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Control Channel Load Balancing in Narrow Band Cellular IoT Systems Supporting Coverage Class

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***Abstract*—In order to support various Internet of Things (IoT) services, 3GPP is working to standardize cellular IoT (CIoT) systems based on the existing GSM & GPRS networks. CIoT systems are aiming to support the massive number of devices, extend the network coverage, and improve the battery life of IoT devices. Furthermore, in order to support more than 50,000 CIoT devices, CIoT systems categorize the devices with different coverage classes and manage control and data channels. However, as a massive number of devices will be deployed in system coverage, traffic loads for each coverage class might be unequal and difficult to release the traffic overload. To solve this problem, in this paper, we propose a novel load balancing scheme for control channel in the CIoT systems. Simulation results show that the proposed scheme can accommodate system loads quickly and effectively.**

***Keywords*–cellular IoT; NB-CIoT; coverage class; load balancing; control channel resource management;**

Figure 1. The Example of IoT Service

I. Introduction

By sharing information to a lot of interconnected devices, internet of things (IoT) can provide the new paradigm for the future industry. With the massive connectivity through network technology, IoT can offer various services such as smart grid, health care, and smart logistics service, and so on. According to the Cisco report, it is expected that the number of connected device will be 21 billion and demand in data traffic will be increased up to 1.6 Zeta Byte by 2018 and Internet Data Corportation (IDC) expects that worldwide IoT market will increase to $ 7.1 trillion by 2020 [1].

In order to provide IoT Services, improved network system is required to gather huge information originating from a large-scale devices. In existing IoT technologies, communication techniques using the unlicensed band such as Bluetooth, WiFi, and Zigbee are mainly considered for the IoT service scenario. However, as IoT service area is broaden by considering metering, logistics tracking, water quality measuring and fire monitoring services as shown in Fig. 1, IoT service requires reliable wide area communications based on licensed-band are considered to provide reliable connectivity [2], [3]. As one of candidate solutions, existing cellular network based IoT Communications has been interested to various manufactures and network operators [4].

3GPP gsm/edge radio access network (GERAN) has standardized general packet radio service (GPRS) based IoT Communication systems as a name of Cellular IoT [5], [6]. In order to meet various service scenarios, CIoT Systems have various requirements as follows. CIoT systems require to support massive devices (more than 50,000) per cell and should extend its coverage to provide reliable connectivity for the massive devices. IoT devices are supported to be located at remote regions and can operate continuously for longer periods. Moreover, CIoT systems also need to improve the battery life time by reducing the power consumption of the devise [7] - [10]. In the CIoT services scenario considered in 3GPP GERAN, massive CIoT devices can be connected to a single cell. These massive triggers from CIoT devices cause large traffic loads to CIoT systems for maintaining the connection and transmitting data. In this paper, in order to solve this excessive overload issue, we propose a mechanism which can adjust radio resources for each coverage classes according to their expected loads. The remainders of this paper is organized as follows. In Section 2, we give background information on coverage class and random access procedure for CIoT. The proposed scheme is

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explained in Section 3, and its performance is evaluated in Section 4. Finally, we conclude the paper in Section 5.

II. PRELIMINARY

Cellular IoT has been discussed in the recent 3GPP standardization meeting. Especially, 3GPP GERAN introduce narrowband-cellular internet-of-things (NB-CIoT), which is a new clean slate solution based on GSM & GPRS for optimizing for IoT communications [10]. NB-CIoT can overcome the CIoT challenges such as poor coverage, low cost, battery life, and limited connection. The NB-CIoT physical layer only uses a minimum system bandwidth of 200 kHz on both downlink and uplink. Therefore, NB-CIoT takes 20dB coverage gain compare to GSM by using power spectrum density (PSD) and has a compatibility with stand-alone deployment in a low minimum system bandwidth in order to support a various deployment options, including GSM and LTE [11]. In order to handle massive number of devices and reduce power consumption, NB-CIoT introduces the coverage class for efficient management of the massive devices depending on the received signal quality of devices. In NB-CIoT random access is operated as coverage class [7]-[9]. In this Section, we give the backgrounds on coverage class and random access.

A. Coverage Class

Coverage class is a way to manage for ensuring the downlink and uplink coverage of IoT devices. The IoT devices with better coupling loss than the worst case can benefit from improved battery life and lower latency, and the network in terms of improved capacity. Multiple coverage classes support for device to be adapted to different path and penetration losses experienced by the IoT device. In the NB-CIoT system, cell coverage is divided by coverage class 1 to 4, according to signal strength. The best case is assigned to coverage class 1 and the worst case is assigned to coverage class 4. Depending on coverage class, NB-CIoT system differentially allocates the radio resources and configure the modulation coding scheme (MCS) and repetition level to devices [10].

1) PDCCH Structure for Coverage Class: In the NB-CIoT system, A frame is divided into 8 subframes of equal duration. Odd-number subframes can include the PDCCH as shown in Fig. 2. The overall PDCCH resources in the sub-frame are segmented into coverage class blocks for multiple coverage classes, and then further divided into PDCCH message resource blocks for carrying multiple PDCCH messages. The overall PDCCH resources occupies a number of subcarriers. One frame can carry not only data but also control information such as 78 PDCCH messages. Totally PDCCH messages of coverage class 1 and 2 are transmitted in every odd-numbered subframe without repetition, and each PDCCH message carries 7 messages of coverage class 2 and 10 messages of coverage class 1. On the other hand, PDCCH messages of coverage class 3 and 4 are transmitted with two bursts to overcome signal attenuation. Fig. 3 shows the resource allocation and capacity of each coverage class.

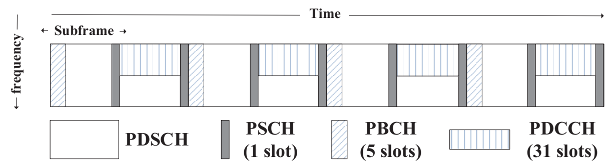

Figure 2. Downlink Frame Structure of NB-CIoT

2) PDCCH scheduling: The base station (BS) uses the PDCCH to schedule downlink and uplink transmissions for sending not only data but also control information such as random access channel (RACH) response, and paging messages. In order to encode and decode, according to coverage class, both BS and IoT devices should know coverage class information of device. PDCCH messages is indicated by the PDCCH configuration field in system information (SI) message in the physical broadcasting channel (PBCH). After receiving SI message after synchronizing with the BS, the SI indicate the details of the structure of PDCCH for each coverage class in each subframe. The devices receive the PDCCH message on the PDCCH corresponding to its coverage class. PDCCH message provides the timing and subcarriers for a downlink allocation or uplink allocation.

3) Initial Coverage Class Selection: In order to decode and encode PDCCH message independently via coverage class, IoT devices have to select initial coverage class when they attach the network. A procedure for the initial coverage class selection is divided with four steps. First, IoT devices perform measurements on downlink pilot

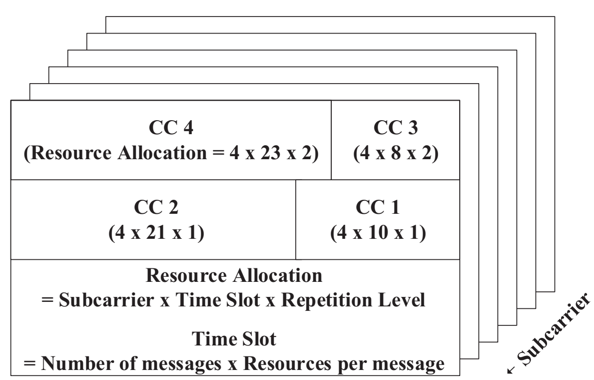

Figure 3. Resource Allocation Structure based on Coverage Class in the PDCCH Subframe

signals and primary synchronization signal (PSS) and secondary synchronization signal (SSS) contained in physical synchronization channel (PSCH). As reading the system information from the PBCH, IoT devices acquire the PDCCH configuration. Then, IoT devices select a candidate coverage class as the most probable class based on measurement result from the first step. And then, IoT devices try to decode the PDCCH messages with the selected coverage class level. If IoT devices fail to decode the PDCCH message more than criteria value, they will change the candidate coverage class one to lower coverage class one or trigger cell (re)selection.

4) Coverage Class Adaption: When radio link quality is changed or IoT devices fail to receive the message from the BS more than predefined number, IoT devices which select candidate coverage class in the above procedure need to update the coverage class index. Especially, when IoT devices move from lower coverage class region to higher coverage class region, IoT devices have to adjust the coverage class for decoding the PDCCH message. This is because IoT devices which move from lower coverage class to higher coverage class will fail to decode the PDCCH message. These IoT devices try to decode PDCCH message until reaching the predefined criteria, it causes unnecessary power consumption. In the Idle mode, IoT devices periodically wake up and listen the paging message on PDCCH. If IoT devices fail to decoding the message more than predefined criteria from the BS, IoT devices adjust the coverage class. Similarly, in the connected mode, IoT devices try to decode the resource allocation for checking scheduling information. With multiple decoding failure, IoT devices adjust the coverage class index from lower coverage class to higher coverage class and report new coverage class to the BS. Through the repetition the above procedure, IoT devices adjust to appropriate coverage class index which can receive the PDCCH message.

B. Random Access Procedure for NB-CIoT

Random access is the initial procedure for a device to connect to the network. IoT devices can access the network with a random number or valid cell radio network temporary identifier (C-RNTI) for avoiding the collision. When the IoT devices in the Idle mode, IoT devices initiate a random access procedure with a random number. Otherwise, IoT devices initiate a random access procedure with a C-RNTI. The random access procedure with random number is shown in Fig. 4. In this section, we give the detail of random access procedure for GERAN NB-CIoT [10] - [13].

In the NB-CIoT system, RACH resources are statically scheduled using system information broadcast. Different RACH resources are also allocated for each coverage class. The IoT devices choose a RACH allocation based on net-

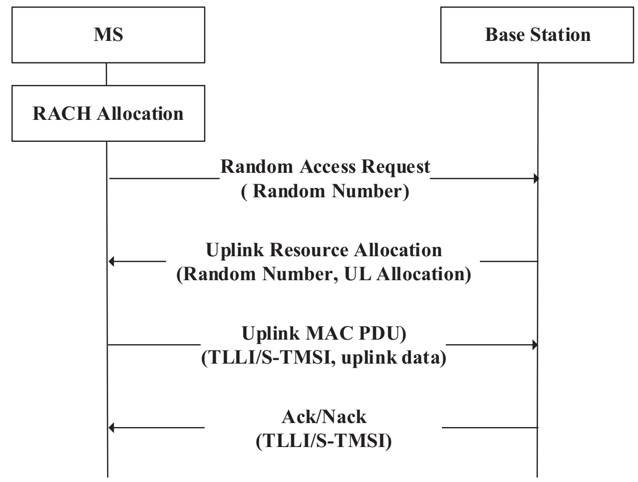

Figure 4. Random Access Procedure with Random Number

work indication, configuration, or desired coverage class. After selecting a RACH resource to use, IoT devices start random access procedure. IoT devices transmits a Random Access Request message to the BS to initiate the random access procedure with random number. random access request message includes the information such as random number, access cause, and coverage class for PDCCH. After transmitting a random access request message to the BS, IoT devices start to monitor PDCCH for a response for the BS.

When the BS receives a random access request message, BS responds with an uplink resource allocation PDCCH message containing random number transmitted in the IoT devices and RACH resource identification of the RACH resource. IoT devices which monitor the PDCCH can identify the RACH resource by matching the random number and RACH resource identification. Then IoT devices respond the BS with uplink medium access channel protocol data unit (MAC PDU) which contains its identify (e.g. temporary logical link identifier (TLLI) or SAE-temporary mobile subscriber identifier (S-TMSI)) and higher layer data or signaling in the uplink allocation. After sending the MAC PDU, IoT devices keep to monitor the PDCCH for receiving the acknowledge (ACK) or negative-acknowledge (NACK) from the BS. Otherwise, IoT devices continue to decode the PDCCH messages for acquiring the response from the BS.

The ACK&NACK message confirms reception of the uplink MAC PDU containing the IoT devices identity. The IoT devices verify the received ACK/NACK message contents and compare to information which IoT devices send to BS. If the verification information matches with the information of the uplink packet, IoT devices confirm that BS received Uplink MAC PDU which IoT devices send, then contention resolution has been completed successfully. Otherwise, IoT devices continue to monitor PDCCH.

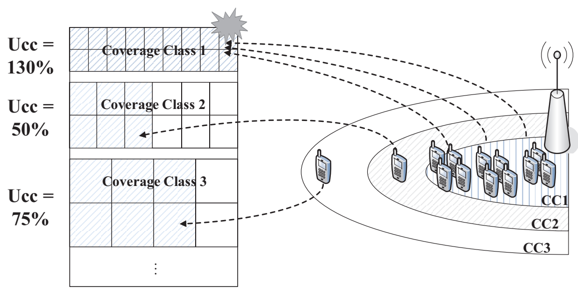

Figure 5. Congestion of PDCCH Corresponding to Covereage Class 1

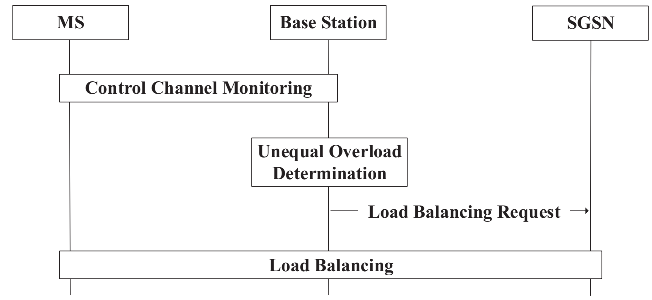

Figure 6. Message Flow for Control Channel Load Balancing

If IoT devices do not received ACK/NACK message containing their information for a period of timer, IoT devices determine that the random access procedure fails, then wait for a period of time before transmitting another Random Access Request message. In this case, IoT devices may increase the transmit power or switch to a different coverage class.

III. Proposed Scheme

A. Problem Statement

Depending on IoT service scenario, IoT devices generally have long discontinuous reception (DRX) cycle compare with that of legacy devices. During the DRX cycle, the coverage class of IoT devices may be changed if these devices move to another location. In this case, there are mismatches between the coverage classes actually experienced by IoT device and those registered by NB-CIoT system. Especially, when IoT devices move from a location having good channel condition to a location with poor channel conditions, the coverage class of IoT devices will change from lower to higher coverage class. Such cases will result in message transmission failure on downlink and uplink control channel, it is because the MCS level of IoT device is lower than predefined MCS level for higher coverage class.

According to IoT service scenario, IoT devices can be located in a certain building or factory. In addition, IoT devices can periodically trigger the network. For example, they can regularly report the measured results to the network on hourly or daily basis. Depending on the distribution of IoT devices in the cell coverage and traffic generation status, the traffic load might be concentrated in a specific coverage class. Therefore, the NB-CIoT system which manages control channel resources by using each coverage class may cause imbalance of traffic load on the PDCCH of each coverage class. Fig. 5 describes an example that the congestion of PDCCH corresponding to coverage class 1.

B. Control Channel Load Balancing

As massive number of devices are deployed in the NB-CIoT system, traffic loads on PDCCH for each coverage class might be unequal and it is difficult to distribute the traffic overload. To solve the problem, we propose a novel load balancing scheme for PDCCH and RACH in the NB-CIoT system. When load congestion occurs in the coverage class, BS dynamically adjusts configuration related to the ratio of resource volumes within coverage class.

Fig. 6 shows the message flow for the proposed scheme. Before SGSN determines whether control channel load balancing is required or not, BS estimates radio resource utilization for each coverage class. We define the radio resource utilization for coverage class i (U_{cc_i}) which is the ratio of required radio resources to total radio resources. U_{cc_i} is defined as $U_{cc_i} = \frac{R_{required_i}}{R_{total}}$, where R_{total} is the total number of PDCCH message blocks transmitting a PDCCH message, and $R_{required_i}$ is the sum of requested PDCCH message blocks in coverage class i for IoT devices to receive paging and random access response. Based on the estimated U_{cc_i}, BS determines the state of load and congestion on PDCCH by using predefined criteria. In this case, BS can estimate U_{cc_i} in every frame or every subframe basis, depending on the setting of the network operator. Once the BS successfully determines the overload condition then it sends the load balancing request message to the SGSN.

As first the proposed scheme dynamically allocates the

TABLE I
Configuration for Dynamic Channel Allocation

			# of PDCCH message			
$U_{cc_i}\_max$	$U_{cc_i}\_min$	$U_{cc_i}\_min2$	CC1	CC2	CC3	CC4
cc1	cc2		+3	-1		
	cc3		+2		-1	
	cc4		+18	+1	+1	-1
cc2	cc1		-3	+1		
	cc3			+2	-3	
	cc4	cc1	+4	+5	+2	-1
		cc3	+6	+5	+1	-1
cc3	cc1		-2		+1	
	cc2			-2	+3	
	cc4	cc1	+10	+1	+5	-1
		cc2	+1	+4	+5	-1
cc4	cc1		-10	-3	-2	1
	cc2		-6	-5	-1	+1
	cc3		-5	-4	-3	+1

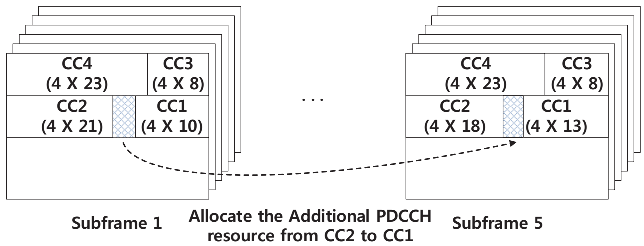

Figure 7. Dynamic Channel Allocation

radio resources according to U_{cc_i} by using configuration field of primary SI message in the PBCH. In order to use this method, a predefine multiple configurations according to different cases of U_{cc_i} is proposed. Table I shows the proposed predefined configurations. We maintain the total number of radio resource blocks for PDCCH.

$$\Delta R \quad = \sum_{i=1}^{4} resource\, per\, message \times \Delta CC\, i \qquad (1)$$

ΔR is always 0 and resource per message from CC1 to CC4 are 1, 3, 2, and 23. Our proposed scheme allocates the radio resource in every frame, when U_{cc_i} is higher than predefined criteria. We allocate the radio resource from $U_{cc_i}\_max$ to $U_{cc_i}\_min$. If U_{cc_i} is lower than predefined criteria, the proposed scheme immediately recover the original state. By sending PSI containing this predefined configuration in every PBCH message, the BS can dynamically allocate the radio resource of PDCCH and RACH via each coverage class. The BS allocate additional PDCCH resources to coverage class 1 from those of coverage class 2 as shown in Fig. 7.

IV. Performance Evaluation

In order to evaluate the performance of the proposed scheme, we developed C language based simulator. Standardization of CIoT is well underway, so we follow the simulation parameters as specified by 3GPP [10]. Coverage classses from 1 to 4 are divided by maximum coupling loss (MCL), which are 149, 159, 169, and more than 169 dBm. We consider a seven macro-cell network, where each cell consists of three hexagonal sectors. IoT devices are located in the center of macro-cell and inter-site distance (ISD) is 1,732 meters. The overall simulation cycle is 36,000 secs, and the paging cycle is 360 secs. We run simulate 30 times and use different seed numbers. For comparison, we simulate legacy scheme that statically allocates radio resource. Further details about simulation parameters are given in Table II.

When number of deployed IoT devices are fixed to 450, Fig. 8 shows that the ratio of IoT devices successfully completing the random access procedure. Note that in this scenario the BS allocate the resource to all IoT devices at same time. It can be observed that the success ratio of proposed scheme is better than legacy scheme and the IoT

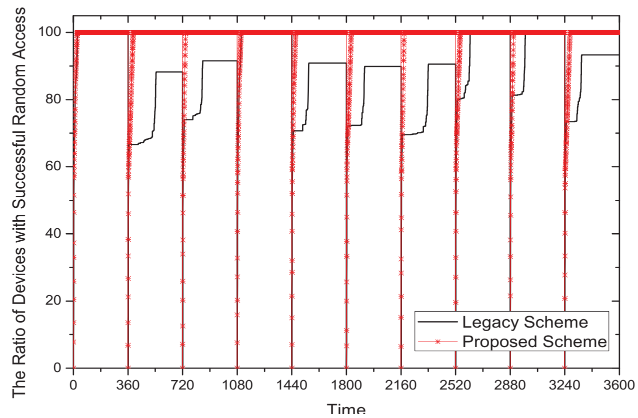

Figure 8. The Ratio of CIoT Devices Successfully Completing the Random Access Procedure

devices in legacy scheme require more time to complete the random access procedure. It is because some of IoT devices in legacy scheme can not successfully complete the random access procedure due to collision on PDCCH. It can also be established from the results in Fig. 8 that the IoT devices in legacy scheme may consume more battery power to successfully complete the random access procedure.

Fig. 9 shows the variation of the average random access successful ratio with varying numbers of IoT devices. The result shows that the proposed scheme can provide higher random access successful ratio compare to legacy scheme. Without control channel load balancing, the ratio of successful random access is between 0.62 to 0.59, when the number of IoT devices are from 1,500 to 7,500. This is because legacy scheme can not distribute the congestion of PDCCH, when traffic load for specific coverage class occurs. On other hand, the success ratio in our proposed random access scheme is between 0.62 to 0.86, when the number of CIoT devices are from 1,500 to 7,500.

As shown in Fig. 10, the average number of transmission for successful random access in proposed scheme is always less than legacy scheme. This is because proposed scheme can decrease the collision between the IoT devices by load

TABLE II
Simulation Parameters

Parameters	Studied Value
Number of Cells	7
Cellular Layout	Hexagonal grid, 3 sectors per site
User Distribution	User dropped uniformly in entire cell
Carrier Frequency	900 MHz
Bandwidth	20 KHz for UL and DL
Antenna Pattern (horizontal)	65° H-plane
Transmission Power BS to UE	43dB
BS Antenna Gain	18dBi
MS Antenna Gain	-4dBi
Noise Power Density	-174 dBm/Hz
PathLoss (PL)	120.9dBm + 37.6log R, R=killometer

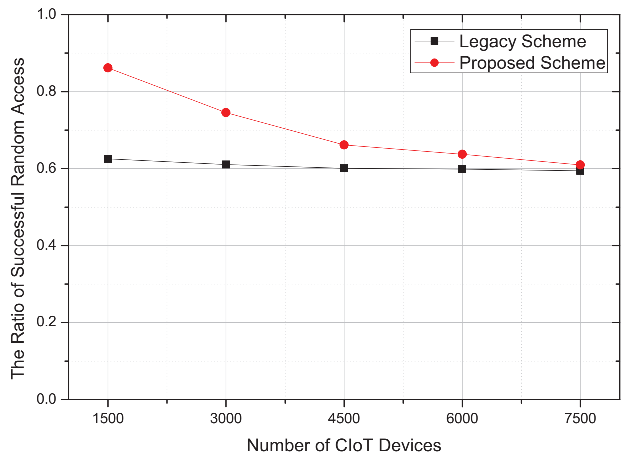

Figure 9. The Ratio of Successful Random Access

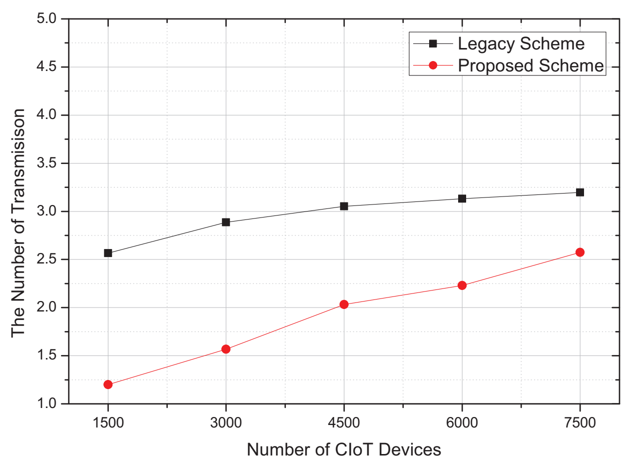

Figure 10. The Average Number of Transmission for Each Successful Random Access Procedure with Varying Number of CIoT Devices

balancing on PDCCH. The number of transmission for random access is decreased from 2.5 to 1.3 when the number of IoT devices are 1,500, and from 3.3 to 2.5 when the number of IoT devices are 7,500. Moreover, by reducing the number of retransmissions, IoT devices can reduce the battery power consumption.

V. Conclusion

In this paper, we propose the control channel load balancing in NB-CIoT systems. When massive IoT devices simultaneously try to access a BS, we indicate a congestion problem on control channel in NB-CIoT system. To solve the problem, we propose the novel scheme for of PDCCH and RACH in the NB-CIoT system. We outline the multiple configuration for dynamic channel allocation and steps for the control channel load balancing considering coverage class. Through the simulation, we evaluate the performance of system and simulation results show that the proposed scheme improve the random access successful ratio and reduce the number of transmission for random access procedure. In addition, it is beneficial to reduce the battery consumption this is because decoding failure decreases. As part of our future work, we plan to optimize the control channel load balancing in NB-CIoT system. We hope that our analysis can be a useful contribution for NB-CIoT system.

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