[NB-IOT AND LINK ADAPTATION]

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Abstract

In present paper was attempted a study in NB-IOT, which introduced by 3GPP in release 13 as a new radio access technology. NB-IOT systems requires at least 180 kHz bandwidth for both downlink and uplink transmission. Also, it can coexist with LTE technology by reusing the LTE design extensively, including numerologies, OFDMA in downlink, SC-FDMA in uplink, channel coding, rate matching and interleaving. NB-IOT focuses specifically in indoor coverage, low cost long battery life and high connection density.

Furthermore, we got involved with link adaptation and especially uplink - link adaptation scheme for NB-IOT systems. Link adaptation has been studied in different types of wireless communication systems. We investigate the uplink adaptation scheme with the repetition number determination, which composed of the inner loop link adaptation to guarantee transmission reliability and improve throughput of NB-IOT systems.

Finally, with simulation process in Matlab we examine the following parameters in graphs: BLER to SNR with different modulation scheme coding, resource unites, number of repetition and transmit block size. Throughput to SNR with different modulation scheme coding, resource unites, number of repetition and transmit block size. Repetition to SNR with different modulation scheme coding and resource unites.

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CHAPTER 1: Narrowband internet of things

1.1 Introduction in NB-IOT

Internet of Things is the next revolution in mobile telecommunication systems. By 2020, will be over 14 billion network – enable devices according to International Energy Agency. Cellular IoT is expected to provide numerous services, such as vending machines, automotive (fleet management, smart traffic, real time information to the vehicle, security monitoring and reporting), medical metering and alerting. Basic aspects of cellular IoT, in order to be enabled and comparative are long battery life, low device cost, low deployment cost, extended coverage and support for massive number of devices [1]. In addition, it should be based on LTE.

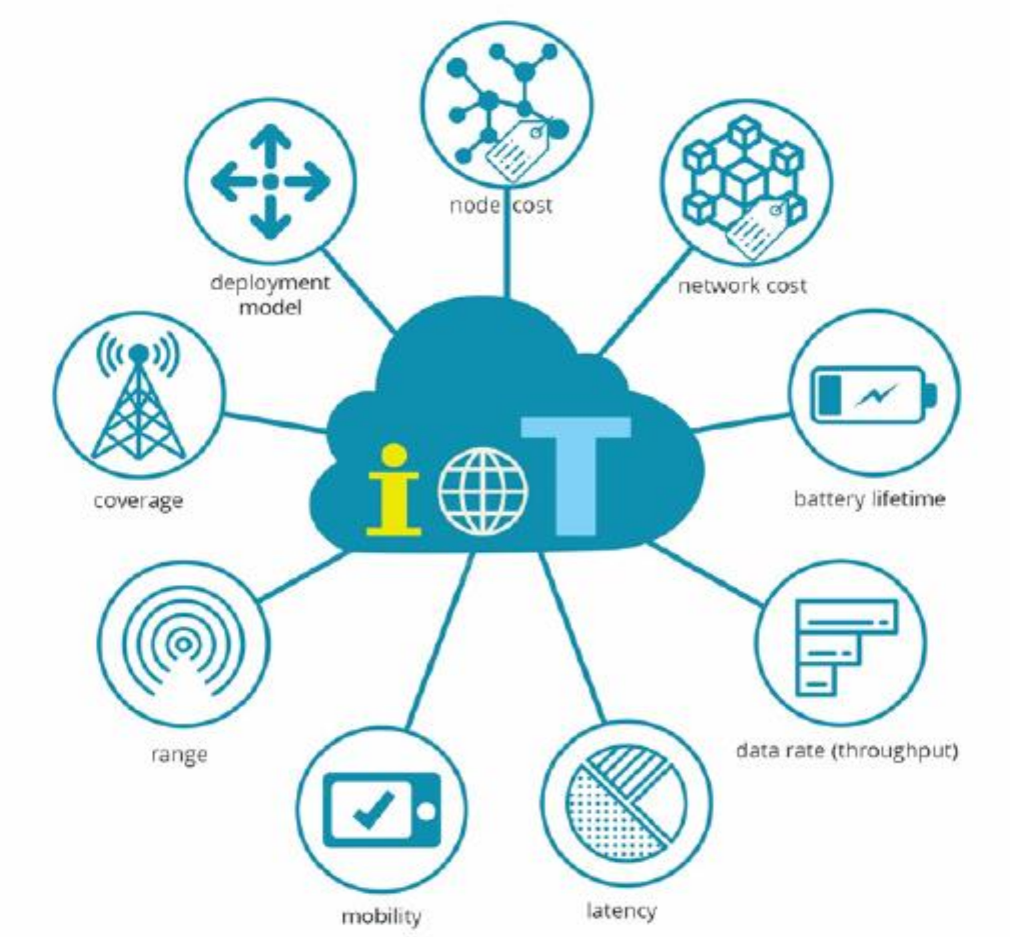


Figure 1. IOT development

Narrowband internet of things (NB-IOT) is a new radio access technology, introduced in 3GPP release 13 for providing wide-area coverage for IoT devices. NB-IOT designed to achieve superior coexistence with legacy GSM, General Packet Ratio Services (GPRS) an LTE technology. Third Generation Partnership Project (3GPP) has introduced the number of features, which provides like cellular IoT extended coverage, long battery lifetime, high capacity, low device complexity and support massive number of devices in a cell.

NB-IOT requires a minimum bandwidth of 180 kHz for both downlink and uplink respectively. It is equal to the size of the smallest LTE Physical Resource Block. Furthermore, as regards the availability of spectrum NB-IOT can be either deployed on its own “standalone operation”, in the guard carriers of existing LTE/UMTS spectrum “guard band operation” or within an existing LTE carrier by replacing one or more PRBs “in band operation”. NB-IOT reuses the LTE design extensively, including the numerologies, orthogonal frequency- division multiple -access (OFDMA) in downlink, SC-FDMA (Single Carrier Frequency Division Multiple Access) in uplink, channel coding, rate matching and interleaving.

Moreover, new features added to ensure the demands of IoT based applications. Design changes from LTE include, random-access preamble, synchronization sequences, control channel and broadcast channel. These changes are motivated by the fact that NB-IOT is required to operate a minimum bandwidth of 180kHz (1 PRB), as, many channels in LTE were designed to span multiple PRBs covering greater bandwidth compared to 180 kHz. These design changes earn IoT requirements while ensuring best co-existence performance with the existing LTE system.

1.2 NB-IOT transmission schemes

1.2.1 Downlink transmission scheme

Downlink of NB-IOT based on OFDMA modulation with 15 kHz subcarrier as LTE. Also, slot, subframe, and frame durations are 0.5ms, 1ms, and 10ms, respectively, such as LTE. Same applies for slot format in terms of cyclic prefix (CP) duration and the number of OFDM symbols per slot. Approximately, an NB-IOT carrier uses one LTE PRB in the frequency domain,15 kHz subcarriers for a total of 180 kHz. Reusing the same OFDM numerology as LTE provide the coexistence performance with LTE in downlink.

1.2.2 Uplink transmission scheme

Uplink of NB-IOT supports both multi-tone and single-tone transmissions. Multi-tone transmission is based on SC-FDMA with 15 kHz subcarrier spacing, 1ms subframe and 0.5ms slot as LTE. Single-tone transmission supports two numerologies, 15 kHz and 3.75 kHz. The 15 kHz numerology is identical to LTE and achieves the best coexistence performance with LTE in the uplink. The 3.75 kHz single-tone numerology uses 2ms slot duration. In uplink, NB-IOT carrier uses a total system bandwidth of 180 kHz.

1.2.3 Deployment

In order to have a minimum system bandwidth we need a number of deployment options. A GSM operator can replace one GSM carrier (200 kHz) with NB-IOT. An LTE operator can deploy NB-IOT inside an LTE carrier by allocating one of the Physical Resource Blocks (PRB) of 180 kHz to NB-IOT. With this selection, the following operation modes are possible:

- Standalone operation. A possible scenario is the utilization of currently used GSM frequencies. With their bandwidth of 200 kHz there is still a guard interval of 10 kHz remaining on both sides of spectrum.
- Guard band operation, utilizing the unused resource blocks within an LTE carrier's guard band
- In-band operation utilizing resource blocks within an LTE carrier.

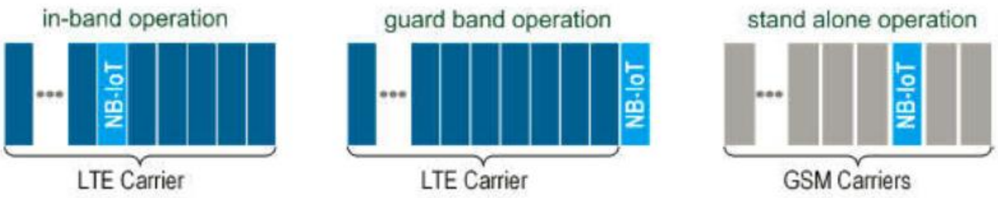
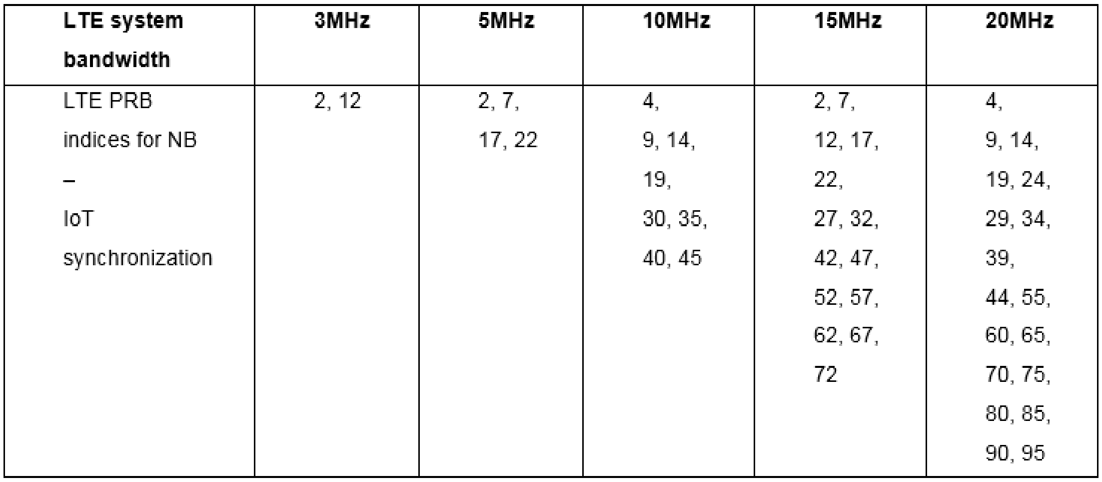


Figure 2. NbIOT in-band operation utilizing resource blocks within an LTE carrier

In the in-band operation, the assignment of resources between LTE and NB-IOT is not fixed. In spite of, not all frequencies, resource blocks within the LTE carrier, are allowed to be used for cell connection. They are restricted to the values given in Table below.



LTE system bandwidth	**3MHz**	**5MHz**	**10MHz**	**15MHz**	**20MHz**
LTE PRB indices for NB – IoT synchronization	2, 12	2, 7, 17, 22	4, 9, 14, 19, 30, 35, 40, 45	2, 7, 12, 17, 22, 27, 32, 42, 47, 52, 57, 62, 67, 72	4, 9, 14, 19, 24, 29, 34, 39, 44, 55, 60, 65, 70, 75, 80, 85, 90, 95

Figure 3. LTE frequencies are allowed for NB-IOT cell connection usage

As recorded in above Table, there is no support for in-band operation of an LTE band with 1.4 MHz bandwidth. A conflict between resources used by the LTE system like the cell specific reference signals (CRS) or the downlink control channel at the start of each sub-frame must be taken into account when resources are allocated for NB-IOT. In addition, an NB-IOT anchor carrier should not be any of the middle 6 PRBs of the LTE carrier. This is due to that LTE synchronization and broadcast channels occupy many resource elements in the middle 6 PRBs, making it difficult to use these PRBs for NB-IOT.

NB-IOT reuses LTE design, including channel coding, downlink orthogonal frequency-division, numerologies, uplink single-carrier frequency-division multiple-access, rate matching etc. This reduces the time, which required developing all the specifications. Furthermore, it is expected that the time required for developing NB-IOT products will be positively reduced for existing LTE equipment and software vendors.

1.2.4 Physical channels

NB-IOT physical channels, are designed based on legacy LTE to a large extent.

1.2.5 Downlink channels

NB-IOT provides the following physical signals and channels in downlink [2].

- NPDSCH, (Narrowband Physical Downlink Shared Channel).
- NPSS and NSSS, (Narrowband Primary and Secondary Synchronization Signals).
- NPBCH, (Narrowband Physical Broadcast Channel)
- NPDCCH, (Narrowband Physical Downlink Control Channel)

- NRS, (Narrowband Reference Signal).

In NB-IOT signals and physical channels are primarily multiplexed in time. Any NB-IOT sub frame spans over one PRB (i.e. 12 subcarriers) in frequency domain and 1ms in the time domain. No PUCCH, PHICH or PCFICH defined for NB-IOT carriers and an accurate HARQ ACK/NACK feedback is applied.

1. NPDSCH, (Narrowband Physical Downlink Shared Channel)

NPDSCH carries data from higher layers as well as paging message, system information and RAR message. There are a number of sub-frames that can be allocated to carry NPDCCH or NPDSCH. To reduce UE complexity, all downlink channels use LTE tail-biting convolutional code. Also, maximum transport block size of NPDSCH is 680 bits, While the LTE without spatial multiplexing supports maximum TBS greater than 70,000 bits.

2. NPBCH, (Narrowband Physical Broadcast Channel)

NPBCH carries the master information block and is transmitted in sub-frame in every frame.

3. NPDCCH, (Narrowband Physical Downlink Control Channel)

The NPDCCH express which UE there is data in the NPDSCH, where to find them and how often they are repeated. Furthermore, the UL grants are provided there, showing the resources the UE shall use for data transmission in the UL. Finally, information like paging or system information update is consist of the NPDCCH as well.

4. NPSS and NSSS, (Narrowband Primary and Secondary Synchronization Signals).

NPSS and NSSS are used by an NB-IOT UE to perform cell search, which includes time and frequency synchronization, and cell identity detection. Since the legacy LTE synchronization sequences occupy 6 PRBs, they cannot be reused for NB-IOT. NPSS is transmitted in sub-frame #5 in every 10 ms frame, using the last 11 OFDM symbols in the sub-frame. NPSS detection is one of the most demanding operations from a UE perspective. To allow efficient implementation of NPSS detection, NB-IOT uses a hierarchical sequence. NSSS has 20 ms periodicity and is transmitted in sub-frame #9, also using the last 11 OFDM symbols that consist of 132 resource elements overall. NSSS is a length-132 frequency domain sequence, with each element mapped to a resource element. NSSS is generated by element-wise multiplication between a ZC sequence and a binary scrambling sequence. Root of the ZC sequence and binary scrambling sequence are determined by narrowband physical cell identity. Cyclic shift of the ZC sequence is further determined by the frame number.

5. NRS, (Narrowband Reference Signal)

NRS used to provide phase reference for the demodulation of the downlink channels. NRSs are time-and frequency multiplexed with information bearing symbols in sub-frames carrying NPBCH, NPDCCH and NPDSCH, using 8 resource elements per sub-frame per antenna port.

1.2.6 Uplink channels

NB-IOT in uplink includes the following channels:

1. NPUSCH, the narrowband physical uplink shared channel.

NPUSCH has two formats. One format is used for carrying uplink data and uses the same LTE turbo code for error correction. The maximum transport block size of NPUSCH Format 1 is 1000 bits, which is much lower than that in LTE. The other format is used for signaling HARQ acknowledgement for NPDSCH, and uses a repetition code for error correction. NPUSCH format one supports multi-tone transmission based on same legacy LTE numerology. In this case, the UE can be allocated with 12, 6, or 3 tones. While only the 12-tone format supported by legacy LTE UEs, the 6-tone and 3-tone formats are introduced for NB-IOT UEs who due to coverage limitation cannot benefit from higher UE bandwidth allocation. To reduce peak-to-average power ratio (PAPR), single-tone transmission uses p/2-BPSK or p /4-QPSK with phase continuity between symbols.

2. NPRACH, the narrowband physical random-access channel.

NPRACH is a newly designed channel since the legacy LTE Physical Random-Access Channel (PRACH) uses a bandwidth of 1.08 MHz, more than NB-IOT uplink bandwidth. One NPRACH preamble consists of 4 symbol groups, with each symbol group comprising of one CP and 5 symbols. Frequency hopping is applied on symbol group granularity, each symbol group is transmitted on a different subcarrier. By construction, this hopping is restricted to a contiguous set - 20 4 -of 12 subcarriers. Depending on the coverage level, the cell may indicate that the UE shall repeat the preamble 1, 2, 4, 8, 16, 32, 64, or 128 times, using the same transmission power on each repetition.

The following table describes the NB-IOT physical signals and channels and their relationship with LTE counterparts.

	PHYSICAL CHANNEL	RELATIONSHIP WITH LTE
DOWNLINK	NPSS	• New sequence for fitting into one PRB (LTE PSS overlaps with middle 6 PRBs) • All cells share one NPSS (LTE uses 3 PSSs)
	NSSS	• New sequence for fitting into one PRB (LTE SSS

		overlaps with middle 6 PRBs) • NSSS provides the lowest 3 least significant bits of system frame number (LTE SSS does not)
	NPBCH	• 640 ms TTI (LTE uses 40 ms TTI)
	NPDCCH	• May use multiple PRBs in time, i.e. multiple subframes (LTE PDCCH uses multiple PRBs in frequency and 1 subframe in time)
	NPDSCH	• Use TBCC and only one redundancy version (LTE uses Turbo Code with multiple redundancy versions) • Use only QPSK (LTE also uses higher order modulations) • Maximum transport block size (TBS) is 680 bits. (LTE without spatial multiplexing has maximum TBS greater than 70000 bits, see [9]) • Supports only single-layer transmission (LTE can

		support multiple spatial-multiplexing layers)
UPLINK	NPRACH	• New preamble format based on single-tone frequency hopping using 3.75 kHz tone spacing (LTE PRACH occupies 6 PRBs and uses multi-tone transmission format with 1.25 kHz subcarrier spacing)
	NPUSCH Format 1	• Support UE bandwidth allocation smaller than one PRB (LTE has minimum bandwidth allocation of 1 PRB) • Support both 15 kHz and 3.75 kHz numerology for single-tone transmission (LTE only uses 15 kHz numerology) • Use P/2-BPSK or P/4-QPSK for single-tone transmission (LTE uses regular QPSK and higher order modulations) • Maximum TBS is 1000 bits. (LTE without spatial multiplexing has maximum

		TBS greater than 70000 bits, see [9]) • Supports only single-layer transmission (LTE can support multiple spatial-multiplexing layers)
	NPUSCH Format 2	• New coding scheme (repetition code) • Use only single-tone transmission

Figure 4. NB-IOT physical signals and channels related with LTE

1.3 NB-IOT objectives

NB-IOT characterized by requirements such as coverage, data rate, latency and battery lifetime. There are thus important metrics. In follow figure presented the main NB-IOT characteristics.

Figure 5. NB-IOT main characteristics

1.3.1. Coverage

NB-IOT achieves a maximum coupling loss 20 dB higher than LTE. Coverage extension is achieved by trading off data rate through increasing the number of repetitions. Coverage enhancement is ensured also by introducing single subcarrier NPUSCH transmission and π/2- BPSK modulation to maintain close to 0 dB PAPR, so that reducing the unrealized coverage potential due to power amplifier back-off. NPUSCH with 15 kHz single-tone gives a layer-1 data rate of 20 bps when configured with the highest repetition factor, and the lowest modulation and coding scheme. NPDSCH gives a layer-1 data rate of 35 bps when configured with repetition factor 512 and the lowest modulation and coding scheme. These configurations support close to 170 dB coupling loss. Compare with the LTE network is designed for up to approximately 142 dB coupling loss.

1.3.2 Capacity

In order to satisfy the capacity requirements NB-IOT needs to multiplex many devices simultaneously and provide connectivity in an efficient manner for all of them irrespective of coverage quality. As a consequence, the design of NB-IOT supports a range of data rates. Data rate depends on the quantity of allocated resources (bandwidth) and channel quality (signal to noise ratio). In downlink, all devices share the same power budget and several may simultaneously receive base-station transmissions. While in the uplink, every device has its own power budget, and this can be used to advantage by multiplexing the traffic generated by several devices, as their combined power is greater than that of a single device. In many locations, NB-IOT devices will be limited by signal strength rather than transmission bandwidth. That devices can concentrate their transmission energy to a narrower bandwidth without loss of performance. This frees up band-width for others. So, increases system capacity without loss of performance.

Furthermore, NB-IOT uses tones or subcarriers instead of resource blocks to enable such small bandwidth allocations. The subcarrier bandwidth for NB-IOT is 15kHz. Each device is scheduled on one or more subcarriers in the uplink, and devices can be packed even closer together by decreasing the subcarrier spacing to 3.75kHz. Due to that in LTE and NB-IOT some resources should be allocated between 3.75kHz and 15kHz to avoid interference.

If we have scenarios, which include devices in both good and bad coverage areas, it is possible to increase the data rate by adding more bandwidth. Good coverage is typical when NB-IOT is rolled out on a dense grid or when most devices are within the original LTE cell coverage area. Data rate is a significant factor when trying to achieve the best design for NB-IOT, as it affects both latency and power consumption.

Also, NB-IOT supports massive IoT capacity by using only one PRB in both uplink and downlink. With one PRB supports more than 52500 UEs per cell. Moreover, NB-IOT supports multiple carrier operation. Thus, more IoT capacity can be added by adding more NB-IOT carriers.

1.3.3 Device complexity

NB-IOT enables low-complexity UE implementation by the designs listed below:

- Support only one redundancy version in the downlink
- Support only single-stream transmissions in both downlink and uplink
- Significantly reduced transport block sizes for both downlink and uplink
- Support only single HARQ process in both downlink and uplink
- No need for a turbo decoder at the UE since only TBCC is used for downlink channels
- A UE only requires single receiver antenna (two are needed for LTE MBB)
- Low sampling rate due to lower UE bandwidth
- Allow only half-duplex frequency-division duplexing (FDD) operation. so that they cannot be scheduled to send and receive data simultaneously, the duplex filter can be replaced by a simple switch, and a only single local oscillator for frequency generation is required. These optimizations reduce cost and power consumption.

- No Connected mode mobility measurement is required. A UE only needs to perform mobility measurement during the Idle mode
- No parallel processing is required. All the physical layer procedures and transmission and reception of physical channels occur in sequential manner.

1.3.4 Throughputs

Peak data rate of NDSCH can be achieved by using the largest TBS of 680 bits and transmitting it over 3 ms. This offers 226.7 kbps peak layer-1 data rate. NPUSCH peak data rate can be achieved by using the largest TBS of 1000 bits and transmitting it over 4 ms. This offers 250 kbps peak layer-1 data rate. Although, the peak throughputs of both downlink and uplink are lower when the time offsets between DCI, HARQ and NPDSCH/NPUSCH acknowledgement are taken into account. Following graph represents the throughputs for different deployments and their dependence of coverage.

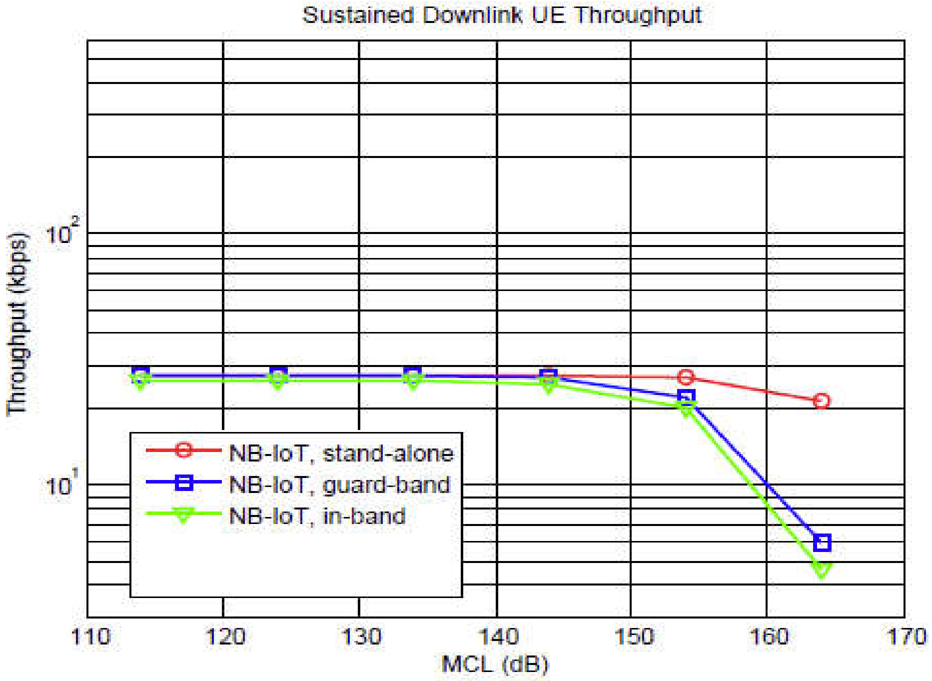


Figure 6. Throughputs for different deployments and their dependence of coverage

1.3.5 Long range and long battery life

The geographical area in which a mobile network can provide coverage depends on link budget and site density. M2M support providing in locations with no direct power source such as water meters and sensors require battery operated devices. Link budget of NB-IOT has a 20dB margin compared with GPRS, WCDMA and LTE and use cases tend to operate with lower data rates. In addition, NB-IOT can reach IoT devices in signal-challenged locations such as basements, tunnels, and remote rural areas. These places cannot be reached by using network’s voice and MBB services.

The coverage target of NB-IOT has a link budget of 164dB, while current GPRS link budget is 144dB and LTE is 142.7 dB. The 20dB improvement corresponds to a sevenfold increase in coverage area for an open environment, or roughly the loss that occurs when a signal penetrates the outer wall of a building. Standardization activities in 3GPP have shown that NB-IOT meets the link budget target of 164dB. Also, meet the MTC application requirements for data rate, latency and battery life.

The battery life of an MTC device depends on technology used in the physical layer for transmitting and receiving data. However, longevity depends on how efficiently a device can utilize various idle and sleep modes that allow to the device to be powered down for extended periods. The NB-IOT specification based both to the physical-layer technology and to the idling aspects of the system. NB-IOT uses two main RRC protocol states: RRC_idle and RRC connected as LTE. In RRC idle, devices save power, and resources while in RRC_connected, devices can receive or send data directly. Discontinuous reception (DRX) is the process which shows when devices can sleep and can be applied in both RRC_idle and RRC_connected. For RRC_connected, the application of DRX reduces the number of measurement reports devices send and the number of times downlink control channels are monitored, leading to battery savings. The 3GPP release 12 supports a maximum DRX cycle of 2.56 seconds, which in release 13 (eDRX) extended to 10.24 seconds.

In RRC_idle, devices track area updates and listen to paging messages. To set up a connection with an idle device, the network pages it. Power consumption is much lower for idle devices than for connected ones, as listening for pages does not need to be performed as often as monitoring the downlink control channel.

In release 12 was introduced the PSM which enabled devices in RRC_idle to enter a deep sleep in every pages are not listened for. Also, they don not need mobility-related measurements. Devices in PSM perform tracking area updates after which they directly listen for pages before sleeping again. PSM and eDRX complement each other and can support battery lifetimes in excess of 10 years for different, transmission frequencies of different applications, reachability requirements and mobility. The range of solutions designed to extend battery lifetime need to be balanced against requirements for reachability, transmission frequency of different applications, and mobility.

1.4 IoT applications

1.4.1 Smart cities

NB-IOT technology can be used in smart cities. Two of these applications can be street lighting and smart parking. Lamp posts fitted with appropriate modules can be switched on and off or dimmed remotely and can trigger an alarm if they malfunction. Also, if cities connect parking space with NB-IOT then in real time citizens can have information's for better parking management. So, drivers can find quick a space to park, this reduce traffic congestions which caused by drivers circling to find a parking space [3].

1.4.2 Transport and logistics

NB-IOT can be a low-cost solution for transportation and logistics which need very small data packets for their information's. In container tracking we can have an analysis which ensures the real time containers of the locations. Furthermore, we can select elements about refillable tanks or bottles, industrial liquid or gas providers monitor levels, pressure and temperature as required.

Alerts and optimized service recommendations will be sent to technicians' mobile phones so they can take preemptive actions in real time. Finally charging model for these applications can be done on a monthly payment or postpaid basis.

1.4.3 Localization

NB-IOT can be suitable for locating pets or for bicycle. As many pets lost or stolen a small device around neck with a NB-IOT chipset can sends location information in real time by using GPS. Also, we can have smart bikes with sim card which gives elements about motion monitoring, position and shifting control.

1.4.4 Smart metering

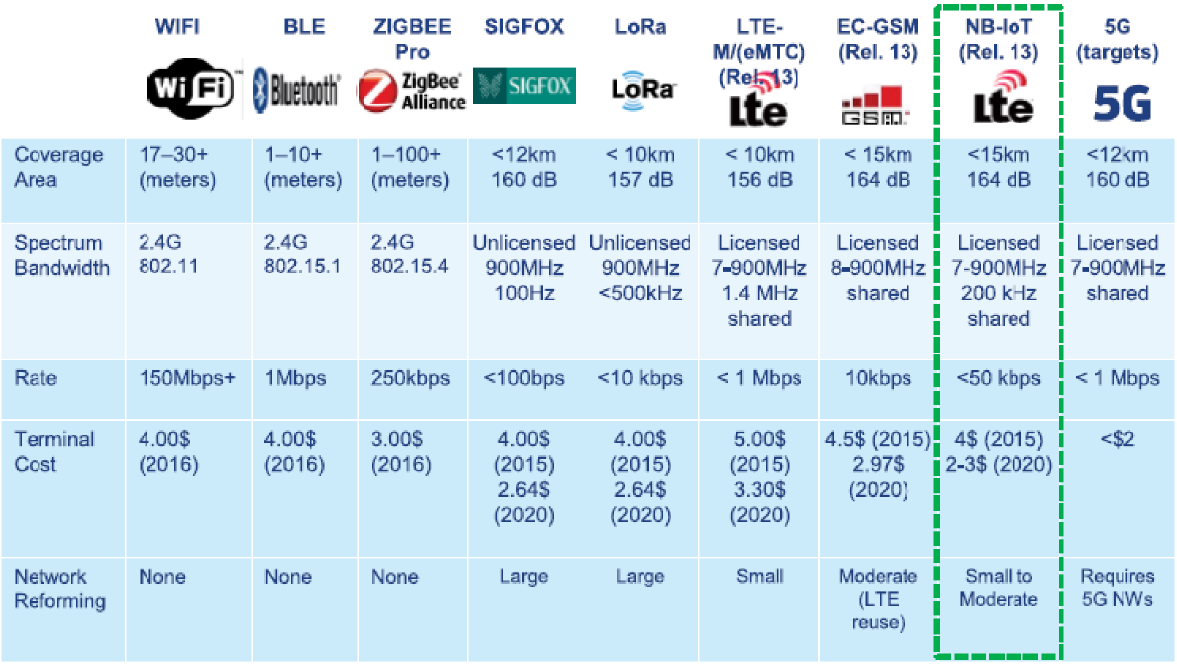
One of the most suitable uses for NB-IOT is smart metering which helps to saves manpower by remotely collecting water, electricity and gas meter data over the cellular network. NB-IOT Battery-powered modules don't need power connection, deliver deep indoor penetration, and thereby establish a reliable connection even in areas where mobile reception is poor. The provider is able to read the meter remotely also, the end customer does not have to stay at home in order to wait for the meter reader to come by.

1.4.5 Farming and forestry

NB-IOT technology is also suitable for agricultural use where there is no power supply or where network coverage is poor. In irrigation of fields or plantations, tank levels, pump pressure and flow rates are measured. Location and health of livestock can be monitored too. With low-cost sensors can be report information such as temperature, smoke development or wind direction.

1.5 Comparison with other IoT technologies

With the development of internet of things technologies, more application of IOT technologies can be found in many industries. The applications areas have specific requirements and considerations so, different technologies are needed. While the short ratio connectivity (Bluetooth, Zig Bee) are not suitable for this scenario as they need long-range performance with low bandwidth The M2M based on cellular technology and can provide large coverage but costumes a lot power. In the other hand Low Pawer Wide Area is more suitable for all this emerging applications and markets due to lower cost points and better power consumptions. The following table shows the basic characteristics of the different technologies.



	WIFI	BLE	ZIGBEE Pro	SIGFOX	LoRa	LTE-M/(eMTC) (Rel. 13)	EC-GSM (Rel. 13)	NB-IoT (Rel. 13)	5G (targets)
Coverage Area	17–30+ (meters)	1–10+ (meters)	1–100+ (meters)	<12km 160 dB	< 10km 157 dB	< 10km 156 dB	< 15km 164 dB	<15km 164 dB	<12km 160 dB
Spectrum Bandwidth	2.4G 802.11	2.4G 802.15.1	2.4G 802.15.4	Unlicensed 900MHz 100Hz	Unlicensed 900MHz <500kHz	Licensed 7-900MHz 1.4 MHz shared	Licensed 8-900MHz shared	Licensed 7-900MHz 200 kHz shared	Licensed 7-900MHz shared
Rate	150Mbps+	1Mbps	250kbps	<100bps	<10 kbps	< 1 Mbps	10kbps	<50 kbps	< 1 Mbps
Terminal Cost	4.00$ (2016)	4.00$ (2016)	3.00$ (2016)	4.00$ (2015) 2.64$ (2020)	4.00$ (2015) 2.64$ (2020)	5.00$ (2015) 3.30$ (2020)	4.5$ (2015) 2.97$ (2020)	4$ (2015) 2-3$ (2020)	<$2
Network Reforming	None	None	None	Large	Large	Small	Moderate (LTE reuse)	Small to Moderate	Requires 5G NWs

Figure 7. Comparison of basic characteristics in IOT technologies

1.5.1 Comparison between NB-IOT and LoRa

NB-IOT and LoRa technology have different technical and commercial qualifications so, they will serve different applications. NB-IOT as we said use many features of LTE including handover, measurements to monitor the channel quality, carrier aggregation, and dual connectivity and so on. It can be regarded as a new air interface which kept as simple as possible in order to reduce device costs and to minimize battery consumption. It uses the licensed frequency bands which are the same frequency numbers as in LTE are used and use QPSK modulation. There are 12 subcarriers of 15 kHz in downlink using OFDM and 3.75/ 15 kHz in uplink using SC-FDMA.

In the other hand LoRa the name of the technology comes from its advantage of long-range capability which benefits from the long great link budget provided by spread spectrum modulation scheme. The LoRa modulation has advantages including adaptive data rate, scalable bandwidth, low-power, high robustness and multipath resistant. LoRa is set up by industrial consortia LoRa Alliance and uses unlicensed ISM spectrum below 1GHz.

Also, LoRa is an asynchronous protocol, which is optimal for battery lifetime and cost but it cannot offer the same quality of services as NB-IOT. Due to the QoS and the high spectrum cost, higher value applications that need guaranteed QoS prefer NB-IOT, while the low cost, high volume solutions prefer LoRa. Furthermore NB-IOT will be the best option for applications that need very long battery lifetime and optimized cost, but do not need to communicate as often, LoRa is a better option. Finally, LoRa protocol is simpler compared to NB-IOT and can be easily implemented with low cost, widely available microcontrollers.

CHAPTER 2: SCHEDULINK AND LINK ADAPTATION

2.1 Scheduling in LTE and NB-IOT

2.1.1 Basics of Scheduling in LTE

Scheduling is the process when eNB (evolved NodeB) decides which UEs should be given resources to send or receive data. In LTE, scheduling is done per subframe level. Basics terms of scheduling are the following:

CQI (Channel quality indicator) is a four-digit value sent to eNB by UE as a feedback for downlink channel. CQI informs eNB about the channel quality in downlink. This helps eNB to allocate proper MCS (Modulation and coding scheme) and RB (Resource block) for UE.

BSR (Buffer Status Report) is a UE way of informing network that it has certain data in its buffer and it requires grants to send this data.

QoS (Quality of Service) defines how a particular user data should be treated in the network. QoS is implemented between UE and PDN Gateway and is applied to a set of bearers.

2.1.2 Factors that affects scheduling

- Traffic Volume: Schedules those UEs with bearers waiting data in buffer
- QoS Requirement: Schedules and allocates resources to UE to meet its QoS requirement
- Radio Conditions: Schedules resources for UE that best suits its radio environment

2.1.3 Scheduling characteristics

The entity which is govern this is as scheduler. A scheduler takes input from OAM as system configuration e.g. which scheduling algorithm is to be enable (round robin, Max C/I, Proportional Fair, QoS aware etc), consider QoS information (Which QCI, GBR/N-GBR etc.) and channel quality information (CQI, Rank, SINR etc) to make the decisions. The LTE downlink scheduler is designed to ensure high Quality of service (QOS), maximization of system capacity, reducing complexity and ensures fairness between all active users. Then, scheduling algorithms should be capable to exploit the channel variation condition with maintaining fairness between the users flows.

A LTE scheduler performs following function for efficient scheduling:

Link Adaptation: It selects the optimal combination of parameters such as modulation, channel Coding & transmit schemes i.e. Transmission Mode (TM1/TM2/TM3/TM4) as a function of the RF conditions.

Rate Control: It is in charge of resource allocation among radio bearers of the same UE which are available at the eNB for DL and at the UE for UL.

Packet Scheduler: It arbitrates access to air interface resources on 1ms-TTI basis amongst all active Users (Users in RRC Connected State).

Resource Assignment: It allocates air interface resources to selected active users on per TTI basis.

Power Control: Provides the desired SINR level for achieving the desired data rate, but also controls the interference to the neighboring cells

HARQ (ARQ + FEC): It allows recovering from residual errors by link adaptation.

2.1.4 Types of Schedulers

Round Robin: The RR scheduler selects and schedules UEs in a round robin manner, thereby creating an equal resource share. The disadvantage of this approach is that UEs with sub-optimalCQIs may be allocated Physical Radio Resources (PRBs), thus reducing the overall cell throughput.

Max CQI : The max-CQI scheduler selects the schedulable UEs based on the experienced CQI. The UEs with the highest CQI therefore become candidates for scheduling thereby increasing the overall cell throughput. The disadvantage of this approach is that UEs with lower CQI are denied scheduling instances, thus being starved for throughput and leading to degraded user experience.

Proportional Fair: The PFS is expected to strike a balance between the traditional Round Robin (RR) scheduler and the max Throughput Scheduler (also known max-CQI (Channel Quality Indicator) scheduler). The PFS scheduler performs in such a manner that it considers resource fairness as well as maximizing cell throughput (in addition to other possible performance metrics).

2.1.5 LTE Services and Scheduling Mechanism

The services / applications are broadly classified into two categories as Real time services and Non-Real time services. Real time services includes Conversational Voice, Video Phony [Conversational Video], MPEG Video [Non Conversational Video], Real-time gaming etc. Non-Real time services include Voice Messaging, Buffered Streaming, ftp, www, email, Interactive gaming. Data transmission characteristics of these services are: Delay tolerance, data packet size (fixed or variable), periodic or aperiodic data transmission, packet error loss rate.

Some or all of these characteristics determine what kind of Packet schedulers are required at the LTE MAC to adhere to the required QoS requirements of the relevant applications. LTE MAC supports the following three types of Scheduling: Dynamic scheduling, persistent scheduling, semi-persistent scheduling.

Dynamic Scheduling: Every TTI, MAC checks for the UEs to be scheduled, the Data Availability for each UE to be scheduled and the feedback from the UE on the Channel conditions. Based on these data, it can schedule the resources for the UE through the PDCCH. If data is not available, UE will not get scheduled. All Services can be scheduled using Dynamic Scheduling, but at the expense of the Control signalling [PDCCH Usage – a scarce resource].

Persistent Scheduling: In this case, Packets are scheduled on a fixed basis, similar to the Circuit Switched fashion. Here, it does not depend on the Channel Condition. The Resource allocation remains constant for the period of the call.

Semi-Persistent Scheduling: It is a Hybrid way of scheduling, which tries to overcome the drawbacks of the Dynamic Scheduling and the Persistent Scheduling.

2.1.6 Uplink scheduling

The radio access technology chosen for the LTE uplink is SC-FDMA (Single Carrier - Frequency Division Multiple Access), in which the radio spectrum is divided into nearly perfect mutually orthogonal sub-carriers. Hence, simultaneous transmissions from different mobile stations (MSs) do not cause intra-cell interference but they do compete for a share in the set of sub-carriers. The total bandwidth that can be allocated to a single MS depends on the resource availability, the radio link quality and the terminal's transmit power budget. The scheduling decision is taken by the packet scheduler, which is located at the base station (BS). Allocation of multiple sub-carries to the same user is possible as long as these sub-carriers are consecutive in the frequency domain. A key feature of packet scheduling in LTE networks is the possibility to schedule users in two dimensions, viz. in time and frequency. The aggregate bandwidth available for resource management is divided in sub-carriers of 15 kHz. Twelve consecutive sub-carriers are grouped to form what we term a `sub-channel', with a band-width of 180 kHz; there are M sub-channels in the system bandwidth. In the time dimension, the access to the sub-channels is organized in time slots of 0.5 ms. Two slots of 0.5 ms form a TTI (Transmission Time Interval). The smallest scheduling unit in LTE is termed a resource block (RB) and has dimension of 180 kHz and 1 ms3). The data rate that a user can realize is in influenced by the number of RBs assigned to it by the scheduler, which determines the allocated bandwidth and the applied transmit power, and by its location, which determines the path loss and the signal to interference plus noise ratio (SNR).

2.1.7 Downlink scheduling

LTE specifications represent Frequency Division Duplexing (FDD) using OFDMA for downlink traffic. OFDMA is one of the key access technologies in the 4G wireless systems because of its high degree of flexibility in allocating resources, scalability, simple equalization and strong characteristics against frequency selective fading. Scheduling is an important factor in RRM mechanism, which is implemented at the eNB. It plays an important role in QoS provisioning by providing mechanisms for the resource allocation and multiplexing at the packet level to guarantee that different types of applications meet their service requirements [13]. It is responsible for the distribution and control of time and frequency domain radio resources to the various users with different service needs, achieving QoS requirements and optimizing system performance in the downlink and uplink of LTE networks. The best PS should be designed to support varieties of traffic with different priorities, channel statistics, queue sizes and traffic loads while improving the Quality of Experience (QoE) for end users. RRM is the method for dynamically allocating radio resources to UE based on the scheduling algorithms involved. The role of RRM is to ensure that the radio resources are efficiently utilized, taking advantage of the available adaptation techniques to serve users according to their QoS attributes. These mechanisms include QoS-aware bearer admission control, multi-user time and frequency domain packet scheduling, HARQ management and LA with dynamic switching between different transmission modes.

2.1.8 Scheduling in NB-IOT

The scheduling process allocates radio resources in PRB to UEs every transmission time interval (TTI) [4]. The NB-IOT scheduling process is located in lower MAC and upper PHY layer. One of the key elements of the network is the ability to control and prioritize bandwidth across UEs. The MAC scheduler is responsible for deciding how and when the channels are used by the eNB and the UEs of a cell. During the NB-IOT scheduling process, an offset is given to each UE to avoid allocation overlapping. NPDCCH is considered as the core element of the downlink control channels as it carries DCI. The DCI contains uplink scheduling grants, downlink scheduling assignments, and the type of modulation being used for NPDSCH. DCI Format N0 is used for the uplink grant. Assignments of PDSCH is transmitted through DCI. It is used for all NPDSCH (user data and NB-SIBs) except NPDSCH carrying paging. DCI is used for paging and direct indications. NPDSCH carries UE’s downlink data and control information. When receiving NPDCCH, the UE searches the DCI in- tended for it according to the UE search spaces. The DCI contains the scheduling delay between the end of NPDCCH transmission and the beginning of NPDSCH or NPUSCH for a UE.

2.1.9 NB-IOT scheduler

The scheduler in the base station controls the allocation of shared time-frequency resources among users at each time instant. The reception of NPDSCH transmission in time-frequency combination for each TTI is determined. The scheduling decision provided by the scheduler must be compliant with more limited NB-IOT specifications. The resource assignment must be in a specific format taking into account reserved signaling resources and capabilities of the UE.

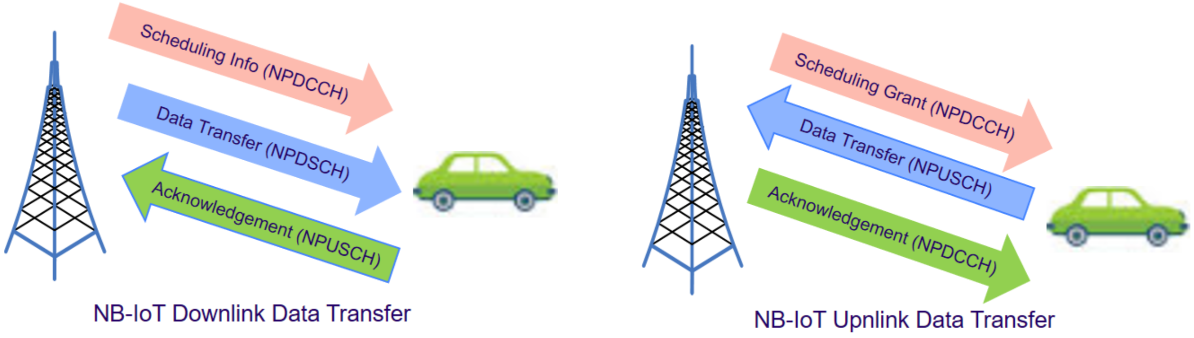


Figure 8. NB-IOT data transfer in uplink and downlink

2.2 Introduction to link adaptation

Link adaptation, or adaptive coding and modulation (ACM), is a term used in wireless communications to denote the matching of the modulation, coding and other signal and protocol parameters to the conditions on the radio link.

Adaptive modulation systems invariably require some channel state information at the transmitter. This could be acquired in time division duplex systems by assuming the channel from the transmitter to the receiver is approximately the same as the channel from the receiver to the transmitter. Alternatively, the channel knowledge can also be directly measured at the receiver, and fed back to the transmitter. Adaptive modulation systems improve rate of transmission, and/or bit error rates, by exploiting the channel state information that is present at the transmitter. Especially over fading channels which model wireless propagation environments, adaptive modulation systems exhibit great performance enhancements compared to systems that do not exploit channel knowledge at the transmitter.

2.2.1 Literature review of Link Adaptation

Link adaptation has been widely studied in different types of wireless communication systems. Below was attempted to collect key publications about aforementioned subject. Link adaptation was first proposed in 1997 from Sampath, Sarath Kumar, Holtzman, in which an analytical outer loop power control model was studied to handle the Signal-to-Interference Ratio (SIR) fluctuation. In 2013 Li in his paper ``Cooperative uplink link adaptation in 3GPP LTE heterogeneous networks,'' investigated the impact of uplink interference on the efficiency of link adaptation in heterogeneous networks, and they further proposed a cooperative uplink link adaptation scheme by exploiting the cooperation among base stations. Durn (2015) designed a novel self-optimization algorithm for improving the convergence speed of the outer loop link adaptation (OLLA) in the downlink of LTE systems. Xia (2009) proposed the Auto-Rate Fallback for High-Throughput (ARFHT) algorithm for the emerging high-throughput IEEE 802.11n wireless networks, that extends the legacy link adaptation algorithms for Single-Input-Single-Output (SISO) wireless networks to Multiple-Input-Multiple-Output (MIMO)-based 802.11n wireless networks. Cavalcante (2016) in the paper ``On the system-level analysis of outer loop link adaptation for IEEE 802.16e systems,'' provided a system-level analysis of OLLA for IEEE 802.16e systems. Sarret (2015) proposed a dynamic OLLA (d-OLLA) algorithm to address the large Signal-to-Interference plus Noise Ratio (SINR) fluctuation for 5G of wireless communication systems. Blanquez-Casado (2016) provided a thorough analysis of OLLA, including its dynamics and convergence conditions. Based on the analysis, they proposed an enhanced OLLA (eOLLA) scheme to adaptively modify the step size and to update the offset according to the reception conditions.

2.2.2 Link adaptation in LTE

Link adaptation in LTE systems dynamically adjusts the data rate of transmitted information (modulation scheme and channel code rate) to equalize the existing radio channel capacity assigned for each user. Link adaptation is therefore closely related to the channel code scheme project used for forward error (FEC).

2.2.3 Downlink transmission

For downlink data transmission in LTE systems, the Base Station or Evolved Node B (eNodeB) usually selects the modulation scheme and the code rate depending on the prediction of the downlink channel conditions [3]. An important piece of information for this selection process is the Channel Quality Indicator (CQI) feedback transmitted by the User Equipment (UE) in the uplink channel. CQI feedback is an indicator of the data rate that the channel can support, taking into consideration the Signal to Interference plus Noise Ratio (SINR) and the receiving characteristics of the UE [4, 5, 6]. This chapter explains the link adaptation principles applied to the LTE system. It will also show how the eNodeB can select one of the two different CQI feedback schemes, namely periodic mode or aperiodic mode. The eNodeB will create a trade-off between the best downlink adaptation, based on the CQI (considering the informed channel quality), and the overload on the uplink channel caused by the CQI itself, i.e., channel quality control traffic. There exists therefore a trade-off between downlink adaptation and uplink overload. LTE specifications are designed to provide the needed indicators for interoperability between eNodeB and UE, enabling the eNodeB to optimize link adaptation. The method that the eNodeB will use to explore available information is not standardized and as such left up to the manufacturer. In general, in response to CQI feedback, the eNodeB can choose between different modulation schemes (QPSK, 16-QAM and 64-QAM) and a wide range of code rates.

The ideal switching point between the different modulation combinations and the code rate depends on a series of factors that include the required Quality of Service (QoS) and the cell throughput. The channel code scheme for FEC, which is the basis for the code rate adaptation mechanism, was the object of an in-depth study during the LTE standardization process. The channel coding theory has been intensely researched over the last decades, especially with the discovery of turbo codes, offering performance close to the Shannon limit and the development of general iterative processing techniques. More advanced channel coding resources were added, with the introduction of link adaptation, including Hybrid Automatic Repeat request (HARQ), a combination of ARQ and channel coding, improving robustness against channel fading. These schemes include incremental redundancy, by means of which the code rate is progressively reduced, transmitting additional parity information at each retransmission.

2.2.4 Uplink transmission

For LTE uplink transmission, the link adaptation process is similar to the downlink adaptation process, again with the eNodeB handling the selection of modulation and coding schemes (MCS). An identical channel coding structure is used for the uplink, while the modulation scheme can be either QPSK or 16-QAM, and for the maximum UE category, 64-QAM modulation is also available. The main difference between the uplink and downlink is that, instead of basing link adaptation on CQI feedback, the eNodeB can make its own estimate of the uplink data rate that the sounding channel can handle, e.g, by using Sounding Reference Signals (SRS). An important final aspect regarding link adaptation is its use for time and frequency scheduling of multiple users, which allows radio transmission resources to be efficiently shared among the users (since the channel capacity for individual users varies). CQI can therefore be used not only to adapt code rate and modulation in response to actual channel conditions, but for optimal time-frequency selective scheduling and for managing interference among the cells.

CHAPTER 3: SIMULATION IN UPLINK ADAPTATION

3.1 Uplink adaptation simulation

We design an uplink link adaptation scheme for 200KHz bandwidth in NB-IOT system by using NPUSCH scheduling [5]. We use single tone transmission in which eleven tones can be scheduled for data transmission with NPUSCH and other single tones can be scheduled as ACK/NACK feedback. Single tones support two numerologies 15 kHz and 3,75kHz. One Resource Unit (RU) is a schedulable unit in Narrowband Physical Uplink Shared Channel (NPUSCH) transmission for the data, which consists of 15 kHz: 1 ms for 12 tones, 2 ms for 6 tones, 4 ms for 3 tones, 8 ms for a single tone, or 32 ms for a single tone of 3.75 kHz. The 15 kHz numerology is identical to LTE and thus achieves the best coexistence performance with LTE in the uplink. The link adaptation for NB-IOT systems need to be performed in two dimensions: 1) the modulation and coding scheme level selection as LTE and 2) the repetition number determination. Different MCS levels influence the throughput of system Low MCS and high power improve the transmitted reliability, enhance coverage but reduce system throughput. More repetition number enhances the transmission reliability but loss special efficiency. Thus link adaptation scheme needs to get trade- off between transmit reliability and throughput of system by selecting suitable MCS and repetition. Furthermore, we introduce an inner loop link adaptation procedure that focuses on adjusting the repetition number based on periodically measured transmission BLER. The purpose of inner loop link adaptation is to guarantee the transmission BLER to the target. Also we select the MCS level and the repetition number based on ACK/NACKs. The Repetition is the key solution adopted by NB-IOT to achieve enhanced coverage with low complexity. Additionally, for one complete transmission, repetition of the transmission should be applied to both data transmission and the associated control signaling transmission. In NB-IOT systems, before each NPUSCH transmission, related control information, including RU number, selected MCS and repetition, should first be transmitted through a Narrowband Physical Down- link Control Channel (NPDCCH). In particular, repetition for NB-IOT can only be selected among 1, 2, 4, 8, 16, 32, 64, 128, the number means the repetition number of the same transmission block. The uplink link adaptation scheme includes the inner loop link adaptation and the outer loop link adaptation. In particular, the inner loop link adaptation is designed to cope with block error ratio variation by periodically adjusting the repetition number. The outer loop link adaptation coordinates the MCS level selection and the repetition number determination.

3.2 Parameter Settings and Metrics

To evaluate the performance of the proposed uplink link adaptation scheme for NB-IOT, we set in system the parameters as they appear in the table below. Every simulation executed in MATLAB r2018b by using LTE Toolbox. Transmission time and resource utilization are concerns in our simulations. Low transmission time and high resource utilization rate can improve throughput of NB-IOT systems.

System bandwidth	200 kHz
Carrier frequency	900 MHz
Subcarrier spacing	15 kHz
Channel coding for NPDCCH	Tail biting convolution code
Aggregation level for NPDCCH	2NCCE
Channel coding for NPUSCH	Turbo codes
Interference Rejection Combiner	MRC
Number of Tx antennas	1

Number of Rx antennas	2
Number of tones	1
Frequency offset	200 Hz
Time offset	2.5 us
Channel model	AWGN
Channel estimation for NPDCCH	DMRS-based

Figure 9. Parameters settings for performance simulation

3.3 Simulation Results

The graphs below (fiq.1- fiq.2) show the relationship between BLER and Signal – to – Noise Ratio with different simulation setting for NPUSCH single tone. The value of index BLER expresses the percentage of fault distortions (or other percentage of NACKs), cooperative with the SNR, which is the signal of noise ratio for the transmission through the channel. The simulation of these diagrams followed the procedure as defined by the LTE network. We use Monte Carlo risk analysis method, as the blocks are going to be sent through the network is generated by a random process. In particular, each block encoded in a code word (hN ULSCH), then encoded in NPUSCH modulation in order to produce a sequence of symbols (hN PUSCH). Then, they are placed into a grid of slots and grouped by the sub-load distance in order to be sent in various resource units. The grid is configured according to the SCFMDA standard, which received by two antennas, after it has gone through a white noise channel with the required SNR value. Also, the signal is demodulated and the symbols are decoded sequentially until we get to the generated block. The process of demodulation is successful when the final block is the same as the one that was sent. When the frequency is 3.75 kHz due to the problem of the toolbox in the demodulation system, we do only the simulation for NPUSCH coding and decoding. Also, from the experimental procedure found that the power of each cell can send a symbol by using the power of the NPUSCH channel as reported in the publication. The following formula was used to calculate the BLER metric:

$$BLER = \frac{\#errorBlocks}{\#blocksTrasmitted}$$

Finally, the results show that BLER deceases as the receive SNR increases (i.e., channel condition is better). Moreover, from the results we can observe when we receive ACK/NACK for a particular MCS level, RU and repetition settings. In the following diagrams, (fiq1-fiq2) we use the parameters as they appear in the table below.

Diagrams	MCS	RU	REPETITION	TBS
Fiq1	0	4	1	88
Fiq2	4	10	1	696

Figure 10. Parameters used for following Bler – SNR diagrams.

In the following diagram (fiq1) when MCS= 0, RU =4 and repetition= 1 and spacing single tone is 15 kHz, we can receive ACK when the SNR is larger than -13 dB.

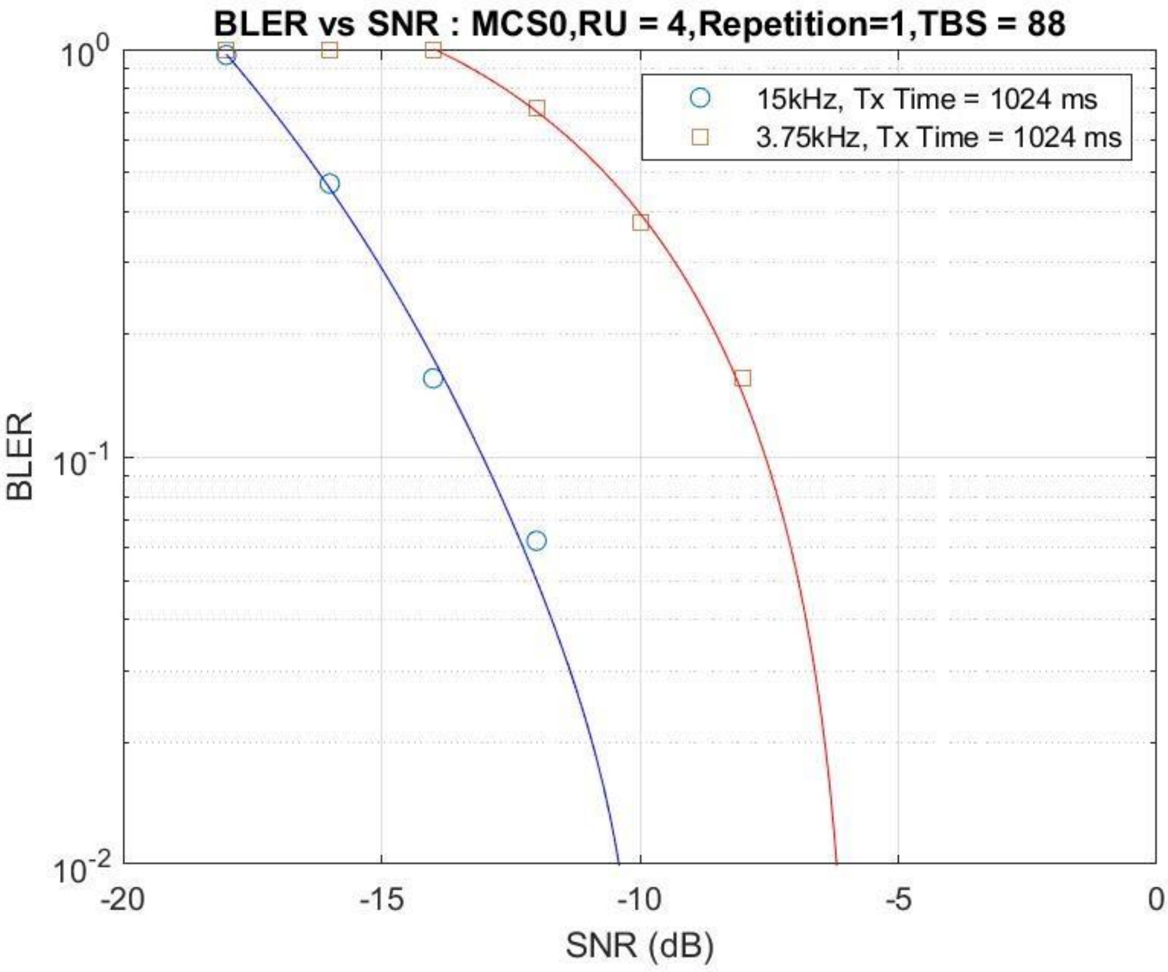


Figure 11. BLER as a function of SNR

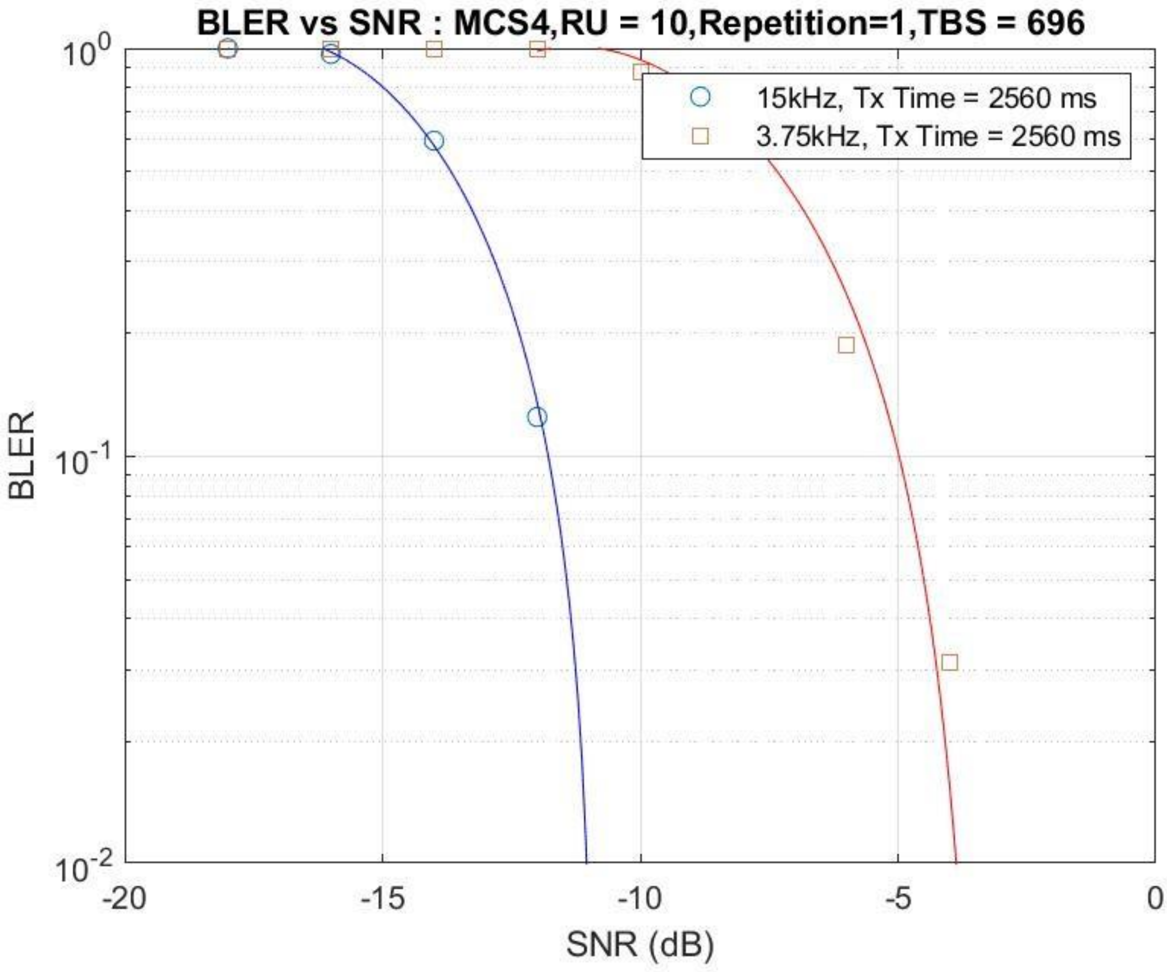


Figure 12. BLER as a function of SNR SNR

In addition, we calculate the percentage of throughput by using the following formula. In order to have a uniform image we don't insert the lines as they given by MATLAB. We plot an interpolation curve on the points. The target of throughput is 100%. Low transmission time and high resource utilization rate can improve throughput.

$$Throughput\textbf{(\%)} = \frac{Simulated\ Throughput}{Max\ Possible\ Throughput}$$

The diagrams of T throughput are given in Figure 3 and Figure 4 for each of the two series of simulations. In following diagrams, (fiq3-fiq4) we use the parameters as they appear in the table below.

Diagrams	MCS	RU	REPETITION	TBS
Fig 3	0	4	1	88
Fig 4	4	10	1	696

Figure 13. Parameters used for following Throughput – SNR diagrams

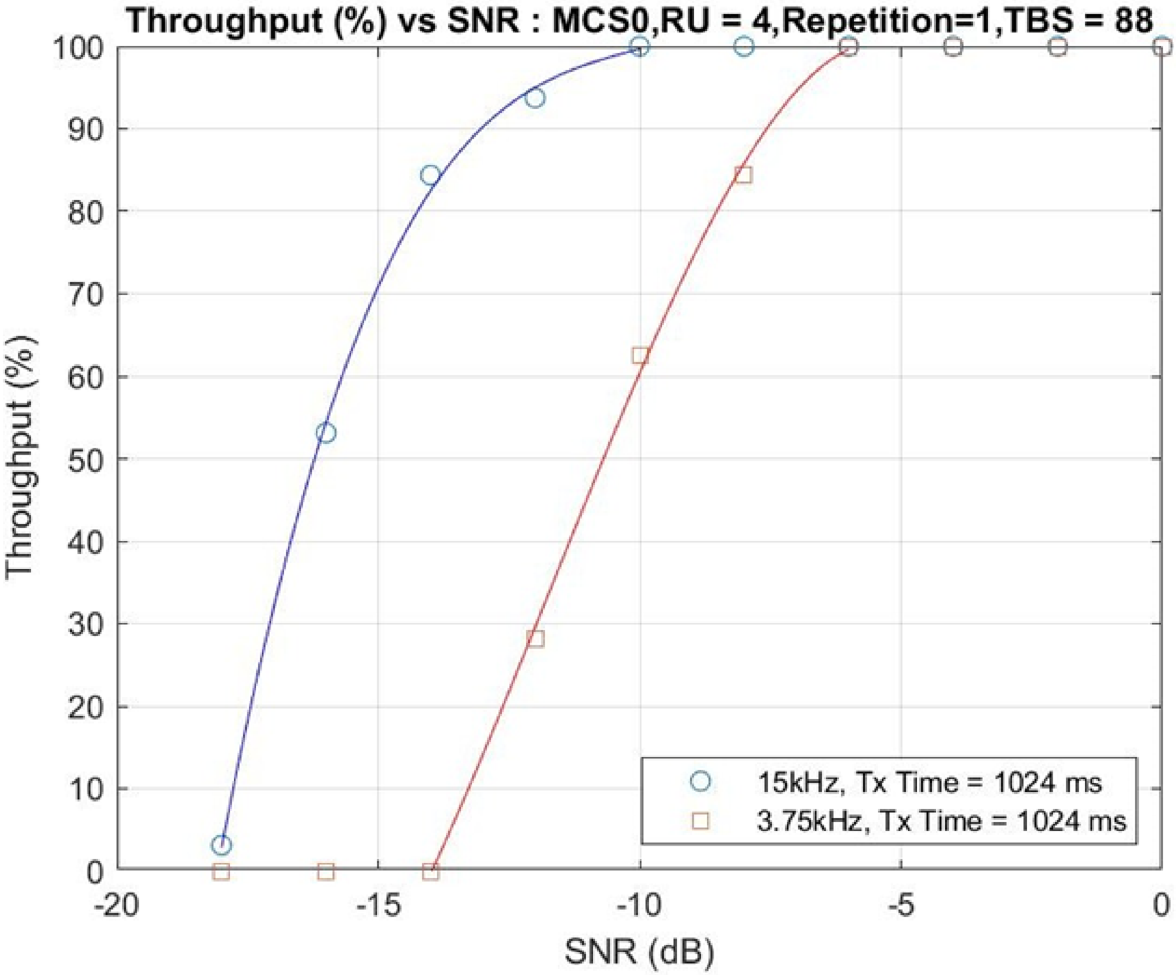


Figure 14. Throughput as a function of SNR

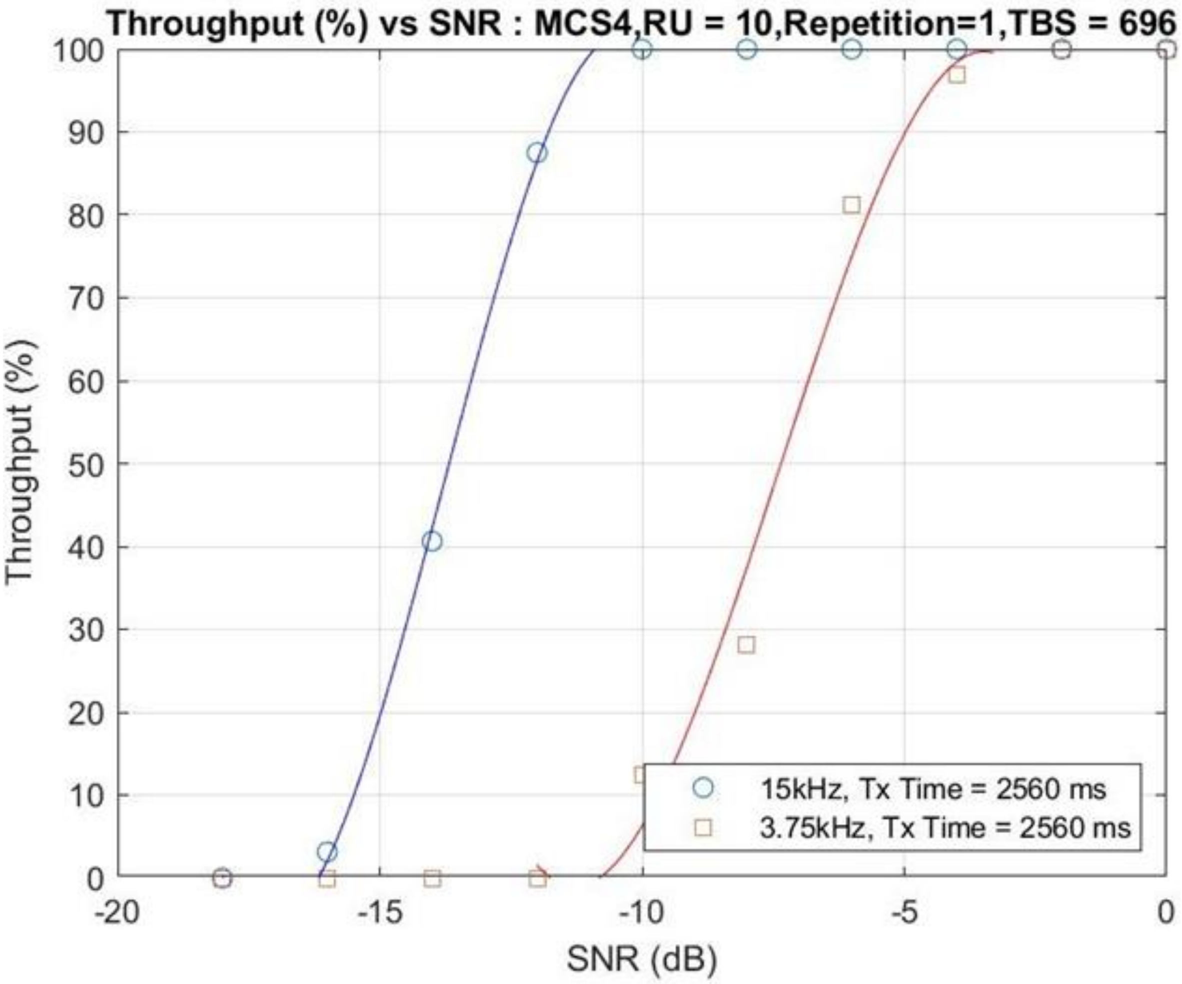


Figure 15. Throughput as a function of SNR

Furthermore, the graphs below (figure 5) shows a number of simulations for all repetition numbers and for all SNR for each of the four desired network settings. The SNR value for each repetition was chosen as the worst SNR value with a BLER value of <0.1. The results show that when we use a larger number of repetitions, we can correctly decode the message with worse channel conditions. In addition, it can be observed that a message can be transmitted successfully with worse channel conditions when we use a larger number of RUs.

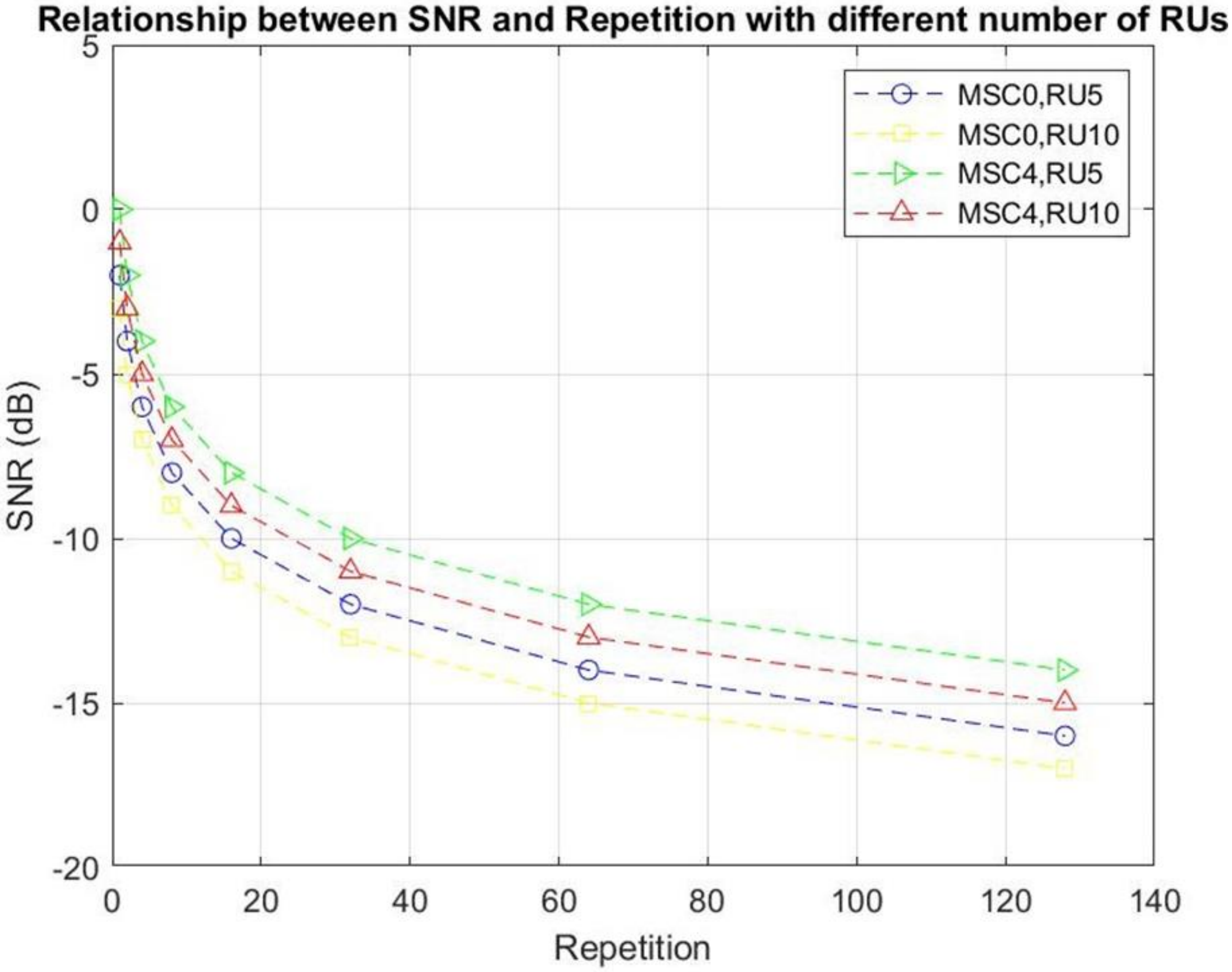


Figure 16. Relationship between SNR - Repetition for different RUs

3.4 Code in matlab

Analyze way form

```
function [ue, rxSlot, estchsGrid, noiseEst] = analyzeWaveform(ue, chs,
rxWaveform, noise, fadingInfo)

    % Perform timing synchronization, extract the appropriate
    % subframe of the received waveform, and perform OFDM
    % demodulation
    offset  = hPerfectTimingEstimate(fadingInfo);

    % Synchronize the received waveform
    rxWaveform = rxWaveform(1+offset:end, :);

    % Perform SC-FDMA demodulation on the received data to recreate the
    % resource grid
    rxSlot = lteSCFDMADemodulate(ue,rxWaveform);
    % Get meaningful part from band
    rxSlot = rxSlot(31:42, 1:7, :);

    % Perfect chs estimation
    ue.TotSlots = 1; % chs estimate for 1 slot
    estchsGrid = lteULPerfectChannelEstimate(ue, chs, offset);
    estchsGrid = estchsGrid(31:42, 1:7, :);

    % Noise Estimation
    noiseGrid = lteSCFDMADemodulate(ue,noise(1+offset:end, :));
    noiseEst = var(noiseGrid(:));
```

```
end
```

Creatmetriks vs snr diagramme

```
function createMetricVsSNRDiagram(SNRdB, metric, metricName, ...
                                  x1, x1Ind, x2, x2Ind, ylimit, ...
                                  mcsLevel, SubcarrierSpacing, ...
                                  txTime, NRU, TBS, ...
                                  loc, plotType, figureName)
    % Generate ThroughPut diagram
    fig = figure;
    if strcmpi(plotType, 'normal')
        plot(SNRdB, metric(1, :), 'o');
    else
        semilogy(SNRdB, metric(1, :), 'o');
    end

    xlim([-20, 0]);
    ylim(ylimit);
    grid on;
    hold on;
    xlabel('SNR (dB)');
    ylabel(sprintf('%s', metricName));
    legendstr = {sprintf('%s, Tx Time = %d ms', SubcarrierSpacing(1), txTime)};

    if strcmpi(plotType, 'normal')
        plot(SNRdB, metric(2, :), 's');
    else
        semilogy(SNRdB, metric(2, :), 's');
    end
```

```
    legendstr = [legendstr sprintf('%s, Tx Time = %d ms', SubcarrierSpacing(2),
txTime)];

    % Generate regression line for first curve
    y1 = get3rdDegreeRegressionCurve(SNRdB(x1Ind), metric(1, x1Ind), x1);

    if strcmpi(plotType, 'normal')
        plot(x1, y1, 'b');
    else
        semilogy(x1, y1, 'b');
    end

    % Generate regression line for second curve
    y2 = get3rdDegreeRegressionCurve(SNRdB(x2Ind), metric(2, x2Ind), x2);
    if strcmpi(plotType, 'normal')
        plot(x2, y2, 'r');
    else
        semilogy(x2, y2, 'r');
    end

    title(sprintf('%s vs SNR : MCS%d,RU = %d,Repetition=1,TBS = %d',...
        metricName, mcsLevel, NRU, TBS));
    legend(legendstr, 'Location', loc);

    saveas(fig,figureName);
end

function y = get3rdDegreeRegressionCurve(x_train, y_train, x)
    coef = polyfit(x_train,y_train,3);
    y=coef(1)*x.^3+coef(2)*x.^2+coef(3)*x+coef(4);
end
```

Decode NPUSCHGRID

```
function [rxcw, dstate] = decodeNPUSCHGrid(...
    ue, chs, rxSlot, estchsGrid, dstate)

    % Get NPUSCH indices
    npuschIndices = hNPUSCHIndices(ue,chs);

    % Get NPUSCH resource elements from the received slot
    [rxNpdschSymbols, npdschHest] = lteExtractResources(npuschIndices, ...
        rxSlot, estchsGrid);

    rxSym = mean(rxNpdschSymbols, 2);

    % Decode NPUSCH
    [rxcw,dstate,symbols] = hNPUSCHDecode(...
                    ue, chs, rxSym, dstate);

end
```

FIQURE 1

```
% Clear previous data from other runs
clc;clear all; close all;

SNRdB = -18:2:0;  % Range of SNR values in dB
```

```
% Initialize BLER and throughput result
maxThroughput = zeros(2, length(SNRdB));
simThroughput = zeros(2, length(SNRdB));
bler = zeros(2,numel(SNRdB)); % Initialize BLER result

spacing = ["15kHz", "3.75kHz"];
% UE transmit power is set properly according to channel condition
NPUSCH_Power = [[9, 7.9, 6.5, 5, 5, 5, 5, 5, 5, 5];...
        [0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2, 0.2]];

for spaceIdx = 1:numel(spacing)
  ue_init = getUEstruct(spacing(spaceIdx));

  chs_init = getCHSstruct(ue_init, 'Data', 0, 'QPSK', 4, 1, 11, 88);

  % For speed enabling paraller for to parallelize different simulations
  parfor snrIdx = 1:numel(SNRdB)

    ue = ue_init;
    chs = chs_init;
    % Set the random number generator seed depending on the loop variable
    % to ensure independent random streams
    rng(snrIdx,'combRecursive');

    % Simulate bler experiment for snr
    [bl, maxTh, simTh] = ...
        performBlerSimulationForSNR(ue, chs, ...
          NPUSCH_Power(spaceIdx, snrIdx), SNRdB(snrIdx), 1024e-3);

    bler(spaceIdx, snrIdx) = bl;
```

```
        maxThroughput(spaceIdx, snrIdx) = maxTh;
        simThroughput(spaceIdx, snrIdx) = simTh;
    end
end

% Generate BLER VS SNR plot
createMetricVsSNRDiagram(SNRdB, bler, 'BLER', ...
                linspace(-18, -10), 1:5, linspace(-14, -6), 3:7, ...
                [0.01, 1.0], 0, spacing, 1024, chs_init.NRU, chs_init.TBS, ...
                'northeast', 'semilog', 'figure9.jpg');

NPUSCHThroughput = simThroughput*100 ./ maxThroughput;

% Generate Throughput VS SNR plot
createMetricVsSNRDiagram(SNRdB, NPUSCHThroughput, 'Throughput (%)', ...
                linspace(-18, -10), 1:5, linspace(-14, -6), 3:7, ...
                [0, 100], 0, spacing, 1024, chs_init.NRU, chs_init.TBS, ...
                'southeast', 'normal', 'throughput9.jpg');
```

FINQURE 2

```
% Clear previous data from other runs
clc;clear all; close all;

SNRdB = -18:2:0;  % Range of SNR values in dB

% Initialize BLER and throughput result
maxThroughput = zeros(2, length(SNRdB));
simThroughput = zeros(2, length(SNRdB));
```

```
bler = zeros(2,numel(SNRdB)); % Initialize BLER result

spacing = ["15kHz", "3.75kHz"];
% UE transmit power is set properly according to channel condition
NPUSCH_Power = [[12, 12, 10.2, 8.55, 7, 7, 7, 7, 7, 7];...
                [3.5, 3.5, 3.5, 3.5, 4, 3.2, 2.5, 2, 2, 2]];

for spaceIdx = 1:numel(spacing)

    ue_init = getUEstruct(spacing(spaceIdx));

    chs_init = getCHSstruct(ue_init, 'Data', 0, 'QPSK', 10, 1, 11, 696);

    parfor snrIdx = 1:numel(SNRdB)
        % Set the random number generator seed depending on the loop variable
        % to ensure independent random streams
        ue = ue_init;
        chs = chs_init;

        rng(snrIdx,'combRecursive');

        % Simulate bler experiment for snr
        [bl, maxTh, simTh] = ...
                performBlerSimulationForSNR(ue, chs, ...
                    NPUSCH_Power(spaceIdx, snrIdx), SNRdB(snrIdx), 2560e-3);

        bler(spaceIdx, snrIdx) = bl;
        maxThroughput(spaceIdx, snrIdx) = maxTh;
        simThroughput(spaceIdx, snrIdx) = simTh;
    end
end
```

```
% Generate BLER VS SNR plot
createMetricVsSNRDiagram(SNRdB, bler, 'BLER', ...
                linspace(-18, -10), 1:5, linspace(-12, -3.3), 4:8, ...
                [0.01, 1.0], 4, spacing, 2560, chs_init.NRU, chs_init.TBS, ...
                'northeast', 'semilog', 'figure10.jpg');

NPUSCHThroughput = simThroughput*100 ./ maxThroughput;

% Generate Throughput VS SNR plot
createMetricVsSNRDiagram(SNRdB, NPUSCHThroughput, 'Throughput (%)', ...
                linspace(-18, -10), 1:5, linspace(-12, -3.3), 4:8, ...
                [0, 100], 4, spacing, 2560, chs_init.NRU, chs_init.TBS, ...
                'southeast', 'normal', 'throughput10.jpg');
```

FINQURE 3

```
repetition = 2.^(0:7);
SNRdB = [-2:-2:-17 ; ...
        -3:-2:-18 ; ...
        0:-2:-14 ; ...
        -1:-2:-15];
symbols=['--ob'; '--sy'; '-->g'; '--^r'];

fig = figure;
for i = 1:4
    plot(repetition, SNRdB(i, :), symbols(i, :));
    if i == 1
        grid on;
```

```
        hold on;
        xlim([0, 140]);
        ylim([-20, 5]);
        xlabel('Repetition');
        ylabel('SNR (dB)');
    end
end

title('Relationship between SNR and Repetition with different number of RUs');
legend({'MSC0,RU5', 'MSC0,RU10', 'MSC4,RU5', 'MSC4,RU10'});

saveas(fig,'figure11.jpg');
```

FINQURE 3 SIMULATION

```
% Clear previous data from other runs
clc;clear all; close all;

repetition = 2.^(0:7);
SNRdB = -8:6;
bler = zeros(numel(repetition), numel(SNRdB));

%mcsLevel = 4;
%RU=5;

for mcsLevel = [0, 4]
    for RU = [5, 10]

        [~, modulation, ~] = lteMCS(mcsLevel, 'PUSCH');
```

```
tbs = lteTBS(RU, mcsLevel);


for repId = 1:numel(repetition)
%repId = 8;
    ue_init = getUEstruct('15kHz');

    chs_init = getCHSstruct(ue_init, 'Data', 0, modulation, RU, ...
                                repetition(repId), 1e-6, tbs);

    txtime = chs_init.NRU*chs_init.NULSlots*chs_init.NRep*5e-4*10;
    parfor snrIdx = 1:numel(SNRdB)


        % Set the random number generator seed depending on the loop variable
        % to ensure independent random streams
        ue = ue_init;
        chs = chs_init;
        chs.NTurboDecIts = 1;
        rng(snrIdx,'combRecursive');

        % Simulate bler experiment for snr
        [bl, ~, ~] = performBlerSimulationForSNR(ue, chs, 1e-6, ...
                                SNRdB(snrIdx), txtime);

         bler(repId, snrIdx) = bl;

         fprintf('%d %d %f \n', repetition(repId), SNRdB(snrIdx), bl);
    end
end
```

```
    end
end
```

GENERATE CODE WORD

```
function [cw, trblk] = generateCodeword(ue, chs, rvSeq)
    if strcmpi(chs.NPUSCHFormat,'Data')
        % UL-SCH encoding is performed for the two RV values used for
        % transmitting the codewords. The RV sequence used is determined
        % from the rvDCI value signaled in the DCI and alternates
        % between 0 and 2 as given in TS 36.213 Section 16.5.1.2

        % Define the transport block which will be encoded to create the
        % codewords for different RV
        trblk = randi([0 1],chs.TBS,1);

        % Determine the coded transport block size
        [~, info] = hNPUSCHIndices(ue,chs);
        outblklen = info.G;
        % Create the codewords corresponding to the two RV values used
        % in the first and second block, this will be repeated till all
        % blocks are transmitted
        chs.RV = rvSeq(1); % RV for the first block
        cw = hNULSCH(chs,outblklen,trblk); % CRC and Turbo coding is repeated
        chs.RV = rvSeq(2); % RV for the second block
        cw = [cw hNULSCH(chs,outblklen,trblk)]; % CRC and Turbo coding is
repeated
    else
        trblk = randi([0 1],1); % 1 bit ACK
```

```
        % For ACK, the same codeword is transmitted every block as
        % defined in TS 36.212 Section 6.3.3
        cw = hNULSCH(trblk);
    end
```

getCHSstruct

```
function chs = getCHSstruct(ue, NPUSCHFormat, NBULSubcarrierSet,
Modulation, NRU, NRep, NPUSCH_Power, TBS)
    %if strcmpi(ue.NBULSubcarrierSpacing,'3.75kHz')
    %    if sum(NBULSubcarrierSet == 0) ~= 48
    %        error('Must include all subcarriers in 3.75kHz spacing.')
    %    end
    %end

    chs = struct();
    chs.NPUSCHFormat = NPUSCHFormat;        % NPUSCH payload type ('Data'
or 'Control')
    % The number of subcarriers used for NPUSCH 'NscRU' depends on the
NPUSCH
    % format and subcarrier spacing 'NBULSubcarrierSpacing' as shown in TS
36.211
    % Table 10.1.2.3-1. There are 1,3,6 or 12 continuous subcarriers for NPUSCH
    chs.NBULSubcarrierSet = NBULSubcarrierSet;     % Range is 0-11 (15kHz); 0-
47 (3.75kHz)
    chs.NRUsc = length(chs.NBULSubcarrierSet);
    % The symbol modulation depends on the NPUSCH format and NscRU as
given by
    % TS 36.211 Table 10.1.3.2-1
```

```
chs.Modulation = Modulation;
chs.CyclicShift = 0;       % Cyclic shift required when NRUsc = 3 or 6
chs.RNTI = 0;              % RNTI value
chs.NLayers = 1;           % Number of layers
chs.NRU = NRU;               % Number of resource units
chs.SlotIdx = 0;           % The slot index
chs.NTurboDecIts = 30;     % Number of turbo decoder iterations

chs.NPUSCH_Power = NPUSCH_Power;
chs.NPUSCHDRS_Power = 1;

if strcmpi(chs.NPUSCHFormat,'Data')
   chs.TBS = TBS;   % Transport block size for NPUSCH format 1
elseif strcmpi(chs.NPUSCHFormat,'Control')
   if ~strcmpi(chs.Modulation,'BPSK')
      error('For NPUSCH format 2 (Control), the modulation must be BPSK');
   end
   chs.TBS = 1;    % ACK/NACK bit for NPUSCH format 2
   if length(chs.NBULSubcarrierSet) ~= 1
      error('The number of subcarriers must be 1 for control information');
   end
end

chs.NRep = NRep; % Number of repetitions of the NPUSCH
%chs = struct;
chs.Seed = 6;                  % chs seed
chs.NRxAnts = 2;                % 2 receive antennas
chs.DelayProfile ='off';        % Delay profile
chs.DopplerFreq = 1;            % Doppler frequency in Hz
chs.MIMOCorrelation = 'Low';     % Multi-antenna correlation
chs.NTerms = 16;                % Oscillators used in fading model
```

```
    chs.ModelType = 'GMEDS';        % Rayleigh fading model type
    chs.InitPhase = 'Random';       % Random initial phases
    chs.NormalizePathGains = 'On';  % Normalize delay profile power
    chs.NormalizeTxAnts = 'On';     % Normalize for transmit antennas

    chs.SeqGroupHopping = true; % Enable/Disable Sequence-Group Hopping for UE
    chs.Deltass = 0;            % Higher-layer parameter groupAssignmentNPUSCH

    % Get number of time slots in a resource unit NULSlots
    if strcmpi(chs.NPUSCHFormat,'Data')
        if strcmpi(ue.NBULSubcarrierSpacing,'3.75kHz')
            chs.NULSlots = 16;
        elseif strcmpi(ue.NBULSubcarrierSpacing,'15kHz')
            if chs.NRUsc == 12
                chs.NULSlots = 2;
            elseif chs.NRUsc == 6
                chs.NULSlots = 4;
            elseif chs.NRUsc == 3
                chs.NULSlots = 8;
            elseif chs.NRUsc == 1
                chs.NULSlots = 16;
            else
                error('Invalid number of subcarriers (%d), should be one of 1,3,6,12',chs.NRUsc);
            end
        else
            error('Invalid subcarrier spacing (%s), should be either 3.75kHz or 15kHz',ue.NBULSubcarrierSpacing);
        end
    elseif strcmpi(chs.NPUSCHFormat,'Control')
```

```
        chs.NULSlots = 4;
    else
        error('Invalid NPUSCH Format (%s), should be either Data or
Control',chs.NPUSCHFormat);
    end
end
```

getNPUSCHGrid

```
unction [slotGrid, txsym, estate, statedmrs] = getNPUSCHGrid(...
                        ue, chs, cw, blockIdx, slotGrid, estate, statedmrs)

    % NPUSCH encoding and mapping onto the slot grid
    [txsym, estate] = hNPUSCH(ue,chs,cw(:,mod(blockIdx,size(cw,2))+1),estate);
    txsym = txsym*db2mag(chs.NPUSCH_Power);
    slotGrid(hNPUSCHIndices(ue,chs)) = txsym;
    % NPUSCH DRS and mapping on to the slot grid
    [dmrs,statedmrs] = hNPUSCHDRS(ue,chs,statedmrs);
    slotGrid(hNPUSCHDRSIndices(ue,chs)) =
dmrs*db2mag(chs.NPUSCHDRS_Power);

    if strcmpi(ue.NBULSubcarrierSpacing,'15kHz')
        slotGrid = [slotGrid, zeros(12,7)];
    else
        slotGrid = [slotGrid, zeros(48,7)];
    end

end
```

getUEstruct

```
function ue = getUEstruct(NBULSubcarrierSpacing)
    ue = struct();                      % Initialize the UE structure
    ue.NBULSubcarrierSpacing = NBULSubcarrierSpacing;   % 3.75kHz, 15kHz
    ue.NBSubcarrierSpacing = NBULSubcarrierSpacing;
    ue.NNCellID = 10;                   % Narrowband cell identity
    ue.NULRB = 6;
    ue.NTxAnts=1;
end
```

```
function [chs, rxWaveform, noise, originSize, scfdmaInfo, fadingInfo] = ...
    lteSendModulatedGridThroughAWGN(ue, chs, slotGrid, snr, slotIdx, tSlot)
    % Perform SC-FDMA modulation to create the time domain waveform
    [txWaveform,scfdmaInfo] = lteSCFDMAModulate(ue,slotGrid);

    % Pad txWaveform to minimum size for demodulation if necessary
    originSize = size(txWaveform, 1);
    if (size(txWaveform, 1) < 1920)
        temp = zeros(1920, 1);
        temp(1:size(txWaveform, 1)) = txWaveform;
        txWaveform = temp;
    end

    % Add 25 sample padding. This is to cover the range of delays
    % expected from chs modeling (a combination of
    % implementation delay and chs delay spread)
    txWaveform =  [txWaveform; zeros(25, size(txWaveform,2))];
```

```
    % Initialize chs time for each slot
    chs.InitTime = slotIdx*tSlot;

    % Pass data through chs model
    chs.SamplingRate = scfdmaInfo.SamplingRate;
    [rxWaveform,fadingInfo] = lteFadingChannel(chs, txWaveform);

    % Calculate noise gain
    if chs.TBS == 88 || chs.TBS == 696
       SNR = 10^(snr/20);
    else
       SNR = 10^(snr/10);
    end



    % Normalize noise power to take account of sampling rate, which is
    % a function of the IFFT size used in SC-FDMA modulation
    N0 = 1/(sqrt(2.0*double(scfdmaInfo.Nfft))*SNR);

    % Create additive white Gaussian noise
    noise = N0*complex(randn(size(rxWaveform)), ...
                       randn(size(rxWaveform)));

    % Add AWGN to the received time domain waveform
    rxWaveform = rxWaveform + noise;

end
```

```
function [bler, maxThroughput, simThroughput] =
performBlerSimulationForSNR(ue_init, chs_init, ...
                    NPUSCH_Power, SNR, TransmissionTime)


        chs_init.NPUSCH_Power = NPUSCH_Power;

        ue = ue_init;     % Initialize ue configuration
        chs = chs_init;   % Initialize chs configuration
        %chs = chs_init; % Initialize fading chs configuration
        numBlkErrors = 0; % Number of transport blocks with errors
        dstateULSCH = []; % UL-SCH, need to be re-initialized for each trblk
        estate = [];      % Initialize NPDSCH encoder state
        dstate = [];      % Initialize NPDSCH decoder state
        trblk = [];       % Initialize the transport block
        txgrid = [];      % Full grid initialization
        statedmrs = [];   % DM-RS state

        % RV offset signaled via DCI (See 36.213 16.5.1.2)
        rvDCI = 0;
        % Calculate the RVSeq used according to the RV offset
        rvSeq = [2*mod(rvDCI+0,2)  2*mod(rvDCI+1,2)];

        % Get the slot grid and number of slots per frame
        if strcmpi(ue.NBULSubcarrierSpacing,'15kHz')
            slotGridSize = [12, 7];
            NSlotsPerFrame = 20;      % Slots 0...1
            tSlot = 5e-4;
        else
            slotGridSize = [48, 7];
            NSlotsPerFrame = 5;       % Slots 0...4
```

```
        tSlot = 5e-4;
    end

    NSlotsPerBundle = chs.NRU*chs.NULSlots*chs.NRep; % Number of slots in a codeword bundle
    numTrBlks = TransmissionTime/(NSlotsPerBundle*tSlot);
    TotNSlots = numTrBlks*NSlotsPerBundle;   % Total number of simulated slots

    for slotIdx = 0+(0:TotNSlots-1)
        % Calculate the frame number and slot number within the frame
        ue.NFrame = fix(slotIdx/NSlotsPerFrame);
        ue.NSlot = mod(slotIdx,NSlotsPerFrame);
        % Create the slot grid
        slotGrid = zeros(slotGridSize);

        if isempty(trblk)
            [cw, trblk] = generateCodeword(ue, chs, rvSeq);
            blockIdx = 0; % First block to be transmitted
        end

        % Set the RV used for the current transport block
        chs.RV = rvSeq(mod(blockIdx,size(rvSeq,2))+1);

        % Get slot to be transmitted with NPUSCH
        [slotGrid, txsym, estate, statedmrs] = getNPUSCHGrid(...
                    ue, chs, cw, blockIdx, slotGrid, estate, statedmrs);

        % If a full block is transmitted, increment the clock counter so that
        % the correct codeword can be selected
        if estate.EndOfBlk
```

```
            blockIdx = blockIdx + 1;
        end

        ue.PUSCH = chs;

        if strcmpi(ue.NBULSubcarrierSpacing,'15kHz')
            % Modulate the Grid to Waveform using SC-FDMA Method and send
            % through an AWGN channel.
            [chs, rxWaveform, noise, originSize, scfdmaInfo, fadingInfo] = ...
                    lteSendModulatedGridThroughAWGN(ue, chs, ...
                    slotGrid, SNR, slotIdx, tSlot);
        else
            % Pass NPUSCH Symbols through AWGN Channel
            snr = 10.^(SNR/20);
            npuschSize = size(txsym);
            noise =
(1/sqrt(2*snr))*complex(randn(npuschSize),randn(npuschSize));
            rxSym = txsym + noise;
        end

        %-----------------------------------------------------------------
        %           Receiver
        %-----------------------------------------------------------------

        if strcmpi(ue.NBULSubcarrierSpacing,'15kHz')
            % Analyze received waveform to slot grid
            [ue, rxSlot, estchsGrid, noiseEst] = analyzeWaveform(...
                    ue, chs, rxWaveform, noise, fadingInfo);
            % Decode grid back to block
            [rxcw, dstate] = decodeNPUSCHGrid(...
                    ue, chs, rxSlot, estchsGrid, dstate);
```

```
        else
            [rxcw, dstate] = hNPUSCHDecode(ue,chs,rxSym,dstate);
        end



        % Decode the transport block when all the slots in a block have
        % been received
        if dstate.EndOfBlk
            % Soft-combining at transport chs decoder
            [out, err, dstateULSCH] =
hNULSCHDecode(chs,chs.TBS,rxcw,dstateULSCH);
        end

        % If all the slots in the bundle have been received, count the
        % errors and reinitialize for the next bundle
        if dstate.EndOfTx
           if strcmpi(chs.NPUSCHFormat,'Control')
              err = ~isequal(out,trblk);
           end
           numBlkErrors = numBlkErrors + err;
           % Re-initialize to enable the transmission of a new transport
           % block
           trblk = [];
           dstateULSCH = [];
           statedmrs = [];
        end
    end
    % Calculate the block error rate
    bler = numBlkErrors/numTrBlks;
    % Calculate the maximum and simulated throughput
```

```
    maxThroughput = chs.TBS*numTrBlks; % Max possible throughput
    simThroughput = chs.TBS*(numTrBlks-numBlkErrors);  % Simulated
throughput
end
```

CHAPTER 4: Open issues and further work

4.1 Open issues

As narrowband Internet of Things (NB-IOT) is a new narrowband radio technology in 5G networks, there are a lot of open issues that need to be investigated, such as performance analysis, scheduling process, link adaptation, design optimization, co-existence with other technologies and security [6].

4.1.1 Performance analysis

Deployment of NB-IOT in some but not all cells can cause coverage problems due to both large path loss and interference. Increased co-channel interference with such partial deployment in synchronous networks can be overcome through PRB blanking in non-NB-IOT cells. Both co-channel interference and adjacent channel interference are potential concerns in asynchronous networks. Even with PRB blanking, co-channel interference due to LTE control symbols resulting from frame misalignment can degrade NB-IOT link performance.

4.1.2 Scheduling issue

Studies were mainly designed for general LTE and UMTS, and the effectiveness on the NB-IOT with massive MTC access is still an open issue. It is important to take into account various NB-IOT parameters and restrictions while conceiving the scheduling mechanism for an optimal resource assignment. Scheduling issues related to resource allocation for UEs in the downlink phase given standardized parameter selection. Scheduler in the base station controls the allocation of shared time-frequency resources among users at each time instant. The reception of NPDSCH transmission in time frequency combination for each TTI is determined. The scheduling decision provided by the scheduler must be compliant with more limited NB-IOT specifications. The resource assignment must be in a specific format taking into account reserved signaling resources and capabilities of the UE. With a large number of UEs and a fixed number of available subcarriers to be allocated, the resources are not guaranteed even with successful random-access procedures. The issue of scheduling is presented as the need for optimization regarding resource allocation [7].

4.1.3 Link adaptation

Link adaptation has several issues, such as resource assignment must be in a specific format taking into an account reserved signaling resources and capabilities of the NB-IOT UE.

4.1.4 Co-existence with other technologies

Since NB-IOT design is based on existing LTE functionalities, it is possible to use existing infrastructure for sites with newer equipment, only with software upgrade. However, older equipment may not be able to support both LTE and NB-IOT simultaneously and a hardware upgrade may be required.

Moreover, regarding the co-existence with other technologies, in some Smart Grid sector a large research effort is still required to be feasible. Some protocols such as Wi-Fi, ZigBee or Bluetooth, require the use of a gateway and several of LPWA technologies (Telesna, Sigfox) need a new network to connect to the IoT, there may be less market adoption of NB-IOT. Furthermore, a lot of the in-use device in Smart Grid need to be upgraded, which need tremendous volume of works. Also, the corresponding hardware costs of power system are also enormous. NB-IOT needs massive data processing and storage to meet higher and stricter requirements. The NB-IOT will generate data traffic with patterns that are expected to be significantly different from those observed in the current Internet.

4.1.5 Security

Security issues like Authentication, Data integrity and Privacy supported by NB-IOT technology were not discussed in most cases.

4.2 Further work

4.2.1 Resource allocation

The efficiency of radio resources of NB-IOT networks to achieve massive connections over next- generation cellular networks is an important issue [8]. As seen in the literature, most of the articles consider single-tone allocation for the simplicity in the simulation, thus, multi-tone allocation is not well studied. This causes a knowledge gap in the effectiveness of different tone-allocation possibilities. Therefore, optimal resource use techniques must be proposed that incorporate repetition, mobility, tones allocation, etc. for efficient spectrum usage.

4.2.2 Interference Mitigation

Interference prediction, estimation, cancellation, and coordination techniques for NB-IOT become a challenge [9]. This is because of the sharing of spectrum resources between NB-IOT and legacy LTE. Similarly, with NB-IOT being deployed in a small cell or macrocell scenarios in heterogeneous networks, interference becomes a concern. Several works have tried to address this by means of resource blanking, power control, or better uplink and downlink scheduling schemes and frequency and timing synchronization, etc. However, it is still challenging to incorporate the NB-IOT features such as repetition, low complexity (which affects channel estimation quality), and mobility in deploying the already existing LTE interference management techniques.

4.2.3 Mobility Management

Most of the simulation works have ignored the mobility impact of NB-IOT channel modeling. The increase in NB-IOT UEs mobility makes the channel suffer from fast varying channel conditions, due to which adaptive transmission schemes that might involve channel estimation, error correction, etc. must be implemented.

4.2.4 Latency

NB-IOT latency tolerance is set to 10 ms. This is due to its support for use cases of UEs that are in environments with bad channel conditions. Initial cell acquisition, frequency, and timing requirements, RACH transmission, half duplex mode of transmission and several repetitions that are performed during transmission are some of the features that play part in the overall data transmission delay. Several works are trying to reduce the timing requirement so as to reduce transmission latency of devices. However, most of the works have not addressed delay by taking into consideration the massive congestion that is expected for the IoT networks, processing delays due to low complex devices, queuing delays, propagation delays especially with long-range feature, as well as errors and error recovery. Early data transmission schemes and the second NB-IOT HARQ process for devices that have good channel conditions are among the features that can be used to reduce the transmission latency and improving the transmission link performance. However, only a handful of research articles have discussed the effectiveness of these processes when applied in NB-IOT.

4.2.5 Battery and range performance

PSM and eDRx were introduced in NB-IOT Release 12 and 13 to lengthen the NB-IOT devices battery life. Moreover, the most recent updates require the UE to be able to transmit during RRC-idle mode which will reduce the required ON time for data transmission. However, devices experiencing bad channel conditions due to hard-to-reach areas will require to perform several retransmissions per session, which will drain the device’s energy and hence shortens the battery life. Similarly, devices that require a relatively large number of reporting sessions per day will consume more energy, which makes energy management a concern. Most of the proposed algorithms are power hungry because most of the power is consumed during transmission and reception. Therefore, energy harvesting alternatives such as solar, biogas, vibrations, etc. that will lengthen the NB-IOT device battery life should be introduced to complement or replace frequent battery charging.

4.2.6 Timing Advance

When the base station responds to NB-IOT UEs about RRC connection request, it incorporates the TA command to be used for NB-IOT UE terminal data uplink transmission timing (i.e., to time-synchronize the UEs to the base station and help to compensate the propagation delays). However, for NB-IOT UE, the TA adjustment accuracy of the signaled timing advance with respect to the prior uplink transmission may highly be affected by the massive number of NB-IOT devices contending for the access. This is because the base station may need to correct some UE timing while for other NB-IOT UEs that had already transmitted NPRACH could receive the random access response which is not intended for them. Some works have addressed the receiver algorithms for NPRACH TA estimation as well as detection timing advance adjustment decoding schemes to improve the estimation but the NB-IOT receiver sensitivity and weak channel estimation quality still negatively affect the TA adjustment.

CHAPTER 5: Conclusion

NB-IOT is still in its infancy. There are many theoretical as well as practical issues needed to be addressed. On this basis, present report has tried to go into this subject, dealing with NB-IOT scheduling and uplink link adaptation. An uplink link adaptation scheme simulated in Matlab for 200KHz bandwidth in NB-IOT system by using NPUSCH scheduling link adaptation, following LTE network procedures and using Monte Carlo risk analysis method. As result of this process, was the relationship between BLER and Signal – to – Noise Ratio with different simulation setting for NPUSCH single tone.

Moreover, with this effort we got into several open issues form NB-IOT literature in performance analysis, scheduling process, link adaptation, and co-existence with other technologies. Finally, resource management and resource allocation appeared as the most critical among others issues, that needs further study for complete implementation in 5G and IOT technology era.

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