NB-IoT optimisation: Holistic view for smart cities applications with smart meters networks case study

Ahmed M. Abbas1,2 | Khaled Y. Youssef3 | Abdelhalim Zekry4 | Imbaby I. Mahmoud5

1 Electronics & Communications Department, Ain Shams University, Cairo, Egypt
2 Nuclear Research Centre, Egyptian Atomic Energy Authority, Qalubia, Egypt
3 Faculty of Navigation Science and Space Technology, Beni-Suef University, Beni-Suef, Egypt
4 Electronics & Communications Department, Ain Shams University, Cairo, Egypt
5 Radiation Technology Center, Egyptian Atomic Energy Authority, Cairo, Egypt

Correspondence
Ahmed M. Abbas, Electronics & Communications Department, Ain Shams University, Cairo, Egypt.
Nuclear Research Centre, Egyptian Atomic Energy Authority, Qalubia, Egypt.
Email: ahmed.abbas@eaea.org.eg

Abstract
The future demands for smart-cities applications impose maximising the resources utilisation. This study achieves two main objectives to comply with fifth-generation networks goals. First one is to enhance the Narrowband-Internet of Things (NB-IoT) spectral-efficiency. The second is to alleviate the burden of two issues: The signalling during each transmission request for smart-meters (SM) and queuing burden. First, we model the uplink scheduler for the NB-IoT access network using state-machine modelling methodology on Simulink environment. The simulation result is verified and validated with trusted modelling technique. Second, we optimise the NB-IoT uplink scheduler which exploits the periodicity nature of SMs applications with putting envisage considering the emergency conditions. This is done by proposing integrated scheduling protocol which classifies the IoT traffic types and rearranges the transmission times of different SMs utilities and draws a map for the transmission schedule of them to better utilise the sparse time resources. The proposal comprises architecture, signalling, and algorithms. The optimisation is evaluated in term of numbers of SMs versus four spectral performance indicators; utilisation, efficiency, setup-success-percentage, and session-drop-rate according to a case study. The simulation results prove the ability of our proposal to increase the spectrum-utilisation to 17.47%. This enhancement reflects on spectral-efficiency that improved doubled.

1 INTRODUCTION

Internet of Things (IoT) applications are one of the emerging technology applications that are considered a key digital transformation enabler for several industries and utilities including smart cities, factories, electricity grids, and so forth [1]. Recently, the IoT would be used as a component in the operational technologies of nuclear power plants and radiation monitoring networks. Therefore, they need reliable and efficient network infrastructure for optimum operation [2].

The IoT communication profile is completely different from what is experienced by smartphones over fourth-generation (4G) cellular networks, where a sufficient number of intelligent objects will become ubiquitous, enabling them to sense and manipulate information in real time. Meanwhile, smartphones sessions start according to the human profile. For periodic applications, a device transmits the sensed data periodically to a network to deliver innovative and real-time services [3, 4]. For example, at smart cities, the smart meter (SM) does not only register periodic reading, but also draws the profile for the object resources consumption. This profile can be used for future predictions of seasonal energy needs. So, the SMs play important role at the decision making at different levels. Consequently, the SMs became one of the most used and prevalent applications in IoT domain [5–8].

1.1 IoT 5G/5G+ networks

The increasing population density worldwide and the evolution of human and community lifestyles have led to the rapid development of mobile communication technology. Thus, the third generation partnership project (3GPP) has standardised the vision for fifth generation (5G) mobile communication technology, which comprises the traditional long term evolution (LTE) network alongside the future 5G network. The 5G and
the 5G+ mobile networks target to overcome the previous cellular standards limitations, and to become an enabling technology for future IoT applications. The 3GPP releases of 5G, starting from release 15 and beyond, introduced enhanced cellular communications services such as enhanced mobile broadband (eMBB) and massive machine-type communications (mMTC), and they also introduced new services such as ultra-reliable low latency communication (URLLC) and time sensitive communications (TSC) [9–11]. The URLLC and mMTC in 5G are closely related to IoT [11]. Compared to the current 4G, it is expected that 5G mobile networks will efficiently support the basic IoT requirements such as good coverage, high data throughput, low latency, high scalability, high energy efficiency, and the ubiquitous connectivity provision for IoT end users [9]. The aim of 5G is to maximise the capacity of the network to be 1000 times larger than 4G [12].

The IoT 5G umbrella includes current technologies such as unlicensed bands (short-range communication technologies including Bluetooth, Zigbee, Wi-Fi, and the unused spectrum band such as cognitive radio [13] and low-power wide area networks (LPWANs). The latter are divided into non-3GPP networks such as SigFox, LoRa [6, 8], and 3GPP networks such as LTE-M in release 12 and Narrowband-IoT (NB-IoT) in release 13 [8, 14–21]. Recently, Fog radio access network (Fog-RAN) and Cloud radio access network (C-RAN) have been proposed for 5G wireless communications to serve IoT applications [22]. For smart city applications, LPWANs are the most suitable alternatives [6]. Therefore, we only focus on 5G cellular IoT in this study.

NB-IoT achieves unrivalled low-power wide area (LPWA) performance in terms of coverage and the variety of data rates and deployment scenarios compared to other LPWA technologies [23]. This technology is a modified design of LTE that aims to serve IoT traffic. In addition, it is able to provide enhanced coverage compared to LTE. It is used in three modes: Standalone, in-band, and guard-band [24]. The subcarrier bandwidth is 180 kHz in the case of co-existence with current LTE networks in order to provide long periods of connections over mobile operator networks because various objects have small amount of data [24]. The aim of NB-IoT is globally covering low-cost or complex ubiquitous IoT devices worldwide [25].

To cater for the massive IoT requirements, the 3GPP has standardised that the mMTC services will be served by further evolving NB-IoT and LTE-M as integral parts of the 5G specifications such that there will be no need for new standards in the near future [26]. Although they are known as 4G technologies, the 3GPP has started a working group in the 5G core network to support LTE-M and NB-IoT radio access networks in order to guarantee the compatibility of these technologies with 5G [26].

1.2 Problem statement

Efficient and profitable IoT communication systems should be cost, size, weight, and power enabled. With the increasing dependence on NB-IoT technology in people’s lives, a large number of NB-IoT terminals need to be connected to the network in order to cater to the various needs of users. According to predictions by Ericsson, the number of connected IoT devices will reach 1.5 billion by 2022 [27].

The rapid increase in the number of massive IoT devices has added a growing challenge to 5G design owing to its contrasting requirements [12] from two main perspectives. First, the narrow bandwidth may restrict the transmission performance of the IoT in addition to the communication overhead that is required before data transmission [12]. Therefore, it is important to achieve continuous improvements with respect to the efficient use of these resources to support the continuous growth of IoT applications [28]. Second, access reservation protocols designed for 5G networks face massive connectivity for IoT applications [6] because the device density is expected to be larger than the capability of the techniques to realise access reservation and random access (RA) procedures, and may significantly affect end-to-end delay. This would be a critical issue, especially for the scenarios of burst arrival [29]. The access requests and the signalling associated with each periodic IoT transmission process are a burden to both IoT device and network resources. These problems are further transferred with uplink (UL) traffic and remain an open issue, as discussed in [24, 30].

Until now, 5G systems have been considered an evolution of the LTE-advanced (LTE-A) standard, where the 5G new radio (NR) access reservation is also based on LTE-A RA procedure [29, 31]. Access class barring (ACB) and its modifications is a standardised technique to process burst access in LTE and NR RA [29]. However, it may not be appropriate for IoT applications [4]. Most adopted solutions focused on random-access phase optimisation and other optimisation techniques as presented in Section 2. Currently, studies and developments for the NB-IoT have been widely adopted by global mobile operators and manufacturing companies [28].

1.3 Study contribution

This study has two main objectives. The first one is to enhance the NB-IoT spectral efficiency through increasing its spectrum utilisation. The second objective is to reduce the signalling burden during each transmission request for periodic IoT applications and avoid access queues. We achieved these objectives through the following two steps:

1. First, we model NB-IoT UL scheduler. The model is executed using the state machine modelling methodology over Simulink because of its ability to provide continuous run at different simulation durations as desired for mathematical and state machine models. The validation results at the four different NB-IoT data rates depict that the NB-IoT single-tone data rates achieves the highest resources-utilisation.
2. In the second step, we present an approach that employs the persistent scheduling strategy based on the periodicity nature of periodic IoT applications to develop integrated scheduling protocol. The proposal handles three modifications: axes—signalling, architecture, and processing algorithm.
The proposal modified the signalling by adding IoT type identification during radio resources control (RRC) connection establishment messaging phase. At architecture axis, the medium access control (MAC) layer was chosen to execute the approached algorithm. The third axis represents processing algorithm. Additionally, our proposal considers the handling of emergency situations.

Our algorithm is quite simple to alleviate the processing burden for both the SM terminal and the access node. For getting fair results, we divide the cell spectrum of NB-IoT equally on four data rates. We apply our proposal to one of the most demand periodic IoT applications that is SMs [1]. The optimisation is applied on a case study for specified geographical location that has SMs for two different utilities. The optimisation is evaluated in terms of number of NB-IoT user equipments (NB-IoT UEs; in our case study, referred as SM terminals or SM UEs) versus four key performance indicators (KPIs); resources utilisation, spectral efficiency, RRC setup success percentage, and session drop rate (SSR). The simulation results prove the ability of our proposal to increase the spectrum utilisation to 17.47%. This enhancement has positive impact on spectral efficiency which was improved doubled.

### 1.4 Study organisation

The remainder of the study is organised as follows. The previous studies for spectral efficiency optimisation techniques will be reviewed in Section 2. Section 3 will describe our model design, our proposed optimisation and SMs case study with its traffic profiles. The analysis and the discussion for simulation results will be presented in Section 4. Finally, our conclusion will be presented in Section 5.

### 2 RELATED STUDIES

The optimisation studies in MAC layer improve spectral and energy efficiency to serve IoT traffic. This study will adopt spectral efficiency approach. The researches of this approach adopted many different directions as follows.

The authors of [32] adopted the random accessing stage in MAC to improve the system throughput by using Markov chain modelling technique. In [33], Begishev et al. studied three band-with allocation strategies: Static allocation, dynamic allocation, and dynamic allocation with reservation between LTE and NB-IoT. The study recommended the 'dynamic resource sharing with reservation' strategy for heterogeneous IoT traffic. The evaluation process was executed through the formulation of a model by using a two dimensional Markov chain. The first trial to improve the resource utilisation was introduced in [34] where Bing-Zhi et al. designed an UL scheduling algorithm that sort NB-IoT UEs based on minimum scheduling delay. Their algorithm was built by using software defined network (SDN). The persistent scheduling strategy for periodic IoT applications was adopted for the first time in [35]. Although it was addressed from energy efficiency perspective, the authors focused only on proposing prediction algorithm to foresee the periodicity of IoT traffic without reviewing the messaging procedures and their impact. Chen et al. [36] optimised the NB-IoT UL scheduling using the improved K-means algorithm. And they considered the IoT distribution model as an additional impact on random accessing and its consequences on system throughput. On contrary, in [37], the periodic IoT traffic was addressed from a different perspective that focusing only alleviate signalling burden. This perspective is achieved via eliminating some RRC procedures and only in limited cases. The NB-IoT group communication technique was adopted clearly in [38]. Their proposal was based on adapting multimedia broadcast multicast service (MBMS) protocol for serving downlink traffic of IoTs. The cashing-based group access was adopted in [12] for Fog-RAN and in [39] for industrial IoT covered by small base stations. Jin in [40] introduced group-based accessing of same location and attributes under group leader. ElHalawany et al. in [41] introduced maximising the cell throughput via adopting the device to device (D2D) communication methodology. However, their clustering idea was based on uniform deployment condition.

All the aforementioned studies did not consider the periodicity nature of periodic IoT applications in addition to handling the emergency conditions. So, the issue of improving the system efficiency is still open due to the traffic management researches being still poor and insufficient in the study for the nature of IoT traffic types. This study presents integrated vision to optimise this issue.

### 3 NB-IOT UL SCHEDULER MODEL

This section describes our modelling methodology, optimisation approach and applying the optimisation on SMs case study at three parts as follows. The first one describes the NB-IoT UL scheduler designed model. The second one describes our proposed approach for NB-IoT UL scheduler. The third part describes the case study.

#### 3.1 Model description

In general, the MAC layer performs four main functions: RA access control, UL and downlink UEs data scheduling control, hybrid automatic repeat request (HARQ) process, and finally mapping between logical and transport channels [42]. Figure 1 explains the message sequence chart (MSC), starting from RA request up to UL data scheduling grant according to 3GPP release 14 [43, 44]. In the figure, the messages sequencing are from one to seven.

Accordingly, MSC is divided into three main super states. The MAC layer sub-block in NB-IoT UE entity consists of three main super states: RA, RRC messaging phase, and UL data scheduling phase. The MAC layer state machine model of eNB consists of four super states as depicted in Figure 2, where there are two super states for UL data scheduling, one for NB-IoT band tones and another super state for LTE band resources (it
is considered for future studies). The four super states are parallel executions to provide concurrent UL services to all traffic model types according to the traffic profile of each traffic model. Each super state consists of sub-states that model the process sequences of the function of its super state, where in the ‘RRC messaging phase’ super state of Figure 2, it consists of five sub-states as depicted in Figure 3. Each sub-state models a message sequence of Figure 1 with the same order. Also in Figure 2, the super states numbered three and four, respectively, model the messages number six and seven of Figure 1. According to the addressed topic in this study, we focus on modelling the UL scheduling and its associated functions.

Also, the SMs applications traffic model with its traffic profile and density was modelled in state machine methodology as presented in Figure 4 using the state flow toolbox of Simulink. The SMs model block consists of two super states. The first one performs session initiation, traffic density, and traffic profile. The second super state manages the transfer of the payload size after receiving acceptance from the RRC layer.

### 3.2 Proposed optimisation

We exploit the periodicity of periodic applications, where the SMs applications have a uniform profile. Therefore, our enhancement proposal is developed to benefit from this feature in order to enhance the utilisation of the NB-IoT spectrum. This is accomplished by proposing an integrated scheduling protocol that classifies the IoT traffic types and adopts the persistent scheduling strategy in order to rearrange the transmission times of periodic data of different utilities, and to draw a map for their transmission schedule to adequately utilise the free radio frame resources. Our approach allocates the NB-IoT single-tone resource spectrum for SM applications and allocates NB-IoT higher data rates for emergency conditions. The proposed approach comprises a combination of three axes: Architecture, signalling, and the algorithms. Each axis represents a modification and addition to standardised NB-IoT by 3GPP [43, 44].

First, the proposed approach classifies the IoT traffic types. Then, it classifies the SM devices in such geographical coverage area, like in our case study, into groups or clusters as shown in Figure 5. This classification is based on the type of utility or service provided by these SMs. For example, groups of SMs transmit periodic meter readings that are related to water (smart water meter (SWM)), gas, power consumption (smart electricity meter (SEM)), and any other types of periodic metering services that have their own periodicity transmission. We use the word ‘cluster’ because this group of SM terminals is associated with a certain utility; consequently, all of these terminals will initiate RA requests simultaneously. In our case study, we apply our proposal on two different utilities: Electricity and water utilities.

### 3.2.1 Architecture

The architectural change focuses mainly on the MAC layer (layer 2) of the protocol as it represents the executive manager for radio resource management in addition to the feasibility and flexibility to apply a modification at this layer compared with the physical layer. The designed algorithms work on an RRC CONNECTION REQUEST message and RRC CONNECTION SETUP message, as depicted in the MSC of Figure 6. After the eNB receives the cluster information that is carried in the RRC CONNECTION REQUEST message, it replies to the cluster using the RRC CONNECTION SETUP message.

### 3.2.2 Signalling

The ultimate goal of this research is to ensure optimum data capacity communications that is suitable for one of the most used and widespread applications at IoT industry like smart metering, and which is economically feasible as well as spectrally efficient. Accordingly, it is necessary to add more functions to the signalling dictionary which could enable negotiation between nodes to achieve efficient operations in addition to the architectural changes proposed.

The proposed changes are summarised by identifying the following four new information fields that will be carried by the RRC CONNECTION REQUEST:

1. **IoT-Type**: Determines the profile of the NB-IoT UE, that is, whether or not it is periodic;
2. **cluster-ID**: A new ID identifies the utility of the cluster;
3. **cluster-periodicity**: Identify the information about the periodicity of the cluster with a millisecond time unit;
4. **cluster-payload**: Determines the payload size per NB-IoT UE.

Subsequently, the proposed algorithms are executed to draw the cluster transmission map. Then, the synchronisation with
the network will reply to the NB-IoT UE via the RRC CONNECTION SETUP message in one additional information field, and will be called cluster-synchronisation. The proposed messages to be modified are related to the 3GPP [43].

3.2.3 | Algorithm

The first task in our proposed procedures is the initialisation where we create a clusters time table as a database for all SM clusters that will be registered on the access network. Consequently, these SM terminals will avoid the RA and the RRC connection establishment procedures during the next periodic data transmissions. Then, the first condition to run the rest of our proposed procedures is to determine the IoT traffic type. As previously mentioned, our proposed approach focuses on periodic IoT traffic. As depicted in Figure 7, the overall proposed procedures consist of four phases, each of which depends on the previous one and has its own algorithm. We model our proposed procedures in the RRC messaging phase by adding two sub-states that have red colour between the MSG3 and MSG4 sub-states as depicted in Figure 8 during the transporting of the RRC messages via the MAC layer as well as after decoding and encoding the required information fields. These algorithms are implemented using MATLAB scripts that are linked as files with

FIGURE 2  NB-IoT eNB medium access control (MAC) layer state machine model

FIGURE 3  eNB state level of ‘RRC Messaging Phase’ sub-state

FIGURE 4  Smart meter (SM) sub-block Simulink model–state level

FIGURE 5  Geographical area has SMs and each SM of utility has GID
our Simulink project. Figure 9 presents the realisation of the proposed model using state flow toolbox of Simulink. Table 1 describes the notations that are used in each algorithm. In the following section, we present a description of the algorithm of each phase.

Initialisations: The base station sets and creates the following variables:

**ALGORITHM 1** First setting

1. Compute \( U_{rf} \), \( U_{rf} = \text{buffer-size-indexing} (p) \)
2. if \( \text{Clusters Time Table Index} = 1 \) then
3. \( t_{C1} = t_e, \text{ where } n = 1 \)
4. else \( t_{Cn} = t_{Cn-1} + U_{rf} \) end if
5. \( C_{n_{start}} = t_{Cn} \)
6. \( C_{n_{stop}} = t_{Cn} + U_{rf} \)

**ALGORITHM 2** Periodicity

1. \( N_{CP} = 1 \)-h duration / \( C_p \)
2. while \( n_{CP} > N_{CP} \) do
3. create \( \text{cluster Map array} \) \([1, C_{n_{start}} \rightarrow C_{n_{stop}}] = C_{ITI}\)
4. \( \text{cluster Map} (1, C_{n_{start}}) = C_{n_{start}} + N_{RF} \)
5. \( \text{cluster Map} (1, C_{n_{stop}}) = C_{n_{stop}} + N_{RF} \)
6. \( n_{CP} = n_{CP} + 1 \)
7. end while

1. Clusters Time Table Index = 1,
2. create Transmission Map array,
3. create Clusters Time Table matrix \([4 \times n]\).

\[
\begin{bmatrix}
    C_{ID} & \cdots & C_n \\
    C_{ID} & \cdots & C_n \\
    U_{rf} & \cdots & U_{rf} \\
    t_{Cn} & \cdots & t_{Cn}
\end{bmatrix}
\] (1)

**Phase 1: First setting.** During this phase, the start and end of the first periodic transmission is determined and accomplish the synchronisation with network. The transmission duration and transmission end time are determined according to the cluster payload.

**Phase 2: Periodicity.** According to the calculation that was done during the first phase (cluster transmission duration and transmission end), the next periodic transmissions were determined over one hour (1 h) based on the cluster periodicity that was given in RRC message 3. The cluster periodicity is the inter-generation time (IGT) for SM terminals. In this phase, the IGT is translated to the number of radio frames. Accordingly, the ‘cluster map’ over a 1-h period is created.

**Phase 3: Masking.** According to the cluster map that was created in the previous phase, a masking or comparison process between the cluster map and NB-IoT eNB transmission map was done to detect any time interference with any other registered cluster transmission schedule during the hour. If the masking results indicate free interfering, then the algorithm returns to the waiting state to await any new cluster transmission scheduling requests.

**Phase 4: Offsetting.** This phase begins depending on the results of the masking process in the previous phase. If any time interference with any other registered cluster is detected, the offsetting process is done for the first periodic transmission. Then, the algorithm returns to the periodicity phase for
verification. This process repeats itself until it is free from interference.

**ALGORITHM 3 Masking**

1. Initialise $Offset-Value = 0$
2. $[MASK] = \text{find the } U_f \text{ numbers in } Cluster-MAP$
3. for $i = 1 \rightarrow \text{length } (MASK)$ do
4. if $Transmission-MAP(1, MASK(1, i)) < 0$ do
5. $Offset-Value = Offset-Value + 1$
6. else
7. end if
8. end for

Also, the SM traffic model was slightly modified as depicted in Figure 10(b). Where the session initiation procedures are executed once upon first registration in the network. Then, the next periodic transmission times will be managed by the second super state after coordination with eNB.

### 3.3 SMs case study

We apply our case study on the urban location of the district number six in Rehab County in New Cairo city, Egypt, which is shown in Figure 11(a) from satellite picture Google Earth [45]. This district comprises 145 residential buildings where each one has 20 apartments. Each apartment has two types of
that is described in [47], we modified the IGT from 60 to 15 min and was applied this profile on SWM. The area of this location is approximately 200 km² as depicted in Figure 11(b). So, this location can be covered by one NB-IoT eNB site according to [48, 49].

4 | SIMULATION RESULTS ANALYSIS AND DISCUSSION

In this section, we describe our simulation setting and model conditions and verify our model. Then we analyse and discuss our simulation results for our optimisation.

4.1 | Simulation setup

First, the simulation state flow of RRC connection establishment and data scheduling procedures is verified according to 3GPP standard release 13 [43, 44] and as depicted in MSC of Figure 1. And our model results are validated with the standard results of the NB-IoT scheduling process which is built by ns-3 simulator in [36]. With the difference that our simulation runs duration is 60 min. The round robin scheduling technique is adopted. We model two SMs groups, ‘SWM’ group of the water utility and ‘SEM’ group of the electricity utility simultaneously accessing the NB-IoT base station. We simulate three scenarios, where the first and second scenarios, (A & B), simulate the SWM and SEM, respectively, and based on the RA, RRC connection establishment, and data scheduling procedures of the 3GPP standard [43, 44]. The third scenario, (scenario C), simulates our proposed approach. The simulation parameters are described and summarised in Table 2. To ensure fair results, the cell spectrum of NB-IoT is divided equally on the four data rates. A uniform traffic density is assumed with linear increasing at each simulation run, and propagation without transmission impairments. We use the state flow tool box of Simulink (Rel.2016).
4.2 Proposed optimisation results analysis

This study improves the NB-IoT spectral efficiency. According to the improvement that was achieved, our model is measured from four aspects as follows: utilisation, throughput, accessibility, and retainability. Its equations statistics are explained in [50] specifically for radio network KPIs and confirmed with 3GPP standard in [51, 52]. We applied our optimisation scheme using the frequency band that is allocated for NB-IoT single-tones as depicted in Table 2. In order to verify the efficiency of our proposed optimisation, we compared our results with the 3GPP standard method [39, 40] graphically and with the improved K-mean method (IKMM) [36] numerically in the discussion section.

| Parameter                                | Value   |
|------------------------------------------|---------|
| eNB bandwidth                            | 20 MHz  |
| Total number of RBs                      | 100     |
| Number of RBs allocated to NB-IoT band   | 80      |
| Number of RBs allocated to single tone   | 20      |
| Number of single tone resource units     | 240     |
| SEM payload                              | 381 byte|
| SWM payload                              | 115 byte|
| SWM packet count                         | 5       |
| Intergeneration time (IGT)               | 15 min  |

4.2.1 Utilisation

Figure 12 presents the results of verification and validation process for our model of NB-IoT MAC layer. The figure explains the NB-IoT resources-utilisation KPI with respect to the number of periodic NB-IoT UEs at the four different NB-IoT data rates. Before our optimisation, the results of this figure depict important fact that the NB-IoT single-tone data rate achieves the highest resources-utilisation percentage.

Figure 13 presents a snapshot of 1 s duration versus the utilisation of the NB-IoT single-tone resource spectrum. Figures 13(a), (b), and (c) show the three simulated scenarios. As previously mentioned, the first and second scenarios follow the standard, and the third follows our proposed scheme. According to our model, the first scenario shows that all SWM group UEs only succeeded to dominate all single-tone bands, and all SEM group UEs failed. The small blue solid circle represents the allocated resources for UL RRC messaging. Then, the large blue solid circle represents the allocated resources for the UL payload. The second scenario shows that all SEM group UEs only succeeded to dominate all single-tone bands, and all SWM group UEs failed. The small green dotted circle represents the allocated resources for UL RRC messaging, and the large...
green dotted circle represents the allocated resources for the UL payload.

In Figures 13(a) and (b), both the small and large red squares represent the tones and its radio frames that are used to carry the control messages and data payload. From Figures 13(a) and (b), we observe free radio frames, which represent unutilised tones during the rest of the second duration. The third scenario presents the channels that are allocated for both groups and the radio frames that are allocated for each group after application of our proposal. Figure 13(c) shows that our proposed approach utilised the resources wasted for signalling and higher layer control messaging at each transmission process. These resources were used instead in the transfer of more periodic IoT traffic. In addition, the proposed approach maximised the utilisation of radio frame resources.

Figure 14 presents the enhancement in the NB-IoT band single-tone utilisation with respect to the number of periodic NB-IoT UEs (in our case study are called SM terminals or SM UEs) during a 1-h duration, where for the SWM group traffic that uses the standard method the spectrum is saturated at 9.88%. Moreover, even when the payloads in the SEM group traffic are increased using the standard, the spectrum is saturated at 22.05%. After applying our proposed approach, the spectrum is saturated at 39.52%. This means that the increase in channel utilisation reached 17.47%.

4.2.2 Throughput

The utilisation enhancement reflects to NB-IoT system throughput. Figure 15 depicts the system throughput versus increasing the numbers of SM UEs. For SWM group payloads, the throughput is 10.7 Mbps. Even with an increased payload in SEM group the maximum achievable throughput is 23.82 Mbps when using the standard. After applying our proposed scheme, the maximum achievable throughput becomes 42.49 Mbps.
Figure 16 presents the relation between the spectral efficiency and the increased numbers of SM UEs, where the maximum spectral efficiency is 5.95 b/s Hz\(^{-1}\) for the SEM group traffic when using the 3GPP standard. The maximum spectral efficiency becomes 10.62 b/s Hz\(^{-1}\) with our proposed approach. Additionally, the number of SM UEs that can be served until the NB-IoT spectrum reach to saturation is depicted in Figure 17. The numbers of SM terminals were doubled after our proposal and increased from 720 terminals before proposal to 1680 after proposal.

### 4.2.3 Accessibility

Figure 18 presents the RRC setup success percentage versus increasing the numbers of SM UEs. The figure depicts the enhancement of the RRC setup success percentage from 660 SM terminals to 100% success at 1540 SM terminals.

### 4.2.4 Retainability

Figure 19 represents the relation between SDR and increasing the numbers of SM UEs. Also, improving the utilisation contributed in saving and increasing the resources not only for more SMs devices but also to complete their session. With the proposed optimisation, the SDR starts at 560 devices with the lowest SDR rate, as depicted in the figure, instead of 240 devices at standard procedures.

### 4.3 Results discussion

In this study, the validation results for our NB-IoT MAC model depicted that the NB-IoT single-tone achieves the highest resources-utilisation. So, the NB-IoT single-tone is the optimum choice to be allocated for the most demanded IoT application like SMs. We allocated the higher data rates for emergencies scenarios and then exploited the persistent scheduling strategy and the periodicity nature of the periodic IoT application like SM. This was done by proposing integrated scheduling protocol which rearranges the transmission times of different SMs utilities and draws a map for the transmission schedule of them to well utilise the free time resources. Our proposal succeeded to improve three main KPIs based on real scenario as follows:

1. The first main KPI is the NB-IoT system bandwidth utilisation percentage during 1 s which is enhanced by 17.47%
CONCLUSION AND FUTURE WORKS

According to the traffic condition of the case that was studied, the highest utilisation achieved was 22.05% and after the proposal became 39.52%. The enhancement in the utilisation strongly influenced on system throughput and spectral efficiency.

a. From the system throughput aspect, it is improved from 23.82 to 42.49 Mbps at 1680 SM terminals after our proposal. Comparing to the optimisation in [36] which the highest achievable throughput was below 500 bps at 5000 IoT terminals with 20 byte for the packet size whereas at our traffic condition the smallest packet size was 23 byte. Our proposal operated on 4 MHz bandwidth comprises 228 NB-IoT single tones of 15 kHz bandwidth.

b. From the spectral efficiency aspect, its improvement doubled, where 5.95 b/s Hz⁻¹ before became 10.62 b/s Hz⁻¹ after our proposal.

2. The second main KPI is the number of served SM terminals from different utilities which simultaneously request access. We examined our optimisation on one of the important economical applications like the smart metering for two different utilities serving a specified geographical area. The number of served SMs was doubled after our proposal. Where the served SMs increased from 720 terminals to 1680 SM terminals after proposal. This number of SM terminals was served by only 20% of the eNB total bandwidth. This optimisation was also validated by RRC setup success percentage KPI. We compared our optimisation values with the model in [32]. The lowest probability of channel busy was 9.37% and could serve only five IoT terminals per one channel with payload size 512 byte. However, our proposal, and with the same calculation methodology, served seven SM terminals per one channel per second.

3. The third main KPI is the SDR. We achieved maximum served terminals with zero session drops and reached to 560 SMs of 1560 SMs of RRC setup success. Referring to the session drop probabilities in [33], our proposal enhanced the session drop by 35.7% of 20% only from the eNB total bandwidth. In [33], the session drop probability was 23% for 60% NB-IoT static reservation from total eNB bandwidth. This means that their session probability will increase 69% if they used only 20% of eNB total bandwidth for NB-IoT. However, our proposal achieved only 33.33% session drop probability with only 20% of eNB total bandwidth for NB-IoT.

Whether it is the payload increase or uses of other techniques, many radio frames are still not effectively utilised (even when they will be allocated later). A comparison of our records with the aforementioned methods show the ability of our approach to utilise the resources wasted for signalling and higher layer control messaging at each transmission process, and to maximise the utilisation of radio frame resources. Therefore, our proposed approach achieves the following:

1. On the IoT terminal side, it reduces the signalling and access request burden on SM terminals at each transmission request;

2. On the NB-IoT eNB side, it enhances the system spectral efficiency;

3. At both the SM terminal and NB-IoT eNB, it will result in a positive impact on energy efficiency.

Well scheduling for radio frames avoid the accumulative delay due to multiple trial of RA requests until success to acquire data channel even with using alternative techniques as D2D [41].

5 | CONCLUSION AND FUTURE WORKS

The future increasing demands for SMS businesses require maximising the resources utilisation to serve maximum possible numbers of NB-IoT UEs. Additionally, the traffic management subject over NB-IoT for efficient spectrum is new opened issue at IoT 5G. In this study, we achieve two main goals. The first one is to improve the NB-IoT spectral efficiency to serve the increasing numbers of SMs. The second one is to reduce the signalling burden during each transmission request for SMs businesses. Therefore, this study introduces new integrated approach to enhance the NB-IoT spectral efficiency that serves the smart cities applications. First, we model the protocol stack of the NB-IoT access network by using the state-machine modelling methodology on Simulink environment. According to our goals, we focus on the NB-IoT UL scheduler in MAC layer model. For fair results, we divide the cell spectrum of NB-IoT equally on the four data rates. Also, we assume ideal propagation without any transmission impairments. The simulation results are verified according to 3GPP standard and are validated with other trusted of different modelling technique. Additionally, the validation results depicted that the NB-IoT single-tone data rate achieves the highest resources-utilisation. Therefore, it is the optimum choice for the most dominant periodic IoT application. Second, we optimise the NB-IoT UL scheduler which exploited the periodicity nature of SMS with drawing envisage considering the emergency conditions. Our approach allocates the NB-IoT single-tone resource spectrum for SM applications and allocates NB-IoT higher data rates for emergency conditions. This was done by proposing integrated scheduling protocol which classifies the IoT traffic types and rearranges the transmission times of different SMs utilities and draws a map for the transmission schedule of them to well utilise the sparse time resources. We applied the optimisation on a case study for specified geographical location that has SMs for two different utilities. The proposed approach encompasses three visions that comprise signalling, architecture, and algorithm. Each vision represents adjustment on in current NB-IoT 3GPP standard. The optimisation is evaluated in term of number of SMs terminals versus four KPIs: resources utilisation, spectral efficiency, RRC setup success percentage, and SSR. Finally, the simulation results prove the ability of our proposal to increase the spectrum utilisation to 17.47% according to the used traffic profiles. This enhancement reflects on spectral efficiency that was improved two times.

In future, we will study the transmission impairments that affect our optimisation approach. Then, we will optimise the
channel holding time, and the channel holding time for different traffic distributions and propagation models. Finally, we will study and optimise the spectral efficiency and channel holding time in the context of hybrid model that conveys multiple 5G-IoT access technologies and considers all IoT traffic models and profiles.

REFERENCES

1. Alsharif, M., et al.: Enabling hardware green Internet of Things: A review of substantial issues. IEEE Access. https://doi.org/10.1109/ACCESS.2019.2926800 (2019). Accessed 04 July 2019

2. Jhye, J., et al.: The conceptual introduction of Internet of Things (IoT) and blockchain technology in nuclear material accounting and control at facilities. In: International Atomic Energy Agency (IAEA) Symposium on International Safeguards, Building Future Safeguards Capabilities, Vienna, Austria, 7 November 2018

3. Towards a definition of the Internet of Things (IoT). https://iot.ieee.org/images/files/pdf/IEEE_IoT_Toward_Definition_ Internet_of_Things_Revision_1_27MAY15.pdf

4. Verma, S., et al.: Energy-efficient group paging mechanism for QoS constrained mobile IoT devices over LTE-A pro networks under 5G. IEEE Internet Things J. 6(5), 9187–9199 (2019). https://doi.org/10.1109/JIOT.2019.2926589

5. Ghasempour, A., Moon, T.K.: Optimizing the number of collectors in machine-to-machine advanced metering infrastructure architecture for Internet of Things-based smart grid. IEEE Green Technologies Conference, Kansas City, pp. 51–55 (2016)

6. Alpakue, G.A., et al.: A survey on 5G networks for the Internet of Things: Communication technologies and challenges. IEEE Access 6, 3619–3647 (2017). https://doi.org/10.1109/ACCESS.2017.2779844

7. https://www.britishgas.co.uk/thesource/yourhome/smartliving/what-is-a-smart-meter (2020). Accessed 8 Jan 2020

8. Chettri, L., Bera, R.: A comprehensive survey on Internet of Things (IoT) towards 5G wireless systems. IEEE Internet Things J. 7(1), 16–32 (2020). https://doi.org/10.1109/JIOT.2019.2948888

9. de Almeida, I.B.F., et al.: 5G waveforms for IoT applications. IEEE Commun. Surv. Tutorials 21(3), 2554–2567 (2019). https://doi.org/10.1109/COMST.2019.2910817

10. Ghosh, A., et al.: 5G evolution: A view on 5G cellular technology beyond 3GPP release 15. IEEE Access 7, 127639–127651 (2019). https://doi.org/10.1109/ACCESS.2019.2939398

11. Li, S., et al.: Energy-efficient resource allocation for industrial cyber-physical IoT systems in 5G era. IEEE Trans. Ind. Inf. 14(6), 6218–6228 (2018). https://doi.org/10.1109/TII.2018.2799177

12. Wang, Q., et al.: LACK: A lightweight label-based access control scheme in IoT-based 5G caching context. IEEE Access 5, 4018–4027 (2017). https://doi.org/10.1109/ACCESS.2017.2678510

13. Alzahrani, B., Eijaz, W.: Resource management for cognitive IoT systems with RF energy harvesting in smart cities. IEEE Access 6, 62717–62727 (2018). https://doi.org/10.1109/ACCESS.2018.2874134.

14. 3rd Generation Partnership Project; Technical Specification Group GSM/EDGE Radio Access Network; Cellular System Support for Ultra Low Complexity and Low Throughput Internet of Things, version 13.1.0 (Release 13), document 3GPP TR 45.820 (2015)

15. 3rd Generation Partnership Project; Evolved Universal Terrestrial Radio Access (E-UTRA); NB-IoT Technical Report for BS and UE Radio Transmission and Reception, version 13.0.0 (Release 13), document 3GPP TS 36.602 (2016)

16. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (EUTRAN); Overall description; Stage 2, version 14.4.0 (Release 14), document 3GPP TS 36.300 (2017)

17. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA);

User Equipment (UE) procedures in idle mode, version 14.4.0 (Release 14), document 3GPP TS 36.304 (2017)

18. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio access capabilities, version 14.4.0 (Release 14), document 3GPP TS 36.306 (2017)

19. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) Radio Transmission and Reception, version 15.0.0 (Release 15), document 3GPP TS 36.101 (2017)

20. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) Radio Transmission and Reception, version 15.0.0 (Release 15), document 3GPP TS 36.104 (2017)

21. 3rd Generation Partnership Project; General Packet Radio Service (GPRS) Enhancements for Evolved Universal Terrestrial Radio Access Network (EUTRAN) access, version 15.2.0 (Release 15), document 3GPP TS 32.401 (2017)

22. Nassar, A., Yilmaz, Y.: Reinforcement learning for adaptive resource allocation in Fog RAN for IoT with heterogeneous latency requirements. IEEE Access 7, 128014–128025 (2019). https://doi.org/10.1109/ACCESS.2019.2939735

23. Cao, J., et al.: Anti-quantum fast authentication and data transmission scheme for massive devices in 5G NB-IoT system. IEEE Internet Things J. 6(6), 9794–9805 (2019). https://doi.org/10.1109/JIOT.2019.2931724

24. Xu, J., et al.: Narrowband Internet of Things: Evolutions, technologies, and open issues. IEEE Internet Things J. 5(3), 1449–1462 (2018). https://doi.org/10.1109/JIOT.2017.2783374

25. Zhang, Y., et al.: Certificated multi-party authenticated encryption for nb-iot terminals in 5G networks. IEEE Access 7, 114721–114730 (2019). https://doi.org/10.1109/ACCESS.2019.2936123

26. Koohi, O., et al.: An uplink UEs group-based scheduling technique for 5G mMTC systems over LEO satellite. IEEE Internet Things J. 6, 6743–67427 (2019). https://doi.org/10.1109/JIOT.2019.2918581

27. Goudos, S.K., et al.: A novel design approach for 5G massive MIMO and NB-IoT green networks using a hybrid jaya-differential evolution algorithm. IEEE Access 7, 105687–105700 (2019). https://doi.org/10.1109/ACCESS.2019.2932042

28. Al-Turjman, F., et al.: Small cells in the forthcoming 5G/IoT Traffic Modeling and Deployment Overview. IEEE Commun. Surv. Tutorials 21(1), 28–65 (2019). https://doi.org/10.1109/COMST.2018.2864779

29. Vilgelm, M., et al.: Dynamic binary countdown for massive IoT random access in dense 5G networks. IEEE Internet Things J. 6(4), 6896–6908 (2019). https://doi.org/10.1109/JIOT.2019.2912424.

30. Xia, N., et al.: Radio resource management in machine-to-machine communications—A survey. IEEE Commun. Surv. Tutorials 20(1), 791–828 (2018). https://doi.org/10.1109/COMST.2017.2765344

31. Centenaro, M., et al.: Comparison of collision-free and contention-based radio access protocols for the Internet of Things. IEEE Trans. Commun. 65(9), 3832–3846 (2017). https://doi.org/10.1109/TCOMM.2017.2767074

32. Y. Sun, et al.: Throughput modeling and analysis of random access in Narrow-band Internet of Things. IEEE Internet Things J. 5(3), 1485–1493 (2018). https://doi.org/10.1109/JIOT.2017.2783318

33. Begishev, V., Petrov, V., et al.: Resource allocation and sharing for heterogeneous data collection over conventional 3GPP LTE and emerging NB-IoT technologies. Comput. Commun. 120, 93–101 (2018). https://doi.org/10.1016/j.comcom.2018.01.009

34. Hsieh, B.-Z., et al.: Design of a UE-specific uplink scheduler for Narrowband Internet of Things (NB-IoT) systems. In: 2018 3rd International Conference on Intelligent Green Building and Smart Grid (IGBSG), Yilan, Taiwan, 22–25 April 2018. https://doi.org/10.1109/IGBSG.2018.8393573

35. Lee, J., Lee, J.: Prediction-based energy saving mechanism in 3GPP NB-IoT networks. Sensors 17, 2008 (2017). https://doi.org/10.3390/s17092008
36. Chen, X., et al.: Performance analysis and uplink scheduling for QoS-aware NB-IoT networks in mobile computing. IEEE Access 7, 44404–44415 (2019). https://doi.org/10.1109/ACCESS.2019.2908985
37. Maldonado, P.A., Ameigeiras, P., et al.: Optimized LTE data transmission procedures for IoT: Device side energy consumption analysis. In: 2017 IEEE International Conference on Communications Workshops, Paris, France, 21–25 May 2017. https://doi.org/10.1109/ICCWW.2017.7962714
38. Tsoukaneri, G., et al.: Group communications in Narrowband-IoT: Architecture, evaluation. IEEE Internet Things J. 1(1), 1–10 (2018). https://doi.org/10.1109/JIOT.2018.2807619
39. Duan, P., et al.: Space-reserved cooperative caching in 5G heterogeneous networks for industrial IoT. IEEE Trans. Ind. Inf. 14(6), 2715–2724 (2018). https://doi.org/10.1109/TII.2018.2794615
40. Cao, J., et al.: Fast authentication and data transfer scheme for massive NB-IoT devices in 3GPP 5G network. IEEE Internet Things J. 6(2), 1561–1575 (2019). https://doi.org/10.1109/JIOT.2018.2846803
41. ElHalawany, B.M., et al.: Uplink resource allocation for multi-cluster Internet of Things deployment underlaying cellular networks. Mobile Networks Appl. 25, 300–313 (2019). https://doi.org/10.1007/s11036-019-01288-6
42. Johnson, C.: Long Term Evolution IN BULLET. 2nd edition, version 1, C. Johnson Corp., Northampton, England (2012)
43. LTE; Evolved Universal Terrestrial Radio Access (EUTRA); Radio Resource Control (RRC); Protocol Specification, version 14.2.2 (Release 14), document 3GPP TS 36.331 (2017)
44. LTE; Evolved Universal Terrestrial Radio Access (EUTRA); Medium Access Control (MAC) Protocol Specification, version 14.2.1 (Release 14), document 3GPP TS 36.321 (2017)
45. https://www.google.com/maps/@30.0648042,31.485601,17.25z (2020). Accessed: 4 Jan 2020
46. Carvalho, R., et al.: Communication system design for an advanced metering infrastructure. MDPI Sens. 18, 3734 (2018)
47. Luan, W., et al.: Data traffic analysis of utility smart metering network. In: 2013 IEEE Power & Energy Society General Meeting, Vancouver, Canada, 21–25 July 2013
48. Lauridsen, M., et al.: Coverage comparison of GPRS, NB-IoT, LoRa, and SigFox in a 7800 km2 area. In: 2017 IEEE 85th Vehicular Technology Conference (VTC Spring), Sydney, New South Wales, Australia, 4–7 June 2017
49. Mekki, K., et al.: A comparative study of LPWAN technologies for large-scale IoT deployment. In: ICT Express, 5, 1–7 (2019)
50. eNodeB V100R005C00 KPI Reference, Huawei Technologies Co., Ltd, Issue 01, 2012-03-30
51. Universal Mobile Telecommunications System (UMTS); LTE; Telecommunication Management; Key Performance Indicators (KPI) for Evolved Universal Terrestrial Radio Access Network (E-UTRAN): Definitions, version 14.0.0 (Release 14), document 3GPP TS 32.450 (2017)
52. Universal Mobile Telecommunications System (UMTS); LTE; Telecommunication Management; Key Performance Indicators (KPI) for Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Requirements, version 14.0.0 (Release 14), document 3GPP TS 32.451 (2017)