mNB-IoT: Concurrent Uplink Transmission for Multiple User Equipments in NB-IoT

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***Abstract*—The Narrow Band-Internet of Things (NB-IoT) is a wireless protocol with low-power, low-cost, and wide coverage, which has a broad application prospect in fields like smart city or manufacturing. In order to expand the network coverage, the repetition mechanism is designed in NB-IoT, where the same information is required to be transmitted repeatedly for the accurate decoding of received signals in low signal-to-noise ratio (SNR) environments. However, such repetition mechanism will cause a dramatic decrease in the spectrum utilization, which will be greatly reduced by up to $1/128$. Literature has explored efficient coding methods, such as Non-Orthogonal Multiple Access (NOMA), but they can only achieve 55% maximum improvement on spectral efficiency.**

To further increase the spectrum utilization, this paper propose a novel uplink repetition mechanism design for NB-IoT, namely mNB-IoT. It can enable multiple user equipments (UEs) to transmit data to base stations in parallel using the same subcarriers. Based on the timing synchronization of NB-IoT, the original repetition mechanism is changed to the repetition based on orthogonal sequences to realize concurrent transmission among multiple UEs. The repetition intervals and times are then unified among UEs to maximize spectral efficiency. Experiments built upon 3 USRP devices and simulations on 128 UEs have proven the efficiency of mNB-IoT in realizing the repetition mechanism without spectral efficiency reduction.

***Index Terms*—NB-IoT, Physical Layer Protocol, Repetition Mechanism, Spectral Efficiency, Orthogonal Sequence**

I. Introduction

The Narrow Band-Internet of Things (NB-IoT) is a technology proposed by 3GPP for IoT networks with low-power, low-cost, and wide coverage, which has aroused wide attention from academia and industry [1]–[4]. The repetition mechanism designed in NB-IoT is one of the key modules to realize wide coverage with low-power, low-cost terminals. The data is required to transmitted repeatedly and aggregated in the receiving end, so that the received signals can be decoded accurately even in low signal-to-noise ratio (SNR) environments. Although this mechanism can expand the coverage of signals, it reduces the carrying capacity of wireless channels. As the maximum repetition time is 128 [5], the spectrum utilization can be greatly reduced by up to $1/128$.

Recent advances have been made on spectrum utilization improvements in NB-IoT [6]–[10]. The state-of-the-art method is applying Non-Orthogonal Multiple Access (NOMA) in NB-IoT [10], [11]. NOMA utilizes the non-orthogonal multiplexing in the power domain to realize high system throughput

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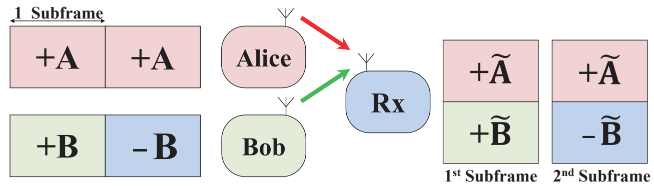

Fig. 1: An example of the uplink transmission in mNB-IoT.

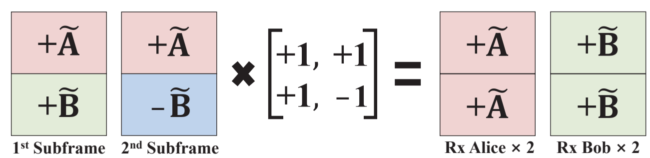

Fig. 2: An example of decoding in mNB-IoT.

and spectrum utilization, which can be generically conducted on massive cellular IoT transmission [12]. However, only 55% spectrum efficiency is increased after applying NOMA, as this method does not fundamentally address the rate deduction caused by the repetition mechanism.

Observed from the practical NB-IoT transmission stream, we found a large amount of repeated subframes, resulting in nonnegligible channel efficiency reduction. According to the timing synchronization in the physical layer of NB-IoT, we propose a optimized repetition mechanism for the uplink transmission, namely mNB-IoT. The "m" in mNB-IoT refers to "multiple", as the mNB-IoT allows multiple user equipments (UEs) to concurrently upload data using the same subcarriers. This design can completely offset the loss of spectrum efficiency caused by the repetition mechanism of NB-IoT, thus can greatly improve spectrum utilization.

To understand how mNB-IoT works, we assume that both Alice and Bob need to repeatedly transmit one subframe of data A and B twice to the base station (BS) using all subcarriers. The original NB-IoT protocol realizes alternative transmission of A and B, resulting in 4 subframes received in the BS. Based on the orthogonal sequence, the mNB-IoT can transmit A and B in parallel and accurately decode them in the receiving end. Specifically, the transmitted A and B are changed with the orthogonal sequences $[1, 1]$ and $[1, -1]$ respectively. When Alice and Bob occupy the same time slot to send signals, due to the timing synchronization of NB-IoT, BS will receive the signal as shown in Fig. 1. As the interval between the two repetitions is very short (*e.g.*, 1ms), we can assume $\widetilde{A_1} \approx \widetilde{A_2} = \widetilde{A}$ and $\widetilde{B_1} \approx \widetilde{B_2} = \widetilde{B}$ with the slight change of channel response between two subframes. Thus, we can decode A and B from received signals making use of the orthogonality of the sequences as shown in Fig. 2.

It can be seen that multiple UEs can transmit data concurrently by using orthogonal sequences. However, the practical deployment of mNB-IoT entails substantial challenges:

1) *Channel response inconsistency:* The original repetition mechanism of NB-IoT introduces a long time interval between each repetition, so it is inaccurate to assume the same channel response between repetitions, which will result in $\widetilde{A_1} \neq \widetilde{A_2}$ and $\widetilde{B_1} \neq \widetilde{B_2}$.
2) *Repetition underutilization:* When the number of subframes or the repetition times for each UE are different, it is impossible to align repetitions among multiple UEs, resulting in the underutilization of all repetitions.

To cope with these challenges, we further designed the Full-M Repetitions (FMR) module to the basic mNB-IoT. To solve the channel response inconsistency, we unify intervals between repetitions. For the M times of repetitions, each slot of data is repeated M times before the next slot. In this way, the interval between each repetition is unified into a slot time (*e.g.*, 0.5ms). Besides, to solve the underutilization of all repetitions, the BS uniformly sets a basic repetition number M_{basic} according to the number of UEs required to be scheduled. If the required repetition time of a UE $M_{require} \leq M_{basic}$, this UE is required to repeatedly transmit M_{basic} times, but the transmission power is adjusted to the original $M_{require}/M_{basic}$. On the contrary, if $M_{require} > M_{basic}$, the UE will repeatedly transmit M_{basic} times and the remained repetitions will be scheduled in the next round.

The main contributions of this paper are as follows:

1) We propose a novel uplink transmission mechanism for NB-IoT, namely mNB-IoT, which realizes concurrent transmission among multiple UEs using the same subcarriers. It can effectively solve the decline of NB-IoT spectrum utilization caused by the usage of repetition technology.
2) We design the FMR module in mNB-IoT to solve channel response inconsistency and repetition underutilization problems in practical NB-IoT transmission. This module ensures the robustness of mNB-IoT and realizes the repetition in NB-IoT without any spectrum utilization reduction.
3) The efficiency of mNB-IoT is evaluated both on simulations and real testbeds based on USRPs, which proves its ability to transmit repeatedly without spectral efficiency reduction for NB-IoT.

II. Preliminary

Before proposing our novel uplink protocol design for NB-IoT, we first introduce the original uplink repetition mechanism in NB-IoT.

The narrowband physical uplink shared channel (NPUSCH) defined in NB-IoT supports two uplink transmission formats depending on data it carries, including format-1 and format-2 [13]. The format-1 is used to carry UEs' uplink data, while the format-2 is used to carry uplink control information with less data. The repetition mechanism we concentrated on is format-1. Taking the transmission of 2 subframes of data with the number of repetitions $M_{rep} = 4$ as an example, when the number of allocated subcarriers N_{sc} is different, the corresponding repetition mechanism is shown in Fig. 3.

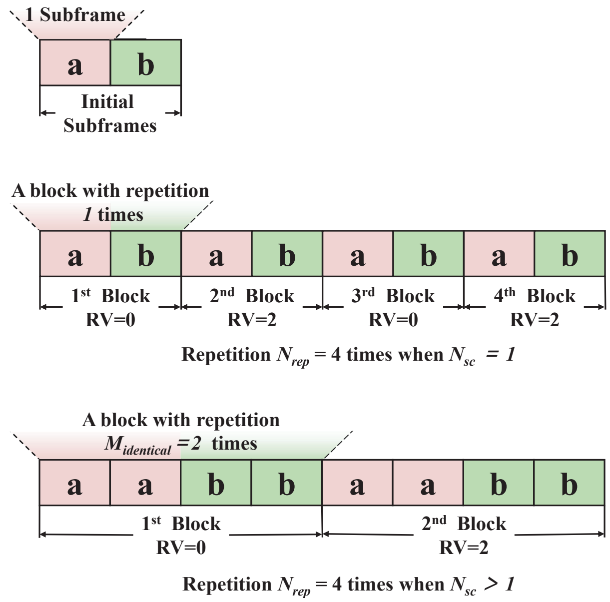

Fig. 3: An example of the original repetition mechanism in NB-IoT.

As shown in the second row of Fig. 3, when $N_{sc} = 1$, all subframes are transmitted in turn to form the first block, and the above process is repeated $M_{rep} - 1$ times to form the following blocks.

While when $N_{sc} > 1$, each subframe is repeated with $M_{identical}$ times until all subframes are transmitted as shown in the third row of Fig. 3. The first block with the $M_{identical}$ times repetition is formed, and then the above process is repeated with $M_{rep}/M_{identical} - 1$ times. The $M_{identical}$ is defined as:

$$M_{identical} = \min(\frac{M_{rep}}{2}, 4). \tag{1}$$

In the original repetition mechanism of NB-IoT, the redundant versions (RVs) between two adjacent blocks are different. The RV for one block is 0 and 2 for another, providing additional coding gain (maximum 2dB) under the soft Turbo hybrid automatic repeat request (HARQ) combining.

III. The design of mNB-IoT

Our proposed mNB-IoT changes the original repetition mechanism of NB-IoT to an efficient one to avoid the deduction of the uplink spectrum utilization due to repetition. It is achieved by the Repetition-Based Division Multiple Access (RBDMA) and Full-M Repetition (FMR) modules.

TABLE I: Notations and explanations.

Notations	Explanations
N_{ue}	The number of UEs
N_{sc}	The number of subcarriers
M_{rep}	The practical number of repetitions of the UE
M_{basic}	The number of repetitions preset by the BS
$M_{require}$	The required number of repetitions of the UE
$P_{require}$	The required transmission power of the UE
X	The data transmitted by the UE
Y	The data received by the BS
W	The Walsh code assigned to each UE
H	The channel response
N	The Gaussian white noise signal

Specifically, the RBDMA proposes the repetition based on orthogonal sequences to realize the concurrent transmission among multiple UEs using the same subcarriers. The FMR additionally unifies their repetition times and intervals between repetitions to achieve maximum improvement of spectrum efficiency. The detailed design of each module is introduced in the following subsections. For the convenience of the reader, we summarize key notations in TABLE I.

A. RBDMA

The RBDMA module is added between the Single-carrier frequency-division multiple access (SC-FDMA) and the Radio Front-End (RF) modules based on the original NB-IoT. As shown in Fig. 4, the repetition data will be encoded with an orthogonal sequence in RBDMA. The k-th bit of the orthogonal sequence will be assigned as the coefficient of the k-th repetition. Similar to the Code Division Multiple Access (CDMA) [14], we also select the Walsh code to generate the orthogonal sequence.

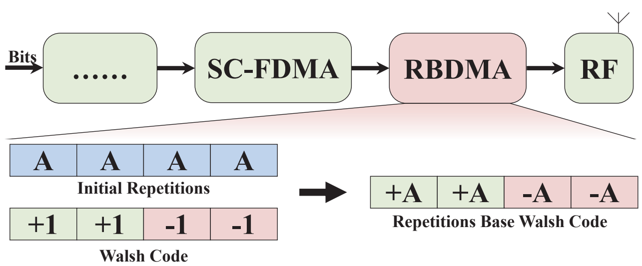

Fig. 4: The illustration of RBDMA in the transmitter side.

Mathematically, when there are N_{ue} UEs transmitting in parallel, and the number of repetitions for i-th UE is M^i_{rep}. We denote $X_i[n]$ as the n-th bit of the data for the i-th UE, and W_i as the Walsh code assigned to the i-th UE. The length of W_i is L_w. We consider a scenario that $N_{ue} = M^i_{rep} = L_w = M, i \in [1, N_{ue}]$, due to the time synchronization of NB-IoT, each UE data arrives at the BS synchronously, then the data received by the BS Y_r for the r-th repetition is as follows:

$$Y_r[n] = \sum_{i=1}^{M} X_i[n] \cdot W_i[r] \cdot H_i[n] + N[n], \tag{2}$$

where H_i represents the channel response of the i-th UE and N represents the Gaussian white noise signal. As assumed that the interval between repetitions is very short, the channel response is roughly unchanged.

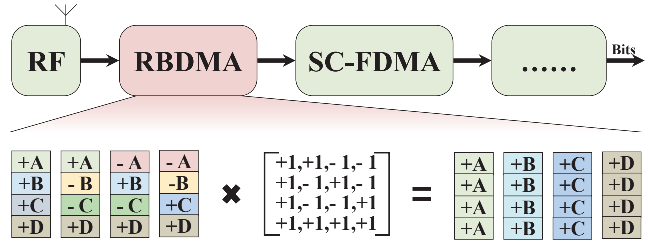

Fig. 5: The illustration of RBDMA in the receiver side.

Symmetric with the transmitter, the BS receiver in mNB-IoT also adds the RBDMA module between the RF and SC-FDMA modules to decode the received repetition data as shown in Fig. 5.

Because the Walsh codes with the length of M have the following orthogonal properties [15]:

$$\begin{aligned} &\sum_{r=1}^{M} W_i[r] \cdot W_j[r] = 0 (i \neq j), \\ &\sum_{r=1}^{M} W_i[r] \cdot W_j[r] = M (i = j). \end{aligned} \tag{3}$$

The data received by the BS is multiplied by the Walsh code of the j-th UE to get the data of the UE. That is,

$$\begin{aligned} &\sum_{r=1}^{M} Y_r[n] \cdot W_j[r] \\ &= \sum_{r=1}^{M} \sum_{i=1}^{M} X_i[n] \cdot W_i[r] \cdot W_j[r] \cdot H_i[n] + N[n] \\ &= \sum_{r=1}^{M} X_j[n] \cdot W_j[r] \cdot W_j[r] \cdot H_j[n] + N[n] \\ &= M \cdot X_j[n] \cdot H_j[n] + N[n]. \end{aligned} \tag{4}$$

By doing so, the repetition data from all UEs can be successfully decoded.

These are the core principles of RBDMA. However, there are still many challenges when applying RBDMA to NB-IoT:

1) *Channel response inconsistency:* The RBDMA is realized based on the assumption that the interval between repetitions is very short. However, according to the existing NB-IoT repetition mechanism, the repetition interval increases with the increase of N_{slot}. In particular, when the subcarrier spacing is 3.75kHz and N_{slot} takes the maximum value of 160, the interval between repetitions can reach 320ms. Thus, it is difficult to ensure the similarity of channel response between repetitions.
2) *Repetition underutilization:* When the N_{slot} of each UE is different, the repetition of each UE will not be fully aligned. When $N_{sc} = 1$, all repetitions can not be aligned. The RBDMA cannot be used right now as the number of repetitions available is 0. Additionally, when $N_{sc} > 1$, the number of repetitions available is $M_{identical}$. Since the

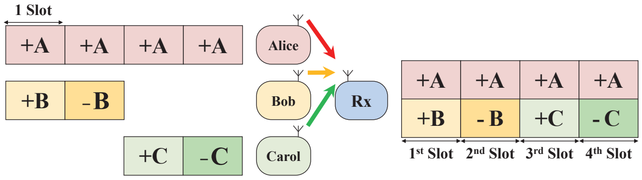

Fig. 6: Repetition time inconsistency.

maximum value of $M_{identical}$ is 4 according to equation 1, only 4 users can transmit concurrently at most.

Beyond that, when the M_{rep} for each UE is different, the length of orthogonal sequence assigned to each UE is also different. Because of the characteristics of orthogonal sequences, the number of UEs that can be transmitted concurrently depends on the minimum number of M_{rep}. For instance, if $M_{rep} = 4$, the RBDMA can realize a maximum of 4 UEs sharing channels. However, when the repetition times are mixed with 2 and 4, the most efficient matching method is shown in Fig. 6. At this time, only 3 UEs can be multiplexed, where two of the UEs are time-division multiplexed.

To solve these two problems, we further propose the FMR module introduced next.

B. FMR

The core idea of FMR is to unify repetition intervals and times. All repetition intervals are unified in a slot time. To achieve M_{rep} repetitions, each subframes will be repeated M_{rep} times before the next one.

According to the principle of RBDMA, when the repetition times among UEs are the same and are equal to the number of UEs, the repetition can be fully used to achieve multiple UEs concurrent transmission. To this end, the BS in FMR sets a uniform repetition time M_{basic} according to the number of UEs required for uplink scheduling at the same time, and schedules $N_{ue} = M_{basic}$ UEs to transmit data concurrently. The remaining UEs will be scheduled in the next round. The M_{basic} is defined as: $M_{basic} = 2^{\lfloor \log_2(N_{ue}) \rfloor}$.

Suppose that according to the existing repetition mode without coding gain, the number of repetitions required is $M_{require}$ and the transmission power is $P_{require}$. As shown in the Fig. 7, if $M_{require} \leq M_{basic}$, its repetition time is set to M_{basic} and the transmission power is controlled to $M_{require}/M_{basic} \times P_{require}$. On the contrary, if $M_{require} > M_{basic}$, the number of repetitions is also set to M_{basic} and the power of transmission remains the same. As the data can not be decoded correctly due to the insufficient number of repetitions, it is necessary to cache the data and continue to schedule in the next scheduling. The FMR will merge the cached data to finally achieve correct decoding. And in order to obtain coding gain, the RV is different in the next scheduling.

For special situations when $M_{basic} \geq M_{require} \geq 2$, the RV of each repetition is the same in one scheduling round, so the additional coding gain can not be obtained under soft Turbo HARQ combining. To compensate such coding gain, the transmission power of each UE is required to be slightly

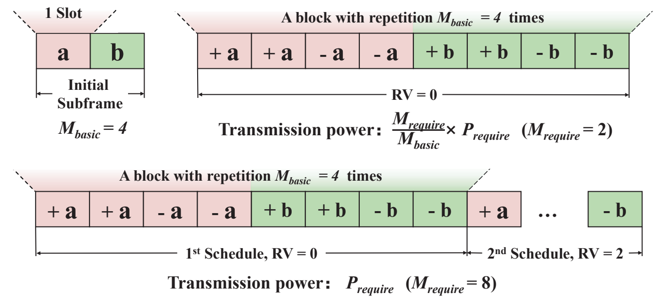

Fig. 7: The illustration of FMR.

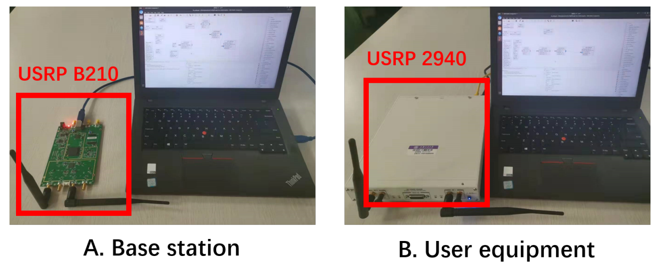

Fig. 8: The evaluation setup with USRPs.

increased. Although the FMR will increase the channel delay for some UEs with better channel quality, the small amount of data transmitted in NB-IoT is not sensitive to the delay, which makes this additional latency acceptable.

IV. Implementation

We evaluate the efficiency of mNB-IoT both on practical USRPs and simulated nodes to simulate transmission in practical and large-scale environments.

The practical evaluation setup is shown in Fig. 8. The BS in mNB-IoT is implemented by a USRP B210. The downlink of BS is consistent with the existing NB-IoT and is implemented by open source software srsRAN components, including narrowband physical broadcast channel (NPBCH) and narrowband physical downlink control channel (NPDCCH). The NPBCH is used to provide synchronization signals to ensure that each UE is synchronized with the BS. The NPDCCH is used to schedule UE uplink data, such as configuring subcarriers, allocating RU, and so on. We develop the novel uplink protocol for BS using C language, which implements the decoding of the uplink data from each UE by making use of orthogonality.

The UEs are implemented by two USRP 2940s. The downlink of UE is also implemented by srsRAN components, which realizes the synchronization with the BS and the decoding on the uplink scheduling information. We develop the uplink protocol for UEs in C language to transform each duplicated data with the orthogonal sequence.

Limited by the number of USRPs, we conduct extensive simulations with the LTE Toolbox components provided by Matlab to evaluate the performance of mNB-IoT in a large scale. The testbed is a laptop with WIN 10 operation system, Intel Core i7-8550U CPU, and 8GB memory.

V. Evaluations

Based on the above mentioned practical and simulated testbeds, we conduct extensive experiments to evaluate the performance of mNB-IoT.

A. Experiment Configuration

We set the subcarrier interval of mNB-IoT to 15kHz, the number of subframe to 1, the size of transmission block to 136, and the modulation mode to QPSK. All 12 subcarriers are assigned to each UE. The number of antennas for BS and UE is 1T1R. The receiving and transmitting gains of BS are set to 60dB, the receiving gain of UE is 30dB, and the transmitting gain is set by the system according to the scheduling scheme. In practical experiments, the BS is placed on the outdoor ground, and the two UEs are placed in different locations in the office building. In simulation experiments, the channel model is set to the Extended Pedestrian A model (EPA) defined in 3GPP, and the Doppler frequency is set to 5Hz.

Two metrics are used for evaluation:

- Throughput: The throughput is defined by the average received bits in one second. A higher throughput indicates that more data can be received in the unit time and the spectrum efficiency of the system is higher.
- Block Error Rate (BLER): The BLER is the rate of erroneous blocks to all received blocks. We consider a packet to be correctly received if its BLER is less than 10%. This setting is in accordance with the typical wireless design.

B. Practical Results

In order to test the throughput and BLER performance of mNB-IoT under different SNR levels, we mix the UE uplink signals with Gaussian white noise signals. The robustness of mNB-IoT to noise is evaluated when increasing the SNR from 3dB to 10dB.

Fig. 9 presents that the throughput of mNB-IoT is twice as much as the one of NB-IoT, indicating the efficiency of mNB-IoT to increase the spectrum utilization.

Fig. 10 shows that the BLER of mNB-IoT is slightly higher than that of NB-IoT under the same SNR. Because when $M_{require} = M_{basic} = 2$, the RVs of two repetitions keep the same, resulting in no additional coding gain with soft HARQ combination in mNB-IoT.

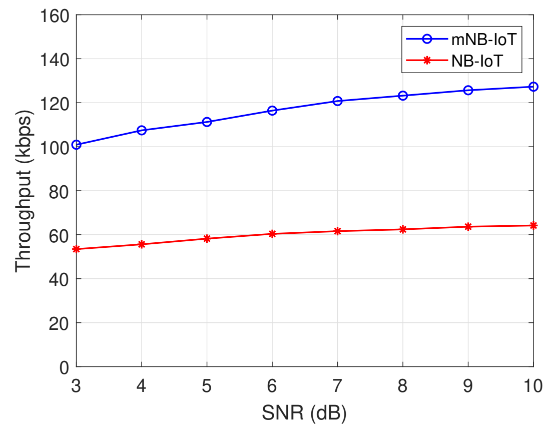

Fig. 9: Practical results: the impact of SNR on throughput when $N_{ue} = M_{rep} = M_{basic} = 2$.

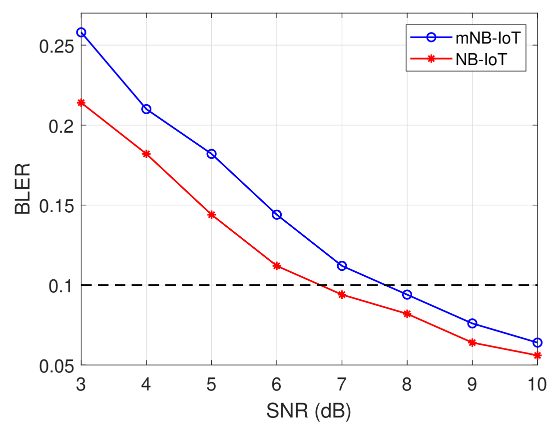

Fig. 10: Practical results: the impact of SNR on BLER when $N_{ue} = M_{rep} = M_{basic} = 2$.

C. Simulation Results

Evaluations on large-scale transmission are conducted by simulations. To evaluate the throughput and BLER performance of mNB-IoT, we conduct simulations when the number of repetitions M_{rep} is 2, 4, 8, 16, 32, 64, 128 and the corresponding number of UEs N_{ue} is also 2, 4, 8, 16, 32, 64, 128. In order to verify the role of FMR, a mNB-IoT scheme without FMR is added to the simulation for comparison, which is represented by w/o FMR.

It can be seen from Fig. 11 that the throughput of NB-IoT continues to decline with the increase of the number of repetitions. For mNB-IoT w/o FMR, when $M_{rep} \leq 4$, the throughput will remain roughly the same. But when $M_{rep} > 4$, the throughput will continue to decline. Although only up to 4 UEs can be multiplexed in mNB-IoT w/o FMR, the spectrum efficiency is still up to 4 times higher than that of NB-IoT. This result is consistent with the discussion in Section III-A. And for mNB-IoT with the FMR module, the throughput remains roughly the same as the number of repetitions increases, so the FMR module can solve the channel response inconsistency and repetition underutilization problems and realize repetition transmission in NB-IoT without spectral efficiency reduction.

It can be seen from Fig. 12 that with the increase of the number of repetitions, the SNR required to meet the minimum BLER decreases gradually. When the number of repetitions is doubled, the minimum SNR required is reduced by about 3db. Besides, the repetition gain does not decrease with the increasing number of multiplexed users.

VI. Related Work

Extensive researches have been proposed to boost the spectral efficiency of NB-IoT.

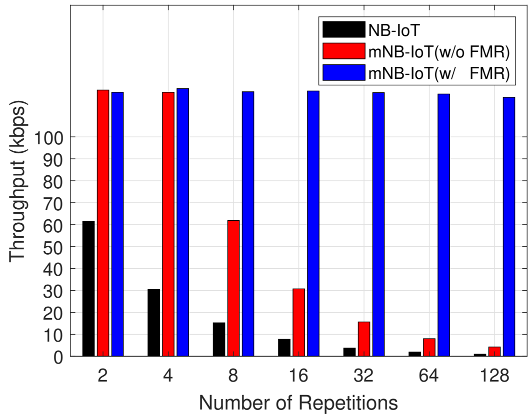

Fig. 11: Simulation results: the performance of throughput for NB-IoT, mNB-IoT w/o FMR, and mNB-IoT w/ FMR.

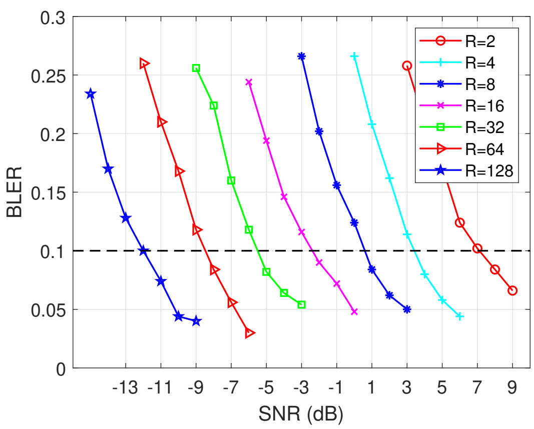

Fig. 12: Simulation results: the performance of BLER for mNB-IoT.

Fast-OFDM [7] provides a compressed signal waveform solution to double the number of connected devices by compressing the occupied bandwidth of each device. But it is specially used for 1-D modulation schemes like binary phase shift keying (BPSK). The authors in [8] aim to boost the spectral efficiency of the OFDM-oriented NB-IoT systems by reducing the Cyclic Prefix (CP) overhead during the repetition procedures. But the CP overhead in NB-IoT results in only 6.67% loss of the spectral efficiency, which is not the main reason for the low spectrum efficiency of NB-IoT. Further enhanced in [9], the authors utilize the repetition with a cooperative relay scheme to improve the system performance of NPUSCH. It makes the uplink more complicated, and can only increase the overall network throughput by 23%. The power-domain uplink NOMA scheme proposed in [10] can achieve better performance. By allowing multiple UEs to share the same subcarrier, NOMA can provide connectivity to more UEs than orthogonal multiple access (OMA). In [11], authors investigate the bottom-up power filling and item clustering-based schemes for maximizing the connection density in NB-IoT with NOMA, which achieves the number of available connections up to 55%.

VII. Conclusion

This paper presents mNB-IoT, a physical layer design to enable multiple UEs concurrent transmission in NB-IoT uplink. First of all, mNB-IoT takes advantage of the time synchronization between UEs, turns the original simple repetition into repetition based on specific orthogonal sequences, thereby realizing up to 4 UEs in parallel transmission. Secondly, by unifying repetition intervals and times, mNB-IoT realizes the multiplexing of up to 128 UEs to further increase the NB-IoT spectrum utilization. We have implemented the mNB-IoT prototype on the USRP-based experimental platform and conduct extensive evaluations on simulations in a large scale. The experiments show that when multiple UEs are multiplexed, the BLER remains almost unchanged, and the BS throughput can reach up to 128 times than that of the existing NB-IoT .

Acknowledgement

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