A literature survey on NB-IoT scheduling techniques, challenges and potential solutions

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***Abstract*—The phenomenon IoT bestows the assurance to revolutionized the way we think, we see and we do. By ensuring seamless connected uninterrupted mobility, unique business patterns, constant communication between ample amount of heterogeneous devices, IoT has the potential to restructure the paradigm of civilization. Therefore, multiple standarization efforts were conducted to define the proper IoT cellular interface and the resource allocation for this technology. It was in 4G where there were important improvements to enhance the operation of MTC networks with LTE-M Category M1/M2 and the introduction of NB-IoT, making LTE flexible to support different constraints like higher data rates, low complexity of the devices and security. Moreover, the imminent arrival of 5G will massify the uses cases for IoT, with the Vehicular-to-Anything (V2X) connectivity, critical IoT and massive Machine Type Communications (mMTC). In this sense, we conduct a literature review on the various resource allocation mechanisms in NB-IoT that will support the aforementioned use cases and be the enablers for IoT applications, given that in NB-IoT the spectrum assigned to operate is less than typical wireless systems, in this context an effective resource allocation procedure needs to be put in place, i.e. scheduling. To this end, we review a variety of approaches intended to solve this problem by analyzing possible candidates to achieve an optimal resource allocation in NB-IoT scenarios. The aim of this work is to explore the various scheduling techniques proposed in NB-IoT scenarios for both uplink and downlink channel along with existing challenges and potential way out. Furthermore, we focused on the survey regarding the scheduling issues related to resource allocation process for the UEs. We analyze the downlink scheduling techniques in the Narrowband Physical Downlink Control Channel (NPDCCH) and the Narrowband Physical Downlink Shared Channel (NPDSCH), covering the Medium Access Control (MAC) and physical layer. In addition, we look into proposed novel uplink scheduling schemes such as link adaptation and single-tone scheduling approaches.**

***Index Terms*—NB-IoT, scheduling, resource allocation, Up-link scheduling, Down-link scheduling**

I. Introduction

The realm of IoT spans a large number of devices which maintains its constant presence in our surroundings and in our pockets in the form of different sensors, like radio frequency identification tags (RFID), sensors, actuators, mobile phones etc. [1]. The specifications regrading NB-IOT was first released in 3GPP Release 13. According to this specification NB-IoT devices can send parallelly in small amounts. NB-IoT is considered to be the most suitable and feasible mobile network solution for cheap and low cost IoT devices and applications which demand low battery consumption and deep penetration of the network service/coverage thus making it suitable solution for Low Power WANs (LPWAN). Narrowband-IoT is also delay tolerant up to 10 seconds which is ideal for devices located in area where coverage and/or signal transmission quality is overall poor. Owing to the continuous development in this area, a significant maturity has been observed in the IoT communication infrastructure over the years [18]. Narrowband IoT as a LPWAN technology operates at 180KHz and 15kHz subcarrier spacing and in uplink typically with a 3.75 kHz or 15 kHz single-tone transmission. This technology is specifically designed to be integrated into Global System for Mobile communication (GSM) and/or Long-Term Evolution (LTE) directly without inferring any extra deployment cost to the operator. During a 2016 meeting for the Third Generation Partnership Project (3GPP) in 2016, in which several major key technology contributors like Ericsson, Nokia, Huawei, ZTE took part and provided valuable time and effort for the standardization of NB-IoT [19], the Narrowband IoT was regarded as the most important technology in terms of 5G IoT evolution.

The research objective or goal in various areas for NB-IoT technology is focused on trying to make the technology to adopt in harsh radio network conditions such as limited coverage, higher delays and noise, limited bandwidth etc. [20]. This is due to fact that most IoT devices work in operational areas where radio network conditions are less than ideal, such as monitoring sensors on an oil pipeline going through rural areas, environmental sensors in industrial areas outside the suburbs etc. Narrowband IoT is Coverage enhancement techniques such as power boosting in downlink or subframe repetition in uplink and downlink, are used by Narrowband-IoT. NB-IoT presents a lot of advantages, but still there are some areas that require time and effort from researchers in this field. For example, the congestion issues due to incoming data form numerous devices, efficient radio resource allocation to each device that will not only help conserve limited radio resource but also device power.

One of the major research areas in Narrowband IoT is scheduling algorithm or techniques. A schedular can be defined as an algorithm or technique which assigns appropriate shared resources among number of requesting terminals. The efficiency and performance of these scheduling algorithm is of utmost importance due to the limited availability of radio resources, as it impacts the overall service delivery, independent of the size and capacity of core network infrastructure. In this paper, we compare and contrast the different solution that have been put forward to resolve the scheduling issues in Narrowband IoT uplink and downlink.

The contributions of this study, are as follows:

- A brief survey of Narrowband-IoT uplink and downlink scheduling, key technologies, applications, and several open issues.
- Comparison, pros and cons of different solutions of uplink and downlink scheduling techniques.

The rest of the article is organized as follows: Section II reviews different literature and solutions for uplink, Section III explores the downlink NB-IoT scheduling techniques, Section IV provides an overview on the comparison performance in both uplink and downlink scheduling, finally, Section V summarizes the conclusions obtained from the present work.

II. Related work

Narrowband IoT is regarded as the most feasible solution for deployment of industrial internet or "industrial revolution 4.0" as it is named nowadays in which thousand if not millions of devices will be able to generate and transmit data to the network for further processing. It provides cost effective and power friendly solution for the easy deployment of these devices into any generation of mobile communication infrastructure preferably LTE, 5G and beyond 5G networks. Before in-depth discussion the different techniques and solutions of Narrowband IoT scheduling issues in uplink and downlink, and addressing their benefits and shortcomings, a short summary of the related works researched in this field is presented here.

A. Uplink scheduling

Uplink scheduling techniques usually include the scheduling of NPRACH (Narrowband Physical Random-Access Channel) and NPUSCH (Narrowband Physical Uplink Shared Channel) channels. In a study by Xingqin et al. [5] a single tone frequency hopping technique has been proposed for Narrowband IoT PRACH channel. The hopping pattern is comprised of both outer layer pseudo-random hopping and inner layer fixed size hopping. The outer layer pseudo-random hopping is applied among symbol groups of 4. Among 1st and 2nd and 3rd and 4th, a single-subcarrier hopping is utilized, while amongst second and third, six-subcarrier hopping is utilized.

In another study [4] HARQ technique was proposed by authors. HARQ stands for Hybrid Automatic Repeat Request and sometimes also referred to as Hybrid ARQ. HARQ in NB-IoT is fundamentally similar to HARQ in the legacy LTE transmission. Narrowband IoT allows HARQ process only once, in both uplink and downlink, which allows the UE to decode NPDCCH and NPDSCH easily with a little extra time provided by HARQ. Adoptive HARQ technique can be adopted to increase the flexibility of scheduling.

The research conducted by Changsheng Yu et al. [1] and other authors developed a simple single-tone uplink scheduling technology. In this study they proposed that 11 tones can used to schedule data transmission over format 1 NPUSCH while another single tone can be used for Acknowledgment and Non-Acknowledgment for downlink transmission with NPUSCH (format 2). Different User equipment (UE) can choose different tones and resource unit from frequency and time dimension respectively [1].

In the study carried out by Bing-Zhi et al. [8] proposed a novel design Uplink Scheduler for NB-IoT. The system model in study placed the schedular at the MAC layer of the design. This scheduler design consisted of four different procedures, MIB/SIB1 scheduling, SIBs scheduling, common scheduling, and UE-specific scheduling [8]. The MIB-NB and SIB1-NB are scheduled by MIB/SIB1 procedure. Common scheduling handles the paging message handling and random-access scheduling, while the UE uplink and downlink transmission scheduling is handled by UE-specific scheduling procedure. In UE-specific scheduling, after sorting the packet order, retransmitted UEs are served first while other UEs are scheduled in the order of packets arrival time. NPUSCH and PUSCH resources are allocated to each UE and the process is repeated until the resource is available.

B. Downlink scheduling

In Narrowband IoT, the DCI in NPDCCH (Narrowband Physical Downlink Control Channel) contains the downlink scheduling assignments and information about the modulation used in NPDSCH (Narrowband Physical Downlink Shared Channel) [10]. When any User equipment receives NPDCCH, it searches for DCI which contains scheduling information. This information is packed between the NPDCCH and NPDCH or NPUSCH. To avoid overlapping between different UEs, the offset index given to each UE varies and are selected from offset pool. However, this scheduling decision has to in compliance with more limited specifications of NB-IoT. Two solutions put forward by this study is, to adopt the critical scheduling process to accommodate more devices with offset index selection with varying size of payloads and limited offset values. Second is to common space search configurations which are UE specific.

The concept design proposed by Ya-Ju and Sheng provides an algorithm which maximizes the downlink scheduling efficiency by using NPDSCH subframes as many as it is possible [9]. The algorithm determines the first available NPDCSH, and all the delay values of scheduling, then unserved device will be allocated NPDCSH frames continuously. The subframes after the last subframes will be allocated to the device who requires more NPDSCH subframes.

III. Uplink scheduling

It is expected that NB-IoT networks enjoy an extended coverage from the base station by employing two techniques: control signals and the repetition of the transmitted data. This way, repeating the transmitted data also has to take into consideration the link adaptation approach in NB-IoT networks, which will work adjusting two dimensions of the wireless link, the modulation and the coding scheme (MCS), for this reason the link adaptation methods need to consider the repetition number, i.e. it is not practical to disregard this parameter when it comes to the transmission of data and resource allocation techniques in NB-IoT systems. In this section we will extensively review in detail a proposed scheduling link adaptation scheme for the uplink direction of the NB-IoT communication channel [1] where the number of transmitted data repeated is calculated by combining the inner loop link adaptation and the outer loop link adaptation in order to enhance the NB-IoT networks throughput and also to secure the reliability levels on the wireless transmission link. Furthermore, we will explore how the link adaptation employs the inner loop technique to face the variation of the block error ratio adjusting periodically the repetition number, i.e. the repetition number is no longer a fixed value but a dynamic parameter that is adjusted in the transmission link. In particular, the outer loop link adaptation determines the parameters of the modulation and coding schemes selecting the combination that suits the best with the channel conditions, and in this way also determines the repetition number for the NB-IoT transmission. In addition, in this section a simple single-tone scheduling proposed scheme is analyzed, along with the review of important technologies in NB-IoT uplink scheduling which are power control and transmission gap. Finally, we will briefly explore an uplink NB-IoT scheduler based on the OpenAirInterface NB-IoT project [8] aimed to cope mainly with the timing management and subcarrier allocation in NPUSCH of the UL scheduler.

A. Uplink scheduling and link adaptation

In the uplink channel for NB-IoT there are mainly two channels specified for the establishment of the communications, the Narrowband Physical Uplink Shared Channel (NPUSCH), used to transmit the payload from the user equipment (UE) to the eNB; and the Narrowband Physical Random Access Channel (NPRACH), used to trigger the initiation of the random access (RA) procedure. When an UL wireless transmission is established, the eNB is in charge of assigning a certain number of resources to the NB-IoT devices, in this case the minimum number of resources is known as Resource Unit (RU), where the different combinations of possible RU configurations depends on the UE specifications and therefore, different resource configurations impacts on the latency of the NB-IoT device communications.

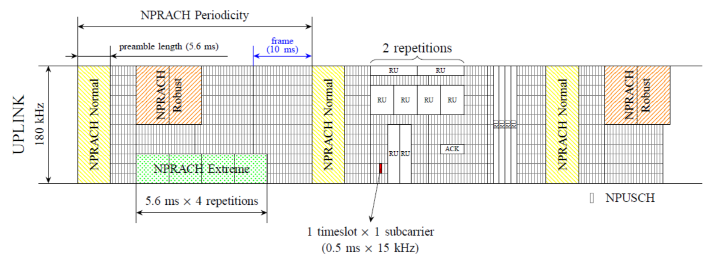

Fig. 1. NB-IoT UL frame [3]

As we observe in the figure 1, the scheduling technologies for uplink communications in NB-IoT systems mainly comprises the scheduling for the NPUSCH and the NPRACH channels. There are available studies regarding the uplink scheduling techniques for these two channels like timing and HARQ [4] and [5], for this reason we will explore how the uplink transmission gap and power control will operate in NB-IoT networks by reviewing a proposed simple single-tone scheduling scheme where eleven tones can be allocated for transmission of the data using the format-1 of the NPUSCH frame and an additional single tone allocated as an ACK/NACK feedback. Furthermore, the NB-IoT devices utilize a different tone in frequency domain and allocate another RU for the time domain, this is done in order to obtain a better uplink throughput performance and also to prevent the wireless channel to suffer of radio link failure. For these reasons is that the uplink power control and transmission gap need to be taken into account.

1) Power control: In the specification of the standard for the physical layer of the E-UTRA [6], it is defined for the NB-IoT communication to support the open loop power control only in the uplink direction, in order to comply with the low complexity requirements for this technology. In NB-IoT systems, the open loop is referred to the capacity of the IoT device to determine the transmission power of the uplink channel based on the convenient selection of parameters in the MCS and RU, for this reason the eNB is not capable to command the power control procedure in the uplink transmission power of the NB-IoT device.

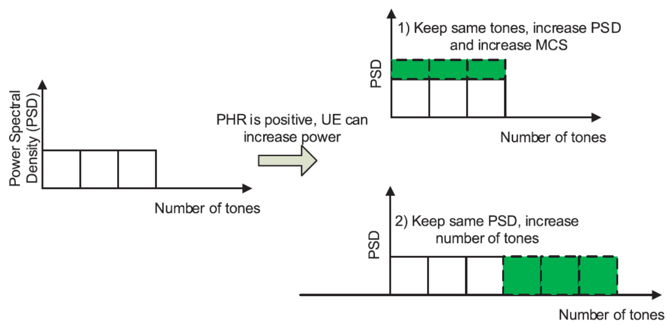

Fig. 2. Power control in NB-IoT uplink [1]

In this case the eNB must select the right frequencies or tones and the corresponding modulation and coding scheme based on the received Power Header Room (PHR) report, therefore, as shown in the figure 2, having a positive value of PHR allows the NB-IoT device to increase its transmission power for the next transmission cycle. Then, from the eNB point of view, it has two methods available for this selection, to increase the Power Spectral Density (PSD) along with the MCS, and to schedule a bigger number of tones to transmit.

2) Transmission gap: The transmission gap is referred to the extra time needed by the UE to complete an uplink transmission in NB-IoT systems, i.e. the total transmission time in the uplink direction is given by the transmission period and an extra gap in milliseconds. This gap may be caused by switch to the downlink channel performed by the UE to perform time/frequency synchronization of the wireless communication. In NB-IoT systems, the 3GPP standard [7] defines that the target delay in the application layer considering the flow from the UE to the S1 interface is of 10 seconds.

3) Applications and Open issues: Given the wide spectrum of use cases for NB-IoT for instance in Massive IoT, Broadband IoT, Critical IoT and Industrial Automation IoT, defining a single set of requirements and use cases for NB-IoT systems is not practical, instead, the group of vertical requirements for IoT applications is divided to specify the most important needs depending on the use case and the sector of the industry where it is applied, e.g. in industry, agriculture, smart grids, logistics, management and fleet tracking, smart homes/buildings/cities, wearables and connected vehicles. For this reason, it is clear that NB-IoT is a promising technology that will enable multiple applications in the IoT era, however, there are some open issues that we will briefly enumerate:

- *Standardization activity:* being NB-IoT a relatively emerging technology, there are still on-going efforts to fully complete the standardization process and reach a maturity level for the industry development and scientific community.

- *Heterogeneity:* there are a wide range of devices and different UEs capable to implement NB-IoT interfaces, making the development of a unique framework for this technology still a challenging endeavor.

- *Security and privacy:* In our current era we can observe an on-going development and deployment of IoT devices leading to an evolution on this technology, however, as the technology grows so do the attackers that intend to leverage any security weakness on the IoT devices that could grant them access to any of the IoT systems where these actuators operate controlling in many cases important functions in an industrial environment. In this sense, the IoT botnets are becoming bigger and more effective by launching powerful attacks that may damage the infrastructure or the internet.

- *Energy management:* In NB-IoT networks the power control and energy management is a key issue to be addressed, given the complicated conditions of the wireless channel and the reduced bandwidth available for this kind of systems, it is crucial to put in place an adequate and efficient energy management procedure for the future deployment of this technology in cellular networks.

4) Link Adaptation: In NB-IoT systems the wireless channel conditions is challenging given the narrow bandwidth reserved for the NB-IoT transmission and the remote locations where the IoT actuators may be deployed to support the applications. In this sense, the link adaptation mechanism is defined in NB-IoT systems to enhance the coverage reliability, improve the system throughput and achieve better peak rates. To this end, the LTE systems support the link adaptation based on the wireless channel conditions for dynamically set the transmission configuration on the link, i.e. adjust the MCS and the Physical Resource Block (PRB) of the radio channel. This is achieved in the eNB by either receiving periodic or non-periodic feedback updates from the UE regarding its channel quality and conditions, with this input the base station is able to select dynamically the proper transmission parameters that will guarantee that the BLER will not exceed the specification threshold of 10% and in consequence achieve the maximum throughput possible with the given channel conditions. Furthermore, a matching table with MCS combination and its corresponding modulation scheme is employed by the UE to determine which modulation and coding scheme should be selected and negotiated with the eNB, moreover, based on this information the transmitted data size and the code rate may also be properly computed by the UE.

5) Challenges in current state: The LTE link adaptation approach is no longer suitable for the NB-IoT systems because the LTE-based link adaptation does not consider the repetition into the process. For this reason, in NB-IoT it is key to establish a proper technique that be able to support the repetition feature in order to perform the uplink link adaptation for NB-IoT systems considering two important aspects: the MCS level selection and the repetition number determination. To this extent, the UE should perform an evaluation of all possible combinations of MCS index and number of repetitions to obtain the best combination for the current channel conditions in that particular moment in order to obtain the optimal combination of link parameters, this calculation is certainly possible to achieve but could result intense computational. Moreover, after the calculations there may be multiple combinations of parameters that meet the BLER transmission threshold resulting in a complex process for the UE, which is not a desired behavior given the low-complexity paradigm specified for NB-IoT. For this reason, we will review the solution proposed in [1] where an uplink link adaptation scheme is proposed for the NB-IoT that complies with the low-complexity approach specified for this technology.

Based on the aforementioned link adaptation paradigm where the MCS and repetition number must be taken into consideration for the link adaptation process, there will be two possible scenarios combining these two dimensions: one scenario with the MCS as a pre-dominant approach where the MCS is adjusted first based on the feedback signals reporting the channel status, in order to adjust the repetition number afterwards. The second scenario is the repetition number pre-dominant approach, where the focus is on calculate the repetition number first and then determine the proper MCS for the radio channel based on the link status feedback signals.

6) Review of the proposed link adaptation solution for NB-IoT: This proposed solution is designed to utilize two link adaptations loops: the inner loop link adaptation, which main focus is to keep the BLER values within the specification parameters (7%~13%) by periodically monitor the channel conditions, and the outer loop link adaptation, which main purpose is to cope with the best selection of the MCS level and repetition number determination.

Inner loop link adaptation

Given the difficult radio channel conditions that normally the NB-IoT systems need to face in their operation is that in NB-IoT networks the BLER changes constantly and sometimes in a drastic way. For this reason, the inner loop link adaptation is necessary to handle this transmission BLER variations, operating this way: the link adaptation algorithm computes the BLER values for all successful and unsuccessful transmissions (ACK/NACK) in a given period, then the number of repetitions is adjusted for that given period of time based on the BLER calculations. Then, if the BLER results to be less than 7%, the number of repetitions can be decreased for that particular transmission period, on the other hand, if the BLER results to be greater than 13% the repetition number must be increased because the channel conditions are not optimal.

Outer loop link adaptation

In the outer loop phase the UE performs two important operations in order to keep the wireless communication link reliable, with the optimal throughput set and below the threshold of 10% BLER: MCS level selection and repetition number determination.

- *MCS level selection:* In LTE networks the MCS level selection is performed based on the ACK/NACK decoded by the eNB, i.e. when there are multiple ACK decoded in the communication, the MCS level is gradually increased, on the other hand, if there are NACKs received, then the MCS level is decreased. Nevertheless, this approach may not be practical in the case of NB-IoT systems, given the narrow bandwidth assigned for the communication and the low data rates achieved. For this reason, the MCS level selection is event-driven conducted. In this case, the solution defines two actions triggered by the radio channel conditions: Fast Upgrade (FUG) and Emergency Downgrade (EDG). This actions make the MCS level to be updated accordingly, when a FUG action occurs, the MCS level is increased by one, on the other hand, the MCS level is decreased by one in the EDG case. In order to trigger an FUG or EDG, there is a compensation value that ranges in [C_{min},C_{max}] and defines the MCS event-triggered actions: perform an FUG or perform an EDG when the compensation value reaches C_{min} or C_{max} respectively. This way, in every uplink transmission, the compensation value is calculated based on the uplink transmission HARQ feedback and is governed by the following formula:

$$\Delta C(t) = \begin{cases} \min\{\Delta C(t-1) + C_{\text{stepup}}, \Delta C_{\max}\}, \\ \qquad\qquad \text{if HARQ feedback} = \text{ACK;} \\ \max\{\Delta C(t-1) - C_{\text{stepdown}}, \Delta C_{\min}\}, \\ \qquad\qquad \text{if HARQ feedback} = \text{NACK;} \\ \Delta C(t-1), \\ \qquad\qquad \text{if HARQ feedback} = \text{N/A.} \end{cases}$$

Where the N/A is the case where the eNB does not detect the NPUSCH signal and the values of the incremental/decremental steps depends on the BLER that we want to achieve in the system and is defined by the following expression:

$$C_{\text{stepdown}} = C_{\text{stepup}} \frac{1 - \text{BLER}_{\text{target}}}{\text{BLER}_{\text{target}}}.$$

- *Number of repetitions calculation:* As explained in previous sections, the specification for NB-IoT communications requires to keep the BLER under 10%, to this end, the repetition of the transmitted data in the uplink channel is the key feature to implement in order to comply with this reliability requirement. This parameter is strongly correlated with the radio channel conditions, i.e. with a bad channel conditions and an MCS index unable to comply with the target BLER, the number of repetitions must be increased, similarly when the radio channel conditions are good enough to keep the target BLER with the current MCS selection, the number of repetitions must be decreased. To illustrate this behavior, the figure X shows the tradeoff between the MCS level and the number of repetitions with the channel conditions as the UE moves away from the eNB (bad channel conditions) and when the UE moves closer to the eNB (better channel conditions):

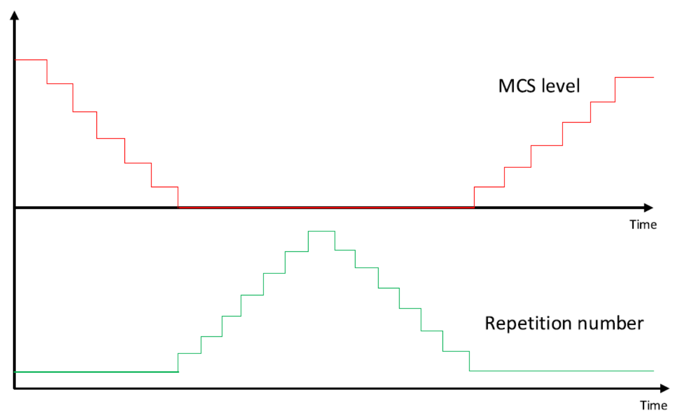

Fig. 3. Variation of the MCS level and repetition with distance [1]

B. NB-IoT uplink scheduler

In NB-IoT systems the eNB is in charge to determine the resource blocks allocation using the Downlink Control Information (DCI), in this sense the UL DCI is used to refer to the uplink direction, i.e. the NPUSCH channel. In this case, the uplink and downlink DCIs are both transported in the Narrowband Physical Downlink Control Channel (NPDCCH), where up to 8 DCIs can be carried. Furthermore, the eNB makes use of the UL DCI to announce the size of a resource block assigned in NPUSCH. In the case of the timing management, an UL DCI can only be delivered in a specific DL subframe, for this reason, the UL scheduler needs to keep track of the DL subframes and match them in a way that it provides information about its availability. A simple way to achieve this is to simply assign the value of '0' to an unavailable subframe and the value of '1' to a free subframe. Regarding the subcarrier allocation, in NB-IoT systems the uplink transmission contains 12 subcarriers (tones) in the frequency domain and 4 scheduling delay options in the time domain [8]. In this sense, the eNB needs to specify two parameters before start the data transmission: the subcarrier and the selected scheduling delay. In this scheduling technique, the delay and subcarriers are being allocated based on the UE needs, this way the eNB assigns each subcarrier one by one determining the minimum scheduling delay in each step of the process.

IV. Downlink scheduling

Comparison the other existing wireless communication types, NB-IoT facilitates lower spectrum allocation. With this context, the proper and efficient distribution of resources for allocation is one of the key points. In this section, first we go through he detailed study of the scheduling architecture for NB-IoT, we analyze the existing issues that results in resource waste ans explore the areas that has potential solution for this.

A. An overview of downlink features in NB-IoT

What makes NB-IoT so flexible to use is the reusing capabilities in exisitng networks like GSM or LTE, ultimately making it lucrative for deployment in 5G network [11]. A basic configuration for NB-IoT should look like the following that supports the features for traditional estimated IoT add-ons like improved power efficiency with lower channel bandwidth, cost-efficiency for deployment, available low cost User Equipment, delivery support for IP and non-IP data and a large number of connected devices considering 5G network. Such as:

Uplink Peak Rate	250 Kbps
Downlink Peak Rate	227 Kbps
Bandwidth	180 Khz
Uplink	SC-FDMA (15 Khz & 3.75 KHz)
Downlink	OFDMA (15 KHz)
Duplex model	Half duplex
MCL (Coverage)	164 dB (< 15Km)
Transmit power	23 dBm
Power saving	PSM, ext-IDRX, C-DRX

Fig. 4. NB-IoT Configuration [10]

1) Downlink design of the MAC and PHY Layer for NB-IoT: The donwlink format of NB-IoT MAC and PHY layer architecture resembles with LTE having 15 Khz subcarrier space. OFDMA is used as the modulation scheme and the frame structure can be visualized from the figure 5.

Spacing	15 kHz
Subcarriers	12
1 frame	10 subframe
1 subframe	14 OFDM symbols
FTT length	128 samples = 66.7 sec
Sampling rate	1.92 MHz (15 kHz * 128)

Fig. 5. Subcarrier spacing [10]

To elaborate, the OFDMA modulation scheme takes place with a 180 Khz bandwidth frame that consists of 10 subframes with Transmission Time Interval (TTI) of 1 ms. The timeslot length is 0.5 ms and in total the frame length is 10 ms which is such as LTE downlink architecture provides [12]. While supporting the operation for one of the two antenna ports, AP0 and AP1, NB-IoT has the same schema for transmission on Narrow-Band Physical Broadcast Channel (NPBCH), Narrowband Physical Downlink Control Channel (NPDCCH) and Narrowband Physical Downlink Shared Channel (NPDSCH) [13]. Ultimately, in the frequency domain, a single NB-IoT carrier utilizes 1 LTE PRB (Physical Resource Block), which indicates 12 subcarriers with 15 Khz os spacing accumulating a total of 180 Khz bandwidth.

2) Overview of NB-IoT Channels (Downlink): Similar to LTE, NB-IoT downlink channel structure mostly comprises of the channels discussed below:

i. Narrow-Band Physical Broadcast Channel (NPBCH): This channels is focused on carrying the initial data and parameter information during accessing the cell. All the relevant information is mostly occupied by the MIB (Master Information Block) and this is based on the QPSK (Quadrature Phase Shift Keying) modulation.

ii. Narrowband Physical Downlink Control Channel (NPDCCH): All the User Equipment that are transmitting data in NPDSCH have particular ID that is carried by NPDCCH. In addition to that, this channel also carries several control information data such as paging information, Uplink/Downlink assignment, response of RACH, ACK push info and others. The transmission od data in between User Equipment and the E-RAN (Mostly eNB) is controlled by this channel. The scheduling information and the other parameters are carried in the form of DCI (Downlink Control Information) message. The length of the time interval between two NPDCCH initiation is indicated by PDCCH period.

iii. Narrowband Physical Downlink Shared Channel (NPDSCH): This channel carrier the System Information Block (SIB) along with the Uplink and Downlink Data packets for the UE to acquire. It also carries the User Equipment unicast information and several control data.

3) Overview of NB-IoT Signal Types (Downlink): Mostly, two types of signal for NB-IoT has significance to discuss. Namely, the first one is the NRS that is the Narrow-Band Reference Signal that is transmitted throughout the time during a broadcast and in downlink subframes and the second one is the Synchronization signals which are there for the initial cell search. It is pretty crucial for the User Equipment to detect the ID of the Physical layer during the procedures for cell search and also to harmonisize with time and frequency by synchronization which takes place with two types of synchronization signals:

i. Narrow-Band Primary Synchronization Signal (NB-PSS): The ID of the Physical Cell is carried by this signal and is transmitted in each 10 ms using the last 11 OFDM symbols of subframe no- 5.

ii. Narrow-Band Secondary Synchronization Signal (NB-SSS): It carries the physical layer cell identity group radio frame synchronization. The signal is transmitted in subframe 9 using the last 11 OFDM symbols every 20 ms.

B. NB-IoT downlink scheduling process

The downlink scheduling process of NB-IoT is the procedure that takes place in the bottom MAC and top PHY layer for allocating resources (PRB) to Ues after a certain time period, that is the TTI (Transmission Time Interval). MAC scheduler has the control over deciding the usage of channels by the eNBs and the Ues of a cell. For the UEs to steer away clear from overlapping from resource allocation, an offset is determined. Here, during the scheduling procedure, NPDCCH channel is considered to be the core element as it carried the DCI information. Mostly three types of DCI format is used during the scheduling process and N0 is assigned for the uplink grant. Whereas, N1 is used for the transmission of assignment of PDSCH in all the cases of NPDSCH except for when it is carrying paging information. N2 is used for paging and direct indications [14].

When UE receives NPDCCH, it searches for the DCI according to the UE search spaces. For detecting if there is any information (NPDSCH) sent for the UE or to find out Uplink grant, UE should constantly keep monitoring different regions within downlink subframes. As the network does not identify or particulate which region for the UE to monitor, it has to go for all the available regions there is for NPDCCH which is called ‘blind decoding’. Although, UE does not attempt to decode all the possible combinations of RE within a subframe as there are already some specified and predefined regions for PDCCH for the UE to search and monitor which is called the NPDCCH search space as stated above. The delay on the scheduling between the transmission of NPDCCH and NPDSCH/NPUSCH is carried through the DCI for a UE. As stated earlier, the offset value here is crucial to avoid overlapping of resource allocation and it is represented by the value of K0. An offset pool is there for the values to be assigned for each UE. Assigning K0 is a nontrivial task, as the selection of offsets is very limited comparing to the number of UEs to schedule.

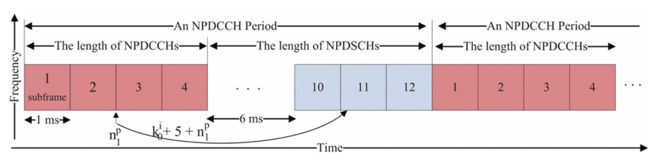

Fig. 6. NT-IoT frame structure and scheduling illustration [9].

C. NB-IoT downlink existing issues

We are adapting a scenario to explain the issue of resource allocation in NB-IoT downlink for better visualization. We

Offset index	K0 for DCI format N1	
	Rmax < 128	Rmax >= 128
0	0	0
1	4	16
2	8	32
3	12	64
4	16	128
5	32	256
6	64	512
7	128	1024

Fig. 7. k_0 for DCI format N1 [10]

Offset Index	K0 for DCI Index N0
0	8
1	16
2	32
3	64

Fig. 8. k_0 for DCI format N0 [10]

consider an IoT application for smart meter system where, 100 smart meters are inter-connected through Narroe-Band IoT network and the specified FFT size for sampling is 128 for the network where the allocation of resources will take place with these subfarmes staring from 0 to 127. The assignment of resources during the NPDCCH period is done by the DCI response dedicated for resource allocation. In the scenario, when a single smart meter is in indoor location, the UE usually transmits a minimal 16 bytes data which is equivalent to 128 bit [15] [16]. As per the specification of 3GPP release 13, the 128 bit data transmitted by the UE mostly occupies 6 subframes of the FFT length [14]. As NB-IoT is facilitated with low-complexity decoding, in order to enhance the decoding probability for each UE, same data is repeated over the time ensuring better coverage. In our case, if we consider 4 repetitions to take place for the UE that is located indoor with lower coverage condition, the subframe allocation will increase accordingly also extending up to a total of 24 (6*4) subframes (Fig. 9 referred). As per the table 1 for K0 value, if our offset is 5 supposedly, the K0 value would be 32, which indicates the smart meter to be scheduled in queue will be after 32 slots. For NB-IoT, it is fixed that per resource block, it has 12 subcarriers each with 15 Khz spacing which makes a total bandwidth of 180 Khz (12*15 Khz). As in our scenario, we have a large number of UE (100 smart meter), but with a fixed value of available subcarriers, we can not guarantee the resources even with successful random access procedures.

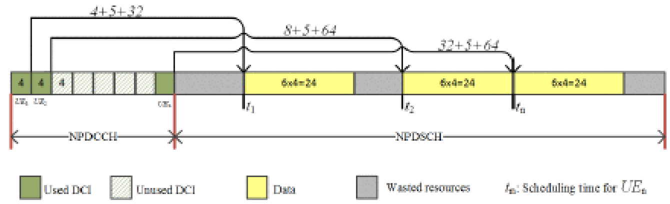

Fig. 9. k_0 assignment for UEs [10].

We consider the following equation to find out the wasted resources:

$$SF_{npdsch} = pp - SF_{npdcch} \tag{1}$$

Here, pp refers to the total number of available subframes. Whereas, SF_{npdsch} and SF_{npdcch} indicates the subframes occupied by each channel. Now, for NB-IoT as we know, NPDCCH channel occupies 32 subframes considering 8 DCIs (8 DCI * 4 subframe), the subframes available for NPDSCH channel would be 96 (128 – 32), which can assign and allocate resources for max. 4 UE (96/24) considering the repetitions mentioned before if there is no wastage of resources. But, we have already seen as for the K0 values, the network can only assign resources to max 3 UE (96/32) resulting in a 25% wastage of the resources.

The above mentioned scenario is mostly related to general LTE amd UMTC network architecture and in addition to this, the effectiveness of this procedure is still in question for mass level MTC connectivity and deployment [17].

D. Solution proposal for NB-IoT DL scheduling issues

In accordance to the scenario and the existing issues shared in the section V, our survey resulted in the following two types of updates and modifications aiming towards better resource distribution and allocation.

1) Modification in the selection of Offset Index: As the available K0 values is limited and we have numerous types of varying payloads, it is crucial adapting the whole scheduling procedure for high resource utilization to accommodate more UE at the same time.

2) UE-Specific and Common Search Space Configuration: The common search space configuration is responsible on deciding the timing of the NPDCCH and NPDSCH for the UE. Ultimately, optimization in the configuration schema can yield better efficiency module.

3) Pre-divided Resource Allocation Strategy: For each UE, especially in lower coverage, the offset index selection k0 is updated to match the pre-divided area considered as the resource allocation unit following the formula expressed below:

$$t_n = n + 5 + k_0 \tag{2}$$

The procedure involves an unique parameter called *dynamic data slicing* that splits the requested resource (for data transmission) of a UE to fit the scattered available resources. This aim of this feature is to maximize the network's resource utilization. As per the conventional method with the increase in the number of repetition per UE in extreme radio conditions, percentage of the resource utilization decreases along with the number of the scheduled UE. Whereas, with the addition of dynamic data slicing to utilize the scattered resources increase the amount of scheduled UE in the same subframe significantly.

V. Comparison

A. Uplink scheduling solutions

The solution specified on [1] regarding the uplink scheduling for NB-IoT systems proposes a Narrowband Link Adaptation algorithm (denoted as NBLA) where the link adaptation scheduling process is conducted in two steps, first an inner loop link adaptation is performed in order to guarantee the link availability by dynamically adjusting the repetition number of the transmitted data. Second, an outer loop link adaptation is executed to adjust the MCS level based on the radio channel conditions and ACK/NACKs feedback signals determining the optimal link parameters. On the other hand, the solution specified on [8] establishes a NB-IoT scheduler based on the OpenAirInterface project for the physical resource allocation, i.e. the time-frequency allocation for NB-IoT subcarriers, based on the feedback of the UL DCI, NPUSCH and NPDSCH channels. We consider that both are complementary solutions for UL scheduling, however, the NBLA algorithm is important to keep the link availability stable given the variant channel conditions and to determine the optimal link parameters to operate with the best throughput possible. For this reason, we will observe the performance of the NBLA algorithm in three cases: MCS-dominated (reviewed extensively in this survey), repetition-dominated and straightforward (where the MCS level is fixed to the minimum value and only the repetition number is changing).

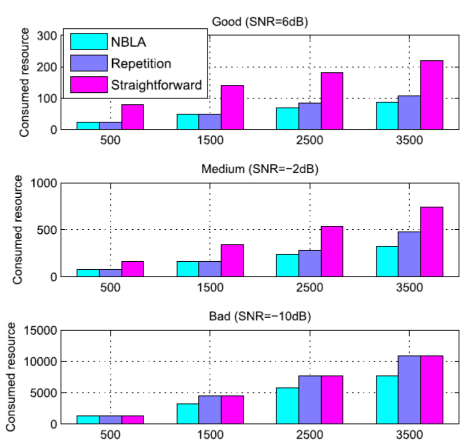

Fig. 10. Resource consumption comparison between the three cases [1]

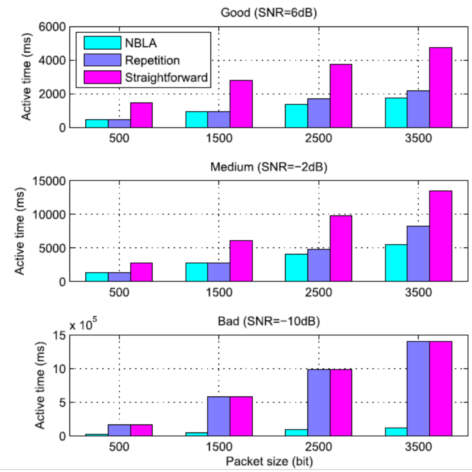

Fig. 11. Active time comparison between the three cases [1]

As shown in figures 10 and 11, the NBLA algorithm performs better when the MCS-dominated approach is utilized, i.e. when the MCS level is adjusted first and then, the repetition number of the transmitted signal is determined. Also, the active time for this algorithm is lower in the MCS-dominated case making it more power consumption efficient, complying with the 3GPP low-complexity and efficient power consumption for NB-IoT.

B. Downlink scheduling solutions

For DL scheduling, the proposed pre-divided strategy depicts significant improvement over the traditional methods. A comparison overview is shared below-

Number of Repetitions	**0**	**1**	**2**	**3**
Straightforward (pp=128)	8	4	3	2
Straightforward (pp=256)	8	6	4	3
Pre-divided resource allocation (pp=128)	8	6	4	3
Pre-divided resource allocation (pp=256)	8	8	8	7

Number of repetitions	**1**	**2**	**3**
Straightforward (pp=128)	66.6%	75.0%	66.6%
Pre-divided resource allocation (pp=128)	100%	100%	100%
Straightforward (pp=256)	42.8%	42.8%	42.8%
Pre-divided resource allocation (p=p256)	57.1%	85.7%	100%

Fig. 12. Comparison on Resource Utilization for UEs [10]

VI. Conclusions

Given the massive amount of IoT devices that will be accessing the cellular networks, the current resource allocation and scheduling techniques employed in the regular LTE systems do not suffice to cope with the specific requirements of IoT applications. For this reason it is crucial to design new scheduling techniques specific for IoT systems. In this survey we focus our attention in exploring the emerging scheduling techniques designed for NB-IoT observing that for the uplink channel it is critical to consider the link adaptation and the dynamic determination of the number of repetition in order to achieve the low complexity and extended coverage for NB-IoT systems, moreover, it was observed that the scheduling algorithm analyzed in this survey outperforms the current technologies in terms of resource allocation and time consumption.

We provide an elaborative study of the architecture of Narrowband IoT downlink scheduling schemes. The scheduling procedure is studied first in details for MAC and PHY layer. Later, we study and analyze the inefficient resource distribution for the UE in downlink channel in extreme radio condition based on case study with key design directions provided. Lastly, we discuss potential solution and modification on LTE and UMTC architecture for better resource utilization and share our observation on pre-divided resource allocation strategy which outperforms the conventional approach.

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