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EFFICIENT CONGESTION CONTROL TECHNIQUES FOR RANDOM ACCESS OF MTC DEVICES IN OFDMA SYSTEMS

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ABSTRACT

This paper introduces how to support machine-to-machine (M2M) terminals that send a small data on 3rd generation partnership project (3GPP) long term evolution-advanced (LTE-A) system. Especially, we consider the lack of random access channel (RACH) and rapidly increasing average latency for both cellular users and countless M2M devices that also are known as machine type communications (MTC) devices. To resolve the overload on physical random access channel (PRACH), this paper studies how to group numerous MTC devices. We also propose a two-way design of efficient congestion control techniques with adaptive access probability and back-off index according to user-defined types. We can expect to improve the average latency by giving fair access opportunity to cellular users, although they have a disadvantage of access compared to MTC users. The simulations have been done under various assumptions for the validation of proposals. Our proposals can alleviate overload over PRACH as well as the average latency for cellular and M2M users through simulations.

Keywords: *M2M, PRACH, Grouping, MTC devices, Congestion control*

1. INTRODUCTION

Machine-to-Machine (M2M) data communications, which involve one or more entities, are used to make decisions without human intervention [1]. Several devices and goods can be replaced by Machine Type Communications (MTC), the concept of which includes the following systems: health care services, remote application techniques, prompt throughput, smart meters, and smart grids [2], [3]. M2M communications are typically constrained in all aspects of power, account, storage, and bandwidth because they have low power, low cost, and nearly complete self-intervention [4]. Furthermore, the restriction of resources drastically increases the average latency because it negatively affects cellular users who exist in the same cell with MTC devices (MTCs).

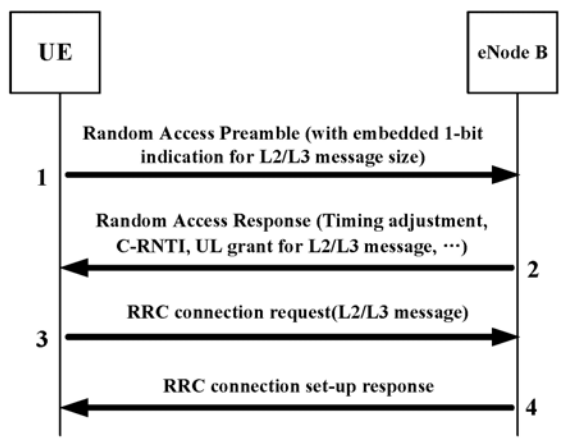

Figure 1: The contention based random access procedure in 3GPP LTE-A.

MTCs might violate the cell range of cellular users for the following reasons: PRACH overload, decreased probability of successful access, collision over PRACH, access delay, rapidly increasing average latency, decreasing data traffic of cellular users, and so on. Therefore, it is expected to lead to congestion because MTCs and cellular users lose load balancing over the cell area [5]. The average latency is also increased by delays and collisions before reaching the random access channel.

In a femtocell network, a group-based time control mechanism was designed for effective overload control by grouping MTCs [6]. This mecha-

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nism makes the best use of traffic load overtime, thereby alleviating the overload in both the radio access network (RAN) and the core network (CN). To achieve the improved average latency, the authors just set the average group size per one cell and then give the random access opportunity as reserved for each random access time [7]. [8] has proposed fixed timing alignment matching algorithms with the slot per unit according to the Random Access (RA) response at the second step shown in Figure 1. The scheme can prevent either delayed access time or collisions among MTCs. However, it is difficult for the reserved resources to overcome the overload at the random access channel because the number of MTC devices increases beyond expectation. Although the number of collisions decreases by grouping MTCs, it should also be a concern that latency will increase as much as the period of access per each group [9].

Based on the above, it can be seen that the problem of lack of PRACH which occurs when a plurality of MTCs coexist with existing cellular users should be solved by simultaneously considering efficient use of resources and increase of latency. Therefore, in this paper, we focus on the solution of the shortage of PRACH that can be controlled within the range where the latency increase does not exceed the tolerance while not using the resource reservation which can cause the resource inefficiency. In order to solve the overload over the random access channel, we will first propose a grouping system for MTCs and then a two-way design of congestion control techniques depending on user-defined types. Because it considers user characteristics, it is expected that the proposed congestion control techniques can improve the average latency of cellular users as well as MTCs.

This paper is composed of five sections. Section 1 provides an introduction, followed by an explanation of the conventional PRACH in Section 2. In Section 3, we will propose a scenario in which MTCs are grouped with two-way congestion control techniques according to user-defined types in order to solve problems related to random access. In order to support our proposals, Section 4 will explain some assumptions and simulation results that verify the mitigation of average latency. Finally, Section 5 gives the conclusion.

2. PHYSICAL RANDOM ACCESS CHANNEL (PRACH)

Once a paging message is sent and received, all users follow the standard LTE-A random access procedure to establish connections with the base station (BS). In this section, we will briefly explain how to work with the conventional physical random access channel.

PRACH is used to access the network when the user equipment (UE) on LTE-A does not have accurate uplink (UL) timing synchronization or when it does not have an allocated uplink transmission resource. If uplink transmission timing for the UE is synchronized, it can be only scheduled for uplink transmission. Hence, PRACH plays a key role as the interface between non-synchronized UEs and the orthogonal transmission scheme of LTE-A uplink radio access.

In WCDMA (Wideband Code Division Multiple Access), PRACH is mostly used by users who want initial network access and short message transmission. LTE-A is also similar to WCDMA PRACH. The LTE-A system uses PRACH for initial network access. However, PRACH in LTE-A cannot carry user data because they are exclusively sent through the physical uplink shared channel (PUSCH). Instead, LTE-A PRACH is used to obtain uplink time synchronization for UE that has not yet acquired uplink synchronization or has lost it. When UE synchronizes the uplink, then the evolved Node B (eNodeB) can schedule the orthogonal uplink transmission resources for it.

There are two different techniques of PRACH procedure in 3GPP LTE-A [10]. One is the contention-based random access procedure composed of terminals that compete with each other for PRACH allocation. This procedure makes reservations according to asking delays or access permissions because the random access channel can collide between terminals. The other one is the non-contention based random access procedure, which allows reserved resources because the eNodeB wants to ask for special access resources. This procedure has achieved even more successful access probability.

Our main purpose is to control PRACH overload in the contention-based random access procedure. Thus, we first examine the random ac-

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cess procedure of 3GPP LTE-A as shown in briefly illustrated in Figure 1.

At first, the UE receives a root index and PRACH configuration index from the eNodeB and gets a maximum of 64 candidates of random access preamble, which is defined by Zadoff-Chu (ZC) sequences per each cell. Subsequently, the UE randomly selects one sequence from a maximum of 64 preamble sequences and then sends the random access preamble to the eNodeB. The eNodeB assigns the UE a cell radio network temporary identifier (C-RNTI) to identify the UE during exchange of all information over the air. The C-RNTI is assigned during the setup of the radio resource control (RRC) Connection between a UE and an eNodeB and is valid only for that RRC Connection. The PRACH configuration index has definitions of both preamble formats and certain sub-frames that can send random access preamble [11], [12].

UEs can collide in the process of random access at the eNodeB because they select the same preamble sequence or access at the same time. In such that case, they can send very short random access preambles. They also may fail to deliver preamble transmission because there is not enough transmission power. If one preamble is correctly received, the eNodeB recognizes that one preamble is received by the random access response (RAR) during the period of response window. This procedure is expected to resolve collision problems because the eNodeB needs to define which is the preamble the UE sends. Therefore, a procedure to resolve the collision problem is required. After random access response processing is accomplished, the UE sends the RRC connection request message though PUSCH. If the UE successfully receives a response message for the RRC connection set-up from the eNodeB, then the random access procedure is complete [10].

3. THE PROPOSED SCHEMES

3.1 Grouping Model

The smaller the cell range of cellular users, the less access probability they will have. Thus, we first propose a grouping scheme in order to alleviate the PRACH overload by reducing the access number of MTCs.

One MTC, referred to as Group Leader (GL), can attempt random access instead of numerous Group Members (GM) due to grouping. Therefore, cellular users compete with much fewer MTCs than before. As shown in Figure 2, there is a cell configuration for cellular users and M2M

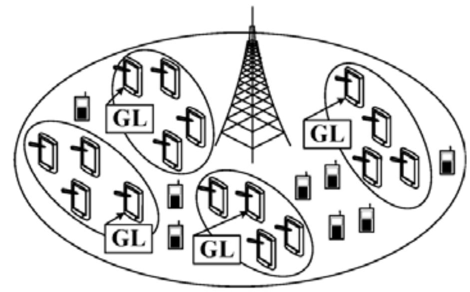

Figure 2: An example of configuration of cellular users and group leaders (GLs) per each M2M group.

groups with each GL and many GMs. Each GL is randomly selected from all MTCs as much as j M2M groups. To compose i MTCs in j-th M2M group, the M2M group is defined by

$$\boldsymbol{G_j} \ni \{ \forall m \in N_m \mid m_{0,j}, \ldots, m_{i,j} \}. \quad (1)$$

Let $m_{l,i,j}$ be a group leader of i-th MTC users in j-th group per each frame T_f (i.e., a time slot at a frequency). For every T_f, the grouping system model randomly chooses one $m_{l,i,j}$ who must want to do random access in $\boldsymbol{G_j}$. In addition, the attempted probability for random access attemptted at T_f can be expressed as:

$$Pr\left[m = m_{l,i,j} \mid m \in \boldsymbol{G_j} \right] = \frac{1}{\tau} \quad (2)$$

where τ is the number of $m_{l,i,j}$ that belong to $\boldsymbol{G_j}$.

In the proposed scheme, only one GL is to have access instead of countless numbers of GMs. We will perform an experiment with the grouping system model and prove the mitigation of the average latency mostly for cellular users. In addition, GLs should know which information MTCs share in the M2M group. Since an eNodeB provides paging, GLs can get the information they need [7], [13].

3.2 Access and Delay Control Techniques

In Figure 2, there are lots of GM-configured M2M groups and cellular users in the same cell. It is still difficult for cellular users to obtain the improved average latency under the influence of MTCs. Therefore, we also propose two congestion control techniques according to user-defined types.

Regarding access probability, there is no distinct definition that distribution cellular users have when they exist with MTCs on the same cell [14]. Thus, we will find their distribution adjacent to the Poisson distribution over access control modeling simulations. When cellular users have an access probability below 3%, they might get the Poisson distribution with the following constraints:

$$A_c(\alpha_c) = \begin{cases} 1 & \text{if } \alpha_c \le 3\%, \\ 0 & \text{otherwise.} \end{cases} \quad \text{for cellular} \tag{3}$$

$$A_m(\alpha_m) = \begin{cases} 1 & \text{if } \alpha_m \le 3\%, \\ 0 & \text{otherwise.} \end{cases} \quad \text{for MTC} \tag{4}$$

where α_c means the access probability of cellular users at T_f, and α_m means the access probability of a MTC user at T_f. $A_c(\alpha_c)=A_m(\alpha_m)=1$ also indicates that a UE succeeds in an access attempt at average latency of cellular users because MTCs also attempt to access below 3%.

First congestion control technique is the access control model where the access probability has different values according to user-defined types. Cellular users have a disadvantage of access over PRACH, compared to MTCs. However, cellular users can gain fair access opportunities because MTCs establish much lower access probability than cellular users. The controlled access probability of MTCs is given by:

$$A_{m^*}(\alpha_{m^*}) = \begin{cases} 1 & \text{if } \alpha_{m^*} \le 1.5, 2, 2.5\%, \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

where α_{m^*} is the access probability for $m^*=m_{i,j}$ in

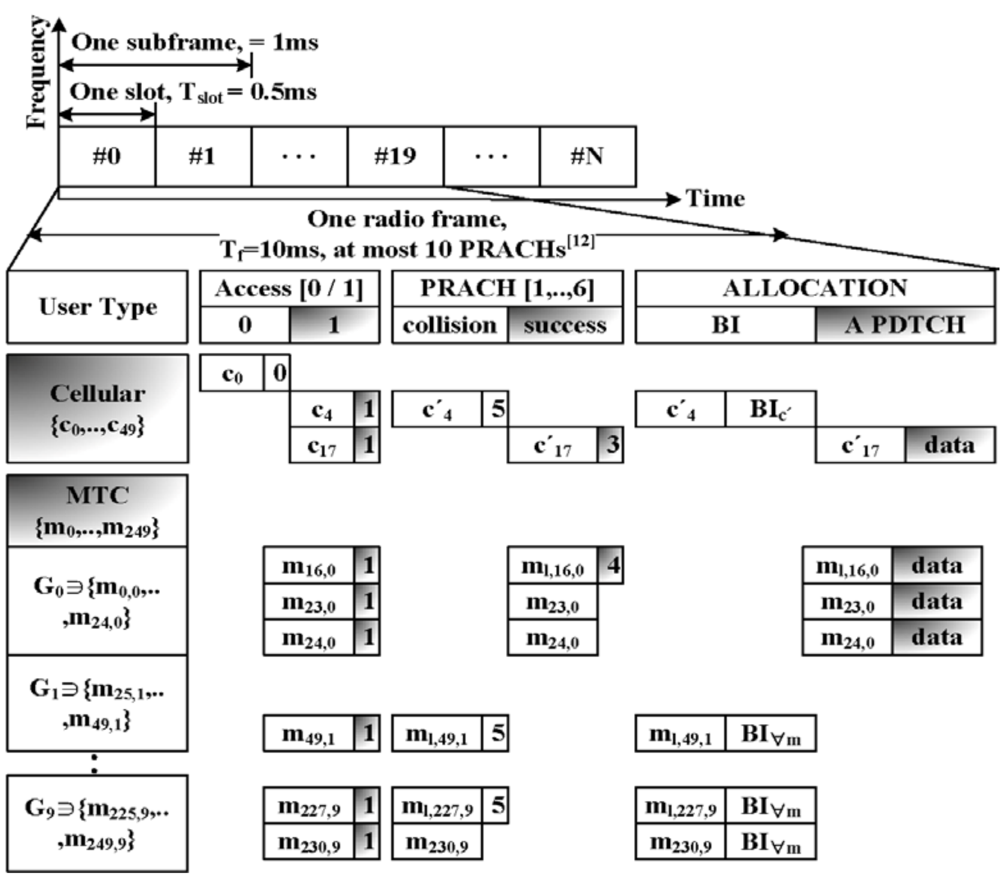

Figure 3: An example of the proposed PRACH procedure with 50 cellular users and 250 MTC devices.

age latency because MTCs have controlled access probability. In addition, it is expected that PRACH collisions will decrease due to the access control technique.

Another congestion control technique is the controlled back-off index (BI) according to user-defined types. If PRACH collisions occur at T_f, a UE should perform repeated attempts until successfully allocating PRACH. The delay period can give more access opportunities like as the access congestion control technique. The shorter the delay period, the more repeated attempts the UE will have. Cellular users can randomly take advantage of low BI allocation, meaning they can get more access opportunities than MTCs.

3.3 The PRACH Procedure

This section proposes the random access procedure for cellular users and M2M groups. This procedure includes grouping systems as well as efficient congestion control techniques according to user-defined types.

Figure 3 illustrates the proposed procedure for 50 cellular users and 250 MTCs. The grouping system divides 250 MTCs into 10 M2M groups with 25 MTCs per unit. Let $\boldsymbol{N_c}$ be the number of cellular users by

$$\boldsymbol{C} \ni \{ \forall c \in \boldsymbol{N_c} \mid c_0, \ldots, c_{Nc} \} \quad (6)$$

and let $\boldsymbol{N_m}$ be the number of MTCs by

$$\boldsymbol{M} \ni \{ \forall m \in \boldsymbol{N_m} \mid m_0, \ldots, m_{Nm} \}. \quad (7)$$

In the grouping section, each $m_{l,i,j}$ are chosen as a substitute that attempts random access instead of other $m_{i,j}$ in $\boldsymbol{G_j}$. Other $m_{i,j}$ of $\boldsymbol{G_j}$ also intend to attempt random access at T_f. Fifty cellular users compete with only a maximum of 10 $m_{l,i,j}$, not all 250 $m_{i,j}$. UEs can select one allocable PRACH out of 6. The following formula shows the probability that a PRACH is selected by cellular users and MTCs. $P_X(x)$ can be expressed as:

$$P_X(x) = \begin{cases} \frac{1}{6} & if\, x \in \{c'\}, \{m_{l,i,j}\}, \\ 0 & otherwise. \end{cases} \quad (8)$$

where $\{c'\}$ means cellular users who can perform access attempts among $\forall c \in \boldsymbol{N_c}$ or $A_c(\alpha_c)=1$, and where $\{m_{l,i,j}\}$ means GLs who can make access attempts among $\boldsymbol{G_j}$ or $A_{m*}(\alpha_{m*})=1$. First of all, c_4, c_{17} are supposed to attempt access except for those who have $A_c(\alpha_c)=0$ of all $\boldsymbol{C}$.

In the case of M2M groups, $m_{16,0}$, $m_{23,0}$, $m_{24,0}$ are supposed to attempt access except for those who have $A_{m*}(\alpha_{m*})=0$ of all $\boldsymbol{G_0}$. $m_{16,0}$ is randomly selected as a group leader $m_{l,16,0}$ of $\boldsymbol{G_0}$. The next step is that UEs, which have either $A_c(\alpha_c)=1$ or $A_{m*}(\alpha_{m*})=1$, choose a PRACH from among 6. c'_4, $m_{l,49,1}$, $m_{l,227,9}$ collide over PRACH 5 and then fail in their access because they choose the same random access channel. c'_{17} succeeds in PRACH 3 and $m_{l,16,0}$ succeeds in PRACH 4 instead of group members $m_{23,0}$, $m_{24,0}$.

When $m_{l,i,j}$ collide over a random access channel, they are allocated for a back-off index up to group members in $\boldsymbol{G_j}$. The proposed delay control technique is applied so that c'_4 gets the back-off index by $BI_{c'}=\{9\}$ and $m_{l,49,1}$, $m_{l,227,9}$ randomly get one of the back-off indices by $BI_{\forall m}=\{10, 11, 12\}$.

It is important to note that if group member $m_{i,j}$s can't get PRACH allocation because group leader $m_{l,i,j}$ fails to access, $m_{i,j}$ are also allocated for the back-off index with $m_{l,i,j}$. Thus, $m_{230,9}$ randomly gets one of $BI_{\forall m}=\{10, 11, 12\}$ likewise. On the other hand, UEs who succeed in their access finally send data through PDTCH such as c'_{17}, $m_{l,16,0}$, $m_{23,0}$, $m_{24,0}$.

We will define the formula for the average latency following the proposed random access procedure. Let $c_{n,S,f}$ be the number of successes for n-th cellular users on T_f. Let $c_{n,D,f}$ be the number of delays for n-th cellular users who fail to access due to collisions on T_f. Let $m_{n,S,f}$ be the number of successes for n-th MTCs on T_f. Let $m_{n,D,f}$ be the number of delays for n-th MTCs who fail to access due to collisions on T_f. The following average latency formula for cellular users and MTCs is expressed as:

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$$latency_{c,m} = \frac{1}{c'_S}\left\{\sum_{n=0}^{N_c}\frac{\left(c_{n,S,f}+c_{n,D,f}\right)}{c_n}\right\} + \frac{1}{m_{l,i,j,S}}\left\{\sum_{n=0}^{N_m}\frac{\left(m_{n,S,f}+m_{n,D,f}\right)}{m_n}\right\} \quad (9)$$

where $\{c'_S\}$ means the number of cellular users who can make access attempts among $\forall c \in \boldsymbol{N_c}$ or $A_c(\alpha_c)=1$, and where $\{m_{l,i,j,S}\}$ means the number of GLs who can make access attempts among $\boldsymbol{G_j}$ or $A_{m^*}(\alpha_{m^*})=1$. In accordance with the abovementioned data, we will conduct experiments and prove the proposal through simulation results.

4. SIMULATION RESULTS

For validity, our simulation assumes that the total period of time domain is 10^8 ms at the uplink frame because the simulation results need to have enough data. In the experiments, the number of cellular users is set for a total of 50, and the number of MTCs is set from a minimum of 50 to a maximum of 250 with 50 per unit. Thus, we can indicate that the average latency of cellular users gets their gains depending on the number of MTCs.

Cellular users have 3% access probability and MTCs have 1.5, 2, 2.5% access probability in the simulation. According to MTC characteristics, we can fix the composition of M2M groups because MTCs have low mobility and aperiodic characteristics, and transmit small amount of data [8].

To find the average latency of cellular users adjacent to Poisson distributions, we have experiments of 20, 40, 60 cellular users who are set from BI 1 to BI 12. The acquired simulation results are given in Figure 4. Our simulations use back-off parameter values in [11]. There is a trade-off in which low BI leads to a higher average latency such as BI 1, 2, 3, but a high BI creates a lesser average latency.

If BI is set from 1 to 3 in order to alleviate the average latency, the shorter the period of delayed frames due to low BI, the more collisions there will be over the random access channel. Otherwise, if BI is set from 10 to 12 to decrease collisions, the longer the period of delayed frames due to high BI, the fewer the access opportunities. Our proposals have the grouping system in mind to decide results set to BI 9 for 50 cellular users.

We assumed that cellular users have 3% access probability. Our simulation uses the PRACH mask index values in [11]. So, the number of allocable PRACH is determined at 6. Therefore, we want to determine which number of PRACH brings the average latency of cellular users adjacent to the Poisson distribution through the simulation results given in Figure 5.

Given the conventional results where only cellular users attempt to access with 3% and BI 9, we will compare how much the average latency of cellular users improves with MTCs. To specifically determine this, there is the average latency for 'cellular' with 'MTC 3% BI 9'. This means that MTCs have a bad influence on cellular users because

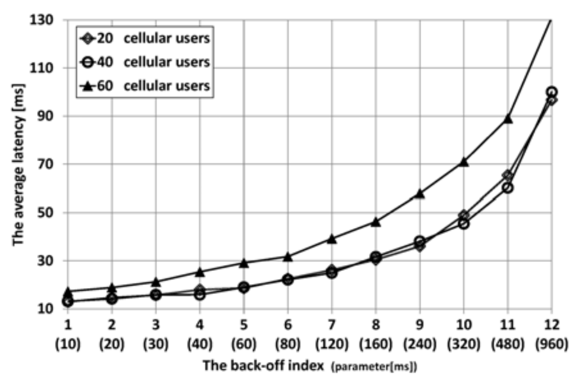

Figure 4: The average latency results of cellular users depending on back-off parameters.

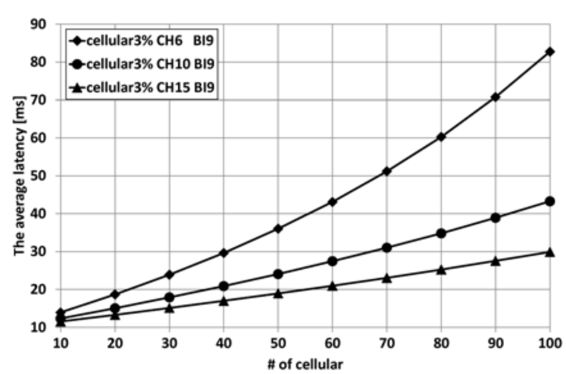

Figure 5: The average latency results to do experiment various assumptions of cellular users.

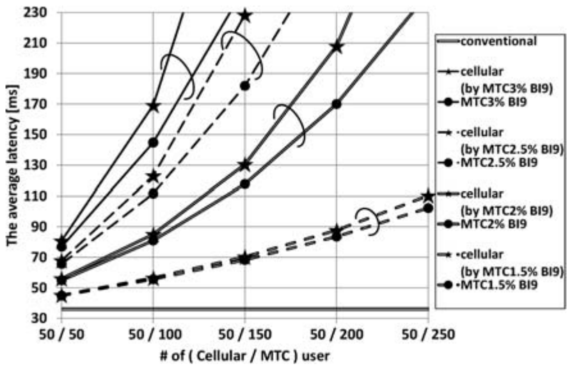

Figure 6: The average latency results with the access control technique for cellular users and MTCs.

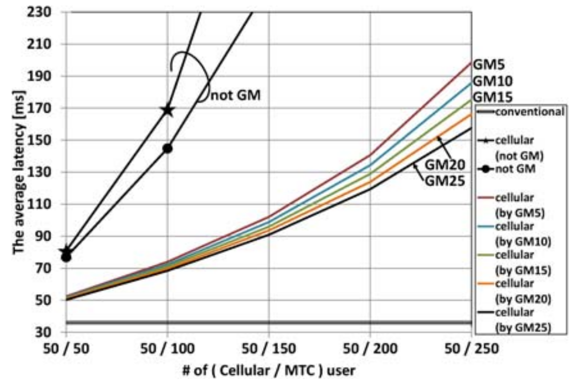

Figure 8: The average latency results with the grouping system just for cellular users (GM: Group Member).

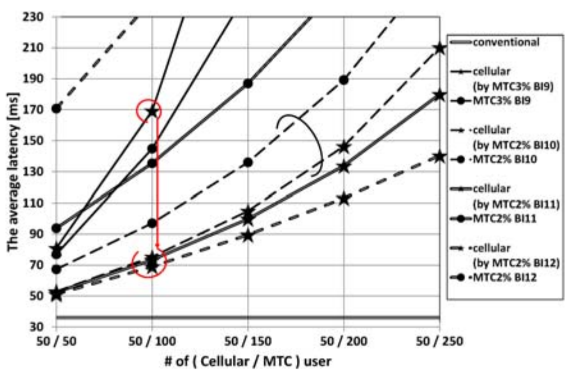

Figure 7: The average latency results with the delay control technique for cellular users and MTCs.

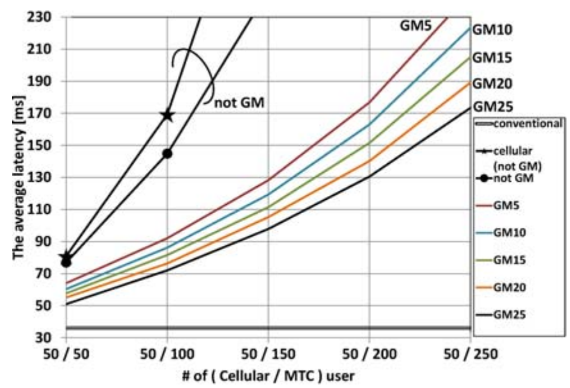

Figure 9: The average latency results with the grouping system just for M2M groups (GM: Group Member).

MTCs simultaneously attempt to access along with cellular users using the limited resources. So, our simulation has suggested several conditions just for MTCs. In the figures, star points mean the results of cellular users and circle points mean the results of MTCs in every simulation.

As shown in Figure 6, we can indicate that the average latency of cellular users gains as much as the access probability of MTCs lowers from 3% to 1.5%. That is, the proposed access control technique is according to the user-defined types. However, if the access probability of MTCs is too small, MTCs can't obtain any access opportunities. Thus, we determine that there are appropriate values when MTCs attempt to access 2%.

For the proposed delay control technique, as shown in Figure 7, MTCs make a large difference depending on BI. When MTC 3% BI 9 is compared with MTC 2% BI 10, 11, 12, cellular users have improved values but MTCs get long delays in the uplink frame regardless of access probability. Thus, we make a decision based on MTC 2% BI 10.

To gain better performance, we also conducted some experiments on the grouping system as illustrated in Figure 8 and Figure 9. In the case of cellular users, cellular users gain less than 10ms as shown in Figure 8. In the case of MTCs, MTCs gain above 18ms when there are 250 MTCs in the optimal number of group members as shown in Figure 8.

5. CONCLUSION

In this paper, we studied RAN overload problems that cellular users and M2M users worked on the 3GPP LTE-A system at the same time. The greater the number of MTCs, the more delay, collision, and overload. Such problems increase the average latency for cellular. To reduce the latency, we proposed efficient congestion control techniques by using the grouping system of MTCs for M2M communications.

We focused on the PRACH procedure with two ways of efficient control techniques. That is, the access probability and the back-off index of the UE are adjusted according to the user-defined type. To obtain improved latency for cellular users, they should take greater advantage of access probability and back-off index than MTCs. The numerical results demonstrate that average latency for the proposed techniques offers a considerable gain for cellular users as compared to the conventional case.

The grouping system determines by how much the average latency of cellular users achieves better gains. As compared to all results, we finally indicate that the following conditions optimize the average latency of cellular users as well as MTCs: [3% access probability, BI 9] for cellular users and [2% access probability, BI 10] for MTCs. It also gives the improved gains when there are M2M groups composed of 5 to 25 group members with 5 per unit. Therefore, our work mitigated the RAN overload problem, and alleviated the average latency for all cellular users and MTCs, as shown in the simulation results.

The simulation results obtained are meaningful, but we cannot guarantee that the proposed schemes can be applied immediately in a real environment. In particular, the optimization point should be determined by the type of MTC and traffic characteristics to which the proposed scheme applies. In order to increase the applicability to the real environment, it is necessary to study how to apply the proposed schemes under various network structures. In this regard, future studies will examine the effectiveness of the proposed mechanism in a heterogeneous network (HetNet) environment.

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