Czech Technical University in Prague
Faculty of Electrical Engineering

Master Thesis

Analysis of Energy Consumption for IoT Devices Communicating in Mobile Network

Study Program: Electronics and Communications
Field of Study: Communication Systems and Networks
Thesis advisers: doc. Ing. Zdeněk Bečvář, Ph.D.
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Prague, January 8, 2019

Čestné prohlášení

Prohlašuji, že jsem předloženou práci vypracoval samostatně a že jsem uvedl veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací.

V Praze, dne 8. 1. 2019 ....

Jan Rindt

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UČENÍ TECHNICKÉ
V PRAZE

ZADÁNÍ DIPLOMOVÉ PRÁCE

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II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Analýza spotřeby energie IoT zařízení komunikujících v mobilní síti

Název diplomové práce anglicky:

Analysis of Energy Consumption for IoT Devices Communicating in Mobile Network

Pokyny pro vypracování:

Seznamte se s principy plánování a přidělování rádiových prostředků ve směru uplink pro jednoduchá elektronická zařízení typu IoT generující malý objem dat přenášených pomocí úzkopásmového IoT (Narrowband IoT, NB-IoT) v mobilních sítích. Analyzujte vliv přenosových parametrů na spotřebu energie pro komunikaci IoT zařízení ve směry uplink. Proveďte rozbor vlivu jednotlivých parametrů a na základě analýzy navrhněte pravidla pro nastavování těchto parametrů s ohledem na energii spotřebovanou IoT zařízeními pro komunikaci. Vliv parametrů demonstrujte pomocí simulací.

Seznam doporučené literatury:

[1] Jinseong Lee, Jaiyong Lee, “Prediction-Based Energy Saving Mechanism in 3GPP NB-IoT Networks,” Sensors, September 2017.
[2] Liberg, O., Sundberg, M., Wang, E., Bergman, J., Sachs, B.: 'Cellular Internet of Things', 1st ed.; Academic Press, 2018.
[3] A. M. Maia, D. Vieiray, M. F. de Castro, Y. Ghamri-Doudane, “Comparative Performance Study of LTE Uplink Schedulers for M2M Communication,” IFIP Wireless Days 2014.

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Datum zadání diplomové práce: **19.09.2018**
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podpis vedoucí(ho) ústavu/katedry

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III. PŘEVZETÍ ZADÁNÍ

Diplomant bere na vědomí, že je povinen vypracovat diplomovou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací.
Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v diplomové práci.

Datum převzetí zadání

Podpis studenta

Summary

With increasing usage of Narrowband Internet of Things (NB-IoT), it is necessary to make sure all aspects of the system are optimized to achieve reliable communication of all devices in the network. The selection of transmission parameters plays a key role in the efficient use of resources and energy consumption of communicating devices. Energy consumption is an essential characteristic of IoT devices as it influences its battery life. The energy consumed for transmitting data from a device to a base station (eNB) takes a significant part of the energy consumed by the device for its whole operation. The impact of uplink transmission parameters in NB-IoT on the energy consumption of the device is analyzed in this thesis. Complex dependency flow is one of the outcomes of this thesis as well as energy consumption evaluation based on input parameters. Furthermore, a new model for choosing transmission parameters based on energy consumption is proposed and compared with the existing solution.

The proposed model can save 61% of the energy spent on the transmission on average over the standard model. The saving in the energy consumption is achieved by adjusting the transmission parameters to every individual device according to its signal attenuation.

Keywords: 3GPP, NB-IoT, uplink, transmission, energy, consumption

Anotace

S postupným rozvojem Narrowband Internet of Things (NB-IoT), je nutné aby komunikace zůstala optimalizovaná a spolehlivá pro všechna zařízení v síti. Nastavení komunikačních parametrů hraje klíčovou roli v efektivním využití rádiových prostředků a energie, kterou mají připojená zařízení k dispozici. Spotřeba elektrické energie je klíčovou charakteristikou pro každé IoT zařízení, protože zásadně určuje životnost jeho akumulátoru. Největší spotřebu energie zařízení vyžaduje odesílání dat směrem k základnové stanici (eNB) a právě proto je v této práci analyzován vliv přenosových parametrů při odesílání na její spotřebu. Jedním z přínosů práce je souhrnný model závislostí, které ovlivňují spotřebu elektrické energie zařízení, včetně přenosových parametrů. Kromě toho byl vyvinut nový model pro zvolení takových přenosových parametrů, jejichž kombinace bude pro dané zařízení nejlepší z hlediska množství elektrické energie, vyžadované k přenosu dat. Tento model byl porovnán s již existujícím, standardním modelem.

Navrhovaný model dokáže ve srovnání se standardním modelem ušetřit průměrně 61% energie, spotřebované při přenosu. Tento rozdíl je dán především optimalizovaným nastavením parametrů pro každé zařízení vzhledem k útlumu signálu mezi zařízením a základnovou stanicí.

Klíčová slova: 3GPP, NB-IoT, uplink, přenos, spotřeba, energie, odesílání

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Abbreviations

3GPP 3rd Generation Partnership Project

BER Bit Error Rate

BLER Block Error Rate

BPSK Binary Phase-Shift Keying

CE Coverage Enhancement

CL Coupling Loss

R Code Rate

CRC Cyclic Redundancy Check

DMRS Demodulation Reference Signal

DRX Discontinuous Reception

EC Energy Consumption

eDRX extended Discontinuous Reception

eNB Evolved Node B

GSM Groupe Spécial Mobile

HARQ Hybrid Automatic Repeat Request

IoT Internet of Things

LTE Long Term Evolution

MCL Maximum Coupling Loss

MCS Modulation and Coding Scheme

MTC Machine-Type Communication

NB-IoT Narrowband Internet of Things

NF Noise Figure

NPRACH Narrowband Physical Random Access Channel

NPUSCH Narrowband Physical Uplink Shared Channel

$\mathbf{N_{REP}}$ Number of Repetitions

$\mathbf{N_{RU}}$ Number of Resource Units

$\mathbf{N_{T}}$ Number of Tones

OFDMA Orthogonal Frequency-Division Multiple Access

PA Power Amplifier

PAPR Peak to Average Power Ratio

PHR Power Headroom Report

PL Path Loss

PRB Physical Resource Block

PSM Power Saving Mode

QPSK Quadrature Phase-Shift Keying

RA	Random Access
RE	Resource Element
RRC	Radio Resource Control
RU	Resource Unit
SC-FDMA	Single-carrier Frequency Division Multiple Access
SNR	Signal to Noise Ratio
TB	Transport Block
TBS	Transport Block Size

I | Introduction

The Internet of Things (IoT) connects many devices in a network and enables effective and power-saving communication. Several communication standards providing suitable conditions for IoT are available today. Narrowband Internet of Things (NB-IoT) is the 3rd Generation Partnership Project (3GPP) standard designed to handle communication of thousands of devices. A typical use case is, for example, reporting a status of a device or reading a value from a sensor. The NB-IoT is designated to be a network for Machine-Type Communication (MTC) with its specific requirements and parameters. Both latency and bit rate are not crucial for good user experience in IoT and relaxing both parameters helps devices to save energy and enables operation times of many years. Energy consumption of IoT devices is essential though for an operator (a company which owns devices) as the company is usually responsible for replacing batteries in its devices. Those devices might be in locations that are difficult/hard to reach. Therefore longer battery life is significantly reducing the maintenance costs.

Several related works have been presented about NB-IoT with focus at a device's energy consumption.

In [2] a detailed description of all possible power saving mechanisms, including Discontinuous Reception (DRX), extended Discontinuous Reception (eDRX), Power Saving Mode (PSM) and their properties are presented. Battery consumption rate according to the duration of Radio Resource Control (RRC) connected state is modeled and evaluated.

In [3] is described, how to save power in RRC Idle state instead of in RRC Connected state. The devices form groups, which share the same operational properties and they are often geographically close. A group leader wakes up every DRX cycle and a group member each 4 DRX cycles, which reduces energy consumption for the group members.

It is proposed in in [4] that link adaptation for NB-IoT systems should be conducted in at least two dimensions: the MCS level selection and the repetition number determination. The authors proposed a simple single-tone scheduling scheme, in which eleven tones can be scheduled for data transmission with NPUSCH, and another single tone can be scheduled as Acknowledge/Not-acknowledge feedback for downlink transmission with NPUSCH. Repetition number and MCS are updated accordingly.

Olof Liberg made a detailed introduction to NB-IoT, where the physical layer in both idle and connected mode is presented [5]. In a separate chapter, performance objectives are examined concerning coverage, throughput, latency, battery lifetime, system capacity and device complexity.

There has been much work done on DRX in the past five to eight years [6], [7] as well as improving the energy consumption in the RRC idle mode [8], [9].

Since the uplink data transmission have most likely the largest largest power demand of the device's battery [5], it is necessary to make uplink transmission as effective as possible. The scheduler decides about two significant aspects of device communication: the time when the device transmits data and the parameters used for transmission. Both the waiting time and transmission parameters influence the energy consumption of the device.

In this thesis, an impact of the transmission parameters on the device's power consumption is analyzed and modeled. The choice of the parameters depends on the signal quality between each device and the Evolved Node B (eNB) and is unique for each transmission. Specifically, the influence of the three parameters, $\mathrm{N_T}$ (number of subcarriers for uplink data transmission), $\mathrm{N_{REP}}$ and Code Rate (R) to energy consumption is described. A major contribution of this thesis is the definition of an energy consumption dependency on the number of sub-carriers allocation, size of transmitted data and SNR. The dependencies are subject of discussion, and mutual relationships are further described. The goal is to set the transmission parameters such that the device has the best chance to achieve the lowest energy consumption from all available possibilities of parameter settings at that time and reliable communication is still possible.

The rest of this work is organized as follows. Chapter 2 contains the introduction to NB-IoT data transmission, and connection related parameters are presented. The system model is described in Chapter 3. A new model is proposed in Chapter 4, including the explanation of the impact of the transmission parameters on energy consumption. The analytical results are summarized in Chapter 5, and the conclusion is made in Chapter 6.

II | Narrowband Internet of Things

In this chapter, the communication in NB-IoT is described first in Section 2.1, after which the introduction to the scheduling of uplink transmission of NB-IoT is made in Section 2.2. Allowed duration and bandwidth of RU, is covered in Section 2.3. Transmission parameters are presented in Section 2.4. The proposed procedure for the determination of the uplink transmission parameters is described in Section 2.5.

2.1 Transmission channels

NB-IoT works with the bandwidth of 200 kHz (effectively 180 kHz) for both downlink and uplink direction. Downlink and uplink transmission are split by frequency division duplex. In uplink transmission, two possible ways of communication are defined. Single-tone communication with 15 kHz or 3.75 kHz subcarriers spacing, which is mandatory for all devices and only one subcarrier is used for the transmission. Multitone communication with 15 kHz subcarriers spacing with Single-carrier Frequency Division Multiple Access (SC-FDMA) allowing the device to extend its transmission over 3, 6, or 12 subcarriers [10].

For NB-IoT uplink transmission, two physical channels are defined. NPUSCH carries uplink data packets, and Narrowband Physical Random Access Channel (NPRACH) is used by devices to initialize the connection. For more information about physical channels, refer to [5], [11].

Downlink multiplexing of physical channels is based on Orthogonal Frequency-Division Multiple Access (OFDMA), and uplink multiplexing uses SC-FDMA for multitone operations [12]. In order to save resources, communication is half-duplex. Half-duplex operation mode also does not require monitoring of more than one channel in time as a device either receives or sends data, but not both at the same time [4], [5].

Coverage Enhancement (CE) is achieved using data repetitions, providing a trade-off between coverage and data rate. 3GPP defines three CE levels (illustration in Figure 2.1, which aims to achieve up to 20 dB coverage improvement over Groupe Spécial Mobile (GSM)/Long Term Evolution (LTE) networks [5].

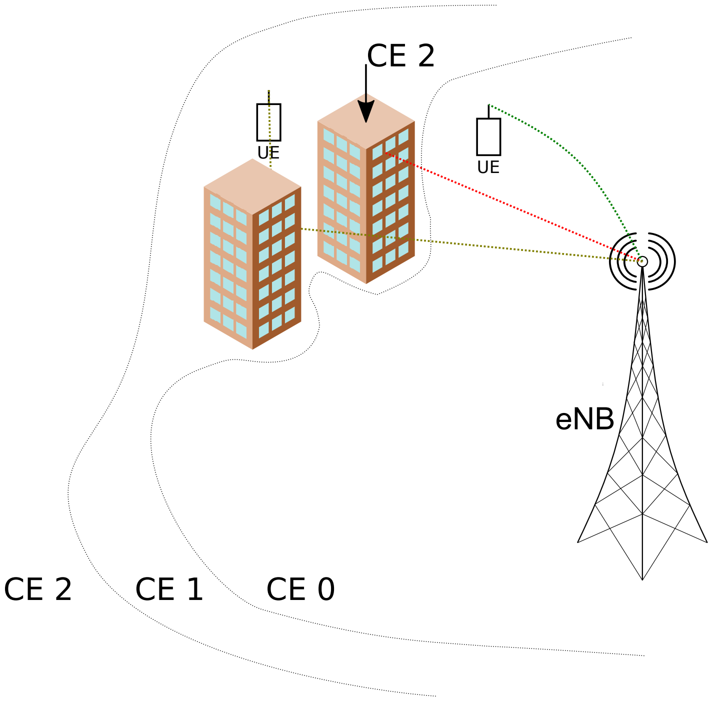

Figure 2.1: Illustration of CE level due to different channel conditions.

2.2 Scheduling

In order to make a transmission, several parameters must be set. They can be split into two groups. The first group contains parameters of transmission which are $\mathrm{N_{REP}}$, $\mathrm{N_T}$, affecting the bandwidth of transmission, MCS and $\mathrm{N_{RU}}$.
The second group contains the placement of RU into frequency and time. RU is the basic scheduling unit, used to map the physical channels on the Resource Elements, defined by individual OFDMA symbols in time and individual subcarriers in frequency. According to the $\mathrm{N_T}$ allocated to the particular device, the appropriate RU needs to be placed in PRB, allocated to NB-IoT. Figure 2.2 illustrates NB-IoT PRB with 15 kHz subcarrier spacing and a combination of two slots into the pair forming a subframe with a duration of 1 ms [5]. The smallest unit, carrying data is called Resource Element (RE), placed over single subcarrier and one OFDMA symbol.

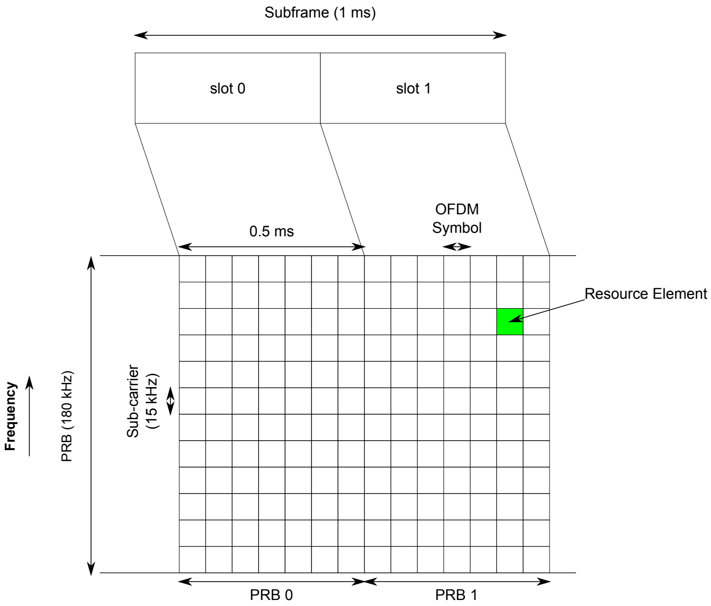

Figure 2.2: Illustration of two PRBs in NB-IoT with a subcarrier spacing of 15 kHz, placed in a pair to form a subframe.

Figure 2.3 illustrates a scheduling situation. Static and dynamic scheduling is captured in the figure. The dynamic RU placement provides more freedom in the matter of tone allocation, e.g., four three-tone blocks can be placed next to each other in frequency (beginning in the same time), or one twelve-tone block can be used, resulting in no space for a single-tone transmission. For simplicity, the static assignment is used in some applications, which reduces the computational complexity of RU placement. Blocks with same bandwidth (sub-carriers) are always placed in the fixed pattern, so they are easier to schedule. The drawback of static approach is that it is not scalable (capable of being easily expanded or changed in order).

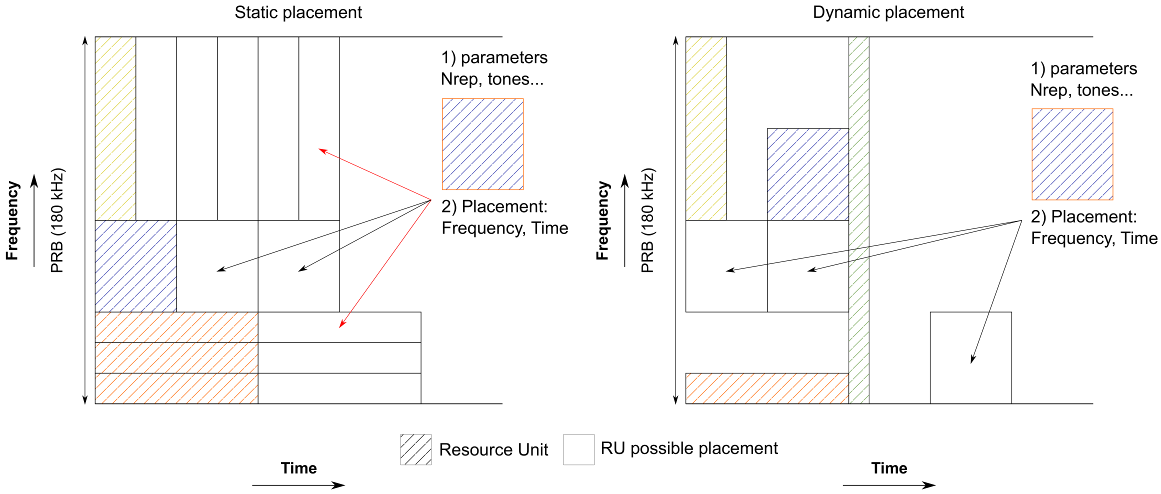

Figure 2.3: Illustration of static and dynamic RU placement in frequency and time.

2.3 Resource allocation

The basic scheduling time unit is referred to as RU. It is specified in both time and frequency, and it provides slots for data transmission depending on allocated bandwidth and NPUSCH format.

A device might be scheduled with 1, 2, 3, 4, 5, 6, 8 or 10 RUs per repetition. This gives time variance from 1ms (1 RU * 180 kHz (12 tones)) to 320 ms (10 RU * 3,75 kHz (1 tone)). Length of individual tone allocations is defined by Table 2.1. Transport Block Size (TBS) for different N_{RU} configurations are given by Table 2.2.

Note that number of REs for Data per RU in Table 2.1 is given as the number of assigned subcarriers (tone allocation) multiplied by Number of Slots per RU multiplied by Number of OFDMA Symbols in each slot [5]. In each slot for NPUSCH Format 1, one OFDMA symbol is assigned for Demodulation Reference Signal (DMRS), which is taken into account (6 OFDMA symbols left). This is important for calculating the number of resource elements for data the RU can transmit. For actual data size, the number needs to be multiplied by the number of bits, encoded by used modulation per one symbol. For Quadrature Phase-Shift Keying (QPSK) modulation, the number of encoded bits per symbol is equal to two. Binary Phase-Shift Keying (BPSK) modulation can encode only one bit per symbol.

Table 2.1: Number of slots and number of data symbols per NPUSCH RU.

NPUSCH Format	Number of Allocated Subcarriers	UE Scheduled Bandwidth (kHz)	Number of Slots per RU	Length of RU (ms)	Number of REs for Data per RU
Format 1 (Data)	12	180	2	1	144
	6	90	4	2	144
	3	45	8	4	144
	1	15	16	8	96
	1	3,75	16	32	9
Format 2 (HARQ)	1	15	4	2	16
	1	3,75	4	8	16

Table 2.2: TBSs for NPUSCH Format 1 in Rel. 13, according to Section 16.5.1.2 in [1].

TBS (I_{TBS})	Number of RUs (N_{RU})							
	1	2	3	4	5	6	8	10
0	16	32	56	88	120	152	208	256
1	24	56	88	144	176	208	256	344
2	32	72	144	176	208	256	328	424
3	40	104	176	208	256	328	440	568
4	56	120	208	256	328	408	552	696
5	72	144	224	328	424	504	680	872
6	88	176	256	392	504	600	808	1000
7	104	224	328	472	584	712	1000	Not used
8	120	256	392	536	680	808	Not used	Not used
9	136	296	456	616	776	936	Not used	Not used
10	144	328	504	680	872	1000	Not used	Not used
11	176	376	584	776	1000	Not used	Not used	Not used
12	208	440	680	1000	Not used	Not used	Not used	Not used

I_{TBS} 11 and 12 in Table 2.2 can be used only for multi-tone operations [4].
Multi-tone transmissions use QPSK modulation.
For single-tone transmission, $\pi/2$-BPSK modulation is used for TBS 0 or 2, and $\pi/4$-QPSK modulation is used elsewhere [13], [14].
$\pi/2$-BPSK and $\pi/4$-QPSK are used for the single-tone transmissions to reduce the Peak to Average Power Ratio (PAPR) close to 0 dB and to improve the Power Amplifier (PA) efficiency [5].

2.4 Transmission Parameters

For transmission between the eNB and each device, the following parameters are set:

N_{REP}	Number of Repetitions of the message. Using repetitions, an effective SNR is enhanced. Figure 2.5 is illustrating the situation in detail. N_{REP} is further described in Section 4.4.
N_T	Number of Tones, in fact, a number of sub-carriers, used by the device to transmit uplink data. By increasing the number of tones, the bandwidth of transmission is expanded (increased). A detailed illustration is in Figure 2.6.
I_{MCS}	Modulation and Coding Scheme in combination with N_{RU}, required to transport NPUSCH Transport Block (TB) with a certain size (=TBS). N_{RU} is used to compensate code rate for same TBS. N_{RU} is based on Table 2.2. A detailed illustration is in Figure 2.7. Further details are in Section 2.3.

Figure 2.4 illustrates all transmission parameters: $\mathrm{N_{REP}}$ in the top part, $\mathrm{N_T}$ as different RUs with a bandwidth of $\mathrm{N_{T_1}}$ and $\mathrm{N_{T_2}}$, and different MCS as two TBs with transmission times τ_1 and τ_2.

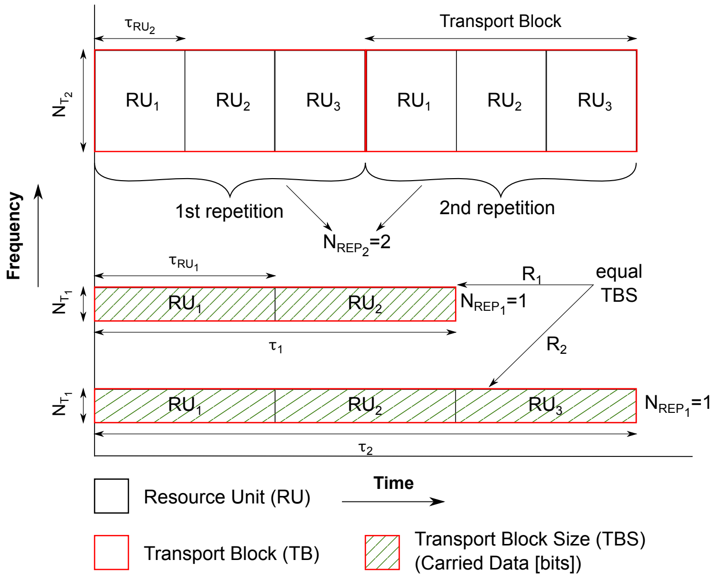

Figure 2.4: Illustration of Transmission Parameters.

All parameters are further illustrated:
In Figure 2.5 the number of repetition is illustrated. A device is re-transmitting whole transport block, including from 1 to 10 RUs according to Table 2.2.

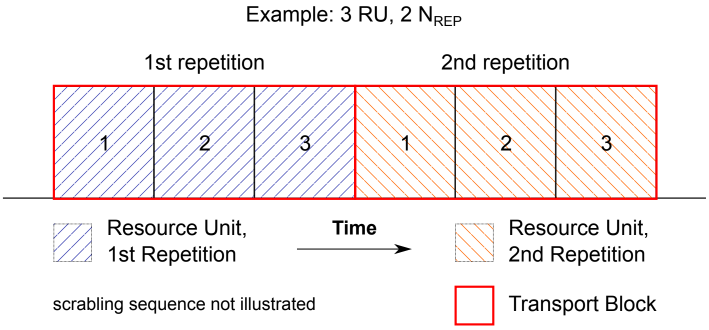

Figure 2.5: Illustration of Transmission Parameters: $\mathrm{N_{RU}}$ and $\mathrm{N_{REP}}$

Figure 2.6 illustrates all available tones in NB-IoT uplink transmission. For every tone size, the specified RU duration is set. NPUSCH may support single-tone (1 tone) and multi-tone (3, 6 or 12 tones) transmissions. Tone allocations are further discussed in Sections 4.1 and 2.3.

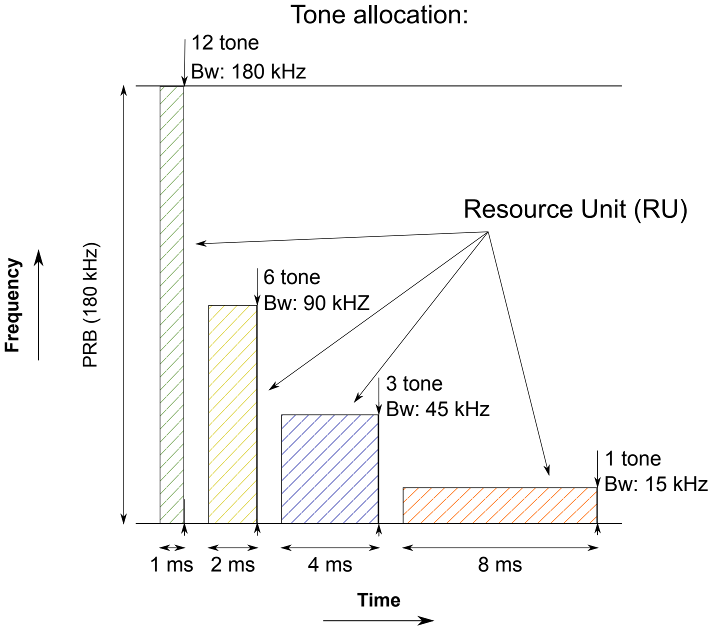

Figure 2.6: Illustration of Transmission Parameters: Tone allocation.

Figure 2.7 shows the fitting of the same amount of data into the different number of RUs, known as MCS or code rate.

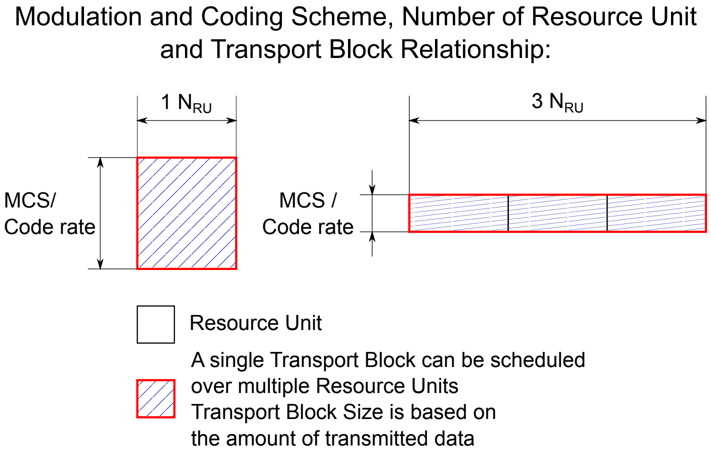

Figure 2.7: Illustration of Transmission Parameters: MCS and N_{RU} relationship.

2.5 Parameters determination procedure

The procedure of setting parameters for uplink transmission is as follows [4].

1. The device provides the serving eNB information about the amount of data to be transmitted and the difference between the nominal device maximum transmission power and the estimated transmission power, known as Power Headroom Report (PHR) [1].
2. The eNB has information about multi-tone support by the device from the NPRACH and its CE level [15].

3. Scheduler sorts devices which request resource allocation (radio resources) and have not been scheduled yet. Sorting is used to prioritize devices based on the chosen set of parameters. A scheduling metric might be used to evaluate the device order.
4. According to the CE level and the device abilities (support for single-tone transmission is mandatory for all devices, multi-tone transmission support is optional), the scheduler decides about the N_{REP}. Repeating of the useful signal increases effective SNR and allows the device to transmit data with acceptable Block Error Rate (BLER). BLER is defined as a ratio of the number of erroneous blocks to the total number of blocks transmitted. A higher BLER of the traffic channel allows transmitting with higher coverage. In NB-IoT, an erroneous transmission can be corrected through Hybrid Automatic Repeat Request (HARQ) retransmissions [16].

   Unlike Bit Error Rate (BER), the BLER is not computed or modeled easily and has to be evaluated using simulation due to the contribution of error correction systems. All channels have their BLER target set individually. In NPUSCH, the BLER target is typically set to 10% (=0.1) [5].

   The BLER is affected by MCS and SNR. Respecting the BLER target, transmission parameters should be set accordingly to keep it in the desired range. Both N_{REP} and N_T affect SNR (affecting BLER) directly, as described in Section 2.4.
5. The SNR is taken into account when a tone allocation decision is made.
6. MCS index is calculated based on tone allocation and SNR. This index corresponds to the TBS index in Table 2.2. Based on the amount of data volume and MCS, the N_{RU} is chosen accordingly.
7. The scheduler selects devices one by one from its list according to the device metric and schedule selected the device in time and frequency for specified subcarrier.

III | System Model

At the beginning of this chapter, the system model is presented, with the general NB-IoT system narrowed down and certain limitations set. Coupling loss and calculation of Signal to Noise Ratio are presented in Sections 3.1 and 3.2, respectively. Device transmitting power is described in Section 3.3.

NB-IoT communication system with three CE levels is assumed. The devices are uniformly distributed in the eNB coverage area. All devices are supposed to be a part of one network, belonging, for example, to one company, and the devices are doing the same job (all of them are, for example, measuring water flow, demanding similar power consumption).

All devices belonging to the same network are demanded to have similar power consumption since it is typically profitable to replace all devices in a specific area at the same time. Having a considerably different energy consumption would force an operator to replace all the devices sooner than it would be required for most of them from the set. The problem is that energy consumption of devices in different CE levels are not balanced (in real conditions even devices in same CE level might have different power consumption). Devices in the CE level 2 have from 2 up to 6 times higher energy consumption compared with devices in CE level 0 [5].

The network of devices is considered alive, as long as all devices have some energy. Network lifetime is defined as the period from the start of its operation to the moment when the first device in the network runs out of energy. Battery replacement or charging is considered very expensive. Therefore the task is to avoid quick discharging of some devices in order to synchronize battery replacements into the same time window.

All devices are considered in RRC connected state (after Random Access (RA) procedure). Therefore the network knows a unique identity and approximate buffer status of each device [17]. Random access procedure guarantees that no more than one device asks for radio resources in each subframe.

During the random access procedure, all devices send its battery status. The eNB knows the CL or SNR of each device. Subcarrier spacing of 15 kHz is assumed, i.e., single-tone transmission with a subcarrier spacing of 3.75 kHz is not allowed. NPUSCH Format 1 carrying data is assumed.

Coupling Loss is characterized in Section 3.1. SNR and its computation are described in Section 3.2. Device transmitting power is mentioned in Section 3.3

3.1 Coupling Loss

CL expresses connection loss that occurs during a signal transmission through a wireless channel. Maximum Coupling Loss (MCL) is defined as the maximum loss in the conducted power level, that a system can tolerate and still be operable. Unlike Path Loss (PL), CL is defined using the antenna connector as the reference point, and gain of the antenna is not considered when calculating CL [5]. The difference between CL and PL is illustrated in Figure 3.1.

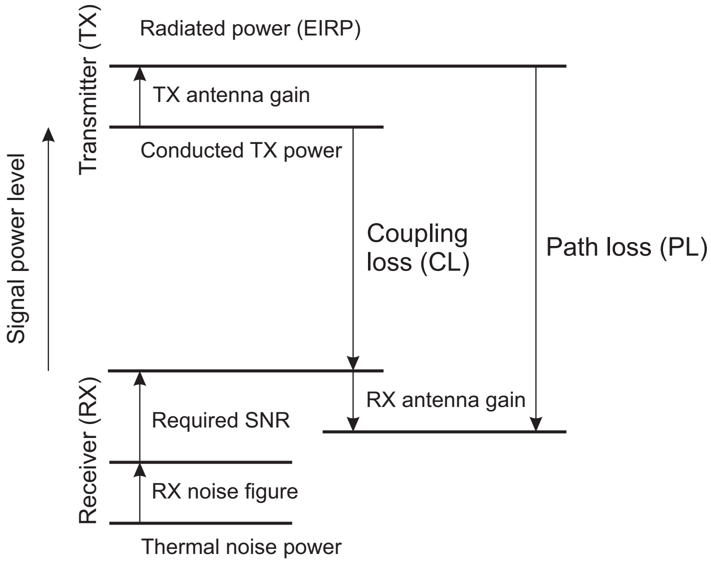

Figure 3.1: Illustration of coupling loss and path loss.

As already mentioned in this thesis CL or SNR, as well as the battery status of the device, are known parameters.

3.2 Signal to Noise Ratio

Signal to Noise Ratio is calculated as [18]:

$$\mathrm{SNR} = \mathrm{P_{Tx}} - \mathrm{P_{NF}} - \mathrm{CL}\ [\mathrm{dB}] \tag{3.1}$$

$$\mathrm{P_{NF}} = 10\log_{10}(k \cdot T_0 \cdot 1000) + \mathrm{NF} + 10\log_{10}(\mathrm{B}) \tag{3.2}$$

where SNR is Signal to Noise Ratio, received at the eNB, $\mathrm{P_{Tx}}$ is the device transmitting power, $\mathrm{P_{NF}}$ is noise floor, composed of the thermal noise, Noise Figure (NF) and the device scheduled bandwidth B, determined by the number of allocated sub-carriers (tones). Bandwidth values are obtained from Table 2.1. The parameter k is the Boltzmann constant.

SNR is converted to Watts by the following formula:

$$\mathrm{SNR_W} = 10^{\frac{\mathrm{SNR}}{10}}\ [\mathrm{W}] \tag{3.3}$$

According to figure 8.3 from [5], data rate varies for different CLs. If the CL is high (more than approx. 145 dB), there is no significant difference in achievable bit rate according to tone allocation.
For lower CL it is advantageous to use higher tone allocation to allow the device to transfer data with a higher bit rate and going to sleep sooner.
For higher coupling loss is advantageous to use single-tone transmission which is more spectrally efficient.
The SNR is further influenced by $\mathrm{N_{REP}}$ as presented later, in Section 4.4, so (3.1) is later adjusted.

3.3 Device transmitting power

Open-loop power control is used in NB-IoT in order to set device transmission power for NPUSCH. For both Format 1 and 2, if the number of repetitions is higher than 2, the maximum configured power P_{MAX} is used in the device [1].
The transmitting power for uplink data transmission on the device side is calculated as [5], [1]:

$$P_{\mathrm{TX}} = \min \begin{Bmatrix} P_{\mathrm{MAX}} \\ 10\log_{10}(M_{\mathrm{NPUSCH}}) + P_{\mathrm{target}}(t) + \alpha_i(j)\cdot PL \end{Bmatrix} [dBm] \tag{3.4}$$

where:

$$P_{\mathrm{target}} = P_{\mathrm{O\_NOMINAL\_NPUSCH}} + P_{\mathrm{O\_UE\_NPUSCH}} \tag{3.5}$$

where P_{TX} is the device transmit power. P_{MAX} is the configured device transmit power defined in [19] in NB-IoT uplink, M_{NPUSCH} is a parameter related to the used bandwidth for NPUSCH data transmission: $1/4$ for 3.75 kHz subcarrier spacing and $1, 3, 6, 12$ for 15 kHz subcarrier spacing, matching number of used subcarriers and P_{target} represents the eNodeB received power per Resource Block assuming a path loss of 0 dB (target power spectral density). According to [20], [21], [22], P_{target} might be interference that the device is expected to overcome, corresponding to the target power level received at the eNB [5]. The parameter $\alpha_i(j)$ is a path loss adjustment factor, provided by higher layers. PL is an estimated path loss. $P_{\mathrm{O\_NOMINAL\_NPUSCH}}$ specifies the cell-specific factor/component. Its value can be anywhere between -126 dBm to 24 dBm. The parameter is provided by higher layers. $P_{\mathrm{O\_UE\_NPUSCH}}$ represents the device-specific component. Its value can be anywhere from –8 to 7 dBm. The parameter is provided by higher layers.
Calculations in this thesis though expect $P_{\mathrm{TX}} = P_{\mathrm{MAX}} = 23\,\mathrm{dBm}$.

IV | Proposed dynamic model

This chapter is organized as follows. Mutual dependencies of NPUSCH parameters are introduced in Section 4.1 followed by the parameters analysis and influence on Energy Consumption (EC). Code Rate is worked out in Section 4.2 and MCS, $\mathrm{N_{RU}}$, TBS relationship, is depicted in Section 4.3. The $\mathrm{N_{REP}}$ and adjustment of the SNR equation are in Section 4.4. The EC computation is stated in Section 4.5.

4.1 The dependency of energy consumption on transmission parameters

Dependency flow of NB-IoT NPUSCH system is introduced in Figure 4.1 in order to help with the understanding of the complicated system of mutual dependencies and relationships among parameters of the system.

The EC is dependent on three values: Transmission Time τ, the device transmitting power and PA efficiency η. EC is calculated as the τ multiplied by transmitting power of the device divided by η of the device. The calculation is further described in Section 4.5, [23].

The parameter τ is directly affected by RU duration τ_{RU}, dependent on the following three parameters: the Subcarrier Spacing (15 or 3.75 kHz), NPUSCH Format and the Number of Allocated Subcarriers. This is further described in Section 2.3. Since NPUSCH Format 1 (uplink data) and 15 kHz subcarrier spacing is assumed, the red color of these blocks infers that their values are static.

In order to get τ, the $\mathrm{N_{REP}}$ is multiplied by τ_{RU} and also by $\mathrm{N_{RU}}$ (4.4).

An important aspect is choosing $\mathrm{N_{REP}}$, $\mathrm{N_T}$, and MCS providing an R, as that affects PAPR, influencing PA efficiency and BLER (refer to Section 4.3), a subject of evaluation with some percentage target.

The $\mathrm{N_{REP}}$ is chosen first as a function of SNR. This relationship is described in Section 4.4. Note that the number of repetitions also affects Effective SNR.

Tone allocation is determined as the second in the scheduler. As a higher $\mathrm{N_T}$ uses a higher bandwidth of an uplink transmission (refer to Table 2.1), SNR is also affected by tone allocation, as can be seen from (3.1). Table 2.1 also shows $\mathrm{N_T}$ effect to RU duration.

PHR is used by the device to inform eNB about remaining power used for transmission. Based on its value eNB can decide if the device can increase MCS or the number of tones.

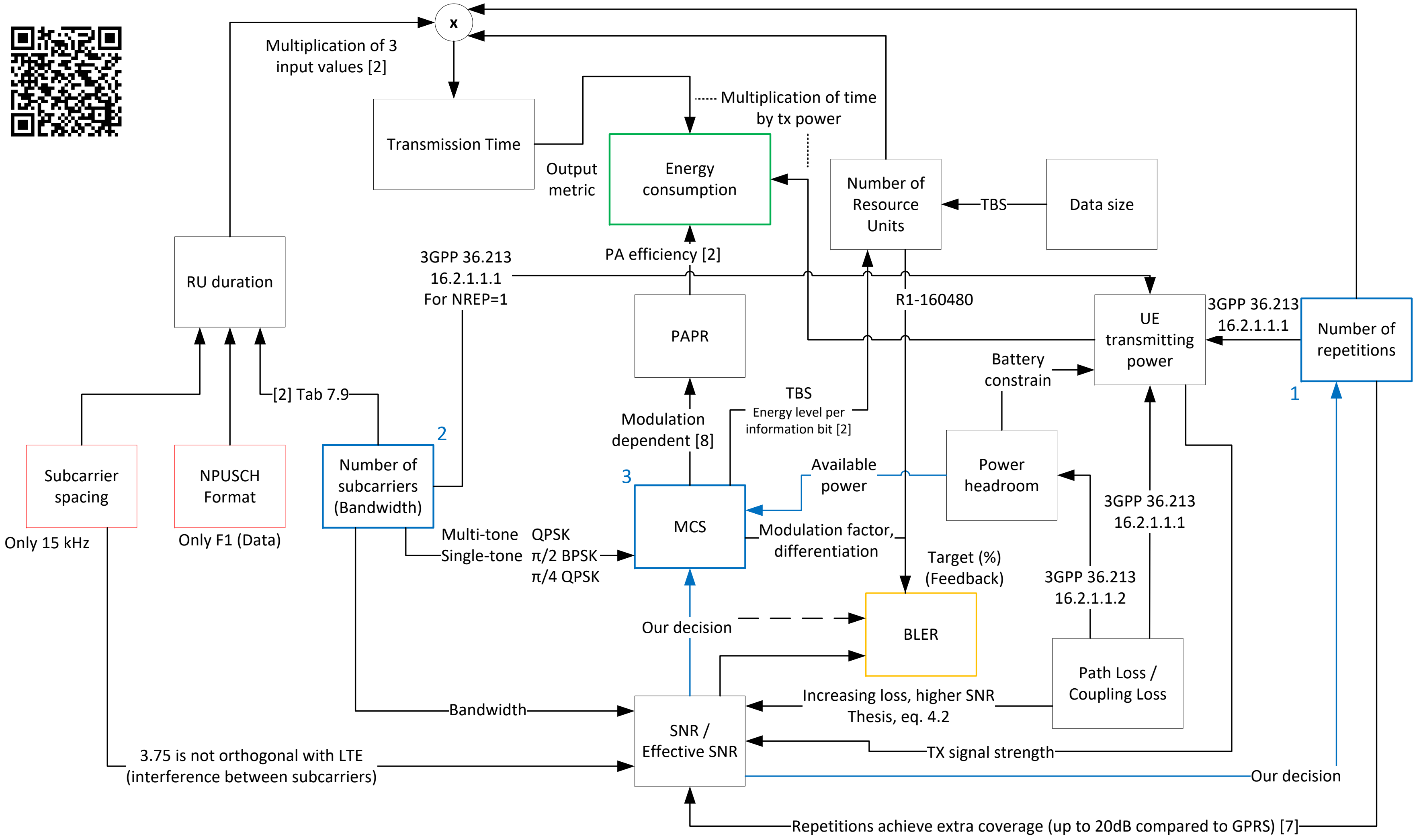

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Figure 4.1: Dependency flow of NB-IoT NPUSCH system.

4.2 Code Rate

For each TBS shown in Table 2.2, the code rates for single-tone and multi-tone NPUSCH Format 1 data transmission are calculated in Tables 4.1 and 4.2, respectively. Code rates are calculated as:

$$\varsigma = \frac{\mathrm{TBS} + \mathrm{CRC}}{\mathrm{N}_{\mathrm{RU}} \cdot \delta \cdot \beta}, \tag{4.1}$$

where ς is the Code Rate for specific TBS, CRC is 24-bit Cyclic Redundancy Check added to the data in each Resource Unit, N_{RU} is Number of Resource Units, δ is the number of REs for data per RU as defined in Table 2.2 and β is the number of encoded bits per symbol, dependent on the used modulation. Code rates are verified with results obtained from [5].

Table 4.1: Code rates for single-tone NPUSCH Format 1 data transmissions.

Code Rate ($\mathrm{I}_{\mathrm{TBS}}$)	Number of RUs (N_{RU})							
	1	2	3	4	5	6	8	10
0	0.42	0.29	0.28	0.29	0.30	0.31	0.30	0.29
1	0.25	0.21	0.19	0.22	0.21	0.20	0.18	0.19
2	0.58	0.50	0.58	0.52	0.48	0.49	0.46	0.47
3	0.33	0.33	0.35	0.30	0.29	0.31	0.30	0.31
4	0.42	0.38	0.40	0.36	0.37	0.38	0.38	0.38
5	0.50	0.44	0.43	0.46	0.47	0.46	0.46	0.47
6	0.58	0.52	0.49	0.54	0.55	0.54	0.54	0.53
7	0.67	0.65	0.61	0.65	0.63	0.64	0.67	Not used
8	0.75	0.73	0.72	0.73	0.73	0.72	Not used	Not used
9	0.83	0.83	0.83	0.83	0.83	0.83	Not used	Not used
10	0.88	0.92	0.92	0.92	0.93	0.89	Not used	Not used
11	Not used	Not used	Not used	Not used	Not used	Not used	Not used	Not used
12	Not used	Not used	Not used	Not used	Not used	Not used	Not used	Not used

Table 4.2: Code rates for multi-tone NPUSCH Format 1 data transmissions.

Code Rate (I_{TBS})	Number of RUs (N_{RU})							
	1	2	3	4	5	6	8	10
0	0.14	0.10	0.09	0.10	0.10	0.10	0.10	0.10
1	0.17	0.14	0.13	0.15	0.14	0.13	0.12	0.13
2	0.19	0.17	0.19	0.17	0.16	0.16	0.15	0.16
3	0.22	0.22	0.23	0.20	0.19	0.20	0.20	0.21
4	0.28	0.25	0.27	0.24	0.24	0.25	0.25	0.25
5	0.33	0.29	0.29	0.31	0.31	0.31	0.31	0.31
6	0.39	0.35	0.32	0.36	0.37	0.36	0.36	0.36
7	0.44	0.43	0.41	0.43	0.42	0.43	0.44	Not used
8	0.50	0.49	0.48	0.49	0.49	0.48	Not used	Not used
9	0.56	0.56	0.56	0.56	0.56	0.56	Not used	Not used
10	0.58	0.61	0.61	0.61	0.62	0.59	Not used	Not used
11	0.69	0.69	0.70	0.69	0.71	Not used	Not used	Not used
12	0.81	0.81	0.81	0.89	Not used	Not used	Not used	Not used

From the dependency model in Section 4.1, it can be observed that PA efficiency is influencing a device energy consumption while transmitting. Being aware of the difference in used modulation as described in Section 2.3 is essential as scheduling single-tone and multi-tone transmission to two devices with same channel conditions might make the device scheduled with single-tone transmission more effective from the perspective of energy consumption. The device scheduled with multi-tone transmission might reach a higher bit rate (depending on the SNR) and save more energy in total by transmitting in a considerably shorter time. On the other hand, using the differential modulation has a negative influence on the signal gain, which is about 2 dB worse in case of single-tone modulation as described in Section 4.3.
This trade-off needs to be simulated and requires an evaluation of PAPR influence on energy consumption.

4.3 Modulation and Coding Scheme

In order to be able to decide about MCS assignation to a device, the scheduler has to know the effects of its decision to BLER and also EC in our case [24]. To express BLER dependency on SNR, 3GPP R1-160480 [25] is used as a reference. The reference provides TBS Simulation results in appendix B, showing BLER-SNR curves for different N_{RU} and MCS combinations. Figures B-1 from the reference are used to create Tables 4.3 and 4.4 for single-tone and multi-tone NPUSCH transmission,

respectively. In figures, only a limited number of values could be deducted, rest of the numbers are computed using a linear approximation.
Since values for particular MCS are almost the same for different N_{RU}, a minimum value is taken as a reference. Figure 4.2 is showing MCS ($=I_{TBS}$) and SINR relation.

Table 4.3: Required SINR for MCS and N_{RU} combinations to achieve 0.1 BLER for single-tone NPUSCH.

TBS (I_{TBS})	Number of RUs (N_{RU})								MIN
	1	2	3	4	5	6	8	10	
0	**-2**	**-3.9**	**-4.1**	**-4**	**-4**	**-4**	-4.00	-4.00	-4.10
1	-1.45	-3.2	-2.95	-2.9	-3	-3	-3.05	-3.08	-3.20
2	**-0.9**	**-2.5**	**-1.8**	**-1.8**	**-2**	**-2**	-2.10	-2.15	-2.50
3	0.05	-1.25	-0.65	-1.15	-1.25	-1.25	-1.30	-1.33	-1.33
4	**1**	**0**	**0.5**	**-0.5**	**-0.5**	**-0.5**	-0.50	-0.50	-0.50
5	2	1	1	0.75	0.75	0.75	0.75	0.75	0.75
6	**3**	**2**	**1.5**	**2**	**2**	**2**	2.00	2.00	1.50
7	4	3.25	3	3	3.25	3	3.00	2.88	2.88
8	**5**	**4.5**	**4.5**	**4**	**4.5**	**4**	4.00	3.75	3.75
9	5.99	5.63	5.46	5.07	5.68	5.09	5.09	4.80	4.80
10	6.99	6.77	6.52	6.17	6.92	6.19	6.20	5.84	5.84

Table 4.4: Required SINR for MCS and N_{RU} combinations to achieve 0.1 BLER for multi-tone NPUSCH.

TBS (I_{TBS})	Number of RUs (N_{RU})								MIN
	1	2	3	4	5	6	8	10	
0	**-4**	**-5.5**	**-6**	**-6**	**-6**	**-6**	-6.00	-6.00	-6.00
1	-3.25	-5	-5	-4.75	-5	-5	-5.13	-5.19	-5.19
2	**-2.5**	**-4.5**	**-4**	**-3.5**	**-4**	**-4**	-4.25	-4.38	-4.50
3	-1.75	-3.25	-2.9	-2.75	-3.1	-3.25	-3.50	-3.70	-3.70
4	**-1**	**-2**	**-1.8**	**-2**	**-2.2**	**-2.5**	-2.75	-3.03	-3.03
5	-0.25	-1.25	-1.4	-1.25	-1.35	-1.625	-1.81	-2.04	-2.04
6	**0.5**	**-0.5**	**-1**	**-0.5**	**-0.5**	**-0.75**	-0.88	-1.06	-1.06
7	1.25	0.5	0	0.25	0.25	0.125	0.06	-0.03	-0.03
8	**2**	**1.5**	**1**	**1**	**1**	**1**	1.00	1.00	1.00
9	2.75	2.41	1.72	1.75	1.82	1.86	1.91	1.96	1.72
10	3.50	3.31	2.46	2.50	2.62	2.73	2.84	2.96	2.46
11	4.25	4.24	3.27	3.25	3.40	3.60	3.78	3.96	3.25
12	5.00	5.18	4.12	4.00	4.19	4.47	4.70	4.96	4.00

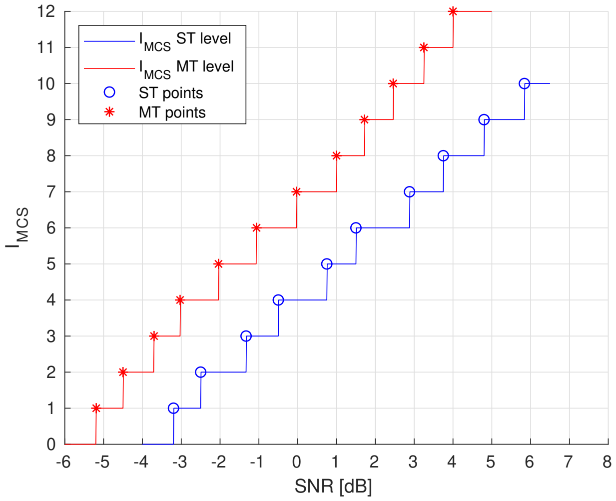

Figure 4.2: I_{MCS} and SNR relation for ST and MT NPUSCH, achieving target BLER=0.1.

Note that in Figure 4.2 the difference between multi-tone and single-tone allocation is about 2 dB, which is expected behavior as the difference is caused by $\pi/2$-BPSK and $\pi/4$-QPSK modulation used in single-tone [26].
Concerning Figure 4.2, an MCS index is chosen according to the SNR of the device and single-tone / multi-tone operation. Then based on the size of transmitted data, N_{RU} is chosen based on Table 2.2.
MCS-NRU relation is presented in Figures 4.3 and 4.4 for different data sizes and single-tone and multi-tone operation, respectively. For single-tone, the case is the same, but I_{MCS}=MCS values end at 10.

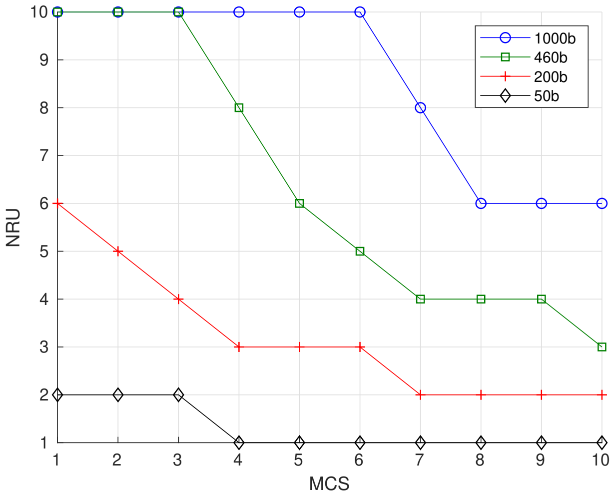

Figure 4.3: Dependency of NRU level on I_{MCS} for four different data-sizes for single-tone.

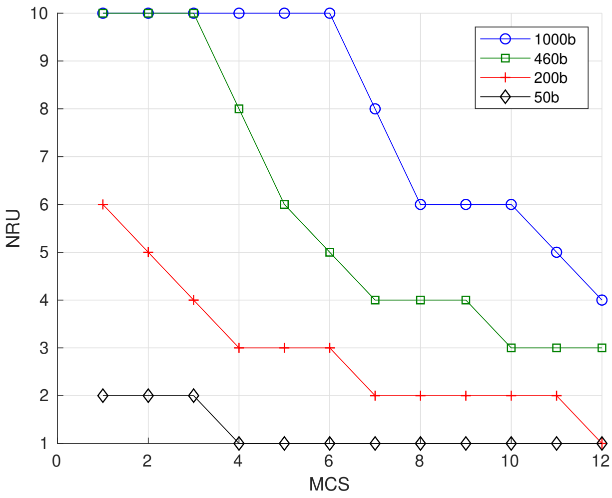

Figure 4.4: The dependency of NRU level on $\mathrm{I_{MCS}}$ for four different data-sizes for multi-tone.

4.4 Repetition number

Repetition number might be based either on the CE level or SNR.
The equation of the effective SNR needs to be adjusted to accommodate the effect of repetition. The number of repetitions in NB-IoT is defined as 2^n for $n \in \{0, ..., 7\}$, where n is the repetition index. Each increase of the repetition index double the signal strength and thus, gives us an additional 3 dB gain in SNR [16].
Effective SNR enhancement ς as a function of a $\mathrm{N_{REP}}$ is assumed. Enhancement is approximated by Table 4.5. Table 4.5 might be verified from [13] and [27], which claim that NB-IoT can achieve a 20 dB improvement over a single repetition transmission.

Table 4.5: Effective SNR enhancement based on repetition number.

Repetition index n	0	1	2	3	4	5	6	7
Effective SNR enhancement ς [dB]	0	3	6	9	12	15	18	21

Then, SNR calculation might be adjusted based on Table 4.5:

$$\mathrm{SNR} = \mathrm{P_{Tx}} + \varsigma - \mathrm{P_{NF}} - \mathrm{CL}\ [\mathrm{dB}] \tag{4.2}$$

$$\mathrm{P_{NF}} = 10\log_{10}(k \cdot T_0 \cdot 1000) + \mathrm{NF} + 10\log_{10}(\mathrm{B}) \tag{4.3}$$

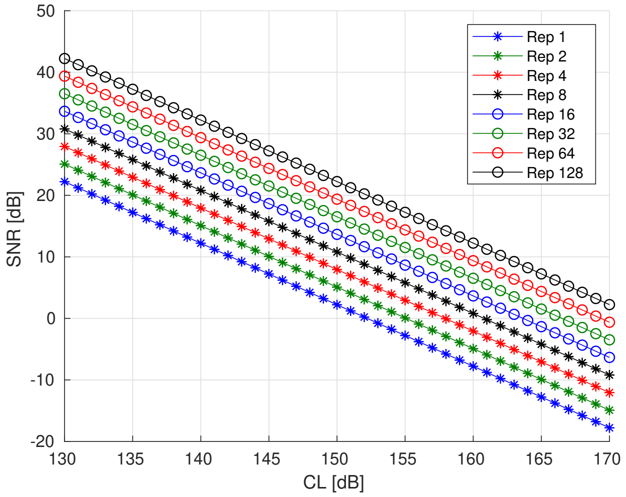

Figure 4.5: SNR-CL relationship for single-tone NPUSCH, N_{REP}=1,..,128.

4.5 Energy consumption

In this section, observations gathered through sections 4.2 to 4.4 are combined into a computation of energy consumption which is later used for choosing a combination of parameters for the uplink transmission. The energy, required to transmit data of the device is calculated as follows [28].

The total number of scheduled NPUSCH slots is determined by the number of RUs (N_{RU}) per repetition, the number of repetitions (N_{REP}) and the length of an RU according to the tone allocation, from Table 2.1.

The time required for UL data transmission is determined as

$$\tau_{UL} = \tau_{RU} \cdot N_{REP} \cdot N_{RU} \text{ [s]} \tag{4.4}$$

Device's power consumption is dependent on device transmit power P_{TX}, PA efficiency η and power demand of other circuitry σ. Energy consumption ε is then computed as a product of Uplink Transmission Time (τ) and device TX power consumption.

$$\varepsilon = \tau_{UL} \cdot (\frac{P_{TX}}{\eta} + \sigma) \tag{4.5}$$

As a secondary product, we also get a peak physical layer bit rate S, calculated as a fraction of data size D and transmission time as:

$$\mathrm{S} = \frac{D}{\tau_{UL}} \tag{4.6}$$

An EC as a function of SNR and N_T is depicted in Figure 4.6. Figure 4.7 is created for CL instead of SNR. The reason why using CL is more vivid than SNR, is because SNR is affected by the N_T parameter. Every tone line in Figure 4.7 is shifted as the bandwidth changes.

It can be seen from both figures that EC is for most of the time the lower for higher N_T if the signal is strong enough. EC increase as the signal is worse for the same N_T - that is the effect of MCS adjustment. For some combination of CL and N_T, the EC is the same, e.g., at 140 dB for $N_T = 12$ and $N_T = 6$. As the signal gets worse, it is not possible to communicate with high N_T values.

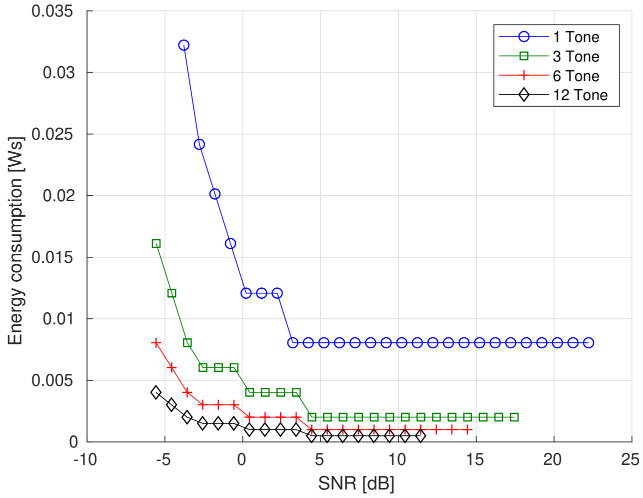

Figure 4.6: Energy consumption for different tone allocations depending on SNR, data size (in this case 200 bits) and the number of repetition (in this case 1).

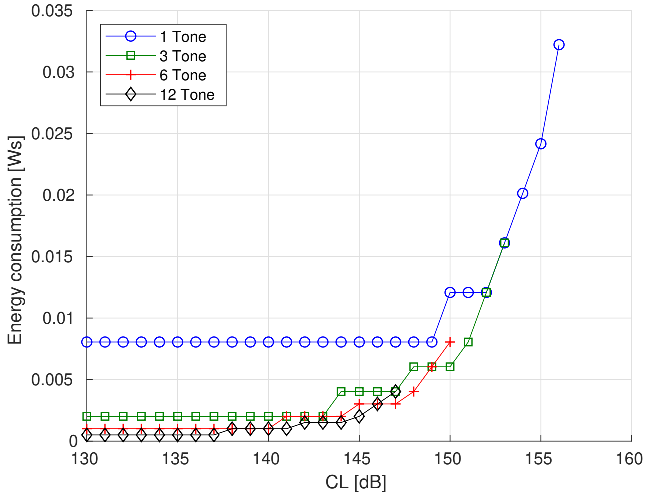

Figure 4.7: Energy consumption for different tone allocations depending on device CL, data size (in this case 200 bits) and the number of repetition (in this case 1).

Based on Figure 4.7 and Section 4.2 it is advantageous to allocate small bandwidth (small number of tones) for devices in bad coverage, thanks to the spectral efficiency of single-tone transmission. It is not possible to achieve a reliable communication using multi-tone transmission because the BLER is too high.
Figure 4.8 is generated using (4.6) and shows a peak bit-rate. The highest bit-rate is achievable with the highest bandwidth (N_T) but is significantly reduced by R trying to compensate signal loss as the CL value gets higher.

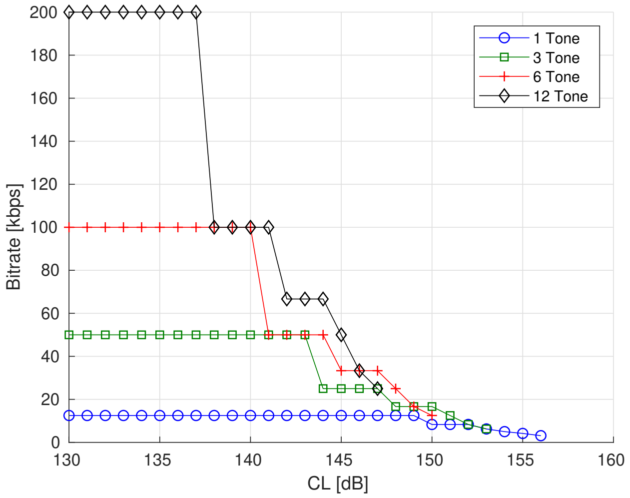

Figure 4.8: Maximum achievable bit rates for different tone allocations depends on the device CL, data size and repetition number.

V | Analytical Results

As already mentioned, the following parameters need to be estimated before transmission: N_{REP}, N_T, MCS, and N_{RU}.
All parameters are determined for each device. In the following section, the values used for the computation are specified first, then in each section, observations about individual parameters are concluded. These parameters are discussed in following subsections.
Finally, results of transmission parameters evaluation model, based on predicted energy consumption, is presented.

5.1 Number of repetitions

N_{REP} value is based on equations estimated in Section 4.4. It might be evaluated based on

- SNR - Higher SNR requires a higher number of repetitions, detailed description in Section 4.4. Target Effective SNR might be specified, and N_{REP} is determined by the received SNR at the random access procedure.
- Coverage Enhancement level - higher CE level requires a higher number of repetitions. Values in Table 5.1 are usually used in simulations in related works [5]. For calculation SNR, the Noise Figure (NF) of 3 dB on the eNB, is assumed. *Note:* In Table 5.1, the CL is used for determination of N_{REP}, because it is also used for determination of CE level.

Table 5.1: Repetition parameters for simulation of NPUSCH Format 2

Maximum Coupling Loss	144	154	164
Number of Repetitions	1	4	32

- Past communication BLER - if BLER is higher than the target range, N_{REP} is increased, if BLER is in the specified range, N_{REP} stays the same, and if BLER is lower than the target range, N_{REP} is decreased [4].
- Energy consumption - EC is computed for all combinations of N_{REP}, N_T, MCS and a combination with the lowest EC is selected.

For the determination of N_{REP} without dependency on other parameters, some combination of the parameters above might be used. For example, it might be advantageous to determine the initial number of repetitions based on the CE level, adjust it according to SNR and use past BLER as feedback for adjusting the number of repetitions in subsequent transmissions based on the assumption that channel conditions are similar.

5.2 Tone allocation

The number of tones is allocated according to the following parameters.

- Device's multi-tone ability.
- Device's CL.
- Battery level (Power Headroom Report).
- Energy consumption.

If the device can communicate in multi-tone, the decision about the number of tones is made according to CL, TBS, and N_{REP}. Otherwise, the device communicates in single-tone.

Based on the estimation of energy consumption, evaluated for all number of tones available, the decision about tone allocation with the aim of minimizing the energy consumption, according to (4.5), is possible to make. The tone allocation is chosen according to Figure 5.1, computed for each tone assignation by estimation mentioned in the previous paragraph. The EC Figure 5.1 changes for different N_{REP}, data size and coupling loss of each device. The tone with the lowest energy consumption according to the computed figure is selected. In case of a tie, a lower number of tones is selected.

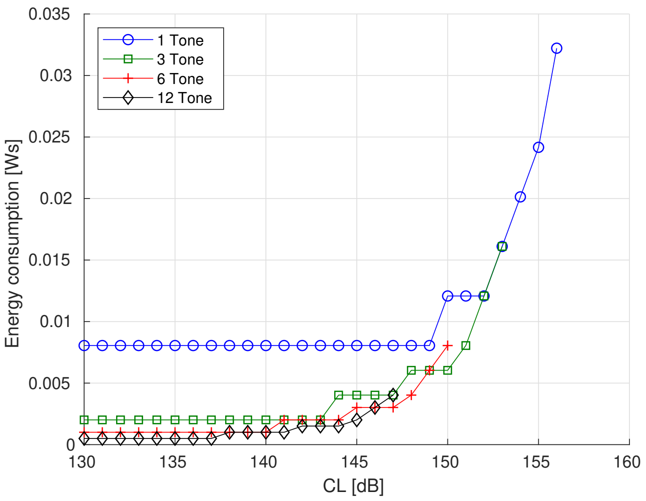

Figure 5.1: Energy consumption for different tone allocations depending on device CL, data size (in this case 200 bits) and the number of repetition (in this case 1).

5.3 MCS allocation

The MCS is dependent on the effective SNR. Figure 4.2 is used to get the MCS for single-tone and multi-tone transmissions. The 2 dB difference is observed between single-tone and multi-tone SNR for same MCS index. The difference is caused by using a differential modulation in single-tone transmission, as described in Section 4.3 [26].

Since the SNR is already dependent on the $\mathrm{N_{REP}}$ and the $\mathrm{N_T}$, evaluation of the MCS parameter is not affected by the $\mathrm{N_T}$, data size, or the $\mathrm{N_{REP}}$. The MCS is chosen from the indexing range from 0 to 10 and from 0 to 12 for single-tone and multi-tone transmissions, respectively. The modulation index is determining the Code Rate used for the transmission. Based on the TBS, the $\mathrm{N_{RU}}$ is then selected.

5.4 Simulation properties

The following model is used for evaluating the energy consumption:
There is a single user, demanding to transmit a specified amount of data, in the following case 200 bits, which can be adjusted. Radio resources are immediately available, and the device does not have to wait for allocation of the radio resources.
Transmitting power of the device is set to 23 dB. Base station receiver NF is 3 dB. A temperature of 290 K is considered. These values were obtained from [5], [4].
Simulation is done for CL in range from 130 dB to 170 dB.
The task is to select all three transmission parameters. Since MCS is determined from target BLER, only $\mathrm{N_{REP}}$ and $\mathrm{N_T}$ have to be selected. From available data, EC is computed for every combination of $\mathrm{N_T}$, and $\mathrm{N_{REP}}$ and the combination of parameters with the lowest EC is selected.

5.5 Simulation results

There is EC computed for every device's CL in figure 5.2. The standard model assumes the static settings for both $\mathrm{N_{REP}}$ and $\mathrm{N_T}$ as specified in [5], [29] and assumes the following values for different MCL:

Table 5.2: $\mathrm{N_{REP}}$ and $\mathrm{N_T}$ parameters settings for simulation of NPUSCH Format 2 according to the standard model

MCL	144	154	164
$\mathrm{N_{REP}}$	1	4	32
$\mathrm{N_T}$	3	1	1

Both parameters are chosen according to the lowest EC in the proposed model, and their values can be seen in Figure 5.3. Furthermore, in the case of occupied Radio resources, the scheduler has the table of EC for all possible combination of $\mathrm{N_T}$, $\mathrm{N_{REP}}$ with a proper MCS, so it can prioritize parameters in such a way that if a different number of tones is assigned, a $\mathrm{N_{REP}}$ is adjusted that communication is still possible (targeting BLER of 10%).

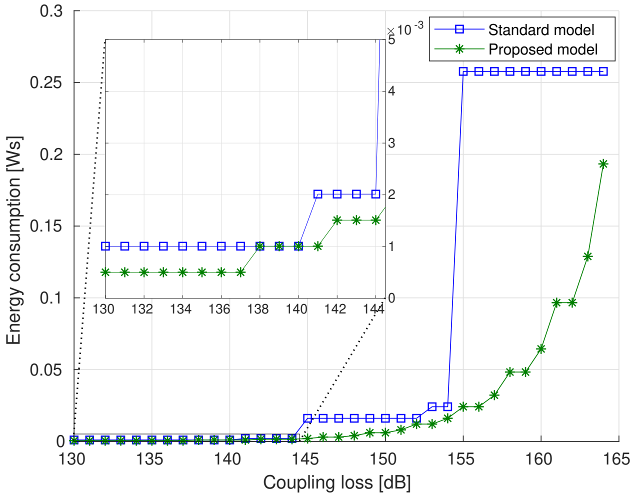

Figure 5.2: Comparison between energy consumption of the standard approach and proposed model for different tone allocations depending on device CL and data size (in this case 200 bits).

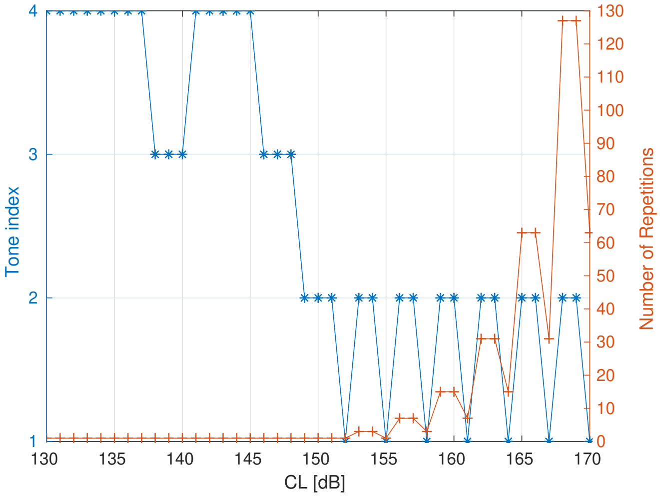

Figure 5.3: Tone index and Number of Repetitions allocation for simulation

VI | Conclusion

The contribution of this thesis is the analysis of how the devices' EC is affected by transmission parameters. Since the EC of the device is the highest during data upload from the device to the base station and the uplink direction offers a variance of an extra parameter (number of subcarriers) compared to downlink transmission. The analysis is therefore focused mainly on the uplink data channel, although most of the principles are applicable for downlink channel too.

Complex dependency model is built first in order to illustrate all variables related to transmissions in NB-IoT and to help with analyzing which parameters affect the EC and how.

Three transmission parameters, affecting the EC are pointed out and their influence on the EC is analyzed. First, the $\mathrm{N_{REP}}$ parameter, providing a 20 dB higher coverage extension, compared to single repetition based transmission systems, by repeating TB, is analyzed. The $\mathrm{N_T}$ (in fact the number of assigned subcarriers to the device), affecting the bandwidth of the transmitted signal, is the second parameter. Depending on the allocated number of tones and used MCS, different modulations are used, influencing the received SNR. The last parameter, possible to adjust, is the MCS, bound to the code rate. Based on the combination of modulation index and $\mathrm{N_{RU}}$, besides dependent on TBS, the code rate is determined, influencing the transmission duration.

One of the most important performance metrics of the system is the BLER, indicating the rate of erroneous messages. The BLER value, set to some target range for each transmission channel, has to be observed since all specified transmission parameters influence it. Thus the transmission parameters have to be set accordingly to the BLER target.

The proposed model first evaluates all three parameters settings based on the signal strength of the device. The energy consumption is calculated for all combinations of transmission parameters provided the combination is sufficient for reliable communication with 10% BLER. A combination with the lowest EC is then selected for the device communication. This EC is compared with the EC of the standard model, which is statically set for every CE level. The proposed model can save 61% of the energy spent on the transmission on average over the standard model. The saving is computed from EC difference in Figure 5.2.

The proposed system might be additionally improved by evaluating the effect of PAPR on η.

VII | Bibliography

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