Uplink Resource Allocation for Narrowband Internet of Things (NB-IoT) Cellular Networks

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***Abstract*—Narrowband Internet of Things (NB-IoT) is a new narrowband radio technology in fifth-generation (5G) networks. In NB-IoT cellular networks, to provide low-power wide-area coverage, there are several different resource allocation units that can be allocated by a base station to NB-IoT devices for uplink transmissions. Traditional resource allocation algorithms without considering the multiple resource allocation units are not appropriate for NB-IoT networks, and we observe that only adopting the same resource unit for each device will result in the radio resource wastage. Therefore, this paper investigates the uplink resource allocation problem with the considerations of the new radio frame structure and multiple resource units for NB-IoT networks. The objective is to minimize the used radio resources while each device can transmit its data. We propose an algorithm to determine a suitable resource unit and allocate the radio resource for each device to solve the target problem. Compared with a baseline, the simulation results show the efficacy of the proposed algorithm and provide useful insights into the resource allocation design for NB-IoT systems.**

***Index Terms*—NB-IoT, uplink resource allocation, massive connections, 5G cellular networks**

I. Introduction

Narrow-band Internet of Things (NB-IoT) is one of the key technologies in fifth-generation (5G) cellular networks and many industries have been spent lots of effort on products and researches for NB-IoT systems. The NB-IoT is designed for low device/deployment cost, delay tolerance, long battery life (i.e., 10 years), high coverage area, and a massive number of low-throughput devices to send and receive small data with delay tolerance around 10 seconds [1], [2]. The NB-IoT should also support massive connections and a network coverage over 160 dB [3]. Ericsson predicts that the number of devices will increase to 28 billion connections [4]. Moreover, the number of mobile-connected devices per capita will reach 1.5 by 2021 forecasted by Cisco [5]. Researchers indicated that a cellular cell should connect 480,000 IoT devices [6]. Therefore, how to efficiently use radio resources of NB-IoT networks to achieve massive connections over next-generation cellular networks is an important issue.

Due to the properties of narrow-band and delay tolerance, its radio access designs including downlink and uplink are different from fourth-generation (4G) long-term evolution (LTE) networks. Specifically, for uplink transmissions, an NB-IoT base station can flexibly provide different resource allocation units for devices to upload their data in order to meet different conditions. For downlink transmissions, an NB-IoT base station generally transmits data to NB-IoT devices in one dimension (i.e., time domain), while a 4G base station can allocate downlink radio resources in two dimensions (i.e., time and frequency domains). This paper observes that traditional uplink resource allocation algorithms without considering the multiple resource allocation units are not appropriate for NB-IoT networks and will result in the NB-IoT radio resource wastage. Therefore, this paper addresses the NB-IoT uplink resource allocation problem to reduce the NB-IoT radio resource wastage.

Nowadays, some researches have addressed different issues for NB-IoT cellular networks. Oh et al. [7] considered the control plane solution designed for transmitting small data packets. Once an NB-IoT device has a small data packet to be transmitted, the uplink control signaling overhead cannot be negligible. The paper proposed a scheme that a device can transmit signaling and data simultaneously to reduce the signaling overhead. Boisguene et al. [8] surveyed the NB-IoT frame structure and introduced an NB-IoT device how to access the radio frames in 3GPP NB-IoT systems. C. Yu et al. [9] introduced new features of repetitions and considered the link adaptation problem over 3GPP NB-IoT systems. This paper proposed a heuristic to determine a repetition number and a modulation-coding scheme level for each NB-IoT device for reducing the active time and the radio resource consumption. However, the related works have not addressed the NB-IoT uplink resource allocation problem and how to allocate multiple resource units for NB-IoT devices.

In this paper, we study the uplink resource allocation problem for NB-IoT cellular networks. The objective is to minimize the consumed radio resources while each device can upload its data. We summarize the contributions of this paper as follows. Firstly, we observe that traditional uplink resource allocation algorithms without considering the multiple resource allocation units are not appropriate for NB-IoT networks and will result in the radio resource wastage. Therefore, we need to design a resource unit adaptation algorithm for NB-IoT systems. Secondly, we describe and formulate the uplink resource allocation problem and propose an uplink resource allocation algorithm to adaptively determine a resource unit for each device. Finally, we develop simulations with realistic parameters to verify the performance of the proposed algorithm. The results agree with our motivation and observations that the NB-IoT uplink resource allocation is an

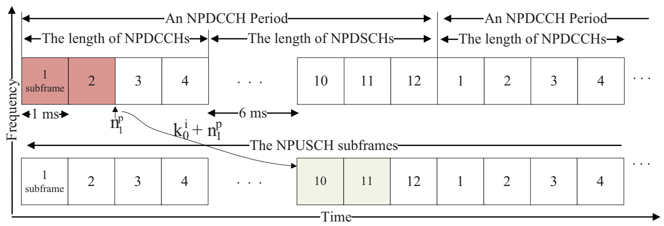

Fig. 1. NT-IoT frame structure and scheduling illustration.

important issue in radio resource utilization and faces many challenges.

The rest of the paper is organized as follows. In Section II, we describe the system model and problem formulation. In Section III, we propose an uplink resource allocation algorithm. Section IV presents simulation results. We conclude this paper in Section V.

II. System Model and Problem Formulation

A. System Model

Narrow-band Internet of thins (NB-IoT) is a promising technology to support massive connections in next-generation cellular networks. To serve massive devices, uplink resource allocation determines the efficiency of the radio resource utilization and is an import issue. The bandwidth of downlink and uplink radio resource is respectively 180 kHz under NB-IoT systems. In the uplink, there are 12 subcarriers and each subcarrier is 15 kHz. The subcarrier is also called tone in this paper. For the uplink resource allocation, there are four different resource allocation units, 12 tones (i.e., subcarriers) with 1 ms, 6 tones with 2 ms, 3 tones with 4 ms, single tone with 8 ms, where a radio subframe is 1 ms. A base station can select one of four resource units for each NB-IoT device defined by 3GPP [10] to upload its data. Fig. 1 shows a simplified frame structure. Before an NB-IoT can upload its data, in NB-IoT cellular networks, the base station uses downlink control indicator (DCI) carried by narrow-band physical downlink control channel (NPDCCH) subframes to notify the device which subcarriers and subframes the device can upload data. Because an NPDCCH subframe only has two control channel elements (CCE) and both CCEs should simultaneously be used to carry one DCI for an NB-IoT device in general [11], an NPDCCH subframe can be only allocated to a device. The uplink data is carried by narrow-band physical uplink shared channel (NPUSCH) subframes. We consider frequency division duplex (FDD), where uplink and downlink use different radio frequencies.

In downlink frequency, each subframe can be an NPDCCH subframe or a narrow-band physical downlink shared channel (NPDSCH) subframe. In uplink frequency, each subframe is an NPUSCH subframe. This paper focuses on the uplink resource allocation. Specifically, in this paper, we address how to allocate NPDCCH and NPUSCH subframes and determine an uplink resource unit from the four units to each device. Each NB-IoT device should first monitor a series of NPDCCH subframes to receive a DCI, where the length of NPDCCH subframes can be adjusted by the parameter R_{max}. The length of NPDCCH subframes follows a length of NPDSCH subframes. The two lengths can be adjusted by two parameters R_{max} and G and are called an NPDCCH period (NP) [11], [12]. The length of NPUSCH subframes is equal to the length of an NP. This paper considers that the length of an NP is given.

For against transmission errors, NB-IoT systems will repeat for transmitting the same data and control information (e.g., DCI) [11], [12]. The repetition numbers for data and control information can be different. For examples, if the repetition number for NPDCCH subframe is 2, an NB-IoT device should continuously receive two NPDCCH subframes for one DCI. In this paper, the number of NPDCCH subframes used to transmit one DCI is called a *candidate*. In Fig. 1, if there are two candidates in an NP, the first candidate resides at subframe 1-2 and the second candidate locates at subframe 3-4. Similarly, if the repetition number for NPUSCH repetitions is 2, one resource unit should be transmitted two times. In this paper, the number of NPUSCH repetitions and the modulation-coding scheme for each device is given according to the distance between the base station and the device. The base station should allocate sufficient subframes and subcarriers to satisfy the *uplink data requirement* of each device. Note that the uplink data size of each device is limited in an NP according to the transport block size specified by 3GPP specification [11]. That is, the number of resource units for a device is limited in an NP.

When a device receives a DCI, the device can get a scheduling delay value k_0. There are several scheduling delay values that can be selected by the base station for each device. Then, the device can upload its data starting from subframe $t^c_{k^i_0}$, called *NPUSCH start subframe*. $t^c_{k^i_0}$ is computed based on the following equation [11].

$$t^c_{k^i_0} = k^i_0 + n^p_c, \tag{1}$$

where k^i_0 is i-th scheduling delay value and n^p_c is the last subframe for c-th candidate in p-th NP. As shown in Fig. 1, In this example, we consider the number of NPDCCH repetitions is 2 so that n^p_2 is 4. If the base station selects the first scheduling delay $k^1_0 = 8$ for a device, the device can transmit data starting at NPUSCH subframe $2 + 8 = 10$. If the base station selects the resource unit, 12 tones with 1 ms, and allocates two units for the device, the device should transmit its data at subframe 10-11 with 12 subcarriers, where we set the NPUSCH repetition number is 1 for the device in this example. Note that we assume that the NPUSCH start subframe is not feasible for an NB-IoT device if the NPUSCH start subframe will across the next NP.

B. Problem Formulation

In this paper, we address the uplink resource allocation problem over NB-IoT cellular networks. The objective is to minimize the number of consumed subframes such that each NB-IoT device can transmit its data to the base station. The system model can be formulated as follows.

This paper considers a base station to serve D NB-IoT devices. The number of consumed NPs used to serve D devices is denoted as P. In uplink radio frequency, each subframe has the number of F subcarriers. Device d has to transmit amount of data size ψ_d. The number of NPUSCH repetitions for device d is β_d and the corresponding modulation-coding scheme is M_d. A set of number of resource units that can be allocated to a device is denoted as $I = \{N^1, N^2, ..., N^H\}$. There is a set of resource units $U = \{u_1, u_2, ..., u_\mu\}$. The number of subcarriers and subframes for resource unit u_α is respectively denoted as f_{u_α} and t_{u_α}. The base station has to determine which resource unit should be used for each device and which number of resource units $N^h_{p,d} \in I$ should be allocated to device d in p-th NP. Then, considering number of NPUSCH repetitions β_d and resource unit u_α for device d, the base station has to allocate continuous $N^h_{p,d} \times t_{u_\alpha} \times \beta_d$ NPUSCH subframes with f_{u_α} subcarriers for device d in an NP. When the base station allocates the number of resource units $N^h_{p,d}$ for device d with modulation-coding scheme M_d, the device can upload data size of $\eta(N^h_{p,d}, M_d)$. The number of NPDCCH subframes can be adjusted by parameter R_{max} and the number of candidates is ξ in an NP. The number of NPDCCH repetitions to transmit a DCI is R, where $R = R_{max}/\xi$. n^p_c is the last subframe index for transmitting c-th candidate in p-th NP. We define a binary indicator function $\mathcal{C}^p_{c,d}$. The indicator function is 1 when c-th candidate in p-th NP is allocated to device d, and 0 otherwise. If c-th candidate is allocated to a device, R continuous NPDCCH subframes should be used for the device.

The length of an NP is $L = R_{max} \times G$. The number of NPUSCH subframes is equal to L. We define a binary indicator function $\mathcal{S}^p_{s,d}$. The indicator is 1 when subframe s is allocated to device m in p-th NP, and 0 otherwise. A set of scheduling delay values is represented as $K = \{k^1_0, k^2_0, ..., k^i_0, ..., k^\zeta_0\}$, where ζ is the number of scheduling delay values. When c-th candidate with scheduling delay k^i_0 in p-th NP is allocated to device d, the device can know the last subframe n^p_c for transmitting c-th candidate. Then, device d can upload its data starting from NPUSCH subframe $t^c_{k^i_0}$ based on Equation (1). Because NPUSCH subframes in an NP are located between subframe 1 and subframe L, this paper assumes that $1 \leq t^c_{k^i_0} \leq L$ is feasible. The objective of this paper is to minimize the number of consumed subframes $P \times L$ to serve D devices. The uplink resource allocation is feasible if the following constraints are met:

Resource Constraint: The allocated subcarriers cannot exceed the number of subcarriers in each subframe.

$$\sum_{d=1}^{D} \mathcal{S}^p_{s,d} \times f_{u_\alpha} \leq F, \forall s, p \tag{2}$$

Requirement Constraint: Each device d has to upload the amount of data size ψ_d.

$$\sum_{p=1}^{P} \eta(N^h_{p,d}, M_d) \geq \psi_d, \forall d \tag{3}$$

NPUSCH Repetition Constraint: For upload $\eta(N^h_{p,d}, M_d)$ data size, the base station has to allocate $N^h_{p,d} \times \beta_d \times t_{u_\alpha}$ continuous NPUSCH subframes in an NP when resource unit u_α is used for device d.

$$\sum_{s=1}^{L} \mathcal{S}^p_{s,d} \geq N^h_{p,d} \times \beta_d \times t_{u_\alpha}. \tag{4}$$

Signalling Constraint: Before device d can use NPUSCH subframes in an NP, the device should receive a DCI carried by a series of NPDCCH subframes.

$$\sum_{s=1}^{L} \mathcal{S}^p_{s,d} \geq 1, \text{subject to } \sum_{c=1}^{\xi} \mathcal{C}^p_{c,d} = 1 \tag{5}$$

We now define the NB-IoT uplink resource allocation problem.

Input instance: There is a base station to serve D NB-IoT devices. Each device d has to upload an amount of data size ψ_d with a modulation-coding scheme M_d. Each subframe has the number of F subcarriers. There is a set of resource units $U = \{u_1, u_2, ..., u_\mu\}$. Resource unit u_α occupies the number of sub-carriers and subframes respectively denoted as f_{u_α} and t_{u_α}. The number of subframes in NP is L. The number of NPUSCH repetitions for device d is β_d. In an NP, the number of NPDCCH subframes is R_{max}. We have ξ candidates in an NP and the last subframe for transmitting c-th candidate in p-th NP is n^p_c. The number of NPDCCH repetitions to transmit a DCI is R. There is a set of scheduling delay values K and a set of number of resource units I that can be allocated to a device in an NP. When the base station allocates the number of resource units $N^h_{p,d}$ for device d, the device can upload data size of $\eta(N^h_{p,d}, M_d)$.

Objective: Our objective is to determine that each candidate $\mathcal{C}^p_{c,d}$ with which scheduling delay value should be allocated to each device. Then, the base station should determine that each device should use which resource unit $u_\alpha \in U$ and how many subframes and subcarriers should be allocated to each device such that the number of consumed $P \times L$ subframes is minimized. We state our objective function formally as follows:

$$\min P \times L \tag{6}$$

subject to constraints (2)-(5).

III. Uplink Resource Allocation

A. Resource Allocation Algorithm

In this section, we propose an uplink resource allocation (URA) algorithm for NB-IoT systems to minimize the consumed number of subframes used to satisfy the uplink requirements of all NB-IoT devices. We observe that the used resource unit for uplink transmissions is important in the radio resource utilization. Therefore, the proposed algorithm attempts to use each resource unit to compute the total upload data size of the allocated devices in each NP. We will adopt the resource unit for the devices such that the total upload data size of the devices is maximized in an NP.

Algorithm 1 NB-IoT Scheduling

Input: $D, \beta_m, I, \psi_m, R_{max}, \xi, t^c_{k^i_0}, R, L, S_{max}, K, U, f_{u_\alpha}, t_{u_\alpha}$
Output: $\mathcal{C}^P_{c,d}, \mathcal{S}^P_{s,d}, P, u_\alpha$
1: $P = 1$
2: **while** True **do**
3: MAX = 0
4: **for** $\alpha = 1$ to $|U|$ **do**
5: $T_\alpha = 0$
6: **for** $\varsigma = 1$ to ξ **do**
7: Select_Candidate_and_k^i_0()
8: Select_Device()
9: Allocate_NPUSCHSubframes()
10: **if** $T_\alpha >$ MAX **then**
11: the uplink resource unit used for the allocated devices is updated as u_α in P-th NP and the corresponding outputs, $\mathcal{C}^P_{c,d}$ and $\mathcal{S}^P_{s,d}$, are also updated.
12: MAX $= T_\alpha$
13: **if** $\psi_d = 0, \forall d$ **then**
14: break
15: **else**
16: $P = P + 1$
17: **return** $P, \mathcal{C}^P_{c,d}, \mathcal{S}^P_{s,d}, \forall c, s, d$

The pseudo code of the proposed URA algorithm is shown in Algorithm 1. In Line 1, the number of used NPs for D NB-IoT devices to transmit data is initialized as 1 (i.e., $P = 1$). In an NP, the proposed algorithm will attempt to use each resource unit and we use variable MAX to record the maximum data size that can be transmitted in an NP among all resource units (Lines 3-4). For each resource allocation unit, we try to allocate ξ candidates and we use variable T_α to record the total upload data size of the allocated devices in the NP when resource unit u_α is used (Lines 5-6). Then, the proposed algorithm will execute three procedures to allocate candidates, subframes, and subcarriers to devices (Lines 7-9). When the allocation in an NP is finished, if the total upload data size of the allocated devices is larger than MAX (i.e., $T_\alpha >$ MAX), we will adopt the resource allocation unit for the allocated device in the NP and the corresponding outputs are updated (Lines 10-11). Then, we check whether all devices can obtain uplink radio resources to transmit its data. If all devices are satisfied, the proposed algorithm is terminated (Lines 13-14). Otherwise, the number of NPs is increased by 1 (i.e., $P = P + 1$) (Lines 15-16).

Procedure 1 : Select_Candidate_and_k^i_0
1: **for** $c = 1$ to ξ **do**
2: **for all** $k^i_0 \in K$ **do**
3: **if** $\mathcal{C}^P_{c,d} = 0, \forall d$ and $\sum_{d=1}^{D} \mathcal{S}^P_{t^c_{k^i_0},d} \times f_{u_\alpha} \le F$ **then**
4: $k' = k^i_0$
5: $c' = c$
6: break

Procedure Select_Candidate_and_k^i_0() is designed to select a candidate and a scheduling delay value for a device (Lines 1-6). This procedure will find an available NPUSCH start subframe from all the available candidates and scheduling delay values (Lines 1-2). If candidate c has not been used by any device and there are unused subcarriers at NPUSCH start subframe $t^c_{k^i_0}$ (Line 3), we use this candidate and the scheduling delay value and respectively set $k' = k^i_0$ and $c' = c$ (Lines 4-5). When we find an available NPUSCH start subframe, this procedure is finished.

Procedure 2 : Select_Device
1: max= 0
2: **for** $d = 1$ to D **do**
3: **if** $\psi_d > 0$ and $\mathcal{C}^P_{c,d} = 0, \forall c$ and $\psi_d \times \beta_d > max$ **then**
4: flag = 0
5: **for** $v = 0$ to $t_{u_\alpha} \times \beta_d - 1$ **do**
6: **if** $\sum_{d=1}^{D} \mathcal{S}^P_{t^{c'}_{k'}+v,d} \times f_{u_\alpha} \le F$ and $\mathcal{C}^P_{c',d} = 0$ **then**
7: flag = 1
8: **else**
9: flag = 0
10: break
11: **if** flag = 1 **then**
12: $d' = d$
13: max $= \psi_d \times \beta_d$

In Procedure Select_Device(), we select the device with the maximum requirement to use candidate c' and scheduling delay value k' from all the devices. In Line 1, variable max is used to record the maximum requirement for all devices. If we have not served device d who has data to transmit in the NP and the requirement is larger than variable max (Line 3), we have to check the available radio resources in time and frequency domain can transmit at least one resource unit u_α with NPUSCH repetition β_d (Lines 5-10). If the resources are not sufficient, we will not select this device to use the candidate with the scheduling delay value. Otherwise, we choose device d and set d' as d to record the selected device (Line 12). Variable max is also updated (Line 13).

Procedure Allocate_NPUSCHSubframes() allocates continuous NPUSCH subframes to device d'. In Line 1, variable x is an index used to indicator the currently allocated subframe. In Line 2, variable δ is used to count the number of allocated NPUSCH subframes. In Lines 3-8, we compute the number of resource units required by device d' in the NP. Because the maximum number of resource units can be transmitted is $N^H_{P,d'}$, when the data size $\psi_{d'}$ of the device is larger than $\eta(N^h_{P,d'}, M_{d'})$, the base station only can allocate $N^H_{P,d'}$ resource units to device d'. Therefore, we set $H' = H$ (Lines 8-9). Otherwise, device d' only requires the number of resource units $N^h_{P,d'}$ to be satisfied and we set $H' = h$ (Lines 4-6). In Line 9, h is the index of the number of resource unit $N^h_{p,d'} \in I$ for device d'

While the index of the number of allocated resource units is less than H', counter x is increased by 1 to indicate the

Procedure 3 : Allocate_NPUSCHSubframes

1: $x = -1$
2: $\delta = 0$
3: **for** $h = 1$ to H **do**
4:   **if** $\psi_{d'} \leq \eta(N_{P,d'}^h, M_{d'})$ **then**
5:     $H' = h$
6:     break
7:   **else if** $h = H$ **then**
8:     $H' = H$
9: $h = 0$
10: **while** $h < H'$ **do**
11:   $x = x + 1$
12:   **if** $\sum_{d=1}^{D} \mathcal{S}_{t_{k'}^{c'}+x,d}^{P} \times f_{u_\alpha} \leq F$ and $t_{k'}^{c'} + x \leq L$ **then**
13:     $\delta = \delta + 1$
14:     **if** $\delta = \beta_{d'} \times N_{P,d'}^{(h+1)} \times t_{u_\alpha}$ **then**
15:       $h = h + 1$
16:   **else if** $\sum_{d=1}^{D} \mathcal{S}_{t_{k'}^{c'}+x,d}^{P} \times f_{u_\alpha} > F$ or $t_{k'}^{c'} + x > L$ **then**
17:     break
18: **if** $h \geq 1$ **then**
19:   $\psi_{d'} = \psi_{d'} - \eta(N_{P,d'}^h, M_{d'})$
20:   $T_\alpha = T_\alpha + \eta(N_{P,d'}^h, M_{d'})$
21:   $\mathcal{C}_{c',d'}^{P} = 1$
22:   **for** $x = 0$ to $\beta_{d'} \times N_{P,d'}^h \times t_{u_\alpha} - 1$ **do**
23:     $\mathcal{S}_{t_{k'}^{c'}+x,d'}^{P} = 1$

current allocated subframe (Lines 10-11). If current subframe $t_{k'}^{c'} + x$ has sufficient subcarriers and resides in P-th NP, the number of allocated subframes δ is increased by 1 (Lines 12-13). Otherwise, we terminate the **while** loop (Lines 16-17). If the allocated subframes δ are equal to $\delta = \beta_{d'} \times N_{P,d'}^{(h+1)} \times t_{u_\alpha}$, the device can use the number of resource units $N_{p,d'}^{(h+1)}$ and index h is increased by 1 (Lines 14-15).

When the subframe allocation for device d' is finished, we set the corresponding indicator functions (Lines 19-23). If index $h \geq 1$, device d' can upload data size $\eta(N_{P,d'}^h, M_{d'})$ and the data size $\psi_{d'}$ of device d' can be decreased by $\eta(N_{P,d'}^h, M_{d'})$ (Line 19). The total upload data size T_α is increased by $\eta(N_{P,d'}^h, M_{d'})$ when resource unit u_α is used in the NP (Line 20). Indicator function $\mathcal{C}_{c',d'}^{P}$ is set as 1 (Line 21). Then, the number of continuous $\beta_{d'} \times N_{P,d'}^h \times t_{u_\alpha}$ subframes from the NPUSCH start subframe $t_{k'}^{c'}$ are allocated to device d' (Lines 22-23).

IV. Performance Evaluation

A. Simulation Setups

In this section, we use a simulation based on realistic parameters according to 3GPP specifications. The proposed *uplink resource allocation (URA)* algorithm is compared with a baseline. The baseline only uses a fixed resource unit, 12 tones with 1ms, to serve each device. For using a candidate, the baseline sequentially finds a device who has not been served and satisfied. The other parts of the baseline are the same as our proposed algorithm.

TABLE I
Parameter settings

Parameter	Value
The number of devices	500 ∼ 2000
The upload data size of each device	1 ∼ 125 bytes
The number of subframes in an NP	4096
The number of NPDCCH subframes	256
The number of NPUSCH repetitions	1, 2, 4, 8, 16, 32, 64, or 128
The number of candidates in an NP	8
The number of scheduling values	4

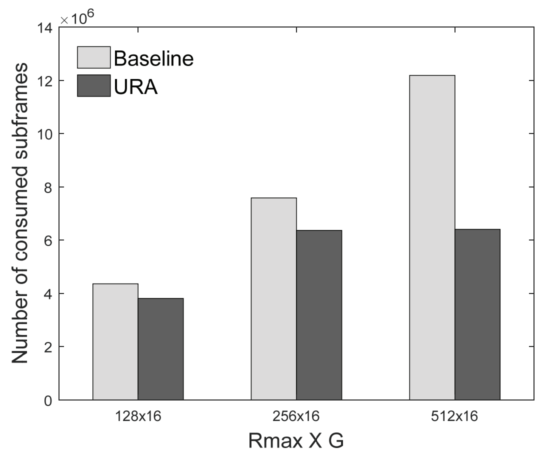

Fig. 2. Impacts of the R_{max} and G on the number of consumed subframes

We set the parameters based on 3GPP specifications for NB-IoT systems [11], [12]. The base station has to serve a number of devices varying from 500 to 2000. The data size of an NB-IoT device is about 125 bytes [6]. Therefore, the upload data size of each device is randomly selected between 1 and 125 bytes. The number of NPUSCH repetitions for a device is randomly selected one of the values, 1, 2, 4, 8, 16, 32, 64, 128. The number of subframes in an NP is set as 4096 (i.e., $R_{max} = 256$ and $G = 16$). R_{max} is the number of NPDCCH subframes. The number of candidates in an NP is set as 8 and the number of NPDCCH repetitions is set as $32 = 256/8$. The number of scheduling delay values is 4. The set of scheduling delay values is $I = \{0, 16, 32, 64\}$ [11]. The set of the numbers of resource units that can be allocated to a device in an NP is $K = \{1, 2, 3, 4, 5, 6, 8, 10\}$ [11]. There are four different resource allocation units, 12 tones (i.e., subcarriers) with 1 ms, 6 tones with 2 ms, 3 tones with 4 ms, single tone with 8 ms.

B. Simulation Results

Fig. 2 demonstrates the impacts of R_{max} and G on the number of consumed subframes under 2000 devices. We can see that our proposed algorithm can reduce more subframes than *baseline* under different NP sizes because our proposed algorithm can adaptively adjust a resource unit for each device to efficiently use radio resources including candidates and NPUSCH subframes. The improvement is more evident when there are more NPUSCH subframes. This is because *baseline*

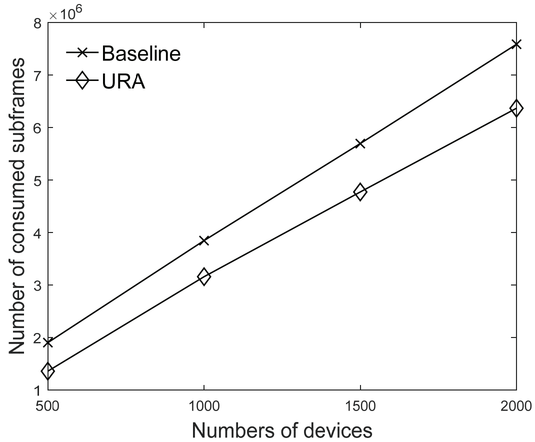

Fig. 3. Impacts of number of devices on the number of consumed subframes

only uses the resource unit, 12 subcarriers with 1ms, for each device so that many NPUSCH subframes are wasted behind the last NPUSCH start subframe. Therefore, when there are more NPUSCH subframes, *baseline* will waste more subframes and our proposed algorithm can adaptively use the resource unit, 1 subcarrier with 8ms, for each device to efficiently use the radio resources. The result also justifies our motivation that the uplink resource allocation to adaptively use the resource units is an important issue for NB-IoT systems. The simulation result shows that our proposed algorithm can reduce more the number of consumed subframes than *baseline* by up to 50%.

Fig. 3 shows the impacts of the number of devices on the number of consumed subframes under $R_{max} = 256$ and $G = 16$. When the number of devices increases, the number of consumed subframes increases. The result is expected because more devices will consume more subframes to upload their data. The proposed algorithm can save more subframes than *baseline* to satisfy the data requirements of all devices because our proposed algorithm can adaptively select a resource unit for each device in each NP. On the other hand, *baseline* always use a fixed resource unit for the devices in each NP such that many candidates and NPUSCH subframes may be wasted. The simulation result shows that *URA* algorithm can reduce more the number of consumed subframes than *baseline* by up to 29%.

V. Conclusion

In this paper, we have studied the uplink resource allocation problem for NB-IoT cellular networks. The objective is to minimize the number of consumed subframes used to satisfy each device's data requirement. We observe that resource unit adaptation is an important issue in NB-IoT uplink radio resource utilization. Then, we formulate the NB-IoT uplink resource allocation problem and propose an uplink resource allocation algorithm to allocate candidates/subframes and determine a resource unit for each device in each NP. The simulation results show that compared with a baseline algorithm, our proposed algorithm can effectively reduce more the number of consumed subframes, especially when there are more NPUSCH subframes.

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