SNR Gain Evaluation in Narrowband IoT Uplink Data Transmission with Repetition Increment: A Simulation Approach

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Article Information:

Received:
20 March 2023

Received in revised form:
5 April 2023

Accepted:
5 May 2019

Volume 5, Issue 1, June 2023
pp. 33 – 40

Universitas Lampung

http://dx.doi.org/10.23960/jesr.v5i1.160

Abstract

Deploying Internet of Things (IoT) on a large scale necessitates widespread network infrastructures supporting Machine Type Communication. Integrating IoT into cellular networks like LTE, known as Narrowband-IoT (NB-IoT), can fulfill this infrastructure need. Standard 3GPP Release 13 introduces NB-IoT's Repetition features, expanding radio transmission coverage while maintaining LTE performance. Focusing on uplink data traffic, this study examines NB-IoT's repetition mechanism, grid resource distribution, and NPUSCH performance through simulations. Results show that at SNR greater than -5 dB, maximum repetitions of 128 yield the highest BLER, while minimum repetitions of 2 result in the lowest. Quadrupling repetitions increases SNR by 5 dB, emphasizing repetition's role in error mitigation and uplink reliability, especially in challenging SNR conditions. For optimal throughput in SNR above -5 dB, maximum repetitions of 128 for NPUSCH format 1 are recommended. These findings underscore the importance of repetition in enhancing Narrowband IoT performance, offering insights for system optimization, where increasing the number of repetitions generally leads to higher SNR gain. The attained BLER and throughput values from Narrowband IoT simulations highlight the robustness of data transmission across varying channel conditions, affirming NB-IoT applicability to a wide range of IoT applications.

Keywords: *NPUSCH, Repetition, NB-IoT, SC-FDMA, Resource Unit*

I. INTRODUCTION

Internet of Things (IoT) seamlessly connects diverse smart devices, including sensors, appliances, and gadgets, enabling global data exchange. It encompasses a network of interconnected devices embedded with sensors and software to collect and share data, fostering intelligent interactions among physical objects. In IoT systems, devices collect environmental and user data, process it locally, and transmit it to centralized servers or cloud platforms via various communication protocols like Wi-Fi or cellular networks. The data then analyzed and stored for further use, facilitating smarter decision-making and enhanced connectivity. [1]

IoT enables remote monitoring and control, enhancing reliability and uptime through real-time equipment monitoring and predictive maintenance. It promises transformation across industries like healthcare, transportation, and smart cities, fostering connectivity and efficiency. By 2025, an estimated five billion devices will integrate into cellular networks, highlighting the importance of accommodating massive Machine Type Communication (mMTC) in future cellular standards like 5G. Narrowband IoT, known for its wide-area cellular connectivity, emerges as a leading choice among Low Power Wide Area Network (LPWAN) technologies, rapidly gaining traction over alternatives like LoRa and SigFox. [2]

The widespread adoption of IoT is set to revolutionize various industries, categorized into high-data-rate and low-data-rate applications. Around 67% of IoT services cater to low-data-rate needs, such as periodic data transmissions in surveillance systems [3]. IoT communication technologies are divided into short-distance options like Zigbee, Bluetooth, and WiFi, and LPWANs for wide-area coverage with low power consumption.

LPWANs, crucial for urban and rural deployments, excel in offering extensive coverage while conserving power. LPWAN technologies are further classified based on spectrum licensing into unlicensed (e.g., SigFox, LoRa) and licensed (e.g., 4G LTE) spectrum options. The evolution of LPWANs, guided by spectrum frequency allocation, has seen advancements like OFDMA and SC-FDMA under the 3GPP standard. OFDMA enhances downlink communication efficiency, while SC-FDMA ensures improved uplink power efficiency, crucial for devices with limited battery life.

OFDMA extends Orthogonal Frequency Division Multiplexing (OFDM) by dividing the carrier bandwidth into multiple sub-carriers, enhancing spectral efficiency and network capacity. It allows multiple users to share sub-carriers across different time slots, resilient against multipath fading and interference. Nevertheless, due to its high value of Peak to Average Power Ratio (PAPR), OFDM is not suitable for uplink transmission. In contrast, LTE employs Single Carrier Frequency Division Multiple Access (SC-FDMA) for uplink transmission, which involves applying a discrete Fourier transform (DFT) before modulation to reduce PAPR, thereby enhancing power efficiency, a critical factor for devices with limited battery life.

In IoT systems, uplink traffic prevails as data is transmitted from devices to central servers or cloud platforms. IoT devices collect data from various environments for industrial monitoring, smart homes, or environmental sensing. Emphasis on uplink communication aligns with energy efficiency goals, as data transmission consumes less power than reception. Energy efficiency is optimized by employing efficient communication protocols, minimizing transfer power, and balancing speed with energy consumption. IoT devices often require prolonged battery life, necessitating careful power management. Achieving balance between data speed, transfer power, battery life, and bandwidth ensures optimal performance and longevity, meeting diverse application needs.

To cater to IoT device requirements, 3GPP has developed two machine-type communication mechanisms: Category M (CAT-M) and Category N (CAT-N) [3]. CAT-M, or LTE-M, balances data rate, coverage, and power consumption, suitable for

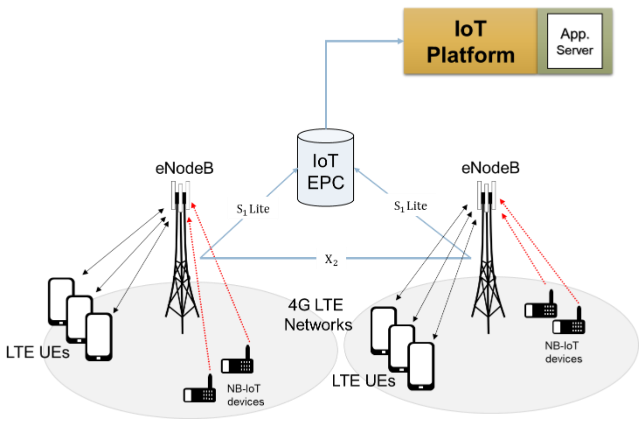


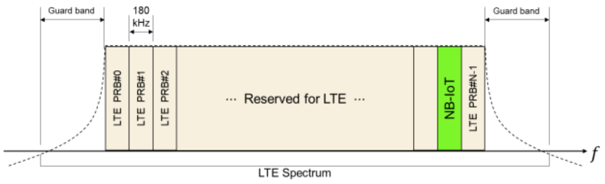
Figure 1. NB-IoT integrated to LTE Cellular Networks

applications with moderate data rates and mobility. In contrast, CAT-N, known as Narrowband IoT (NB-IoT), operates on a narrowband spectrum, offering extended coverage and prolonged battery life, albeit with lower data rates than CAT-M. NB-IoT emerges as a highly suitable solution for mMTC in IoT developments compared to CAT-M. Its narrowband operation enhances coverage and penetration into challenging environments, crucial for mMTC deployments spanning vast areas. Additionally, NB-IoT features ultra-low power consumption, ensuring prolonged device lifetimes in mMTC scenarios. Its architecture facilitates efficient resource utilization and scalability, accommodating the massive volume of connected devices typical in mMTC applications as shown in Figure 1. These attributes position NB-IoT as the preferred choice for future mMTC-centric IoT deployments.

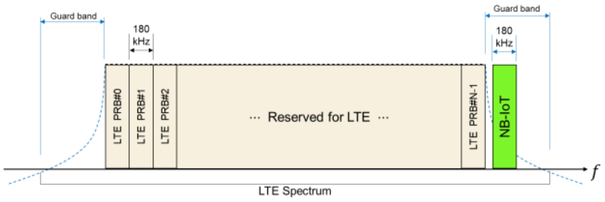
Block Error Rate (BLER) stands as a critical metric for assessing NB-IoT system performance by measuring the probability of erroneous data blocks received at the receiver's end. In NB-IoT, characterized by challenging channel conditions, BLER reflects system robustness and error resilience [4]. Lower BLER values indicate higher reliability and better performance, while higher BLER values suggest increased susceptibility to errors. BLER assessments enable comparisons of transmission strategies and error correction mechanisms. This study evaluates NB-IoT's uplink data transmission performance, specifically analyzing BLER under varying Signal to Noise Ratios (SNR) and repetition numbers. This work is structured into sections, with Section II delving into a literature review on LTE and its extension to NB-IoT, Section III detailing the simulation parameters employed, and Section IV discussing the results derived from the simulations.

II. Related Works

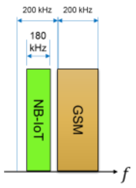
NB-IoT technology engineered to address the unique requirements of MTC applications, renowned for their



(a). In-band mode



(b). Guard-band mode



(c). Stand-alone mode

Figure 2. Operation Mode of NB-IoT

stringent demands for low power consumption and expansive coverage, with the development commenced under the 3GPP Standard Release 13 (R13). Operating within a narrow Radio Frequency (RF) bandwidth, NB-IoT strategically optimizes spectral efficiency while offering deployment flexibility across various operational modes, namely Stand-alone mode, Guard-band mode, and In-band mode as shown in Figure 2. [5]

In Stand-alone mode, NB-IoT operates within a dedicated spectrum, distinct from existing LTE or GSM networks. This independence allows for efficient spectrum resource utilization, enabling NB-IoT functionality in regions where LTE or GSM coverage may be limited or unavailable. Stand-alone mode finds particular suitability in applications necessitating dedicated NB-IoT coverage, such as remote monitoring in rural or indoor environments with weak LTE signals.

Guard-band mode leverages the unused frequency bands between adjacent LTE channels, known as guard bands, for NB-IoT deployment. These guard bands can be repurposed for NB-IoT communication without causing interference with LTE services. This mode facilitates efficient spectrum resource utilization and seamless integration of NB-IoT into existing LTE networks, making it well-suited for scenarios where coexistence with LTE is imperative, such as densely populated urban areas or locations with robust LTE coverage.

In-band mode sharing carrier frequencies and time resources with LTE services, where NB-IoT operates within the same spectrum as LTE. This mode optimizes spectrum utilization and enables coexistence with LTE services without requiring additional spectrum allocation. In-band mode is advantageous in scenarios

Tabel 1. PRBs Allocation of legacy LTE System

Available LTE Bandwidth (MHz)	**1.4**	**3**	**5**	**10**	**15**	**20**
Number of PRBs	6	15	25	50	75	100

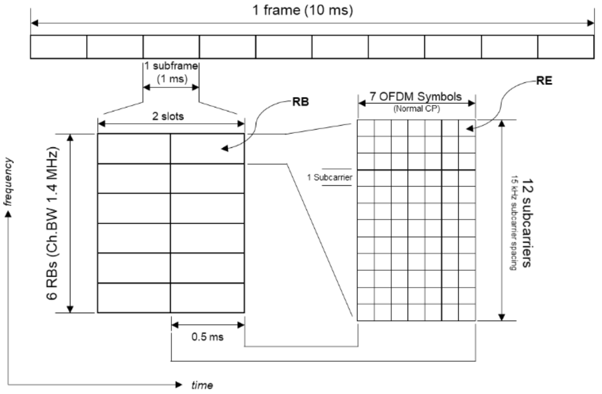
where maximizing spectral efficiency is paramount and where NB-IoT can leverage existing LTE infrastructure, such as smart city deployments or industrial IoT applications.

NB-IoT employs Quadrature Phase Shift Keying (QPSK) modulation and OFDMA in the downlink direction to effectively transmit data to multiple devices simultaneously. OFDMA partitions the available spectrum into orthogonal subcarriers, facilitating parallel data transmission and enhancing spectral efficiency. In the uplink direction, depending on the specific requirements of the IoT devices, NB-IoT can utilize Binary Phase Shift Keying (BPSK) or QPSK modulation and SC-FDMA, which effectively reduces PAPR, making it well-suited for battery-operated devices with limited power resources. [6]

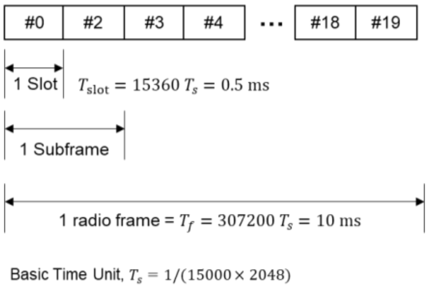
One of NB-IoT's key advantages is its exceptionally low power consumption, making it highly suitable for battery-operated devices with extended operational lifespans. NB-IoT devices can maintain an extended battery life of up to 12.8 years, even in scenarios with a coupling loss of 164 dB, while transmitting a modest 200-byte message once per day [2]. The duplexing technique, Frequency Division Duplex (FDD) and Time Division Duplex (TDD) modes, is supported by NB-IoT. FDD, a widely adopted duplexing technique, divides the available frequency spectrum into separate bands for uplink (UL) and downlink (DL) communications. This enables simultaneous data transmission and reception, thereby enhancing network efficiency and reliability. By leveraging FDD, cellular operators can efficiently manage spectrum allocation, optimize network performance, and ensure seamless connectivity for a broad range of IoT devices, including those utilizing NB-IoT technology. [3]

NB-IoT is designed to seamlessly coexist with existing GSM and LTE technologies, requiring a minimum system bandwidth of 180 kHz for both uplink and downlink operations, 200 kHz of GSM carrier can be replaced with NB-IoT. Similarly, LTE operators enabled to integrate NB-IoT into an LTE carrier by allocating a single Physical Resource Block (PRB). This approach ensures smooth interoperability and efficient spectrum utilization, enhancing connectivity across various network environments. The number of PRBs available for different LTE channel bandwidths is shown in Table 1.

In the downlink configuration, NB-IoT utilizes a subcarrier spacing of 15 kHz, with slot durations of 0.5



(a). LTE Resource Grid



(b). FDD Frame Structure type 1

Figure 3. NB-IoT Resource Grid and Frame Structure

ms, subframe durations of 1 ms, and frame durations of 10 ms, as illustrated in Figure 2. One PRB, consisting of 12 subcarriers spaced 15 kHz apart. For uplink transmission, NB-IoT provides both multitone and singletone transmission modes. In multitone mode, a subcarrier spacing of 15 kHz is used with a slot duration of 0.5 ms. In singletone mode, subcarrier spacing options include 15 kHz and 3.75 kHz, with a slot duration of 2 ms. The total system bandwidth for both downlink and uplink operations is approximately 180 kHz, ensuring efficient spectrum resource utilization. Each frame in NB-IoT comprises 10 subframes, each lasting 1 ms, further divided into two slots, each with a duration of 0.5 ms [7].

In the uplink, NB-IoT utilizes SC-FDMA with subcarrier spacing options of 15 kHz or 3.75 kHz, corresponding to slot sizes of 0.5 ms and 2 ms, respectively. It integrates the Narrowband Physical Random Access Channel (NPRACH) and the Narrowband Physical Uplink Shared Channel (NPUSCH). NPUSCH format 1 is employed for data transmission, with a maximum transport block size of 1000 bits. Moreover, NB-IoT signals must be mapped to Resource Elements (REs), which are not utilized by the legacy LTE system. [8]

III. METHODOLOGY

The experimental methodology employed in this study consists of parameter-based simulations aimed at evaluating the efficacy of an MTC communication system utilizing NB-IoT technology. The simulation setup features a 15 kHz subcarrier spacing for the Narrowband Physical Uplink Shared Channel (NPUSCH), transmitting data in format 1 within an in-band deployment mode, as depicted in Figure 2.a. In this configuration, 12 contiguous subcarriers are utilized and modulated using QPSK modulation schemes. QPSK enables the encoding of four different binary combinations into each symbol, thereby facilitating higher data rates. In this simulation, the transmitted signal traverses a Rayleigh fading channel, where signals reach the receiver via multiple paths with varying lengths and phases. By integrating Rayleigh fading into the simulation, a more realistic evaluation of the communication system's performance under dynamic channel conditions is achieved. The number of uplink slots is determined based on the specifications provided in TS 36.211 Table 10.1.2.3-1. The slot grid, with a 15 kHz subcarrier spacing, consists of 12 subcarriers and 7 OFDM symbols, resulting in 20 slots per frame, with the slot number $n_s \in \{0, 1, 2, \cdots, 19\}$ for $\Delta f = 15$ kHz.

In NB-IoT communication, each element within the resource grid is designated as a resource element, identified uniquely by an index pair, denoted as (k, l), where k signifies the subcarrier index, pinpointing the frequency location within the available bandwidth, while l denotes the symbol index, indicating the time slot within the frame, where

$$k = 0, \cdots, N_{\text{sc}}^{\text{UL}} - 1 \tag{1}$$

$$l = 0, \cdots, N_{\text{symb}}^{\text{UL}} - 1 \tag{2}$$

The simulation process commences with encoding and mapping NPUSCH data into a predefined slot grid structure, which organizes data transmission in terms of time and frequency resources. Subsequently, the encoded data undergoes SC-FDMA modulation, converting it into analog signals suitable for wireless transmission. Subsequently, the modulated data undergoes simulation through a channel model, including the introduction of Additive White Gaussian Noise (AWGN) to the received signal. The time-continuous signal $s_l^p(t)$ for antenna port p in SC-FDMA symbol l in uplink slot for Number of Resource Unit ($N_{\text{sc}}^{\text{RU}} > 1$) is defined by,

$$s_l^p(t) = \sum_{k=-\lfloor N_{\text{sc}}^{\text{UL}}/2 \rfloor}^{\lceil N_{\text{sc}}^{\text{UL}}/2 \rceil - 1} a_{k^{(-)},l}^{p} \cdot e^{j2\pi\left(k+\frac{1}{2}\right)\Delta f\left(t - N_{\text{CP},l} T_s\right)} \tag{3}$$

Time-continuous signal $s_{k,l}(t)$ for subcarrier index k in SC-FDMA symbol l in uplink slot is defined by, [9]

$$s_{k,l}(t) = a_{k^{(-)},l} \cdot e^{j\phi_{k,l}} \cdot e^{j2\pi\left(k+\frac{1}{2}\right)\Delta f\left(t - N_{\text{CP},l} T_s\right)} \tag{4}$$

$$k^{(-)} = k + \lfloor N_{\text{SC}}^{\text{UL}}/2 \rfloor \tag{5}$$

Algorithm 1 Simulation of NB-IoT Uplink Data Transmission

Input: SNR
Output: BLER
Initialisation : N_{TB}, N_{rep}, Δf, P_{type}, M_{UL}
LOOP Process

```
for i = 1 to N_rep do
    channel.define = 'ETA'
    for j = 1 to N_SNR do
        lteNPUSCHIndices (Coded TRB)
        lteSCFDMAModulate
        lteNULSCH (CRC and Turbo coding)
        lteNPUSCHDRS (mapping onto slot grid)
        txWaveform
        lteFadingChannel
        rxWaveform = rxWaveform + noise
        lteSCFDMADemodulate
        lteNULSCHDecode
        numBlkErrors = numBlkErrors + err;
    end for
end for
return BLER
```

In the given context, $N_{\text{CP},l}$ represents the number of cyclic prefix (CP) samples for symbol l for uplink NPUSCH, $a_{k^{(-)},l}$ represents the modulation value of symbol l, where the index $k^{(-)}$ refers to the subcarrier index. The phase rotation $\phi_{k,l}$is further defined in TS 36.211 part 10.1.5 [9]. This phase rotation providing additional information on the phase of the signal at each specific subcarrier and symbol.

The modulated signal is then demodulated using SC-FDMA demodulation, and channel estimation is performed to enhance the accuracy of the received signal and mitigate channel effects. Upon completion of channel estimation, the decoded NPUSCH data is retrieved, and the simulation calculates the BLER. BLER indicates the percentage of data blocks with errors over the total number of transmitted data blocks.

NB-IoT has been specifically designed to cater to low data rate machine-type communications within existing LTE system. To evaluate the performance of the NPUSCH, the block CRC result at the output of the channel decoder is used. The block CRC is obtained by decoding the equalized symbols after receiver operations such as SC-FDMA demodulation, channel estimation, and equalization are performed. The baseband waveform is formed by SC-FDMA modulating the grid subsequent to the generation of a resource grid filled with NPUSCH symbols. These operations are conducted on a slot-by-slot basis for each SNR point. Both NPUSCH and the narrowband Demodulation Reference Signal (DRS) are transmitted in all slots during the simulation.

This simulation is conducted to generate an NB-IoT NPUSCH BLER curve across various SNR points and transmission parameters. Algorithm 1 outlines the steps involved in simulating the NB-IoT uplink

Table 2. Simulation Parameters

No	Parameters	Values
1	Subcarrier Spacing (Δf)	15 kHz
2	PHY Channel Payload Type (P_{type})	Data/Format 1
3	Time Slot Size (T_s)	0.5 ms
4	Multiple Access	SC-FDMA
5	Modulation (M_{UL})	QPSK
6	Number of Subcarrier ($N_{\text{sc}}^{\text{UL}}$)	12
7	Number of SC-FDMA symbols ($N_{\text{symb}}^{\text{UL}}$)	7
8	Number of slot (N_{s})	20
9	Number of Resource Unit (N_{RU})	1
10	Number of Transport Block (N_{TB})	15
11	Number of Repetition (N_{rep})	2, 4, 8, 16, 32, 64 128

communication process. During NPUSCH generation, the payload type is explicitly designated for NPUSCH transmission, with Format 1 allocated for data transmission in the uplink direction and Format 2 reserved for control transmission. In Format 1, the User Equipment (UE) dynamically adjusts its transport block size based on a combination of modulation and coding scheme (MCS), alongside resource assignments signaled via the Downlink Control Information (DCI). According to the standards outlined in TS 36.213 on Table 16.5.1.2-2 (pg.517), the transport block size for NPUSCH transmission Format 1 is precisely defined as 136 [10]. Simulation parameters strictly adhere to the specifications of Fixed Reference Channels (FRC) for NB-IoT NPUSCH Format 1, with specific attention to Reference Channel A16-5, as detailed in Table A.16.1-1 (TS 36.104 Annex A.16 pg.184) [11]. The simulation parameters are provided in Table 2.

In a multipath fading environment, performance measurements rely on multi-path delay profiles, defined by the Extended Typical Urban (ETU) model specified in annex B of TS 36.213 Table B.2-3 [10]. The Control Channel estimator's behavior is influenced by an imperfect estimator, determined by the values of the received NPUSCH DRS. For DRS signals in NPUSCH format 1, sequence-group hopping is activated to enhance the robustness and reliability of the control channel estimator. Sequence-group hopping systematically varies the sequence of reference signals transmitted by the UE or NB-IoT devices over time and frequency. This variation, occurring in predefined groups or sequences, introduces diversity in the transmission of reference signals, mitigating the impact of multipath fading and improving channel estimation accuracy at the receiver. This diversity ensures reliable estimation of channel characteristics, even when certain signal parts experience deep fades or interference. In NPUSCH format 1, sequence-group hopping assumes a pivotal role in bolstering the performance of the control channel estimator, particularly in demanding multipath fading scenarios characterized by the ETU model.

The simulation procedure for NPUSCH format 1 encompasses several sequential steps. Initially, a random bit stream is generated with a size tailored to the desired transport block. This stream undergoes successive stages including CRC encoding, turbo encoding, and rate matching to generate the NPUSCH bits. Subsequent to bit generation, a time-first mapping technique is employed to interleave the bits per resource unit, resulting in the creation of the NPUSCH codeword. Following codeword generation, a series of operations including scrambling, modulation, layer mapping, and precoding are executed to construct intricate NPUSCH symbols. These symbols, alongside their corresponding DRS, are then mapped onto the resource grid to produce the time domain waveform via SC-FDMA modulation. The waveform is subsequently subjected to a fading channel with AWGN. Upon reception, the transmitted grid is retrieved through synchronization, channel estimation, and MMSE equalization procedures. NPUSCH symbols are then extracted from the received grid, and the transport block is reconstructed by demodulating the symbols and channel decoding the resultant bit estimates. Following descrambling, repetitive slots are soft-combined to facilitate rate recovery. Ultimately, the transport block error rate is computed for each SNR point. The evaluation of the block error rate is predicated on the assumption that all slots within a bundle are utilized for transport block decoding at the NB-IoT UE.

IV. Result and Discussions

On the uplink side, the resource grid in an LTE system is defined by a number $N_{\mathrm{SC}}^{\mathrm{UL}}$ of subcarriers and a number $N_{\mathrm{Symb}}^{\mathrm{UL}}$ of SC-FDMA symbols. In a radio frame of an OFDM-based system, there are a number of n_s slots with subcarrier spacing of $\Delta f = 15$ kHz, where $n_s \in \{1, 2, \cdots, 20\}$. The 180 kHz allocation of a Physical Resource Block (PRB) of LTE contains $N_{\mathrm{SC}}^{\mathrm{UL}}$ subcarriers with $N_{\mathrm{SC}}^{\mathrm{UL}} = 12$ and slot duration $T_{\mathrm{slot}} = 15360 \cdot T_s$ where $T_s = 1/(15000 \times 2048)$ is a basic time unit of LTE frame structure, thus the frame duration $T_f = 307200 \times T_s = 10$ ms.

In this simulation, BLER Performance of NPUSCH for various SNR and repetition number is evaluated with QPSK Modulation within SC-FDMA. The evaluation show that number of repetition enhance the radio access performance as shown in Figure 4. It is shown that increasing number of repetition giving higher SNR Gain which can enlarging the coverage enhancement. Increasing repetition by 4 fold giving SNR gain by 5 dB to achieve approximately similar

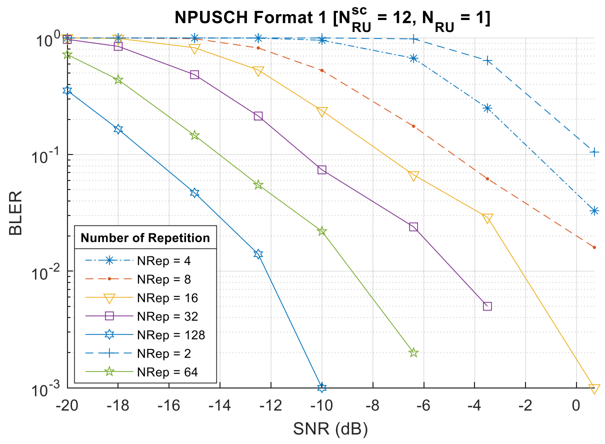


Figure 4. BLER NPUSCH with QPSK Modulation

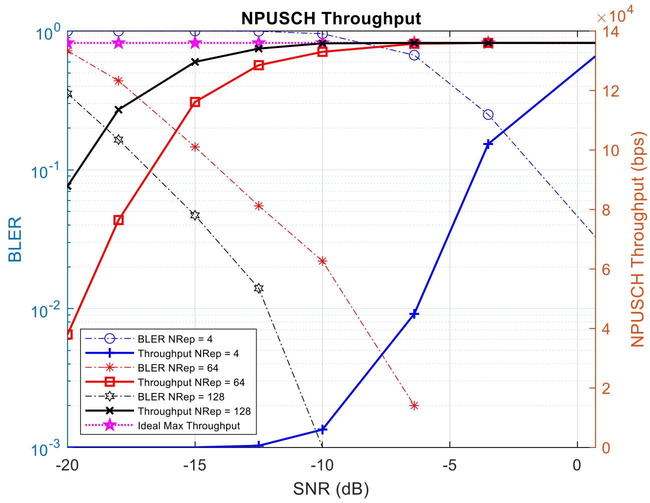


Figure 5. NPUSCH Data Throughput

BLER level. The highest number of repetition, $N_{\mathrm{rep}} = 128$, which is the maximum allowable number of repetition, give maximum BLER performance.

As the SNR decreases from -20 dB to 0.7 dB, the BLER progressively decreases, indicating improved reliability in data transmission. This trend aligns with the expected behavior, as higher SNR levels typically result in better signal quality and lower error rates. At very low SNR levels (e.g., -20 dB to -10 dB), the BLER values are relatively high, suggesting increased susceptibility to errors in data transmission. However, as the SNR improves (e.g., -6.4 dB to 0.7 dB), the BLER values decrease significantly, indicating a more resilient transmission performance. At SNR values of -6.4 dB and above, the BLER approaches zero, indicating near-perfect data transmission with negligible errors. Higher SNR values contribute to lower BLER values. BLER measures the ratio of erroneous data blocks to the total number of data blocks transmitted in a communication system. Unlike BER, which focuses on individual bits, BLER considers the entire data block as a unit of measurement.

For Number of Repetition set to 128, the BLER values decrease significantly as the SNR increases, indicating that with a higher number of repetitions, the system achieves better error performance, especially at lower SNR levels. At an SNR of 0.7 dB, the BLER is very low, indicating near-perfect performance. For Number of Repetition set to 64, Similar to Repetition 128, increasing the number of repetitions leads to lower BLER values across all SNR levels. However, the reduction in BLER is less pronounced compared to Repetition 128, particularly at higher SNR levels. For Repetition 32, 16, 8, 4, 2, as the number of repetitions decreases, the BLER values increase, indicating degraded error performance. This effect is more significant at lower SNR levels, where the system struggles to maintain reliable communication. For Repetition 2, the BLER remains high even at moderate SNR levels, suggesting that with fewer repetitions, the system may not meet the desired error performance requirements.

From the simulation result, it is shown that there is a clear relationship between SNR and BLER of NPUSCH data transmission, as the SNR increases, the BLER decreases. This relationship is consistent across different repetition levels. At higher SNR levels, the received signal becomes stronger relative to the noise, making it easier for the receiver to accurately decode the transmitted data. Consequently, the probability of errors occurring in the received data decreases, leading to lower BLER values. Conversely, at lower SNR levels, the received signal is weaker compared to the noise, making it more challenging for the receiver to distinguish the transmitted signal from the background noise. As a result, the probability of errors occurring in the received data increases, leading to higher BLER values. Therefore, in NPUSCH Format 1 uplink transmissions, a higher SNR generally corresponds to lower BLER values, indicating better error performance and improved reliability of data transmission. A lower BLER implies a more reliable communication link, while a higher BLER indicates a higher error rate. BLER directly affects the throughput of the NPUSCH. Higher BLER results in reduced the effective throughput of the NPUSCH channel. Conversely, lower BLER allows for more efficient transmission of data, leading to higher throughput.

From the simulation result, as shown in Figure 5, the maximum possible throughput is consistently achieved when the SNR is at its highest level (0.7 dB) for all repetitions. Generally, higher repetition levels lead to higher throughput rates, especially at lower SNR values. This is evident from the fact that the throughput values increase as the repetition level increases. The simulated throughput values approach the maximum possible throughput as the SNR increases and the number of repetitions also increases. However, at lower SNR levels or with fewer repetitions, the simulated throughput may fall short of the maximum possible throughput due to increased transmission errors.

The transport block size for NPUSCH format 1 is constant 136 bits and a total of 1000 transport blocks were simulated yielding maximum possible throughput 136 kbps which is the system's capacity to transmit data efficiently under optimal conditions. In NPUSCH format 1, with a fixed transport block size of 136 bits, the amount of data that can be transmitted in each block is constant. Based on the provided data, employing 128 repetitions for SNR values greater than -5 dB seems to be the best choice as it maximizes throughput while maintaining a negligible block error rate.

For worse SNR conditions, where the SNR is lower, it's essential to prioritize configurations that minimize the block error rate (BLER) while still achieving reasonable throughput. From the provided data, the best choice for worse SNR conditions depends on finding a balance between throughput and BLER. At this extremely low SNR level, none of the configurations achieve any throughput, and the BLER is close to 100% for 4 repetitions. It indicates that the channel conditions are very unfavorable, and data transmission is not feasible without significant enhancements or alternative approaches such as adaptive modulation and coding, improving antenna gain, employing advanced error correction techniques, or utilizing different modulation schemes may be necessary to achieve reliable communication.

Several factors can contribute to a worsening SNR in uplink Narrowband IoT communications such as distance from the Base Station, interference from other nearby devices or adjacent channels, Multipath Fading, Physical obstructions, and Variations in channel conditions, such as fading, shadowing, and Doppler effects. Base on the simulation data, the best choice for achieving maximum throughput in Narrowband IoT systems would depend on the specific SNR conditions. The best choice for maximizing throughput in conditions where SNR is greater than -5 dB would be to select the maximum number of repetitions (128) for NPUSCH format 1. In scenarios where SNR is significantly lower, selecting the maximum number of repetitions (128) may not be optimal due to diminishing returns. In such cases, it may be more effective to choose a lower number of repetitions, such as 4 or 8, to minimize the impact of noise and interference on data transmission. In situations where SNR is significantly degraded, it may be beneficial to reduce the number of repetitions. According to the data, lower repetition values, such as 4 or 8, exhibited lower throughput but potentially higher reliability in adverse SNR conditions.

The selection of the optimal number of repetitions should be based on a trade-off between SNR level, desired throughput, and communication reliability in NB-IoT systems.

The data demonstrates that increasing the number of repetitions generally leads to higher SNR gain. For example, when comparing different repetition values (e.g., 2, 4, 8, 16, 32, 64, and 128), it is evident that higher repetition values result in greater SNR gain, particularly in adverse SNR conditions. As SNR improves (i.e., becomes less negative), BLER tends to decrease, indicating improved transmission reliability and fewer errors. Conversely, as SNR deteriorates, BLER increases, reflecting higher error rates and reduced reliability. Based on the data, an SNR greater than -5 dB appears to be the optimal range for achieving maximum throughput and minimizing BLER.

V. Conclusions

Narrowband IoT emerges as a compelling cellular technology for the IoT landscape, offering a robust framework for ultra-low data rate transmission and energy-efficient operations. Our analysis of uplink data transmission via NPUSCH Format 1 underscores the effectiveness of repetition strategies in enhancing data transmission reliability in NB-IoT networks. By carefully selecting the appropriate number of repetitions based on desired error performance and SNR conditions, network operators can ensure reliable and efficient communication for IoT applications requiring uplink transmission.

The provided data highlights the impact of repetition on the error performance of Narrowband IoT uplink transmissions, emphasizing the importance of considering repetition strategies in network design and deployment. Moreover, the analysis of SNR gain underscores the critical role of SNR optimization in achieving reliable and efficient communication in NB-IoT systems. Exploring further research into optimization avenues is essential, particularly with the integration of NB-IoT with 5G networks. This convergence holds tremendous potential for addressing the demand for massive machine-type communication applications. As digital transformation accelerates, the seamless integration of NB-IoT with 5G networks is poised to revolutionize connectivity, unlocking new opportunities for businesses and industries alike. The achieved BLER values for Narrowband IoT simulations underscore the robustness of data transmission under different channel conditions, confirming NB-IoT's suitability for diverse IoT applications.

VI. Acknowledgment

The authors acknowledge Universitas Lampung for the support provided through Grand DIPA-023.17.2.677516/2023, which significantly contributed to the completion of this research project.

VII. References

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