations will be not tested over the real network due to this limitation.
4.3. Transmissions in Idle Mode

The firsts tests performed are done when the device is attached to the network and in idle mode. As it has been mentioned, the RF Shield Box is used to emulate two coverage conditions. The procedure previously mentioned to send a packet of data has been performed 6 times for the case of intermediate coverage with the box almost closed and 6 more times for a bad coverage scenario with the box closed. Using the oscilloscope, screenshots of all the tests will be explained, and when the tests are similar there will be a common explanation.

4.3.1. Transmission of an 8 byte packet

In this section, the transmissions will be performed with 8 bytes of data. The first analyzed case will be with the RF shield box almost closed representing a scenario of good coverage. Table 4.4 contains the CI, CSQ and RSSI in dBm of the 6 performed tests. The quality measures should be done using the RSRP. This device only gives the measurement of the RSSI and this may cause errors. It would be possible to have a good RSSI with a bad channel in presence of high interferences. Due to the fact that NB-IoT operates in licensed band and it is a relatively new system, no relevant interference is expected. Hence, the RSSI is considered a valid indicator of useful received power. It can be seen that the device is always connected to the same cell and the RSSI presents variations in a range of 12 dB, being always higher than -85 dBm.

<table>
<thead>
<tr>
<th>TEST</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI</td>
<td>151883D</td>
<td>151883D</td>
<td>151883D</td>
<td>151883D</td>
<td>151883D</td>
<td>151883D</td>
</tr>
<tr>
<td>CSQ</td>
<td>14</td>
<td>15</td>
<td>18</td>
<td>17</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>RSSI (dBm)</td>
<td>-85</td>
<td>-83</td>
<td>-77</td>
<td>-79</td>
<td>-73</td>
<td>-81</td>
</tr>
</tbody>
</table>

In Figure 4.4 the beginning of the transmission of the first test is displayed. All the images captured from the oscilloscope have the same format. The images display the two different channels that have been used. The yellow one represents the current consumption of the module. The green one is the uplink transmissions detected through the antenna. The blue values represent the gaps of time in ms observed between peaks of consumption. The red values represent the transmission time in ms of the module, whereas the yellow values represent the gaps observed between these transmissions also in ms.

Analyzing Figure 4.4 it can be observed that once the AT command is sent, there is a first packet of 11.2 ms recognized as the preamble thus the message 1 of the random access procedure. From its length, it is deduced that the preamble is of format 0 type (5.6 ms) repeated two times.

After the preamble, the different messages of the random access procedure can be identified. There is a first 24.8 ms gap which is equivalent to 24 subframes plus the one where the preamble finished. Inside this gap a pair of NPDCCH and
NPDSCH happen for message 2, but DL messages are not distinguishable from noise at the oscilloscope.

Next, message 3 is observed. We can see that the scheduler allocated an NPUSCH F1 with length of 8 ms. However, there are several combinations of RU length and repetitions for the subcarrier spacing of 15 kHz that fit this time considering that the TB can be transmitted in one RU. Some of them are 8 ms RU length with 1 repetition, 4 ms with 2 repetitions or 1 ms with 8 repetitions. Based on the fact that the scenario is of intermediate coverage and the preamble was with two repetitions, the first two possibilities are the most probable. This is confirmed in the next paragraph after looking at the following transmission event.

The next gap of 25 ms accommodates a new pair of NPDCCH and NPDSCH for message 4. The next message is the ACK of message 4, transmitted via NPUSCH F2. It may be observed that this signal is transmitted with higher power than the other NPUSCHs. NB-IoT standard states that if NPUSCH is transmitted with more than 2 repetitions, the UE shall use its maximum power. Thus we can conclude that the previous NPUSCH F1 only used 1 or 2 repetitions and used power control. Going back to the ACK, it is a 15 kHz signal with 2 ms RU and 4 repetitions. Another valid configuration would be a 3.75 kHz single tone signal with an RU length of 8 ms and 1 repetition. This option can be discarded because no power control is used. Right after the ACK, a radio resource control message should be sent (message 5) but it can be seen that this is the end of the random access procedure.

Figure 4.4 Test 1 - 8 bytes transmission (1st part)
Next, a gap of 563 ms is measured until there is new uplink transmission that will be called zone 2. This gap was 561 ms for tests 3 and 5. A new NPRACH preamble is observed with the same characteristics as the first one. For some reason data transmission did not happen after the first access to the network and the device used a second attempt.

Such type of situation was not considered by the simulator and it may increase transmission time in a high percentage. In particular, the observed distance from the beginning of the first random access and this one, is 640 ms. In Section 1.3.2.1 the different values for the NPRACH opportunities periodicity were explained and one of the values was 640 ms. It can be concluded then that this is the value of periodicity for a given CEL in Vodafone’s network.

Then, the same random access pattern is observed until the last message which has a longer length of 32 ms. It is likely that this longer message carries a message 5 indicating “RRC Connection Setup Complete” or “RRC Connection Resume Complete” and containing the user data. This is possible because NB-IoT allows to send data in control messages like this one. This feature is named “control plane cellular IoT optimization” and allows a more agile data transmission. In this case, the ACK to message 4 is not present.

It is observed that the total transmission time has been 754 ms which leads to an effective data rate of 84.88 bps. The comparison between the real obtained value and the simulated one may not be accurate. As it has been mentioned in chapter 3, the influence of the selected subcarrier to transmit uplink data (NPUSCH configuration) and the random access configurations may vary a lot the throughput. The obtained throughput is inside the range of values obtained for the best case scenario with the simulator ranges from 71.35 bps to 571.42 bps. It is important to remember that the simulator does not take into account this type of case where there is an additional NPRACH procedure before sending the data.

There is another pattern in that zone observed in test 2 (Figure 4.5). In this case, there was no need to transmit a second NPRACH and the data was immediately transmitted 150 ms later than the ACK to message 4. After the data, a 4 ms transmission happens. This one is not identified but it may be an NPUSCH F2 ACK to a downlink message after the data transmission. Next, there is a final exchange of information with an uplink transmission of 4 ms, followed by a 17 ms gap. It is likely that this gap contains an NPDCCH followed by an NPDSCH. The sequence ends with and another uplink transmission of 8 ms. There is an inactivity timer that when expires, it starts the procedure to go to Connected-DRX (C-DRX) so these messages may be the indication.

In a nutshell, the total transmission time for this second test was 350 ms that leads to a 182.86 bps effective data rate. This value is within the range of values obtained with simulations. The throughput has been doubled with respect to the test 1. The uplink resource allocation may be coinciding with some NPRACH preamble opportunities because it is far away than the maximum throughput obtained in the simulator. The reader can find the rest of tests in ANNEX 4, with slight differences with respect to test 1 and 2, as for example, additional retransmissions due to packet losses.
When the device it is in C-DRX it should remain in this state until the active timer finishes. This state was interrupted in all the tests after a time ranging from 2 to 4 s indicated as the time between zone 1 and 2 in Figure 4.6. An exchange of information similar to the previous one indicating that the device was going to C-DRX (4 ms UL + NPDCCH + NPDSCH + 8 ms UL) can be again observed but with a new random access to send the second packet (Figure 4.7). Then, the device goes again into C-DRX. The C-DRX state remains for 21.41 s. All the tests revealed a duration between 20 and 22 seconds. The C-DRX cycle is 2.048 seconds so the active timer (determines how long the C-DRX cycle will
last) is composed by 10 C-DRX cycles. When the C-DRX cycle finishes, the device goes into Idle-DRX (I-DRX) with a paging cycle of 2.56 s. The device remains in that state until receives downlink data or wakes up to perform a TAU (every 12 minutes in Vodafone’s network).

![Figure 4.7 Test 1 - 8 bytes transmission (2nd part)](image)

When the active timer finishes, the device has to go to idle mode. In Figure 4.8 the exchange of information to enter to idle mode is represented. The eNodeB is who initiates this exchange of information sending a NPDCCH and an NPDSCH. The exchange of information continues with two UL messages of 4 and 8 ms. The second one is likely to contain an “RRC Connection Release” after which the device goes to idle mode.

Subsequently, results are presented when the RF shield box was completely closed, thus representing a scenario of bad coverage. Table 4.5 contains the CI, CSQ and RSSI in dBm of 6 different tests. In this case, it can be seen that the device connects to two different cells, 151883D and 13C163E, the second one showing between 4 and 10 dB less RSSI. The coverage loss with respect to the previous case is around 20 dB.

<table>
<thead>
<tr>
<th>TEST</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI</td>
<td>151883D</td>
<td>151883D</td>
<td>151883D</td>
<td>13C163E</td>
<td>13C163E</td>
<td>13C163E</td>
</tr>
<tr>
<td>CSQ</td>
<td>7</td>
<td>7</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>RSSI (dBm)</td>
<td>-99</td>
<td>-99</td>
<td>-103</td>
<td>-107</td>
<td>-109</td>
<td>-109</td>
</tr>
</tbody>
</table>
Measurements over real network

Figure 4.8 Test 1 - 8 bytes transmissions (3rd part)

The beginning of the transmission in test 1 is shown in Figure 4.9. The random access procedure is seen on the green channel. The preamble is format 0 (5.6 ms) repeated 8 times thus 44.8 ms of NPRACH. This contrasts with the previous case and indicates that the network has configured different NPRACH formats for different coverage conditions and the UE decides to use one or another based on its RSRP.

Message 3 now has length of 48 ms, 6 times larger than in the intermediate coverage scenario. This means that the redundancy has been increased to be able to face more challenging coverage conditions.

The ACK to message 4 takes longer as well by the same reason, 16 ms. This may be a transmission of 15 kHz subcarrier spacing with 8 repetitions or a 3.75 kHz subcarrier spacing transmission with 2 repetitions.

The time between the first and the second zone is 357 ms and there is a new random access procedure. It is remarkable that the gap between the two random accesses is also 640 ms, so the NPRACH cycle is not changed with the coverage level.

We can conclude then, that Vodafone has at least one RSRP threshold (Section 1.3.2.1) for the CI 151883D, because it has two configurations of random access opportunities for different coverage levels with the same periodicity and different preamble repetitions.
One of the tests with worse conditions is number 5 (Figure 4.10). In this case, the preamble was even longer: 179.2 ms. That is to say a 5.6 ms preamble with 32 repetitions. The message 3 was transmitted over 4 packets, the first three with 256 ms of transmission separated by the mandatory transmission gap of 40 ms and the last one of 128 ms. In conclusion, all messages are much longer and challenging coverage conditions are overcome by increasing the number of repetitions.

Given the previous results, three NPRACH configurations have been detected. If we assume that all cells are equally configured, it can be concluded that the limits of the coverage levels happen for an RSSI between -85 and -99 dBm and for an RSSI between -99 and -103 dBm.

It is also remarkable that for these tests that were performed under the cell 13C163E, the time until the procedure of connection release was initiated, was around 15 seconds, that may be the active timer for this cell.

The reader can find in ANNEX 5 the rest of tests with slight differences with respect to test 1 and 5.

The transmission time for the 8 bytes data packet, is defined from the time it starts the random access procedure until the last message of the mentioned zone 2 is sent. This is the time where the eNodeB received the data for sure and both parts know that the transmission was successful. In Figure 4.11 there are two plots. The left plot represents the transmission time with the RF shield box almost closed and the right one with the RF shield box closed. The y-axis represents the transmission time and each bar represents one test. For the sake of clarity, the RSSI is indicated inside the bars. For the right plot, the cell-ID is indicated too.
Measurements over real network

**Figure 4.10** Test 5 - 8 bytes transmission (1st part)

**Figure 4.11** Transmission time almost closed box (left) and closed box (right)

For the transmissions with the box almost closed, there is no pattern with respect to the RSSI (recall that the interferences are not an issue in this scenario). For tests 1, 3 and 5 the transmission time was the same due to identical transmission pattern. The same happened with the test 2 and 4 where the transmission time was reduced to almost one half due to the fact that just one random access procedure was needed and the data was transmitted immediately after it. The 6th test had the same pattern as 2 and 4 but the time between the first and the second zone was shorter.

For the tests where the box was closed there are two patterns based on the CI. When the device was connected to the cell 151883D the RSSI was better and the transmission times were of 908 ms with the same pattern. When the device decided to connect to the cell 13C163E the coverage was worse and the transmission times increased to values between 4.88 s and 9.195 s. As previously
Theoretical and experimental analysis of NB-IoT technology

seen, the number of repetitions increased a lot with respect to the first three tests and this was what made the transmission times larger.

When comparing these values with the simulated ones, differences are observed. It is important to remember that the configuration of Vodafone’s network is not known and the comparison is not 100% fair. The simulations for the best case scenario revealed transmission times between 112 ms and 897 ms whereas the measurements over the real network revealed times between 175 ms and 754 ms. The highest time which is 754 ms was obtained when the random access procedure was performed two times before sending the data. When it is about the bad case scenario tests it is even more difficult to make a fair comparison. The conditions of the bad scenario test were for sure not as bad as the worst coverage case analyzed in the simulator. The times are shorter for the measurements, 0.9 s for the CI 151883D (170 times shorter than the maximum obtained transmission time in the simulator) and 4 to 9 seconds for the CI 13C163E (17 to 38 times shorter than the maximum obtained transmission time in the simulator). This difference in the bad case scenario was led by the lower redundancy with respect to the simulator.

4.3.2. Increasing Packet Size

In order to analyze the performance for different data packet sizes two sets of experiments were done for both coverage conditions. Results are presented in Figure 4.12 and Figure 4.13. The x-axis represents the packet size in bytes whereas the y-axis represents the transmission time in ms.

In Figure 4.12 the transmission times with the RF shield box almost closed are shown. The cell to which the UE was connected during all the tests was 151883D. A little tendency of larger transmission times when the packet size increases can be observed. This is a logical tendency because the number of TBs necessary to transmit the data increases with the packet size. This tendency is broken for example by the transmission of 300 and 350 bytes that are 2.07 and 2.11 s respectively. Also with these two values, it can be observed that it does not depend on the RSSI because -87 dBm is the lowest value in all the tests whereas the -79 dBm is one of the highest values. The transmission of 250 bytes reinforces this theory because it has also -87 dBm and it is transmitted in half of the time it takes to transmit 300 bytes. All this variability is caused by different factors that were explained during the previous experiments: The retransmissions, the extra random access procedures for scheduling resources or a variable number of repetitions during the tests. The highest achieved effective data rate is 4.37 kbps for 900 bytes. Recall that the peak data rate is 250 kbps for uplink transmissions, but the effective data rate takes into account the rest of transmissions including random access procedure and scheduling gaps between transmissions.

Having a look at a range of what may be a real typical sensor reports, from 20 to 100 bytes the transmission times are acceptable. For most of the IoT applications these are not noticeable delays, e.g. soil moisture, pressure of a water pipe...
With the help of the results obtained in the previous section, the same scenario and configuration were reproduced with the maximum possible fidelity in the simulator. The NPRACH configuration was reproduced with a distribution of 12 subcarriers per CE level giving 12 free subcarriers. The periodicity and repetitions were obtained from the results of the previous measurements. The NPUSCH F1 configuration has been generated to obtain a 32 ms transmission (as was observed in the previous chapter measurements) for an 8 bytes transmission. The transmission of the NPUSCH F1 was done over the free subcarriers. The rest of parameters were roughly adjusted since the real value was unknown. Then, using the same NPUSCH F1 the simulation was performed over different packet sizes. Table 4.6 presents the comparison between the simulated and the real transmission times of some packet sizes.

**Table 4.6 Measured vs simulated transmission time**

<table>
<thead>
<tr>
<th>Packet Size (bytes)</th>
<th>Transmission Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simulated</td>
</tr>
<tr>
<td>20</td>
<td>134</td>
</tr>
<tr>
<td>50</td>
<td>165</td>
</tr>
<tr>
<td>100</td>
<td>197</td>
</tr>
<tr>
<td>200</td>
<td>294</td>
</tr>
<tr>
<td>300</td>
<td>389</td>
</tr>
<tr>
<td>400</td>
<td>485</td>
</tr>
<tr>
<td>500</td>
<td>584</td>
</tr>
<tr>
<td>600</td>
<td>647</td>
</tr>
<tr>
<td>700</td>
<td>744</td>
</tr>
<tr>
<td>800</td>
<td>839</td>
</tr>
<tr>
<td>900</td>
<td>935</td>
</tr>
</tbody>
</table>
The differences are significant, the simulator does not take into account the possible retransmissions as it happened in some measured transmissions. Furthermore, the gaps were programmed to the minimum values since they could not be extracted from the measurements. This facts plus slight differences on the configuration of the rest of parameters lead to the differences between the transmission times.

In Figure 4.13 the transmission times with the RF shield box closed are displayed. There is a lot of variability between the different packet sizes and there is no clear tendency now. It is interesting to analyze the test where the packet size was 100 bytes, and that took 7.38 s. Even though the RSSI was the best registered for the bad coverage cases, the time was the worst one. The RSSI measured and displayed inside the bar corresponds to the measurement at the beginning of the transmission and the RSSI level might vary during the transmission of the data. The shortest transmission was for 50 bytes of data with 756 ms. The second fastest transmission was achieved with 450 bytes of data with 1.175 seconds and the worst RSSI achieved during the tests. This reinforces the theory that the RSSI varies during the transmission of the data and so, the number of repetitions and retransmissions. The highest achieved effective data rate was 3.06 kbps for a transmission of 450 bytes.

The observed variability may be a problem for real applications with devices under bad coverage. The contrast between the transmission times for a packet of 50 bytes (0.76 seconds) and 100 bytes (7.38 seconds) reveal that for a slight change of the coverage or transmission configuration, the time may be multiplied almost 10 times. Application developers will have to take into account this fact. An interesting study would be to test several times the transmission for the same data size. This study, should help to take a decision, if the report is not urgent, it does not matter if it is transmitted in either 1 or 10 seconds.

The same procedure to compare the results with the simulator was done for this case, giving again significant differences between the measured and the simulated cases.
Figure 4.13 Transmission time RF shield box closed
CONCLUSIONS

The NB-IoT standard accomplishes all the basic features required by the 3GPP for IoT services in scenarios with a massive deployment of devices. Thanks to its flexibility of configuration, power consumption reduction, very narrow bandwidth allocations and integration with LTE, NB-IoT might become one of the most used technologies for IoT services and a natural successor to GPRS.

The objective of this project has been to provide a comprehensive study of NB-IoT from very different viewpoints. Theoretical study and calculations have been combined with the creation of a simulator and the realization of measurements over a real network.

The theoretical calculations show that for the best possible conditions, a data rate of 7.27 kbps (22 ms) can be obtained for a 20 bytes DL transmission. The standard can correctly deal with small packet transmissions, typical to poll sensors or send basic reconfigurations. On the other hand, also with the same coverage conditions, firmware updates of 1 Mbyte would take 5 min, meaning an important occupation of the DL channel that would require additional PRBs or the introduction of transmission gaps. The small bandwidth combined with high levels of redundancy in the form of channel coding and transmission repetitions allow connectivity under deep coverage situations. However, a high presence of devices under such conditions would be very questionable unless the number of PRBs is far more than one. This is because the 20 B message would require 5 minutes to be transmitted. On the other hand, firmware updates for such devices seems out of the debate, since a 1 Mbyte transmission would take 12 days. Similar conclusions are extracted for UL transmissions, where the variable bandwidth to transmit data offers a high number of combinations and then transmission times. For the selected scenario on the calculations, transmission times were of 140 ms for the best case and 1 minute for the worst. So the number of reports done by the sensors could also be adapted depending on the coverage level. Still, if the service is intended for giving reports every 24 hours, 1 minute may be a tolerable delay.

Thanks to the simulator, all the possible combinations for downlink, uplink and NPRACH configuration can be tested. NB-IoT has been shown to be a highly configurable system, with many tunable parameters. The number of combinations is huge and the results may vary a lot depending on the selected configuration. The program was done with Matlab and was used to obtain more interesting insights on NB-IoT performance. The initial transmission point within the downlink frame may affect in a few ms to the total transmission time. The theoretical calculations usually assume the average occupation of signaling. But this calculation contains an error with respect to exact simulated values, this has to be taken into account by the developers because it may generate up to 10 s of error in the transmission times. The uplink performance has been analyzed for different RU and NPUSCH allocations revealing that the impact can be up to 700 extra milliseconds for the best coverage cases and up to 125 extra seconds for the worst coverage case (8 bytes transmission) if the selected configuration is not the most appropriated with respect to the NPRACH configuration.
Finally, with the measurements over the real network, the real performance of NB-IoT has been analyzed. It has been observed that Vodafone’s deployment is done in a LTE guard band and currently just uses one PRB. With the use of AT commands, a NB-IoT category NB1 device has been used to evaluate the system performance. Some new effects that were not included in the simulator have been observed, as for example the use of several NPRACHs before transmitting the data itself or long periods of time between the NPRACH procedure and the data transmission. This meant longer than expected transmission times in some cases. In this respect, the comparison with simulations was somehow difficult since it was unknown the exact configuration of Vodafone in terms of scheduling gaps, NPRACH configurations, etc. However, several of those parameters could be guessed by comparing the results of different tests. Indeed, it could be concluded that the network was not configured with the most extreme data protection levels. Two coverage situations were analyzed. The intermediate coverage scenario revealed transmission times within the range of values obtained with the simulator (best case scenario), 175 ms the fastest transmission and 754 the slowest one. As indicated, the bad coverage situation was definitely not the worst coverage case scenario of the simulator and the transmission times were much shorter, 0.9 seconds the fastest and 9.19 seconds the slowest one. Several transmissions of different packet sizes were performed and a high variability of transmission times on the bad coverage case has been identified.

In my opinion, NB-IoT will be the most used standard for a certain group of IoT services. These services should transmit a small amount of sensor data especially if the coverage conditions are not the best ones. NB-IoT penalizes the use of high data transmissions. It will be perfect for water metering, street lightning control, check the level of trash in a trash cane… All these services will need reports every several hours which will also help with the battery lifetime. The variable bandwidth allocation will allow the network planner to give a certain priority over some services allocating more bandwidth to the desired device in case there is a massive amount of devices transmitting at the same time.
REFERENCES


ANNEX 1. AGGREGATION LEVEL DESCRIPTION FOR NPDCCH

The $R_{\text{max}}$ value (Section 1.3.1.4) is also used with the Aggregation Level (AL) for deciding the NPDCCH search space candidates (see chapter 7.3.2.1 in [4]).

An NPDCCH subframe is divided in two Narrowband Control Channel Elements (NCCEs). The first one called NCCE0 has assigned the six lowest subcarriers whereas the second one called NCCE1 takes the upper six subcarriers. Depending on the deployment mode and the number of logical antenna ports, the subcarriers available for one NCCE may vary. For the in-band deployment the configuration of the LTE cell may affect and NPDCCH is not mapped in the first few OFDM symbols due to that REs may be used by the LTE DL signaling (Figure 1.1).

![Figure 1.1 DL subcarrier allocation](image)

Each of the previous mentioned DCI can be mapped into one NCCE or both NCCEs called AL 1 or AL 2 respectively. The AL 2 is used for increased the coverage of NPDCCH, the higher the number of subcarriers used the higher the energy per bit.
ANNEX 2. 1 MBYTE FIRMWARE UPDATE - WORST CASE SCENARIO

This annex has the analysis of the transmission time for 1 Mbyte firmware update with the worst case scenario. The characteristics considered are the next ones:

- MCL: 164 dB
- NPDSCH repetitions: 2048
- NPDCCH maximum repetitions: 2048
- NPDCCH repetitions: 2048
- NPUSCH F2: 8 ms RU with 128 repetitions, 1024 ms

The conditions at the RLC layer are the same one as for the best case scenario, 681 packets of 1480 bytes and 1 packet of 304 bytes. The selected TBS index is 0 and 256 of TBS transmitted in 10 subframes. The number of MAC packets for the IP packets of 1480 bytes is:

\[
MAC \text{ packets} = \frac{1480 \text{ bytes} \times 8 \text{ bits/byte}}{240 \text{ bits}} = 49.3 \text{ packets} \quad (2.1)
\]

There are 80 bits of data remaining, the nearest TBS is 120 bits transmitted in 5 subframes so finally there will be 49 packets of 120 bits and 1 packet of 120 bits in every IP packet of 1480 bytes.

Furthermore, the network has to transmit the RLC packet of 304 bytes, this packet will be divided in:

\[
MAC \text{ packets} = \frac{304 \text{ bytes} \times 8 \text{ bits/byte}}{240 \text{ bits}} = 10.13 \text{ packets} \quad (2.2)
\]

There are 32 bits of data remaining that are transmitted with a TBS of 56 bits in 3 subframes with TB size index 0.

To sum up, these are the packets that the eNodeB is going to transmit:

- 33.379 packets with TB size index: 0, TBS: 256 bits and transmitted in 10 subframes.
- 681 packets with TB size index: 0, TBS: 120 bits and transmitted in 5 subframes.
- 1 packet with TB size index: 0, TBS: 56 bits and transmitted in 3 subframes.
The time it takes to transmit the NPDSCH is:

\[
T_{\text{NPDSCH}} = \left( 33.379 \text{ packets} \times 10 \text{ subframes} + 681 \text{ packets} \times 5 \text{ subframes} \right) \times \\
+ 1 \text{ packet} \times 3 \text{ subframes} \
\times 1 \text{ ms} \times 2048 \text{ rep} \times \frac{20 \text{ ms}}{15 \text{ ms}} = 920775.339 \text{ s} \quad (2.3)
\]

Then, the NPDCCH:

\[
T_{\text{NPDCCH}} = 1 \text{ ms} \times 2048 \text{ rep} \times \frac{20 \text{ ms}}{15 \text{ ms}} = 2.73 \text{ s} \quad (2.4)
\]

Finally, the calculation of the total transmission time which is the time between the network sends the first DCI Format N1 and the reception of the NPUSCH F2 corresponding to the last packet. All the transmission gaps are considered and an NPUSCH F2 of 128 ms is applied:

\[
T_{\text{TX}} = T_{\text{NPDSCH}} + 34.061 \times T_{\text{NPDCCH}} + 34.061 \times 4 \text{ ms} + 34.061 \times 12 \text{ ms} + \\
+ 34.060 \times 3 \text{ ms} + 34.061 \times 1024 \text{ ms} = 1049287.489 \text{ s} \quad (2.5)
\]

The total transmission time it is 12 days 3 hours 28 min and 9 seconds.

Once the total transmission time is calculated, the data rate is computed as:

\[
r = \frac{8 \text{ Mbytes}}{1049287.489 \text{ s}} = 7.62 \text{ bps} \quad (2.6)
\]
ANNEX 3. 8 BYTES REPORT - BEST CASE SCENARIO

Once the worst case scenario is calculated in Chapter 2.4.1, the case of the best case scenario is going to be analyzed. The following facts are going to be considered:

- MCL: 144 dB
- NPUSCH F1 repetitions: 1
- NPUSCH F2: 15 kHz subcarrier index 0, time offset value 13 and 1 repetition with a RU of 2 ms.
- NPRACH repetitions: 2
- NPDCCH maximum repetitions: 1
- NPDCCH repetitions: 1
- NPRACH Format 0: 5.6 ms
- NPRACH CE 0
- NPRACH repetitions: 2

As for the best case scenario, the total size of headers without considering the MAC layer is 12 bytes. The best case scenario requires the highest TB size index for in-band deployment which is 12. The packet size is 20 bytes (160 bits) at the MAC layer but there are 16 bits remaining because of the MAC header which also must be inside the TB. Looking at the table, the nearest upper value for the TB size index 12 is 208 bits transmitted over 2 RU.

A unique packet of 208 bits + 24 bits (CRC) will be sent over 1 RU. The transmission of NPUSCH Format 1 can be done using 3.75 kHz or 15 kHz subcarrier spacing. The different possible RU are shown in Table 2.2.

The calculation of the NPUSCH transmission time depending on the RU length is:

\[ T_{\text{NPUSCH}} = 1 \text{ RU} \times \text{RU length} \times 1 \text{ rep} \]  

(3.1)

Table 3.1 shows the total transmission time of the NPUSCH containing the 8 bytes of data that the device sent.

Table 3.1 NPUSCH total transmission time

<table>
<thead>
<tr>
<th>Δf</th>
<th>Num. Subcarriers</th>
<th>Num. Slots</th>
<th>Slot length</th>
<th>RU length</th>
<th>Tx time (without RA procedure)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.75 kHz</td>
<td>1</td>
<td>16</td>
<td>2 ms</td>
<td>32 ms</td>
<td>32 ms</td>
</tr>
<tr>
<td>15 kHz</td>
<td>1</td>
<td>16</td>
<td>0.5 ms</td>
<td>8 ms</td>
<td>8 ms</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>8</td>
<td></td>
<td>4 ms</td>
<td>4 ms</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>4</td>
<td></td>
<td>2 ms</td>
<td>2 ms</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>2</td>
<td></td>
<td>1 ms</td>
<td>1 ms</td>
</tr>
</tbody>
</table>
In the following, it is assumed that the shaded case in the table has been chosen. Since just 1 subcarrier is used, it is assumed that first one in the PRB is allocated by the control channel. From the table, raw data transmission time can be obtained, but the control channel and the access procedure need to be added too. In particular, the time it takes to transmit the scheduling information in the corresponding downlink control channel (DCI Format N0 in NPDCCH) is:

\[
T_{\text{NPDCCH}} = 1 \text{ ms} \times 1 \text{ rep} \times \frac{20 \text{ ms}}{15 \text{ ms}} = 1.3 \text{ ms}
\]  

(3.2)

As it is known from the previous example it is necessary to consider the configuration selected for the NPRACH opportunities. This problem is solved with the following configuration (Figure 3.1):

- **NPRACH CE 0**: The opportunities for the devices under CE 0 level occupy 24 subcarriers (3.75 kHz) from the subcarrier number 25 to 48. The size in time is 2 repetitions of 5.6 ms thus 11.2 ms, as the last subframe is completely used, 12 ms of opportunity. The periodicity is 40 ms.

- **NPRACH CE 1**: The opportunities for the devices under CE 1 level occupy 24 subcarriers (3.75 kHz) from the subcarrier number 1 to 24. The size in time is 16 repetitions of 5.6 ms thus 89.6 ms, as the last subframe is completely used, 90 ms of opportunity. The periodicity is 1280 ms.

- **NPRACH CE 2**: The opportunities for the devices under CE 2 level occupy 12 subcarriers (3.75 kHz) from the subcarrier number 13 to 24. The size in time is 128 repetitions of 5.6 ms thus 716.8 ms, as the last subframe is completely used, 717 ms of opportunity. The periodicity is 1280 ms.

![NPRACH Structure](image)

**Figure 3.1** NPRACH configuration

The subcarrier number 1 it is going to be assigned again. The device will not transmit when the NPRACH CE 1 opportunities are placed so 89.6 ms every 1280 ms. The percentage of time that the device cannot transmit is:

\[
\text{Occupation NPRACH} = \frac{90 \text{ ms}}{1280 \text{ ms}} \times 100 = 7.03 \%
\]  

(3.3)
So, the 93% of time this subcarrier will be available for the transmission of the NPUSCH, every 1280 ms, 1190 ms will be used for the transmission of the RUs.

The characterization of the downlink parameters necessary for the RA procedure calculations are:

- NPDSCH repetitions: 1
- NPDCCH repetitions: 1

The message 1 is the NPRACH, in that case is under CE 0 so:

\[ T_{\text{msg1}} = 12 \text{ ms} \] (3.4)

The message 2 will occupy:

\[ T_{\text{msg2}} = (1 \text{ ms} \times 1 \text{ rep} + 1 \text{ ms} \times 1 \text{ rep}) \times \frac{20 \text{ ms}}{15 \text{ ms}} = 2.6 \text{ ms} \] (3.5)

The message 3 is an NPUSCH with 1 RU assigned, the time it takes to transmit it is:

\[ T_{\text{msg3}} = 32 \text{ ms} \times \frac{1280 \text{ ms}}{1190 \text{ ms}} = 34.42 \text{ ms} \] (3.6)

The message 4 is again a message like the message 2 so the time it takes to transmit the packet, 2.6 ms.

After the message 4 the last step is an NPUSCH F2 with the acknowledgement that the message 4 has been received. This configuration will be done with one subcarrier for the NPUSCH F2 as it has been mentioned previously. This subcarrier will be allocated in the subcarrier number 1 considering a 15 kHz subcarrier spacing which is equivalent to the subcarriers 1-4 with the 3.75 kHz subcarrier spacing. Therefore, the percentage of time for NPUSCH F2 transmission is the same one.

\[ T_{\text{NPUSCH F2}} = 2 \text{ ms} \times 1 \text{ rep} \times \frac{1280 \text{ ms}}{1190 \text{ ms}} = 2.15 \text{ ms} \] (3.7)

The total time of the RA procedure can be calculated as the sum of all the messages. The total duration considering all the gaps is:

\[ T_{\text{RA}} = T_{\text{msg1}} + T_{\text{msg2}} + 4 \text{ ms} + 12 \text{ ms} + T_{\text{msg3}} + 3 \text{ ms} + T_{\text{msg4}} + 4 \text{ ms} + 12 \text{ ms} + T_{\text{NPUSCH F2}} = 88.89 \text{ ms} \] (3.8)

Once the transmission of the RA procedure is calculated it is time to re-calculate the time it is going to take the NPUSCH with the 8 bytes of data. As it has been mentioned previously even though initially the time had been calculated for some
combinations of RUs, to simplify the calculations, are going to be finished with RU of 32 ms (Table 2.3) and a configuration of 3.75 kHz subcarrier spacing. The new transmission time of the NPUSCH considering that some subcarriers are reserved for the NPRACH opportunities is:

\[
T_{\text{NPUSCH}} = 32 \text{ ms} \times \frac{1280 \text{ ms}}{1190 \text{ ms}} = 34.42 \text{ ms}
\]  

(3.9)

The total transmission time for the report of 8 bytes considering all the gaps is:

\[
T_{\text{TX}} = T_{\text{RA}} + 3 \text{ ms} + T_{\text{NPUSCH}} + 2 \times T_{\text{NPDCCH}} + 8 \text{ ms} + 3 \text{ ms} = 139.98 \text{ ms}
\]  

(3.10)

Finally, the uplink data rate can be calculated as:

\[
r = \frac{8 \text{ bytes} \times 8 \text{ bits/bytes}}{139.98 \text{ ms}} = 457.2 \text{ bps}
\]  

(3.11)
ANNEX 4. 8 BYTES TRANSMISSION IN IDLE MODE AND INTERMEDIATE COVERAGE (TESTS 3, 4, 5 AND 6)

Tests 3 (Figure 4.1) and 5 (Figure 4.3) have the same pattern as the test 1 were a random access was performed before the data transmission in the second zone of the picture. For tests 4 (Figure 4.2) and 6 (Figure 4.4) the same pattern as in test 2 is observed, with the pattern of data followed by a packet.

Tests 3 and 6 have the same pattern as test 1 and 2 in the third zone, where two uplink data packets were transmitted.

In test 4 and 5, two different patterns were found to send these messages. In test 4, the channel conditions changed and the device had lost the network synchronization, this leads to a new random access procedure to send the last packet. In test 5, three retransmissions of the first packet can be observed. This may be cause by an incorrect reception of the message at the eNodeB.

![Figure 4.1 Test 3](image-url)
8 bytes transmission in idle mode and intermediate coverage (tests 3, 4, 5 and 6)

Figure 4.2 Test 4

Figure 4.3 Test 5
Figure 4.4 Test 6
ANNEX 5. 8 BYTES TRANSMISSION IN IDLE MODE AND BAD COVERAGE (TESTS 2, 3, 4 AND 6)

In this section, the first part of the transmission for tests 2 (Figure 5.1), 3 (Figure 5.2), 4 (Figure 5.3) and 6 (Figure 5.4) of a data packet of 8 bytes under the case of bad coverage with the RF shield box closed can be found.

Figure 5.1 Test 2

Figure 5.2 Test 3
Figure 5.3 Test 4

Figure 5.4 Test 6