Extreme Coverage in 5G Narrowband IOT: a LUT-based Strategy to Optimize Shared Channels

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Abstract-One of the main challenges in IoT is providing communication support to an increasing number of connected devices. In recent years, narrowband radio technology has emerged to address this situation: Narrowband Internet of Things (NB-IOT), which is now part of 5G. Supporting massive connectivity becomes particularly demanding in extreme coverage scenarios such as underground or deep inside buildings sites. We propose a novel strategy for these situations focused on optimizing NB-IOT shared channels through the selection of link parameters: modulation and coding scheme, as well as the number of repetitions. These parameters are established by the base station (BS) for each block transmitted until reaching a target block error rate ($BLER_t$). A wrong selection of these magnitudes leads to radio resource waste and a decrease in the number of possible concurrent connections. Specifically, our strategy is based on a look-up table (LUT) scheme which is used for rapidly delivering the optimal link parameters given a target QoS. To validate our proposal, we compare with alternative strategies using an open source NB-IOT uplink simulator. The experiments are based on transmitting blocks of 256 bits using an AWGN channel over the NPUSCH. Results show that, especially under extreme conditions, only a few options for link parameters are available, favoring robustness against measurement uncertainties. Our strategy minimizes resource usage in all scenarios of acknowledged mode and remarkably reduces losses in the unacknowledged mode, presenting also substantial gains in performance. We expect to influence future BS software design and implementation, favoring connection support under extreme environments.

Index Terms—NB-IoT, 5G, extreme coverage, lookup table, LUT, physical shared channels

I. INTRODUCTION

I NTERNET OF THINGS (IOT) paradigm is the seamless integration of potentially any object with the Internet [1]. Currently, there are more than 16 billion connected devices worldwide and 2.2 connected devices per person with an expected growth to nearly 28 billion connections and 3.4 networked devices per capita in 2020 [2]. This context imposes a strong need for increasing communication networks capacity. Low power wireless technologies have the potential to connect 60% of the devices to the Internet [3], alleviating the need for further costs in standard network infrastructure. These technologies, known as low power wide area network (LPWAN), are designed according to the following principles: communication distance up to 40 km, thousands of devices supported by each base station (BS), availability for over a decade without battery replacement, and module price below U 5 [4].

Within LPWAN technologies, the 3rd Generation Partnership Project (3GPP) introduced Narrowband Internet of Things (NB-IOT), a novel narrowband radio technology specifically designed for IoT [5] and low-cost deployment. NB-IoT can satisfy the requirements of non-latency-sensitive and lowbitrate applications (time delay of uplink can be extended to more than 10s, and uplink or downlink for a single user are supported at 160 bit s^{-1} at least), with coverage enhancement (coverage capacity is increased 20 dB), ultralow power consumption (a 5 Wh battery can be used by one terminal for 10 years), and massive terminal connections (a single sector can support 50000 links) with transmission bandwidth of 180 kHz [6]. This technology can be directly deployed in Long-Term Evolution (LTE) networks in order to reduce deployment costs [5]. Moreover, 3GPP recognizes the importance of this technology describing the open issues to be addressed during the future 5G standardization process [7]. To address these points, continuously growing efforts were made, mainly over the last two years: radio resource optimization of physical channels such as NPRACH [8, 9], energy efficient uplink scheduling schemes [4, 10], among others.

In this work, we focus on one of the key challenges in NB-IOT and 5G environment: to extend the coverage to a massive amount of user equipment (UE) deployed in extreme scenarios. Most of the related literature is focused on analyzing coverage performance and comparing it with other LPWAN technologies. Only some authors propose improvements to the coverage-related issues. Chafii et al. [11] use a dynamic spectrum based on machine learning techniques for coverage enhancement and energy consumption reduction. In particular, the random selection procedure was replaced by a more efficient selection method that chooses the channels with the highest probability to be available, with the best coverage and with the lowest number of repetitions. Kocak et al. [12] show how UEs with limited battery life, under extended coverage, can reduce power consumption through payload transmissions savings. Particularly, by means of narrowband resource allocations, the use of preamble acknowledgments, and low power targets. Concomitantly, Yu et al. [5] propose an iterative uplink channel adaptation scheme obtaining significant savings in radio resource consumption. In line with these growing efforts, we propose a novel strategy focused on channel link adaptation enhancement, extending the work proposed by Yu et al. [5] to extreme coverage scenarios.

For each block transmitted from a UE, the BS adapts

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the communication link in terms of modulation and coding scheme (MCS), as well as the number of repetitions (NR), with an associated cost in radio resources. The link adaptation finishes when reaching a target block error rate ($BLER_t$) or range of BLER values which defines a target QoS. Here we present a strategy for increasing the number of connections in NB-IOT channels subject to this link adaptation process, namely the physical uplink shared channel (NPUSCH) and physical downlink shared channel (NPDSCH). In order to achieve this goal, the number of the link adaptation iterations is reduced to a minimum, replacing this process by the use of precalculated values, i.e. a lookup table (LUT). An open source NPUSCH uplink simulator was developed to assess the performance of this strategy compared with alternative techniques.

In summary, we present:

- A strategy for increasing connection massiveness in NB-IOT shared channels, based on decreasing resource consumption.
- A LUT-scheme for minimizing link adaptation iterations.
- An analysis of this strategy under extreme coverage scenarios, comparing it against alternative strategies.
- An NPUSCH uplink simulator used to test the proposed strategy.

This article is organized as follows: in sections II and III an introduction of NB-IoT uplink as well as link adaptation is presented. In section IV, we present our LUT-based strategy jointly with other alternative strategies. Section V reports a brief description of the developed simulation tool and details about the performed experiments. Then, in section VI results are presented and discussed. Finally, conclusions are drawn in section VII.

II. NB-IOT UPLINK

In this section, we introduce the main concepts related to the NB-IOT uplink. NB-IOT supports three deployment modes: independent deployment mode, guard-band deployment mode, and in-band deployment mode; which utilizes a physical resource block (PRB) of LTE carrier wave [6].

The physical random access channel (NPRACH) and the physical uplink shared channel (NPUSCH) are the two specialized uplink channels used to exchange information between an UE and a BS. These channels are multiplexed in time or frequency over the assigned bandwidth. On the other hand, the downlink channels are the physical broadcast channel (NPBCH), the physical downlink control channel (NPDCCH), and the physical downlink shared channel (NPDSCH) [2].

The uplink transmission bandwidth is 180 kHz (regardless of the deployment mode) and two sub-carrier spacings are supported, 3.75 kHz and 15 kHz. In 3.75 kHz, single sub-carrier is adopted. In 15 kHz, single or multiple sub-carrier transmission can be adopted [6]. For both single sub-carrier and multiple sub-carrier, the uplink uses single carrier frequency division multiple accesses (SC-FDMA). For 15 kHz sub-carrier spacing, the NB-IoT uplink frame structure (frame size and time slot length) is the same as the LTE network (0.5 ms slot, and 1 ms subframe). In 3.75 kHz sub-carrier spacing there is a newly defined time slot of 2 ms. One radio frame contains five narrowband time slots and each narrowband time slot contains seven symbols [5, 6]. Both, single sub-carrier and multi sub-carrier should be supported by the UEs, nevertheless, some devices may not support multi sub-carrier mode in the first implementation phase of NB-IOT systems. On the other hand, single sub-carrier mode should always be supported [5].

III. NB-IOT LINK ADAPTATION

In this section, we shortly describe the uplink data transfer process and highlight the elements that will be optimized in the following sections. NB-IOT uplink communication starts with a request from a UE to the BS using the NPRACH. Once the BS receives the request for transmission, it returns a scheduling grant to the device including the time and frequency resources allocated. Subsequently, the UE transmits a sequence of transfer blocks (TBs) to the BS. Algorithm 1 depicts this process from the BS point of view. At the beginning of the uplink communication, the size of the buffer which contains the data that will be transmitted is informed to the BS. While this buffer is not empty (line 1), the BS determines the next tuple (MCS, NR) based on the previous one and the BLER_t (line 2). This is sent to the UE (lines 3 and 4) in the downlink control information (DCI) in conjunction with other control data (like the NACK of the last TB). When the BS receives the new TB with a piece of the data buffer, transmitted through the NPUSCH (line 6), it checks if the block has arrived without errors (line 7). The simulator developed for this work implements this link adaptation process. The function nextMCS&NR() encapsulates the implementation of our proposed LUT strategy, as well as the other evaluated strategies. Notice that the function nextMCS&NR() returns the tuple (MCS, NR).

while not bufferTransmitted() do
 mcs,nr = nextMCS&NR(mcs, nr, BLER_t)
 dci = createDCI(mcs, nr, harq-ack, ...)
 send(ue,dci, NPDCCH)
 // waiting response ...
 data = receiveFrom(ue,NPUSCH)
 harq-ack = check(data)
 end while

Algorithm 1: BS procedure for uplink adaptation.

Data that is sent to the BS from the UE is partitioned in a sequence of TBs. The size in bits of each block is called transfer block size (TBS). The UE transmits its blocks to the BS through the NPUSCH. The success of the block arrival to the BS strongly depends on the signal-to-noise ratio (SNR) of the channel. Extreme communication scenarios, with respect to LTE, are characterized by low SNR values (less than $-10 \,\mathrm{dB}$ [5]). The quality of the communication channel is

assessed by the block error rate (BLER) which is defined as the ratio of the number of erroneous blocks received to the total number of blocks sent. The BS can estimate the BLER based on the ACKs and NACKs in a given period (e.g. 300 ms [5]).

An erroneous block is a TB whose cyclic redundancy check (CRC) is wrong [13]. In general, high BLER implies many block losses, hence it has to be reduced until a tolerable

threshold is reached. If the SNR is very low, BLER will be high, unless corrective actions are applied. For this purpose, NB-IOT system makes use of two mechanisms: changes to MCS and NR.

The MCS is a number that determines the modulation, which can be QPSK or BPSK [14]. Furthermore, for a particular TBS, the MCS also defines the coding scheme. This scheme is represented as the pipeline: CRC, turbo-coding, and rate-matching [15, §6.3.2], which transforms the TB at each stage. In general, a low MCS implies a greater level of redundancy, and therefore, lower BLER.

NR is the number of transmission repetitions. High NR also helps to reduce BLER and enhance coverage. In the uplink process, NR has the following power-of-two sequence: [1,2,4,...,128]. Another important characteristic of this NB-IoT mechanism is that BLER's dependency on (MCS,NR) is associated with the TBS of each TB. Summarizing, the relation between the latter parameters responds to the function *BLER (TBS, SNR, MCS, NR)*.

The use of these two mechanisms has an intrinsic cost: the number of required RUs. In NB-IoT, one RU is the minimum schedulable unit in NPUSCH transmissions. For 15 kHz it consists of two slots (1 ms) for 12 sub-carriers, four slots (2 ms) for six sub-carriers, eight slots (4 ms) for three sub-carriers, 16 slots (8 ms) for a single sub-carrier; and for a single sub-carrier of 3.75 kHz, 16 slots (32 ms) [5]. Depending on the MCS assigned by the BS, each TB is coded, in turn, in a sequence of RUs. The relation between TBS, MCS, and RUs, disregarding repetitions, is established in Table I and can be formalized by the following function: RUs_{no-rep} (TBS, MCS).

RUs_{no-rep} $MCS \equiv I_{TBS}$	1	2	3	4	5	6	8	10
$0 \equiv 0$	16	32	56	88	120	152	208	256
$2 \equiv 1$	24	56	88	144	176	208	256	344
$1 \equiv 2$	32	72	144	176	208	256	328	424
3 = 3	40	104	176	208	256	328	440	568

TABLE I: Payload (TBS) for different combinations of coding scheme for NPUSCH, in single sub-carrier uplink [14].

In extreme coverage scenarios, where SNR is very low, achieving small values of BLER (modifying MCS and NR) has an important RU cost. To obtain the total number RUs, the number of repetitions has to be considered by multiplying it by RUS_{no-rep} (*TBS*, *MCS*).

IV. LINK ADAPTATION STRATEGIES

In this section, we analyze the resource usage and the impact of convergence for any link adaptation strategy. Then we introduce our proposed LUT-based strategy jointly with a set of alternative ones used for evaluation.

A. Resource usage in (MCS, NR) scheduling

The parameters MCS and NR contain information about the modulation and coding scheme, the number of used RU, and the number of repetitions. Their values affect the resource usage of the NPUSCH, which is characterized by RU consumption and is directly associated with the number of devices capable of transferring information to the BS. As uplink HARQ retransmissions are stopped when a maximum threshold is reached [16], this analysis considers two main scenarios: unacknowledged and acknowledged services, where retransmissions are disabled and enabled, respectively.

In an unacknowledged service, if a block is lost due to transmission problems (for example due to high noise in the channel), no attempt is made to detect the loss or to recover it. This class of service is appropriate when BLER is very low, so recovery is left to higher layers. It is also suitable for time-critical applications, such as real-time traffic, where having late data is worse than having bad data [17]. In this kind of service, decreasing RU cost can be achieved through the selection of an (MCS, NR) tuple which increases the incoming BLER and the block losses. Despite that it degrades connection quality (BLER is not the lowest), an RU consumption decrease is associated with a reduction in BS waiting time, which in turn, causes an improvement over NPUSCH resource usage. Therefore, this technique can help to provide service to a larger number of devices.

In an acknowledged service, each block sent by the UE is individually acknowledged by the BS. If the block has not arrived within a specified time interval, it can be sent again. This kind of service is useful for noisy channels, such as cellular systems. The downside of this strategy is that it can be inefficient, but on (inherently unreliable) wireless channels it is well worth the cost [17].

In the latter case, in order to estimate resource usage, RU cost needs to be calculated. If current BLER is equal to zero, the probability of TB successful arrival is 1, which means that no retransmission is required. Therefore the RU cost for this transmission is basically RUs. On the other hand, if BLER is greater than zero, the probability of the TB arrival is more complex due to retransmissions. In particular, we analyze the limiting case in which the maximum retransmission threshold (N) is as high as needed, i.e TB will be transmitted repeatedly until its arrival is successful arrival $(1 - BLER_i)$ increases due to HARQ mechanism. Information about the latest transmissions is used at the BS to decrease BLER, *ergo*: BLER_i > BLER_{i+1}. Therefore, in a constant SNR channel, the expected RU cost is:

$$\overline{\text{RUS}} = \text{RUS} \sum_{i=0}^{N-1} \left\{ (i+1) \left(\prod_{j=0}^{i-1} \text{BLER}_j \right) (1 - \text{BLER}_i) \right\}$$
(1)

Here, the technique consists in determining the tuple (MCS, NR) which approximates BLER to BLER_t, which in turn minimizes \overline{RU} cost. If this cost is decreased, resource usage will be decreased as well.

B. Convergence in (MCS, NR) scheduling

The strategies that will be presented are single sub-carrier scheduling schemes which dynamically determines MCS and NR for reducing BLER until BLER_t is reached. The first approach to this problem was proposed in Yu et al. [5],

wherein each rescheduling BLER is estimated and then a tuple (MCS, NR) is determined with the aim of approximating BLER_t (which they fix to 10%). Since BLER also depends on current SNR and TBS, there are many tuples (MCS, NR) that could achieve the target threshold: *candidates* = $\{(MCS, NR) \setminus BLER (TBS, SNR, MCS, NR) = BLER_t\}$. Only in the scenario in which the algorithm converges to BLER_t the number of block losses is the expected one. If the number of options (i.e. candidates size) is large, convergence time will be probably high increasing the number of blocks losses. Therefore, convergence time is an important parameter to be minimized.

Absolute convergence to $BLER_t$ is unlikely, because (MCS,NR) are discrete numbers, which are associated with discrete changes in BLER. The probable scenario is an oscillatory one, in which BLER cannot reach $BLER_t$ but oscillates around it. An important issue occurs when oscillations are big enough to set block losses far above or below the pretended tolerable value. In particular, the oscillatory scenario where block losses are high is worsened when retransmissions are enabled because all lost blocks need to be retransmitted.

C. Alternative Strategies

Before proposing our LUT-based strategy, in order to help to analyze its performance, a set of alternative strategies is presented. They use the previously detailed technique based on the convergence to $BLER_t$, although they do not try to minimize convergence time. Table I presents an extract of the available payload for some combinations of coding scheme and number of resource units used. As can be seen, the variation of MCS is not directly related with an increased level of redundancy. For this reason and following the standard practice in this area, the transport block size index I_{TBS} is used during the rest of the work.

• I_{TBS} -NR: in this first strategy (Alg. 2), each time rescheduling is executed, BLER is estimated. BLER surpassing BLER_t suggests that channel quality is poor and I_{TBS} is decreased. If I_{TBS} cannot be decreased any more, NR is increased. On the other hand, if the estimated value falls bellow BLER_t, it means that too many RUs are being used and opposite corrective actions need to be taken.

Analogously, we can define other strategies to be used as a base of comparison:

- NR- I_{TBS} : this is the inverse case of I_{TBS} -NR approach; i.e., when estimated BLER is poor, NR is increased. When the NR limit is achieved, I_{TBS} is modified.
- I_{TBS} : only I_{TBS} is used. NR is set to a fixed value.
- NR: similar to the strategy above, here only NR is used. I_{TBS} is fixed to the average value $(I_{TBS}^{max} / 2)$.
- I_{TBS} &NR: in this approach both, I_{TBS} and NR, are changed at the same time; e.g., when measured BLER is high, I_{TBS} is decreased in one point, and NR is duplicated.

D. LUT-based strategy (LUTS)

In the traditional approach, for each block transferred from the UE, the BS determines a tuple (I_{TBS}, NR) . This process

```
Require: TBS, BLER<sub>t</sub>
Ensure: (I_{TBS}, NR) \in candidates, when iterations \rightarrow \infty
     repeat
 1:
          Estimate BLER
 2:
 3:
         if BLER > BLER_t then
 4:
             \begin{array}{l} \text{if } I_{TBS} > I_{TBS}^{min} \text{ then} \\ I_{TBS} \leftarrow I_{TBS} - 1 \end{array}
 5:
              else if \tilde{N}R < \tilde{N}\tilde{R}^{max} then
 6:
 7:
                 NR \gets NR * 2
 8:
             else if then
 9:
                 Bad channel quality.
10^{\circ}
                 Target BLER can't be achieved.
11:
             end if
12:
         else if BLER < BLER_t then
            if I_{TBS} < I_{TBS}^{max} then

I_{TBS} \leftarrow I_{TBS} + 1

else if NR > NR^{min} then
13:
14:
15:
                  NR \leftarrow NR/2
16:
17:
             else if then
                 Good channel quality.
18:
                 RU consumption can't be decreased.
19:
20:
             end if
21:
         else if then
22:
             BLER is in range.
23:
         end if
```

24: **until** $BLER = BLER_t$ {re-scheduling is not needed}

is iterative and converges when a target BLER is achieved. During those iterations many transfer blocks could be lost, requiring retransmissions which, in turn, increase the resource usage. In order to reduce this RU consumption, we propose replacing the described iterative process by memory use, i.e. a lookup table (LUT). Our LUT-based strategy (LUTS), needs three input parameters: the TBS, the SNR, and the $BLER_t$. The first parameter, the TBS, is known by the BS and UE, the BS impose this magnitude at the beginning of each transmission. The second parameter is the SNR, unlike the former strategies which use a BLER estimation. An SNR estimation is taken after the equalization and compensation stages (a comparison of SNR estimation techniques is shown in Pauluzzi et al. [18]). The estimated magnitude can absorb some level of uncertainty. We exemplify this in Fig. 1, for a TBS of 256 bit, we show how the SNR varies with respect to the consumed RUs. As can be seen, the effective SNR estimation can absorb uncertainties up to 0.5 dB or even 1 dB in some ranges without modifying RU consumption.



Fig. 1: RUs vs SNR for different optimal tuples (I_{TBS} , NR).

The last parameter is the $BLER_t$, thus the target (or tol-

erable) block error rate. For any given pair TBS and SNR, there are just a few possible $BLER_t$ values available. In the following LUT extract (see Table II), it can be seen that BLER jumps from near 0 to 0.7, and then reaches almost 1. Each available $BLER_t$ or BLER range represents a QoS.

TBS \bits	SNR $\ \ B$	BLER _t	QoS	I_{TBS}	NR	RUs
256	-24	0.00006	good	0	128	1280
256	-24	0.00491	good	1	128	1024
256	-24	0.70477	poor	2	128	768
256	-24	0.98001	bad	0	64	640
256	-24	1	bad	0	1	10

TABLE II: LUT extract sample. Some of the BLER values can be collapse into a single QoS.

Based on this information, LUTS can use the lookup table to retrieve the I_{TBS} and NR. If the row containing the TBS, estimated SNR, and BLER_t exists then its associated tuple: $(I_{TBS}^{opt}, NR^{opt})$ is the optimal row, providing the minimum RU consumption under these conditions. Nevertheless, in some cases, the row could not be found and an approximation policy has to be implemented. This policy consists of retrieving the row with BLER and SNR values less or equal to BLER_t and the estimated SNR, respectively, with the addition of minimum RU cost. LUTS is reduced to the following straightforward pseudo-code presented in Alg. 3.

Require: $TBS, BLER_t, LUT$ 1: Estimate SNR2: $SNR^{new}, BLER_t^{new} \leftarrow$ $LUT.getClosestMinRU(TBS, SNR, BLER_t)$ 3: $I_{TBS}, NR \leftarrow$ $LUT.getTuple(TBS, SNR^{new}, BLER_t^{new})$

Algorithm 3: The LUT-based strategy selects the optimal codification and number of repetitions based on the estimated SNR and the selected $BLER_t$ or QoS.

E. LUT initialization

A LUT initialization method is proposed. An exploratory algorithm (Alg. 4) begins with the LUT uninitialized. Every time a UE is connected, the algorithm estimates the SNR. A tuple (I_{TBS}, NR) is obtained using one of the strategies presented in the previous section (e.g. I_{TBS} -NR), which guarantees a BLER closer to BLER_t. If the row with key (TBS, SNR, BLER_t) does not exist, it is added to the LUT. If it exists, RU consumption is compared between new and old (I_{TBS}, NR) . The LUT is updated with the tuple with minimum resources (which is also the tuple that is used for the transmission). Ideally, this process is repeated until each row converges to minimum RUs, i.e., LUT is completed. The BS needs a large number of connections from different type to populate the LUT. Furthermore, as it was mentioned in the previous section, few QoS are presented in the LUT, therefore a limited number of BLER ranges are reasonable to be used (e.g. 'good'). On the other hand, a more pragmatic approach could use physical layer simulations, like the ones used in our simulator, to create a pre-calculated LUT. In this case, the BS can use this table and update it during the interaction with the devices. Moreover, concerning LUT size, it ranges from some kilobytes (e.g. 200 KB) to some megabytes (e.g. 3.4 MB), depending on the implementation. Finally, even though the initialization is time-consuming, it is also a one-time process.

Rec	quire: $TBS, BLER_t$
Ens	Sure: LUT is complete, when iterations $\rightarrow \infty$
1:	repeat
2:	Estimate SNR
3:	$I_{TBS}^{new}, NR^{new} \leftarrow ITBS-NR(BLER_t)$
4:	if $LUT.rowExists(TBS, SNR, BLER_t)$ then
5:	I_{TBS}^{old}, NR^{old}
6:	\leftarrow LUT.getTuple(TBS, BLER _t , SNR)
7:	if $RUs(I_{TBS}^{new}, NR^{new}) < RUs(ITBS^{old}, NR^{old})$ then
8:	LUT. $setRow(TBS, SNR, BLER_t, I_{TBS}^{new}, NR^{new})$
9:	end if
10:	else
11:	$LUT.setRow(TBS, SNR, BLER_t, I_{TBS}^{new}, NR^{new})$
12:	end if
13:	until LUT is complete
	*

Algorithm 4: LUT initialization.

V. SIMULATION

In order to test the proposed strategies, we introduce an open source NPUSCH uplink simulator. It models the uplink iterative sub-process, where the BS determines the (I_{TBS}, NR) tuple and sends this information to the UE. The software is implemented in Python and LUT values are obtained from a simulation based on the NB-IoT Uplink Waveform Generation from the Matlab Toolkit. In this simulation, for each $(I_{TBS}, I_{RU}, I_{REP})$ 3-tuple, BLER curves were traced for a single sub-carrier mode NPUSCH over a simulated AWGN channel. The TX-RX chain is based on the standard specifications ([19, §10.1.3] & [15, §6.3.2]). Project source code can be found in [20]. Preliminary results generated using a previous version of this simulator were presented at [21].

All proposed scheduling algorithms in this work were implemented in our simulator. In all the experiments, it is assumed that the LUT initialization stage had been completed before performing the experiment.

LUTS algorithm is designed to reduce BLER convergence interval. The larger this interval is, compared to the number of TB that must be sent, the greater the gain in resource usage. In this context, the experiments consisted of 500 realizations of a UE transmitting to the BS blocks of 256 bit, i.e, the magnitude of a possible alarm message. Extreme coverage scenarios were characterized by SNRs of $-24 \,\mathrm{dB}$, $-20 \,\mathrm{dB}$ and $-16 \,\mathrm{dB}$. Analyzed BLER_t corresponds to a 'good' QoS (in section VI a discussion about this value is presented).

VI. RESULTS AND DISCUSSION

A. Unacknowledged Service

Based on the outcome provided by our uplink simulator, we obtain a table with the structure previously showed in Table II (which can be found in the simulator repository [20]). This information is used to calculate the relation between NPUSCH resource usage (measured in RUs) and the percentage of block losses (BLER*100). This relation is presented in Fig. 2, considering different extreme coverage scenarios, represented by low SNRs. This figure shows that the RU cost significantly diminishes between 0% and 5% of block losses, and then remains without strong variations. We found that a BLER_t of 0.05 is an adequate trade-off between losses and resource usage, thus a 'good' QoS. In particular, when calculating the average of the differences (#RU(BLER=0) - #RU(BLER=0.05)) between the SNRs, NPUSCH resource usage is reduced to 63%.



Fig. 2: NPUSCH resource usage *vs* percentage of block losses for different extreme coverage scenarios, in unacknowledged mode.

Savings mentioned above are only possible when the algorithm that selects the tuple (I_{TBS}, NR) converges instantaneously. In a more realistic scenario, this convergence takes some iterations as can be seen next.

Fig. 3 presents the evolution of two previously described algorithms: I_{TBS} -NR and LUTS. The top x-axis shows the number of transferred blocks, the bottom x-axis shows the NPUSCH resource usage measured in terms of the accumulated RUs. These axes also have a correspondence with time, which is not depicted in the figures because it would imply the addition of downlink channels information, not being addressed in this work. In both figures, each circle tags the time of a new transmission from the UE to the BS. Each figure is composed of four gray subfigures. The first two subfigures show how I_{TBS} and NR vary. The third subfigure shows how BLER, measured at the BS, varies at each new transmission. Finally, the fourth subfigure shows the number of successful transmissions at each moment. In the experiment shown in Fig. 3, 20 TBs with TBS of 256 bit are sent from the UE to the BS, under a constant extreme coverage condition of $-24 \,\mathrm{dB}$ SNR. It can be observed that while I_{TBS} -NR took five transmissions to converge to the optimal tuple $(I_{TBS} = 0, NR = 128)$, LUTS took only one iteration due to the use of pre-calculated values. Furthermore, in this particular experiment, when approximately 3500 RUs were used, LUTS achieved three successful transmissions, while I_{TBS} -NR none. These savings are better analyzed next.

In Fig. 4 the previous experiment is extended with all the algorithms presented in sub-section IV-C, and with the different extreme coverage SNR values presented in section V. Three parameters were analyzed: block losses, resource usage, and performance. Subfigure 4(a) shows that LUTS is the algorithm that minimizes block losses in all cases. It only loses less than 10% of the blocks, while the other algorithms lose 35% or more. Subfigure 4(b) shows the resource usage

of NPUSCH, LUTS is one of the algorithms that consume more RUS. Consequently, a performance parameter is needed to compare the algorithms considering their impact on block losses and resource usage simultaneously. To address this, we introduce P which represents the performance:

$$P = \text{Efficiency} \cdot (1 - \text{BLER}) = \frac{(1 - \text{BLER})^2}{\#\text{RU}} \quad (2)$$

The efficiency is defined by the quotient between the proportion of successful block arrivals by the transmission cost (#RUs). The efficiency could present high values even if only a small number of blocks can be successfully transmitted. To consider the number of transmissions and successfully received blocks simultaneously, the efficiency should be multiplied by (1-BLER), obtaining the performance (P). Figure 4(c) introduces P obtained with all the algorithms. LUTS presents the highest performance in all coverage scenarios.

B. Acknowledged Service

Fig. 5 is analogous to Fig. 2, with the addition of retransmissions. In this case, Eq. 1 is necessary to calculate NPUSCH resource usage. For all the analyzed block losses percentages, the number of retransmissions remained near three. As before, 5% of block losses provides a reasonable trade-off between RU usage and block losses, which represents a 'good' QoS. This time NPUSCH resource usage was reduced to 56.7%, calculated as the average of the differences (#RU(BLER=0.05)) between the SNRs. Analogously to Fig. 2, this result is only valid when tuple (I_{TBS} , NR) convergence is instantaneous. The algorithms analyzed in the figures below propose more realistic scenarios, where convergence time is not null.

Fig. 6 presents the evolution of the algorithms I_{TBS} -NR and LUTS when retransmissions are available. This figure is similar to Fig. 3. Here, I_{TBS} -NR needs 15 transmissions to converge to optimal (I_{TBS} , NR) tuple while LUTS needs only one. Additionally, in the third subfigure of I_{TBS} -NR, during convergence stage, BLER oscillations emerged. This behavior was described in section IV-B. Furthermore, in the fourth subfigure, when near 8000 RUs were consumed LUTS successfully transmit seven blocks, while I_{TBS} -NR only four. LUTS transmission efficiency is broadly depicted in Fig. 7.

Finally, Fig. 7 shows NPUSCH resource usage in different extreme coverage SNR scenarios and for the different algorithms, over an acknowledged service. In this experiments all blocks were transmitted as many times as necessary, i.e., all blocks successfully arrived so it was not necessary to analyze performance (Eq. 2). While in an unacknowledged service (Fig. 4) LUTS resource usage was one of the highest (but with maximum performance); here, LUTS is the algorithm which minimizes this value in all scenarios. In particular, in the worst case analyzed (-24 dB), when an average between consumption differences (e.g. #RU(ITBS) - #RU(LUTS)) is calculated, LUTS reduces this resource usage consumption by around 28%.



Fig. 3: I_{TBS} -NR and LUTS algorithms evolution in extreme coverage condition of -24 dB SNR. The x-axes show the number of transferred blocks (top) and the accumulated RUs (bottom). Both axes have a correspondence with time. The y-axes show main algorithm parameters: I_{TBS} , NR, BLER and the No. of successful arrivals.



Fig. 4: UE sends 500 blocks of 256 bit each to the BS using 'good' QoS under different SNRs.



Fig. 5: NPUSCH resource usage *vs* percentage of block losses for different extreme coverage scenarios in acknowledged mode.

VII. CONCLUSION

We have proposed a strategy with the aim of improve massive connectivity in NB-IoT under extreme coverage scenarios. Our technique is based on reducing radio resource usage of shared channels through link adaptation optimization. Particularly, we use a lookup table to accelerate the convergence of the main link parameters: modulation and coding scheme, as well as the number of repetitions. For this purpose, a case-specific open source simulator was developed. An extensive analysis was performed over the NPUSCH using SNR of $-24 \,\mathrm{dB}$, $-20 \,\mathrm{dB}$ and $-16 \,\mathrm{dB}$. Results show that

few target BLER ranges, thus QoS, are actually available at the LUT. SNR estimation uncertainties are absorbed up to 1 dB without modifying consumption. Simulations of six scheduling strategies, composed by 500 realizations of the transmission of 256 bit blocks (which could be generated by an activated alarm) over mentioned extreme coverage SNRs were performed in acknowledged and unacknowledged modes. In the first mode, our strategy minimizes resource usage in all scenarios, reducing RU consumption an average of 28% under the most extreme SNR. In the second mode, the LUT-based strategy duplicate performance, calculated based on losses and consumption, with respect to the other alternatives on every SNR. In closing, we expect our proposed strategy could be relevant for future BS software design and will contribute to the extension of massive terminal access in scenarios of extreme coverage.

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Fig. 6: I_{TBS} -NR (a) and LUTS (b) evolution in acknowledged mode. The x-axes show the number of transferred blocks (top) and the accumulated RUs (bottom). Both axes have a correspondence with time. The y-axes show main algorithm parameters: I_{TBS} , NR, BLER and the No. of successful arrivals.



Fig. 7: NPUSCH resource usage (average and standard deviation) in acknowledged mode, for different SNRs and QoS: 'good'. UE sends 500 blocks of 256 bit each to the BS.

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