Evaluation, Modeling and Optimization of Coverage Enhancement Methods of NB-IoT

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***Abstract*—Narrowband Internet of Things (NB-IoT) is a new Low Power Wide Area Network (LPWAN) technology released by the Third Generation Partnership Project (3GPP). The primary goals of NB-IoT are enhanced coverage, low cost, and long battery life. In order to enhance coverage, NB-IoT has new features, such as increasing transmission repetitions, decreasing bandwidth, and adapting the Modulation and Coding Scheme (MCS). In this paper, we present an implementation of these three features of NB-IoT in NS-3, an end-to-end network simulator. Using the developed simulation framework, the influence of the coverage enhancement features on network reliability and latency is evaluated. Furthermore, we propose a hybrid link adaptation strategy based on all three features, which tries to achieve optimal latency and coverage. To achieve this, we formulate and solve an optimization problem that finds the optimal value of repetitions, bandwidth and MCS such that the latency is minimum and the reliability is maintained. Based on the hybrid link adaption strategy, a new scheduler is implemented and evaluated in the NS-3 simulator. Through numerical results we show that the hybrid link adaptation method achieves lower latency and higher coverage than any of the coverage enhancement techniques. We also show that the proposed optimization method achieves the same performance as the exhaustive search method but with lower complexity.**

***Index Terms*—NB-IoT, Coverage enhancement, Link adaptation, Optimization, NS-3.**

I. Introduction

The Internet of Things (IoT) refers to the idea of connecting everyday objects to the Internet, enabling them to send and receive data. There is a wide range of applications for IoT in the areas of smart cities, asset tracking, smart agriculture, health monitoring and so on. The IoT landscape consists of wireless technologies that operate in licensed or unlicensed bands, achieving ranges from less than ten meters up to tens of kilometers with data rates from a few bps to Mbps. Low Power Wide Area Network (LPWAN) targets low-power and long-range applications with data rates from 10 bps up to a few kbps. Narrowband-IoT (NB-IoT) [1] is a licensed LPWAN technology, which was standardized in 2016 by the Third Generation Partnership Project (3GPP). NB-IoT uses a new physical layer design that facilitates a wide range of IoT applications in the licensed spectrum that require long range, deep indoor penetration, low cost, low data rate, low power consumption, and massive capacity [2].

Among the aforementioned requirements, this paper focuses on uplink coverage enhancement. Many solutions are proposed in the standard to achieve coverage enhancement for NB-IoT. The first solution, referred as *tones*, is to reduce the bandwidth and to perform resource allocation based on tones (or subcarriers) instead of Resource Blocks (RBs). A lower number of tones enables the User Equipment (UE) to transmit in a narrower bandwidth. The second solution is *repetitions*, which refers to repeating the data transmission multiple times. The last solution is *Modulation and Coding Scheme (MCS)*, which is already used in LTE to achieve better coverage [3]. Considering the new features of tones and repetitions, uplink link adaptation needs to be performed in three dimensions - using tones, repetitions and MCS. In this paper, we focus on uplink scheduling and designing a hybrid link adaptation scheme for NB-IoT systems. The contributions of this paper can be summarized as follows:

- Implementation of the coverage enhancement features i.e., tones, repetitions and MCS in NS-3.
- Evaluation of the impact of these features on reliability and latency through NS-3 simulations.
- Design, implementation and evaluation of the scheduler which performs hybrid link adaptation in NS-3.

A. Background

NB-IoT has a bandwidth of 180 kHz which corresponds to one RB of LTE. In the uplink, the bandwidth of 180 kHz can be distributed among 12 subcarriers or tones with 15 kHz spacing, or 48 subcarriers with 3.75 kHz spacing. The subframe duration for 3.75 kHz spacing is 4 ms, which is four times that of 15 kHz spacing [4].

NB-IoT supports single-tone and multi-tone communication in the uplink. In case of multi-tone, there are three options with 12, 6 and 3 subcarriers. In case of single-tone, there is only 1 subcarrier with either 15 kHz or 3.75 kHz spacing. A higher number of tones is used to provide higher data rates for devices in normal coverage, while a lower number of tones is used for devices that need extended coverage. A single packet of a fixed size is transmitted over 1 ms in case of 12 tones, 2 ms in case of 6 tones, 4 ms in case of 3 tones, 8 ms in case of 1 tone (15 kHz spacing) and 32 ms in case of 1 tone (3.75 kHz spacing) [5].

MCS is the feature that influences the type of modulation and code rate. MCS is directly proportional to the code rate and Transport Block Size (TBS) and can take values from 0 to 12 [6]. As the channel quality deteriorates, the MCS becomes lower and thus the code rate and TBS become lower. MCS, tones and repetitions are assigned based on channel quality. Repetitions of uplink data can take values of 1, 2, 4, 8, 16, 32, 64 and 128. When channel quality is poor, tones and MCS are decreased and repetitions are increased.

B. *State-of-the-art*

Constituting a relatively new technology, there are a lot of open issues that need to be investigated for NB-IoT, such as performance analysis, link adaptation, design optimization, and co-existence with other technologies. The performance of NB-IoT with respect to coverage, capacity, and co-existence with LTE has been studied in, for instance, [7], [8], [9] and [10]. The focus of our paper is towards implementation and evaluation of coverage enhancement techniques and link adaptation based on coverage enhancement methods.

NS-3 is an open source network simulator and the NS-3 LTE module is well-tested and can be used as a base for developing the NB-IoT module. The work on NB-IoT module in NS-3 began in [11], in which the authors modified downlink signaling traffic such as the Master Information Block (MIB) and the System Information Block (SIB) to comply with NB-IoT specification. In [12], the authors restricted the bandwidth to one Resource Block (RB) which is 180 kHz and separated the control and data channels. This paper aims to extend [12], by implementing the single and multi-tone uplink features, including repetitions in the uplink and implementing a hybrid scheduler that allocates tones, repetitions and MCS.

With respect to uplink link adaptation of NB-IoT, the authors of [13] propose a 2D link adaptation strategy based on MCS and repetitions and use link-level simulations to evaluate the performance of their solution. In this paper, however, we use a system and network level simulator (NS-3) to evaluate our solution through end-to-end simulations. Further, they do not take tones into account, which is an important dimension to be considered for link adaptation. Furthermore, they do not consider a hybrid solution instead they fix one parameter while varying the other. In [14], the authors derive analytic equations that model the impact of repetitions, tones and MCS. They also propose an exhaustive search method that searches all possible combinations of repetitions, tones, and MCS to minimize the transmission latency. However, their analysis of the coverage enhancement features is entirely based on analytic models and they do not perform network simulations or experiments. In this paper, we analyze the coverage enhancement features theoretically and also implement these features in the NS-3 simulator. The implementation in NS-3 facilitates the use of end-to-end simulations to evaluate these features, by including factors such as scheduling and network delays. Furthermore, instead of an exhaustive search method, we propose a closed-form solution which achieves the same result with lower complexity.

II. NB-IoT IMPLEMENTATION AND EVALUATION

The authors of [12] implemented the basic features for eMTC and NB-IoT modules using the LTE module of NS-3. Based on the NB-IoT module described in [12], we implement the uplink coverage enhancement features which can be found on github[1].

A. *Implementation of tones and repetitions*

In order to implement tones, modifications are made in both time domain (extending a packet according to tone) and frequency domain (transmitting over a narrower bandwidth). It is know that reducing bandwidth improves the Signal-to-Noise Ratio (SNR) as the transmitted power spectral density increases. In order to support bandwidth lower than 180 kHz (1 RB), the existing resource allocation is modified from RB-based allocation to subcarrier-based allocation.

In order to implement repetitions, major modifications are made in the time domain (repeating a data packet). Whenever repetition is used, the subsequent repetitions of the same data are aggregated at the eNodeB. Hence, the resulting SNR after the aggregation is the sum of the SNRs of each received repetition. Therefore, repetition of two results in an improvement of approximately 3 dB in SNR [14]. In order to achieve this behavior, we have modified the physical layer of the base station in NS-3 to aggregate all the repetitions, and use the final sum of SNR as input to the error model described in [15].

B. *Implementation of link adaptation*

Link adaptation is performed based on the SNR received from the Secondary Reference Signal (SRS). SRS is a signal that is sent periodically by the UE. Fig. 1 shows the link adaptation mechanism. The SNR received from the SRS is provided as input to the error model of NS-3 to find the Block Error Rate (BLER) corresponding to the SNR [15]. If the BLER is less than the target BLER of 0.1, the MCS and tones are fixed to the highest value (12 tones) and repetitions are fixed to the lowest value (1 repetition). If the target BLER is not met, MCS, tones and repetitions are adapted and re-evaluated using the error model. This process is repeated until a BLER

[1] https://github.com/imec-idlab/NB-IoT

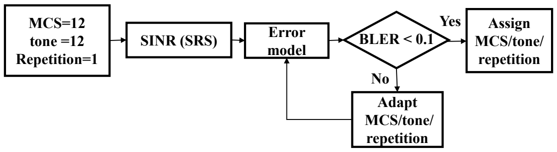


Fig. 1: The link adaptation mechanism.

of 0.1 or less is reached. The final value of the MCS, tones or repetitions that resulted in the BLER of 0.1 or less is assigned to the UE. Three independent methods of link adaptation are performed:

1) MCS value is adapted based on SNR (repetitions value is fixed to 1 and tones value is fixed to 12).
2) Tones value is adapted based on SNR (repetitions value is fixed to 1 and MCS value is fixed to 12).
3) Repetitions value is adapted based on SNR (MCS value is fixed to 12 and tones value is fixed to 12).

C. Evaluation

The performance evaluation is carried out for two scenarios: open area and urban. In open area, the eNodeB is located in the center and UE's are arranged in a random fashion at different distances from the eNodeB. In urban scenario, we include buildings and we assume that 80-90% of the users are located inside the buildings. For a given distance, SNR is relatively lower inside a building than outside. Based on the distance, the nodes are grouped among 16 zones at different distances from the eNodeB as indicated by Table I. The simulation parameters for these scenarios are shown in Table II.

TABLE I: Coronas or division based on distance

Zone	Distance (m)	Zone	Distance (m)
1	0-200	9	2750-3000
2	200-400	10	3000-3500
3	400-600	11	3500-4000
4	600-800	12	4000-5000
5	800-1000	13	5000-6000
6	1000-2000	14	6000-8000
7	2000-2500	15	8000-10000
8	2500-2750	16	10000-40000

TABLE II: Simulation parameters

Parameter	Value
Number of UE	100 - 600
UEs distribution	random
Propagation model	Okumura-Hata(Open area) Hybrid building(Urban)
Frequency Band	DL: 925 MHz, UL: 880 MHz
Tx Power	eNodeB: 46 dBm, UE: 20 dBm
Packet Size	12 bytes
# Runs	100 runs
Inter-packet interval	10 seconds

Fig. 2(a) shows the average value of the assigned MCS, repetitions and tones in different zones. It is important to note that, the farther the zone, the lower the value of SNR. We can observe that due to indoor deployment in urban scenario the values of MCS, tones and repetitions are modified at closer distances. In urban scenario, UE's that are located inside buildings have very low values of SNR compared to the open area and the MCS, repetitions and tones are adapted more rapidly in order to improve reliability.

Similarly, as shown in Fig. 2(b), the reduction in Packet Delivery Ratio (PDR) is steeper in urban scenario. We can observe from the PDR graph that MCS starts to fail in zone 7-8 in the open areas while it starts to fail in zone 4-5 in urban areas. Tones start to fail in zone 12-13 for open areas and zone 7-8 in urban areas. Repetitions start to fail at zone 14-15 in open areas and zone 12-13 in urban areas. None of the link adaptation methods were successful in zone 16. Repetitions have the best performance in both urban and open areas. However, an increase in repetitions has to be traded off for a corresponding increase in the energy consumption.

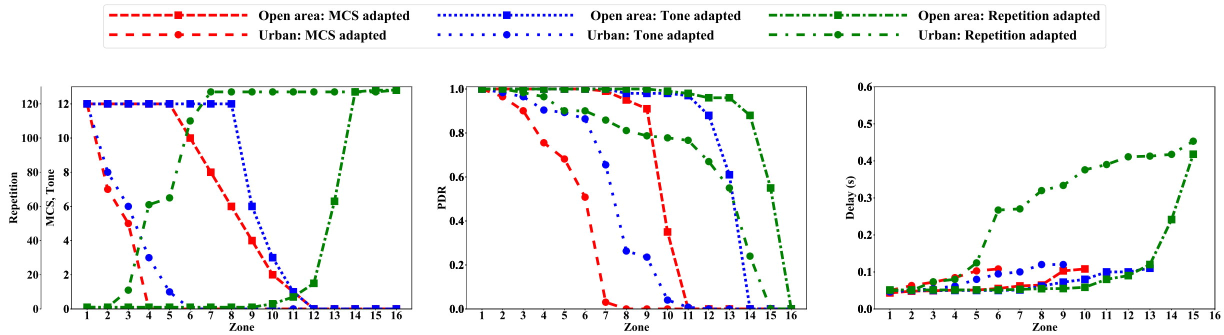
Fig. 2(c) shows the average delay or latency at different zones. We can observe that the delay starts to increase at a lower distance for urban compared with open area. This clearly shows that the latency of transmission increases as we move from open areas to urban areas. The delay follows the adapted value and increases towards farther zones. Based on the above results, we can conclude that the improvement in coverage comes at the cost of a higher delay.

III. Hybrid link adaptation

The link adaptation strategies described in the previous section adapt only one of the three coverage enhancement parameters, which result in saturation before achieving a good coverage. However, a more useful solution will be to adapt all three of them and extend the coverage. When MCS, tones or repetitions are adapted to improve the reliability of a UE that has a poor coverage, there is a corresponding increase in the transmission delay of the UE. Therefore, in our hybrid solution, tones, repetitions and MCS are evaluated in an optimized manner such that the delay per user is minimal, while the reliability is not compromised.

We formulate an optimization problem, with transmission delay per user as the objective function, and the reliability as the constraint. Then, we implement the solution to the optimization problem as a new hybrid scheduler in NS-3 in order to allocate tones, repetitions and MCS in an optimized manner.

The delay of a UE is composed of synchronization delay, Random Access Channel (RACH) delay and data transmission delay. In this paper, we only consider the *data transmission delay*, as it is the delay that can stretch in time based on the amount of data. The uplink data transmission delay per UE consists of Downlink Control Information (DCI), transmission of data, and



(a) Assigned value vs zone (b) Achieved PDR vs zone (c) Achieved delay vs zone

Fig. 2: Performance of link adaptation in open area and urban scenarios.

transmission and reception of the acknowledgment. The data transmission delay per UE for the uplink (UL) transmissions is obtained from [12] and can be written as,

$$Delay = TL \times \left\lceil \frac{Datalength}{TBS(MCS, RU)} \right\rceil, \qquad (1)$$

where TL is the transmission latency, $Datalength$ is the data size per user and TBS is the transport block size. TL depends on the duration of a single transmission of DCI (t_{PDCCH}), repetitions of control transmission ($RLDC$), downlink to uplink switching delay (t_{DUS}), duration of a single subframe (t_{PUSCH}), the time factor (t), number of repetitions of the data transmissions ($RLUS$) and time taken for acknowledgement (t_{ACK}) as shown in Fig. 3. The Narrowband Physical Uplink Shared Channel (NPUSCH) is used for uplink data transmission and the Narrowband Physical Downlink Control Channel (NPDCCH) is used for downlink control transmission. Hence, TL can be written as,

$$\begin{aligned} TL = {} & RLDC \times t_{PDCCH} + t_{DUS} \\ & + RLUS \times t \times t_{PUSCH} \\ & + t_{UDS} + RLUC \times t_{ACK}. \end{aligned} \qquad (2)$$

The time factor t depends on the number of tones assigned to the UE and can take values as 1, 2, 4, 8, and 32 for 12, 6, 3, 1 tones of 15 kHz spacing and 1 tone of 3.75 kHz spacing, respectively. The acknowledgement and retransmissions are disabled to better analyze the performance of our solution i.e., t_{UDS} and t_{ACK} are set to zero. For simplicity, we assume that there are no repetitions in the DCI ($RLDC = 1$) and that the number of resource units is one ($RU = 1$).

Let us denote t_{PUSCH} by K_0, $Datalength$ by K_2 and $RLUS$ by r. Hence, we can rewrite (1) as follows,

$$Delay = (K_1 + K_0 \times r \times t) \left\lceil \frac{K_2}{TBS(m)} \right\rceil, \qquad (3)$$

where r is the number of repetitions, t is the time factor, K_2 is the datalength, K_0 and K_1 are constants and TBS is the transport block size that depends on MCS denoted by m. The table showing the relationship between MCS and TBS is specified in [1]. Considering the delay expression given in (3), the optimization problem can be formulated as,

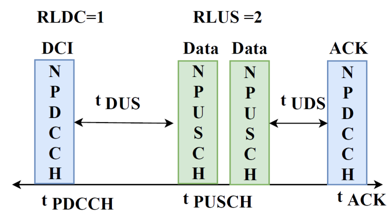


Fig. 3: Uplink transmission latency in NB-IoT

$$\begin{aligned} \min_{r,t,m} \quad & Delay(r,t,m) \\ \text{s. t.} \quad & \mathrm{SNR} \geq \mathrm{SNR_{Th}}(m) \\ & r \in R,\ t \in T,\ m \in M, \end{aligned} \qquad (4)$$

where $\mathrm{SNR_{Th}}(m)$ is the threshold SNR value that depends on MCS. m is an integer value that belongs to the set $M = \{0, 1, 2..., 12\}$, r, representing repetitions, is an integer value that belongs to the set $R = \{1, 2, 4, 8, 16, 32, 64, 128\}$ and t, representing the time factor, is an integer value that belongs to the set $T = \{1, 2, 4, 8, 32\}$. In order to achieve good reliability, the received SNR should be above $\mathrm{SNR_{Th}}(m)$. The received SNR depends on propagation loss, repetitions and tones and is given by,

$$\mathrm{SNR} = K_3 \times f \times r, \qquad (5)$$

where $K_3 = P_{TX}/(180\text{kHz} \times N_0 \times PL)$, P_{TX} is the transmitted power, N_0 is the noise power spectral density, PL is the pathloss and f is the frequency factor. The frequency factor, f, can take values of 1, 2, 4, 12, and 48 for 12, 6, 3, 1 tones of 15 kHz spacing and 1 tone of 3.75 kHz spacing, respectively.

The SNR obtained in (5) should be greater than a given threshold ($\mathrm{SNR_{Th}}(m)$) to achieve a good reliability and low BLER. The value of $\mathrm{SNR_{Th}}(m)$ depends on

MCS and it can be obtained from the NB-IoT BLER curves generated for each MCS. Fig. 4 shows the generated BLER curves on the uplink for different MCS values under Additive White Gaussian Noise (AWGN) channel. Hence, $\text{SNR}_{\text{Th}}(m)$, for all m, can be obtained from Fig. 4 by setting the value of BLER to be 0.1.

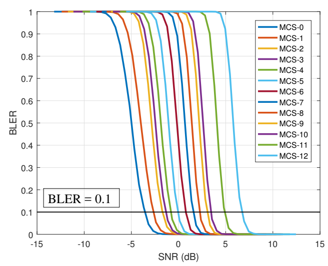


Fig. 4: BLER curves for AWGN channel.

The obtained $\text{SNR}_{\text{Th}}(m)$ needs to be met in order to guarantee that the packet is received at the base station without any corruption. Using the expressions given in (3) and (5), the optimization problem can be written as:

$$\begin{aligned} \min_{r,t,m} \quad & \frac{K_2\ (K_1 + K_0\, r\, t)}{TBS(m)} \\ \text{s. t.} \quad & K_3 \times f \times r \geq \text{SNR}_{\text{Th}}(m) \\ & r \in R,\ t \in T,\ m \in M. \end{aligned} \tag{6}$$

Note that the ceiling in (1) is dropped since it will not alter the outcome of the optimization. The objective function given in (6) is non-convex and it is hard to solve. In order to solve the optimization problem and to have a closed-form solution, we simplify it by fixing the value of MCS, m. Thus, for each value of $m \in M$, we search for the optimum values of r and t, and then select the value of m, r and t that yield the minimum delay. We also relax the integer constraint on r and t.

We should note that the objective function is based on t whereas the SNR is based on f. The parameters f and t are both based on the number of tones and are interrelated. For example, for a 15 kHz single-tone, t is equal to 8 and f is equal to 12. Hence, in order to further simplify the optimization problem, we create an expression that relates f to t using the curve fitting function in MATLAB and it is given by,

$$f = p_1\, t^3 + p_2\, t^2 + p_3\, t + p_4, \tag{7}$$

where $p_1 = -0.004994$, $p_2 = 0.2031$, $p_3 = 0.08811$, and $p_4 = 0.834$. The mean square error between the actual and the approximated function is very small and is equal to 0.015. Based on the approximation described in (7), the optimization problem for a given m, can be re-written as,

$$\begin{aligned} \min_{r,t} \quad & \frac{K_2\ (K_1 + K_0\, r\, t)}{TBS(m)} \\ \text{s. t.} \quad & K_3\, r\ \left(p_1\, t^3 + p_2\, t^2 + p_3\, t + p_4\right) \\ & - \text{SNR}_{\text{Th}}(m) \geq 0 \\ & 0 \leq r \leq 128,\ 0 \leq t \leq 32. \end{aligned} \tag{8}$$

The optimization problem in (8) is convex and it can be solved using Lagrangian method. Hence, we can define the Lagrangian (L) as:

$$\begin{aligned} L = & \frac{K_2\ (K_1 + K_0\, r\, t)}{TBS(m)} \\ & - \lambda\, K_3\, r\ \left(p_1\, t^3 + p_2\, t^2 + p_3\, t + p_4\right) \\ & + \lambda\, \text{SNR}_{\text{Th}}(m), \end{aligned} \tag{9}$$

where r, t and the Lagrangian multiplier λ are the variables or unknowns. Hence, in order to find the optimum value of r, t and λ, the partial derivatives of the Lagrangian (L) are calculated for r, t and λ as shown below:

$$\frac{\partial L}{\partial r} = 0, \quad \frac{\partial L}{\partial t} = 0, \quad \frac{\partial L}{\partial \lambda} = 0. \tag{10}$$

$$\frac{K_0\, K_2\, t}{TBS(m)} - K_3\, \lambda\ \left(p_1\, t^3 + p_2\, t^2 + p_3\, t + p_4\right) = 0. \tag{11}$$

$$\frac{K_0\, K_2\, r}{TBS(m)} - K_3\, \lambda\, r\ \left(3\, p_1\, t^2 + 2\, p_2\, t + p_3\right) = 0. \tag{12}$$

$$\text{SNR}_{\text{Th}}(m) - K_3\, r\ \left(p_1\, t^3 + p_2\, t^2 + p_3\, t + p_4\right) = 0. \tag{13}$$

Solving (11) and (12) for t for a given m, we get

$$\frac{2p_1 t^3 + p_2 t^2 - p_4}{3p_1 t^2 + 2p_2 t + p_3} = 0. \tag{14}$$

In order to get t, we solve $2p_1 t^3 + p_2 t^2 - p_4 = 0$ such that $3p_1 t^2 + 2p_2 t + p_3 \neq 0$. Solving these equations for the given parameters p_i, we get the following

$$t = -1.936,\ 2.142,\ 20.128. \tag{15}$$

$$t \neq -0.215,\ 27.327. \tag{16}$$

Out of these t values, the negative value is discarded and the only possible values are 20.128 and 2.142. We can obtain r by substituting the values of t in (13). Then, we search for the integer combination of r and t that gives minimal delay and a SNR value higher than SNR_{Th}. The value of m is chosen by performing an exhaustive search and obtaining the values of t and r for each value of m. The optimum solution is obtained by choosing the combination r, t and m that yield the lowest delay, while achieving good reliability, i.e., $\text{SNR} \geq \text{SNR}_{\text{Th}}$. This algorithm is implemented and evaluated in the NS-3 simulator. Furthermore, the scheduler in NS-3 is modified to include the new hybrid link adaptation strategy.

IV. Numerical Results

In order to evaluate the proposed optimization algorithm, we compare it with the exhaustive search method in terms of complexity and the achieved minimum delay. This method is implemented by searching for all possible combinations of m, r and t and then selecting the combination that yields the smallest delay and satisfies the SNR constraint.

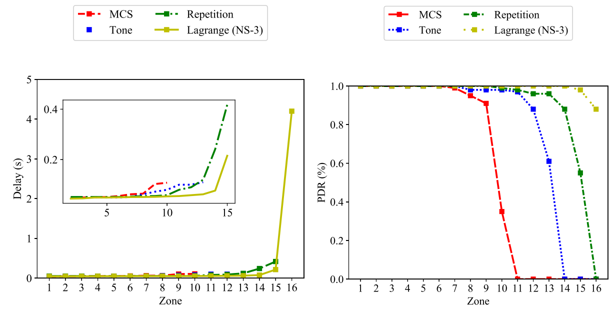
In order to allocate tones, repetitions and MCS, the base station needs to perform the link adaptation at runtime for all the UE's, whenever there is a change in SNR. Hence, the speed of the optimization algorithm is an important factor to be considered. The exhaustive method has a complexity of $O(M \times T \times N)$, where M, R, T refer to the possible number of values of MCS, tones and repetitions respectively and N represents the number of UE's. The Lagrange method has a lower complexity of $O(M \times N)$. In terms of execution time, Lagrange method was about eight times faster than the exhaustive approach. Finally, the mean square error of the delay obtained using the Lagrange approach compared to the delay obtained using the exhaustive approach was found to be 1028×10^{-4} (no units), which is minimal. Hence, the Lagrange method is as accurate as the exhaustive approach but has a lower complexity.

In order to evaluate the proposed hybrid scheduler, we compare it with the basic scheduler that adapt one of the enhancement coverage techniques, i.e., tones, repetitions or MCS. The same random deployment scenario described above for open areas in II-C is used to perform the comparisons in NS-3. Fig.5a depicts the delay obtained by adapting MCS, adapting tones, adapting repetitions and adapting all the three parameters, i.e. hybrid scheduler based on Lagrange method in NS-3, for different zones. In the zoomed part of Fig. 5a, we can observe that between zones 5 and 15, the hybrid solution, 'Lagrange (NS-3)', gives the lowest delay among the other methods and yields similar delay value at closer zones. Furthermore, the repetitions-only approach starts to fail at zone 14. Based on Fig. 5b, the hybrid solution is able to deliver a good amount of packets in zone 16 (i.e. 40 km). Thus, hybrid solution offers better network efficiency, lower delay or latency per user which also means lower energy consumption.

In addition to latency and reliability, we also evaluate the network performance in terms of scalability. The maximum number of users that can be supported in a network is obtained from [12] and is given by,

$$max\, N_{UE} = \left\lfloor \frac{Reporting\; Period}{Delay_{UE}} \right\rfloor \times \left\lfloor \frac{N_{SC}}{SCU} \right\rfloor, \quad (17)$$

where N_{SC} is the total number of subcarriers available for allocation, $Delay_{UE}$ is the average delay per user obtained in (1), and SCU is the number of subcarriers allocated to one user. The $Reporting\; Period$ is assumed to be the same for all users. Fig. 6 depicts the results obtained using NS-3 simulator and using the theoretical expression given in (17) for the different aforementioned methods.



(a) Delay (b) PDR

Fig. 5: Hybrid approach

Fig. 6 shows the maximum number of users that can be supported when N_{SC} is 24, i.e., number of RBs is two, and the reporting period is 10 s. We can observe that the hybrid method has the highest maximum number of users, mainly because it is optimized to achieve lower delay per user ($Delay_{UE}$). Furthermore, in tone and hybrid approaches, resource allocation is performed in terms of subcarriers (SC) and multiple users can share the same RB whereas, in repetition and MCS approaches, the resource allocation is performed in terms of resource blocks (RB). It can be observed that there is a huge difference between theoretical and NS-3 results for the tone and hybrid approaches. This is because it is difficult to simulate beyond 600 users in NS-3 due to memory and processing constraints. In a practical scenario, this limitation will not occur and hybrid strategy will support the same number of users as the theoretical result shown.

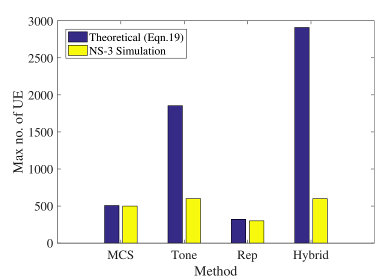


Fig. 6: Scalability for reporting period of 10s.

V. Conclusion

In this paper, we describe an implementation of uplink coverage enhancement methods of NB-IoT in NS-3 simulator. We evaluate the performance of tones, repetitions and MCS with respect to reliability and latency. We show that, an improvement in reliability at longer ranges comes at the cost of a corresponding increase in latency. In order to achieve improved coverage and lower latency, we propose a hybrid strategy and formulate an optimization problem that allocates the different enhancement coverage features in such a way that the latency is minimum and the reliability is maintained. We compare our proposed optimization method with the exhaustive search method in terms of achieved latency and complexity. The proposed method for hybrid link adaptation has a lower complexity than the exhaustive search approach and yields similar latency. Furthermore, we showed that the hybrid solution achieves a range of 40 km for open areas and has better scalability than optimized tone, optimized repetition and optimized MCS approaches.

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