Design of a UE-specific Uplink Scheduler for Narrowband Internet-of-Things (NB-IoT) Systems

+Bing-Zhi Hsieh, +Yu-Hsiang Chao, +Ray-Guang Cheng, and ++Navid Nikaein
+Department of Electronic and Computer Engineering,
National Taiwan University of Science and Technology, Taipei, Taiwan
++Department of Communication Systems, EURECOM, France

Abstract— Narrowband internet-of things (NB-IoT) is a 3GPP standard designed for Internet-of-Things (IoT) application. This paper presents the design consideration and possible options of a UE-specific uplink (UL) scheduler for NB-IoT system. We developed a unitary C emulation platform to verify the effectiveness of the proposed approaches, which is currently under integration within the OpenAirInterface NB-IoT project.

Index Terms— UE-specific uplink scheduler, OpenAirInterface™ (OAI)

I. Introduction

Narrowband internet-of things (NB-IoT) is a new 3GPP standard aiming to support a massive number of low complexity, low power, and low data rate devices in an enhanced coverage area [1]. NB-IoT adopts frequency division duplex (FDD). Both uplink (UL) and downlink (DL) occupy 180 kHz bandwidth [2]. 3GPP supports three coverage enhancement (CE) levels, where each user equipment (UE) can choose a suitable CE level base on its signal quality [3]. A UE with worse signal quality has to select a higher CE level and use more repetitions to compensate the extra signal attenuation.

Figure 1 shows physical channels of NB-IoT and an example showing the time-frequency allocation of the physical channels [4]. The narrowband primary synchronization signal (NPSS) and narrowband secondary synchronization signal (NSSS) are used by a user equipment (UE) to synchronize its frequency and timing with the eNB. The UE acquires master information block (MIB) from narrowband physical broadcast channel (NPBCH) and system information block (SIBs) from narrowband physical downlink control channel (NPDSCH). Narrowband physical random access channel (NPRACH) is used by UEs to transmit preamble during random access procedure. The DL and UL data packet are carried by narrowband physical downlink shared channel (NPDSCH) and narrowband physical uplink shared channel (NPUSCH), respectively. NPUSCH may support single-tone and multi-tone (i.e., 3, 6, and 12 tones are supported) transmissions. Each tone occupies 15 kHz bandwidth. A base station (i.e., eNB) uses a downlink control information (DCI) to specify the resource blocks allocation in NB-IoT [5]. The UL DCI and DL DCI are used to identify the resource allocation in NPDSCH and NPUSCH, respectively. Both UL and DL DCIs are carried in narrowband physical downlink control channel (NPDCCH). In each NPDCCH, a maximum of 8 DCIs can be transported, and each UE can receive up to one DCI. The time interval between two successive NPDCCH opportunities is referred as a NPDCCH period (PP). Each UE will be assigned by a UE-specific PP based on the chosen CE level during radio resource control (RRC) connection establishment procedure [3]. In general, a higher CE level may set a longer PP since a higher repetition is used.

The eNB uses UL DCI to indicate the dimension of a resource block allocated in NPUSCH. As illustrated in Fig. 1, a resource block is determined in terms of a scheduling delay indicating the starting time of the allocated resource; a number of tones allocated in frequency domain; and a transmission duration reserved in time domain [6]. In NB-IoT, the modulation coding scheme (MCS) used for a UE in downlink can be determined based on the CE level chosen by the UE and the power header room (PHR) reported by the UE during initial random access [7].

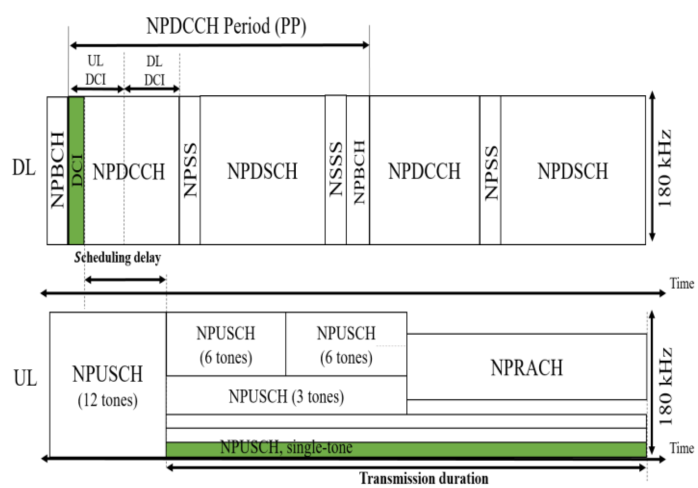

Fig.1 Timing diagram of NB-IoT physical channels [9]

Several works have been presented in designing an NB-IoT system. A preliminary system design of NB-IoT is given in [4]. One of the design targets is to reduce complexity. The link adaptation for NB-IoT is presented [9]. The authors proposed a link adaptation for NB-IoT to improve transmission time and resource utilization of uplink scheduling. Issues and solution for NB-IoT downlink scheduling are summarized in [10]. The authors presented potential solutions for resource allocation in

NB-IoT downlink scheduling. To the best of our knowledge, this is the first work addresses the UL scheduling of NB-IoT.

In this paper, we introduce the design of the UL scheduling algorithm for the UE-specific scheduler. The issues of timing management, NPDCCH allocation for multiple CE levels, and subcarrier allocation in NPUSCH of the UL scheduler are addressed. A proof-of-concept UL scheduler is developed in the context of OpenAirInterface NB-IOT project, and its performance is evaluated under three representative scenarios.

II. System Model

This paper considers an NB-IoT system containing three CE levels as shown in Fig. 2. Let $m_{i,j}$ be the jth UE in CE level i ($i \in \{0,1,2\}$). During communication, UE $m_{i,j}$ will transmit a buffer status report (BSR) to indicate the number of packets to be transmitted to the eNB. The MAC scheduler uses a DCI on NPDCCH to inform the UE the timing and subcarriers in NPUSCH reserved for transmitting its UL data. We consider a single tone example to demonstrate the operation of UL scheduler. Note that the NPDCCH resource is shared by UL DCIs and DL DCIs. For simplicity, it is assumed that up to half of the NPDCCH resources is used to transmit UL DCIs. In the implementation, we can dynamically adjust the allocated resource based on the expected offered load of UL and DL traffic.

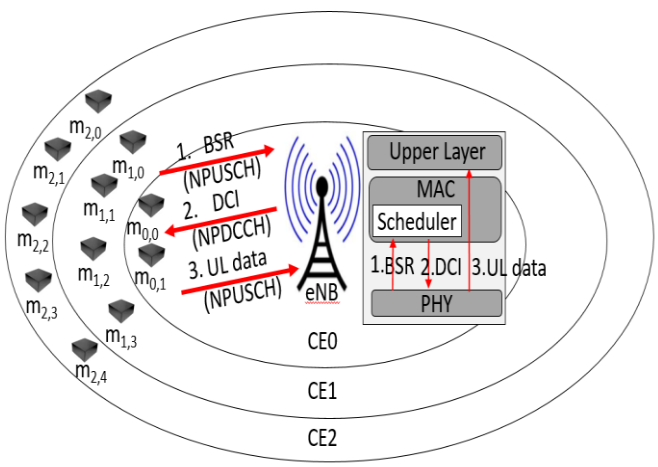

Fig. 2 NB-IoT system architecture

Let UE_List[i] be the structure that stores UEs (UE's scheduling input) in CE level i; BS[m] be the buffer size mapped from BSR for the m^{th} UE [7]; Ta[m] be the arrival time of first UL transmission for m^{th} UE; Round[m] be the retransmission times for the m^{th} UE; DCI_List be the structure to store UE's scheduling output; $T_{DCISt}[m]$ be the starting time of DCI for the m^{th} UE; $T_{DCIEt}[m]$ be the end time of DCI for the m^{th} UE; $I_{Delay}[m]$ be the scheduling delay for the mth UE, which is the time difference between $T_{DCIEt}[m]$ and the starting time of NPUSCH; and $I_{sc}[m]$ be the subcarrier indication for the m^{th} UE showing its frequency location of NPUSCH; and $I_{RU}[m]$ be the number of used resource unit for the m^{th} UE indicating its transmission duration on NPUSCH, Round[m] and Ta[m] are used to determine the transmission order of packets from UEs in UE_List[i]. Note that NPRACH shares the same channels with NPUSCH. Therefore, the eNB has to reserve resources for NPRACH base on the NPRACH configuration [11] in UL channel.

In this work, the UL resource utilization, system processing time and average delay are selected as the performance metrics. The UL resource utilization is the ratio of used resource element by devices to the total available resource element. The average delay is the average time (Unit: sub-frame) of UEs spend to complete all their UL data transmissions, starting from the first UL data transmission. The average delay is calculated for all CE levels together.

III. NB-IoT UL Scheduler

In April 2017, an NB-IoT project is launched in the open source community of OpenAirInterface™ (OAI). This project aims at developing a software-defined-radio-based NB-IoT eNB. Before going into details, we briefly introduce the main procedures adopted in the MAC scheduler in an OAI NB-IoT system. In OAI, the physical layer generates an UL indication to the MAC scheduler every subframe (i.e., 1 ms). The MAC scheduler consists of four main procedures: MIB/SIB1 scheduling, SIBs scheduling, common scheduling, and UE-specific scheduling. The MIB/SIB1 scheduling procedures are responsible for scheduling MIB-NB and SIB1-NB. Indicatively, they can be triggered once every 640 ms and 2560 ms for MIB-NB and SIB1-NB, respectively [8]. The SIBs scheduling procedure is responsible for scheduling of all the SIBs-NB with the exception of SIB1-NB. The SIBs scheduling procedure is triggered based on the periods of SIBs-NB configured in SIB1-NB. The common scheduling procedure is responsible for scheduling random access and paging messages. The common scheduling procedure is triggered whenever it receives an indication of a preamble transmission in NPRACH from the physical layer or a paging message from the RRC layer. The UE-specific scheduling procedure is responsible for scheduling the transmission of UL and DL data packets from all UEs. It is triggered once in every UE-specific PP.

Figure 3 shows a flowchart illustrating the operation of the UE-specific UL scheduler. First of all, the transmission order of packets from different UEs in a UE-specific PP is determined. The retransmitted UEs are first scheduled and the rest of the UEs are scheduled based on the arrival time of the packets from the radio link control (RLC) layer following first-come-first-served queuing policy. For each UE, the UL scheduler executes 'NPDCCH resource allocation' procedure to allocate the resource for the UL DCI on NPDCCH; execute 'NPUSCH resource allocation' procedures to allocate resource blocks in PUSCH for UL data transmission; and calculate the scheduling delay between UL DCI and starting time of UL data transmission (i.e., k_0) to fill in the UL DCI [7]. The procedure repeats until the resource on NPDCCH is exhausted.

In this section, the design of an NB-IoT UL scheduler is presented. The timing management of DL subframe will be elaborated in Sec. III A. Sec. III B addresses the issue related to NPDCCH allocation for multiple CE levels. The impact of the length of PP on the performance of the NB-IoT system will also be addressed.

A. Timing Management

In NB-IoT, UL DCI can only be transmitted on specific *DL subframes*. The *DL subframe* excludes subframes reserved for the transmission of the downlink broadcasting information (i.e. NPSS/NSSS/NPBCH/NB-SIB1 and the other SIBs) [6]. Hence, the UL scheduler has to keep a list to manage the timing of *DL subframes*. A simple method to indicate the status of a DL subframe is to create a bitmap to indicate the availability of each subframe. The length of the bitmap depends on the periodicity of NPSS/NSSS/NPBCH/ NB-SIB1 and the other SIBs. The occupied subframe is marked by '0' and the available subframe is marked by '1.'

The downlink broadcasting information is transmitted periodically every 2560 *ms*. In the implementation, we use a timing management bitmap to indicate the location of the downlink broadcasting message in each subframe. The timing management bitmap can then be obtained by performing an 'AND' operation to two bitmaps. The first bitmap indicates the fixed locations of NPSS/NSSS/NPBCH/NB-SIB1 subframes. The second bitmap is to indicate the configurable locations of the other SIBs' based on the information provided by SIB1.

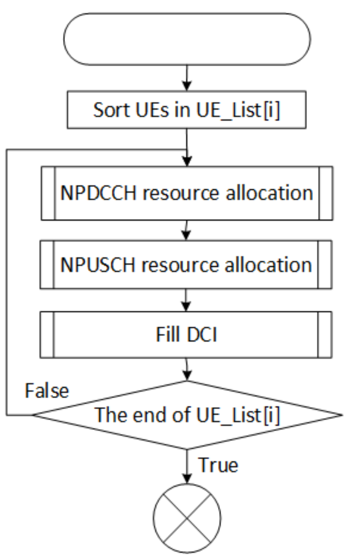

Fig. 3 The flowchart of the UE-specific UL scheduler

B. NPDCCH allocation for multiple CE levels

The UE-specific PP can be divided into two parts. The first part is reserved for NPDCCH and the second part is used by NPUSCH. In our implementation, the UL scheduling is executed at the last subframe of the previous UE-specific PP (see Fig. 1). The UE-specific PP can be set for each UE based on its CE level or QoS requirement. For simplicity, we let the length of UE-specific PP for the same CE level be identical for all UEs. Therefore, the eNB can schedule all UEs in the same CE level together without considering the repetition of each UE. The benefit of this approach is the low complexity and simplicity at the cost of inflexibility. It's more suitable for UEs with homogeneous traffic. The eNB has to determine the scheduling order of UEs from different CE level if the NPDCCH part of UE-specific PP from two or three CE levels overlap. Two methods are presented to determine the scheduling order of the three CE levels. In the first method, the UEs in CE level 0 will be scheduled first and UEs in CE level 2 will be scheduled at last. The second method is opposite to the first one, the scheduling order for the UEs is from CE level 2 to CE level 0. Note that UEs in higher CE level normally occupy more resource due to a large number of repetitions. Hence, the two methods are considered as a trade-off between the resource utilization and the scheduling delay. Note that

C. Subcarrier allocation in NPUSCH

In NB-IoT UL transmission, there are 12 subcarriers in the frequency domain and 4 different scheduling delay options in the time domain. The eNB has to specify the subcarrier indication and a selected scheduling delay in UL DCI such that the UE can start its UL transmission. In NB-IoT, a two-bit field of k_0 is used to indicate the scheduling delay between UL DCI and the resource reserved for the UL data transmission. The possible values of k_0 are 8, 16, 32, and 64. Two methods are presented. In the first method, the scheduler allocates subcarrier(s) to each UE based on a given scheduling delay k_0. The shortest scheduling delay is chosen first and the subcarrier is then allocated from a lower value to a higher value based on the required resource of a UE. In case that the remaining resource is not good enough to support the chosen UE, a longer scheduling delay will be chosen. The process repeats until all of the four scheduling delays and the subcarrier(s) cannot meet the requirement of the UE. In the second method, we first allocate subcarrier(s) to the UE based on its resource demand and then find the minimum scheduling delay that can satisfy the subcarrier allocation. The eNB will allocate next available subcarrier and determine the minimum scheduling delay if none of the scheduling delay can be used in the current subcarrier allocation.

IV. Simulation Results

We developed a unitary C emulation platform to verify the effectiveness of the proposed approaches, which is currently under integration within the OpenAirInterface NB-IOT project.

The traffic model defined in 3GPP TS 45.820 [12] was used. In the simulation, the number of NB-IoT devices was set to be 60, the average number of UL traffic report was set to be 20/sec, and payload size of each device ranges from 20 to 200 bytes, and the success probability of each UL transmission was set to be 90%. In the simulations, each point represented the average value of 10000 samples. Each sample was obtained by (observing the interval) from the 1st UL transmission to the end of UL transmission.

Three scenarios are considered in the simulations. Scenario A is designed to investigate the impact of PP length on the average delay and resource utilization. Scenario B is designed to decide the scheduling order of PP for different CE level when these PPs overlapped. Scenario C is designed to compare the impact of two subcarrier allocation schemes on the utilization of NPUSCH resource. In this paper, we assumed that the starting points of the UE-specific PPs for the three CE levels are synchronous. Hence, all three CE levels share a common search space and the eNB has to decide how to prioritize the transmission order of UEs for different PP.

A. Impact of PP Length

Two cases are considered in Scenario A. In case 1, we set the UE-specific PPs of CE level 0, 1, and 2 to be 64, 128, and 256, respectively. In case 2, the UE-specific PPs of CE level 0, 1, and 2 are set to be 32, 64, and 128, respectively. The UE-specific PP for each CE level in case 2 is shorter than those in case 1. Fig. 4 shows the average delay for an UE. It can be found in Fig. 4 that case 2 has a lower average delay than case 1. It is because the receiving time of a DCI for a UE decreases as the length of PP decreases. This result verifies a shorter PP will get a lower average delay. The resource utilization for both cases is shown in Fig. 5. It is shown that the resource utilization in the two cases are both increased as the payload size increases. It can also be found that a shorter PP has a higher resource utilization than that of a longer PP since there are more DCIs in the same time interval if a shorter PP is adopted. It seems that shorten the PP may achieve a better performance. However, it is noted that the utilization may also depend on the number of repetitions to be used in each CE level. In this preliminary study, the payload length and repetitions are not big enough and thus, the resource is not highly utilized. As the number of repetition or the payload size increase, the situation may be changed. We will leave it as our future work.

B. Sorting Strategy

Figures 6 and 7 show the performance comparison of the two proposed sorting strategies. When the PP of three CE levels start at the same time. In sorting 1, the lower CE level has the higher priority to be scheduled. In sorting 2, the higher CE level has the higher priority to be scheduled. We apply these two sorting policies respectively to our simulation. From Fig. 6, sorting 1 has the lower average delay than sorting 2. Also, Fig. 7 shows that the resource utilization in sorting 2 is higher than in sorting 1. Therefore, sorting 2 outperforms the sorting 1. The reason is that the lower CE level has a shorter PP. A short PP tends to result in non-contiguous resource in NPUSCH. Hence, it might leave many small resources unused if we first schedule the UEs from the lowest CE level. As the resource is first allocated to UEs from lowest CE levels, the remaining resource may not be sufficient to support UEs from higher CE levels since they normally require a big amount of resource due to high repetition. Later, there might be a lot of resources wasted. Because the lower CE level may have already finished their scheduling process.

C. Consideration of NPUSCH resource allocation

As mentioned in III, there are two different orders when doing NPUSCH resource allocation. Fig. 8 shows the average delay of the two orders. In case 1, the scheduler allocates subcarrier(s) to each UE based on a given scheduling delay. In case 2, we select the subcarrier(s) first and then find the minimum scheduling delay based on the subcarrier allocation. We can see that case 1 has a slightly lower average delay than case 2. Although their resource utilization are quite close, this approach has a better performance. It is because the gap between the 4 scheduling delay options are quite big. In case 2 the scheduler has to keep adding scheduling delay to find an available subframe. This cause the resource utilization decreases. This result provides a useful technic when doing an implementation.

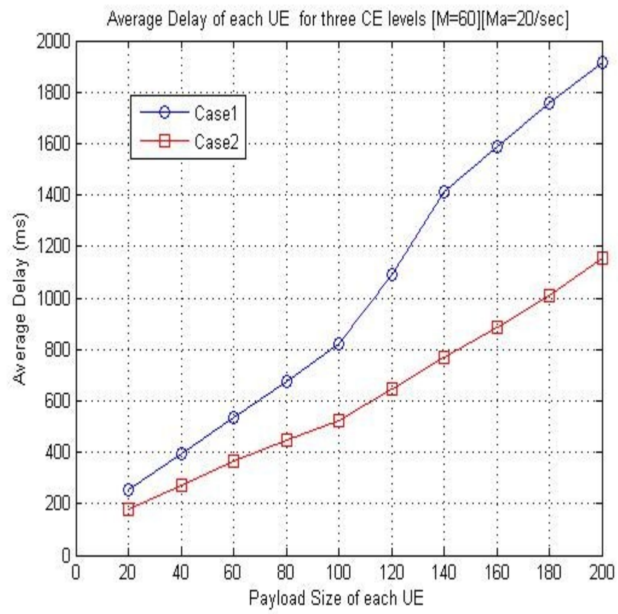

Fig. 4 Average delay for two PP settings

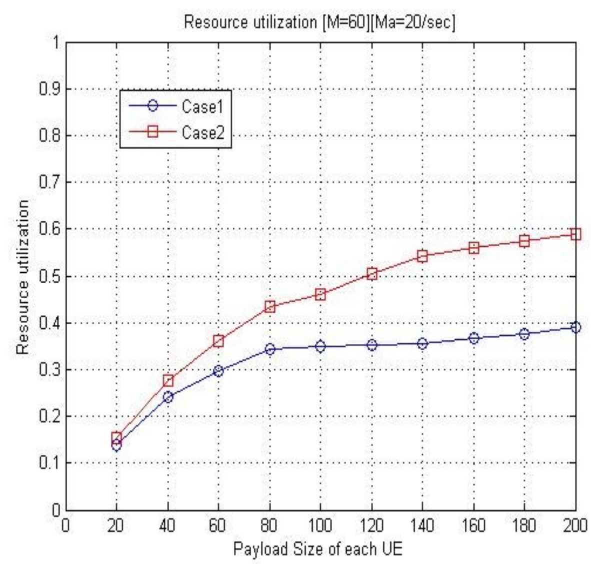

Fig. 5 Resource utilization for two PP settings

V. CONCLUSION

NB-IoT is designed to support massive low complexity machine devices in a wide area. This paper presents a basic NB-IoT UL scheduler to investigate the improvement of the processing time, average delay, and resource utilization. It is found that the selection of a shorter UE-Specific PP may reduce the average delay of UE and increase resource utilization of the system. It may be beneficial to schedule UEs from the higher CE level to maximize the resource utilization but at the cost of increasing access delay. It is also shown that it is better to determine the scheduling delay k_0 first and then allocate the subcarrier(s).

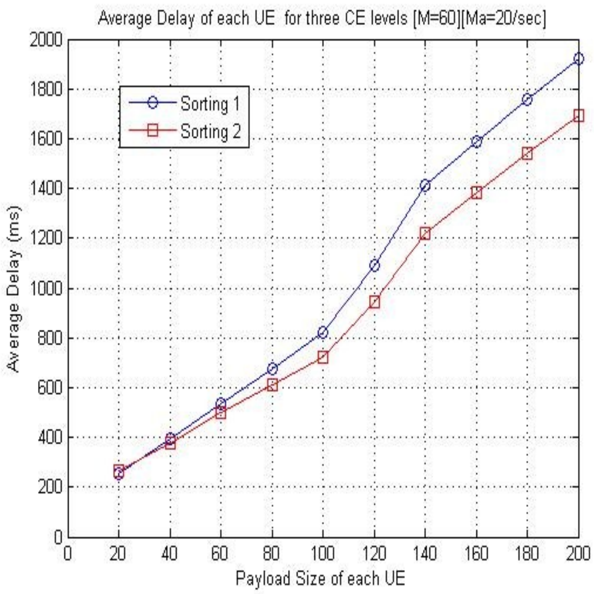

Fig. 6 Average delay for two sorting strategies

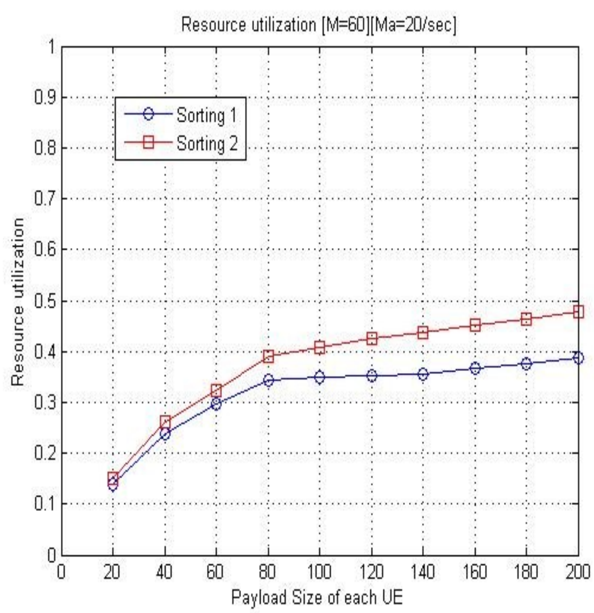

Fig. 7 Resource utilization for two sorting strategies

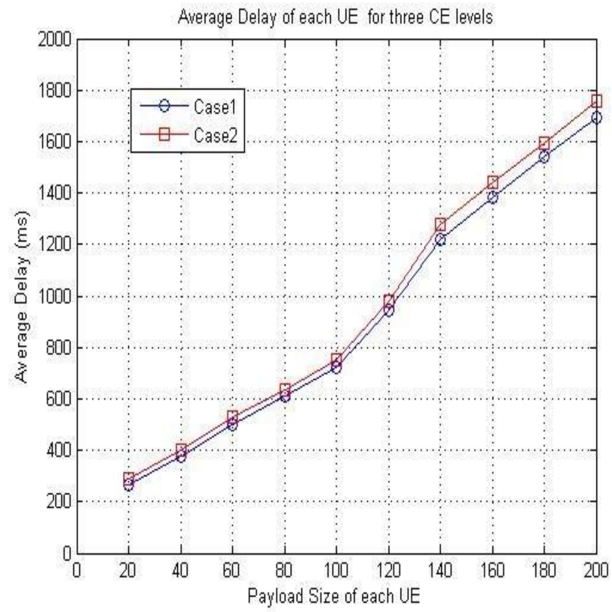

Fig. 8 Average delay for two different orders

REFERENCES

[1] N. Mangalvedhe, R. Ratasuk and A. Ghosh, "NB-IoT deployment study for low power wide area cellular IoT," *IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, Valencia, 2016, pp. 1-6.

[2] Y.-P. E. Wang, X. Lin, A. Adhikary, A. Grövlen, Y. Sui, Y. Blankenship, J. Bergman, and H. S. Razaghi, "A primer on 3GPP narrowband Internet of Things (NB-IoT)," *IEEE Communications Magazine*, vol. 55, no. 3, pp. 117-123, Mar. 2017.

[3] 3GPP TS 36.331, "Radio resource control (RRC) protocol specification," V14.1.0, Dec. 2016.

[4] R. Ratasuk, B. Vejlgaard, N. Mangalvedhe and A. Ghosh, "NB-IoT system for M2M communication," *IEEE Wireless Communications and Networking Conference*, Doha, 2016, pp. 1-5.

[5] Rohde & Schwarz, "Narrowband Internet of things whitepaper," 2016.

[6] 3GPP TS 36.213, "Physical layer procedures," V13.1.0, Nov. 2015.

[7] 3GPP TS 36.321, "Medium access control (MAC) protocol specification," V13.2.0, Jun. 2016.

[8] Small Cell Forum, "FAPI and nFAPI specifications," May. 2017.

[9] C. Yu, L. Yu, Y. Wu, Y. He and Q. Lu, "Uplink scheduling and link adaptation for narrowband Internet of Things systems," *IEEE Access*, vol. 5, pp. 1724-1734, March 2017.

[10] R. Boisguene, S. C. Tseng, C. W. Huang and P. Lin, "A survey on NB-IoT downlink scheduling: Issues and potential solutions," *2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC)*, Valencia, Spain, 2017, pp. 547-551.

[11] 3GPP TS 36.211, "Physical channels and modulation," V13.1.0, Nov. 2015.

[12] 3GPP TS 45.820, "Cellular system support for ultra-low complexity and low throughput Internet of Things (CIoT)," V13.1.0, Nov. 2015.