Enhanced Cooperative Access Class Barring and Traffic Adaptive Radio Resource Management for M2M Communications over LTE-A

Yi-Huai Hsu
Department of Computer Science
National Chiao Tung University
Hsinchu, Taiwan
vince010549.cs99g@nctu.edu.tw

Kuochen Wang and Yu-Chee Tseng
Department of Computer Science
National Chiao Tung University
Hsinchu, Taiwan
{kwang, yctseng}@cs.nctu.edu.tw

***Abstract*— We propose *enhanced cooperative access class barring (ECACB)* and *traffic adaptive radio resource management (TARRM)* for M2M communications over LTE-A. We use the number of Machine-Type Communication (MTC) devices that attach to an eNB, which is the base station of LTE-A, as a criterion to determine the probability that an MTC device may access the eNB. In this way, we can have a better set of access class barring parameters than CACB, which is the best available related work, so as to reduce random access delay experienced by an MTC device or user equipment (UE). After an MTC device successfully accesses an eNB, the eNB allocates radio resources for the MTC device based on the random access rate of the MTC device and the amount of data uploaded or downloaded by the MTC device. In addition, we use the concept from cognitive radio networks that when there are unused physical resource blocks (PRBs) of UEs, the eNB can schedule MTC devices to use these PRBs to enhance network throughput. Simulation results show that the proposed ECACB's average (worst) access delay of UEs is 33.19% (29.89%) lower than CACB's. Its average (worst) access delay of MTC devices is 12.15% (15.1%) lower than that of CACB. Its average (worst) throughput from UEs is 20.93% (26.44%) higher than that of CACB. Its average (worst) throughput from MTC devices is 19.95% (12.25%) higher than that of CACB. The proposed ECACB+TARRM's average (worst) throughput from UEs is 26.16% (31.42%) higher than CACB's. Its average (worst) throughput from MTC devices is 25.11% (20.76%) higher than that of CACB. To the best of our knowledge, no existing approach integrates access class barring with radio resource management for M2M communications over LTE-A.**

***Keywords*—access class barring, LTE-A, M2M communications, radio resource management, random access.**

I. INTRODUCTION

It is booming for the development of Machine-to-Machine or Machine-Type Communication (M2M or MTC) based on 4th generation (4G) cellular networks, such as LTE-A (Long Term Evolution-Advanced), because of better coverage, higher data rate, and lower network deployment cost of 4G. However, as the number of MTC devices increases so greatly, it results in severe congestion in a physical random access channel (PRACH), which is used by UEs or MTCs to send a preamble to an eNB for initial access, handover, and connection reestablishment. Besides, the MTC device should not affect the performance of the UE. Thus, how to efficiently handle the congestion in the PRACH and guarantee the performance of the UE has become a critical issue when designing M2M communications over LTE-A.

M2M communication will be one of main focuses in LTE-A, as the need for M2M communication is increasing so rapidly recent years and might finally exceeds that of the human-to-human (H2H) communication [3]. In M2M communications, MTC devices communicate with each other and exchange data without direct human intervention [2]. To enable full automation, each MTC device can play multiple roles among a sensor, a decision maker, and an action executor [7]. In recent researches, a few implementations of M2M communications have been proposed, such as utilizing Bluetooth (IEEE 802.15.1), Zigbee (IEEE 802.15.4), or WiFi (IEEE 802.11b) technique. However, there is still no general agreement on the network architecture of a general scenario for M2M communications [7]. Some believe that the most popular wireless technology used in personal area network (PAN) for M2M communications is Zigbee [1].

In the first generation of M2M communications, a critical part of M2M leverages short message service (SMS) as the communication means, and the MTC devices only transmit small amount of data each time. It may not be a problem when there are few MTC devices in the network [3]. When the number of MTC devices is increasing greatly, MTC devices may interfere with UEs. Thus, managing a large number of MTC devices in the M2M networks is one of the key future tasks [5]. For example, in the mobile network, there is the rapid growth of data traffic in the world widely. Increase of smart-phones and video-contents result in rapid growth of data traffic. In the near future, M2M communications are also going to increase the traffic significantly [4]. Nowadays, the number of M2M services is rapidly increasing in cellular communication systems. In order to guarantee a maximum system capacity, the impact of this special kind of traffic on H2H communication needs to be analyzed [6]. Supporting trillions of MTC devices is a critical challenge in M2M communications, which may result in severe congestions in random access channels of cellular systems that have been recognized as promising scenarios enabling M2M communications [9].

Table 1: Comparison of the proposed ECACB+TARRM with related work.

Feature Method	Design focuses/improvements	Average throughput (for both UEs and MTCs)	Average access delay (for both UEs and MTCs)	UEs mixed with MTC devices
Grouping-based radio resource management [7]	**MTC devices are grouped according to the packet arrival rate and delay jitter**	**Medium**	**High**	**Yes**
Access barring check [8]	**Using different combinations of H2H's and M2M's preambles based on access barring check to evaluate network performance**	**Low**	**High**	**Yes**
CACB [9]	**Enabling eNBs to cooperate with each other so that it can obtain a set of access class barring parameters *p* to significantly reduce the congestion in a PRACH**	**Medium (MTCs only)**	**Medium (MTCs only)**	**No**
Proposed ECACB+TARRM	**1. Considering the number of MTC devices that attach to an eNB to obtain a better set of access class barring parameters *p* than CACB** **2. MTC devices and UEs use different PRBs of a PRACH and separate preambles to perform random access with eNBs** **3. MTC devices are clustered according to their random access rates and the amount of data uploaded or downloaded**	**High**	**Low**	**Yes**

In this paper, we propose *enhanced cooperative access class barring* and *traffic adaptive radio resource management* for M2M communications (called *ECACB+TARRM*) over LTE-A. The objective is reducing the random access delay experienced by MTC devices or UEs and improving network throughput which addresses the average throughput and the worst throughput. To the best of our knowledge, no existing work integrates access class barring and radio resource management for M2M communications over LTE-A.

II. RELATED WORK

In [7], it proposed a group-based radio resource management, which allocates PRBs (physical resource blocks) according to the packet arrival rate and delay jitter of the MTC device. Although it may increase throughput performance, its improvement may be restricted because of the packet arrival rate and delay jitter of the MTC device cannot fully reflect the real random access rate and the amount of data uploaded or downloaded. In addition, it does not mention how to resolve the problem of congestion in a PRACH. In [8], it used different combinations of H2H's and M2M's preambles based on access barring check to evaluate network performance. However, it did not propose any mechanism to resolve the channel congestion in a PRACH and radio resource scheduling to increase network throughput. In [9], it proposed a CACB scheme, which enables eNBs to cooperate with each other so that it can obtain a set of access class barring parameters $\boldsymbol{p}$ to reduce the congestion in a PRACH. However, it did not consider the number of MTC devices that attach to an eNB as a criterion of determining the probability that an MTC device accessing the eNB. It may restrict the improvement of access delay of each MTC device or UE. Moreover, it did not propose a radio resource management to improve network throughput, and it did not consider the situation that UEs mixed with MTC devices.

The above problems motivate us to design an enhanced cooperative access class barring and traffic adaptive radio resource management scheme for M2M communications over LTE-A. The proposed ECACB+TARRM can reduce the random access delay experienced by each MTC device or UE and greatly improve the throughput performance. Table 1 summarizes the differences between the proposed ECACB+TARRM and related work.

III. PROBLEM FORMULATION

Consider the random access of M2M communications in LTE-A with M eNBs, indexed by $m = 1, \ldots, M$ and N active MTC devices, indexed by $n = 1, \ldots, N$. In [9], it assumes that an MTC device is able to access an eNB unattached by the MTC device when the MTC device locates within the overlapped coverage area of multiple eNBs. This part is different from the access class barring [10] that each MTC device can only access the eNB attached by the MTC device [9]. To formulate such a random access problem, [9] uses the following notations.

1. Denote A_m as the set of MTC devices that attach to the m^{th} eNB and $\| A_m \|$ as the norm of A_m which represents the number of MTC devices that attach to the m^{th} eNB. With the ability to cooperate with other eNBs, A_m for all m are known by all eNBs. Note that $\sum_{m=1}^{M} \|A_m\| = N.$
2. Denote M_n as the set of eNBs that the n^{th} MTC device can probably access. The n^{th} MTC device chooses one eNB from M_n to perform the random access. In LTE-A, an eNB can request an MTC device to perform the exploration of surrounding eNBs, and report the exploration result. Thus, M_n for all n are available for all eNBs. However, M_n is unknown by the other MTC devices, except for the n^{th} MTC device.
3. Denote N_m as the set of MTC devices accessing the m^{th} eNB. In the traditional access class barring, $\| N_m \|$ for all m are known by each eNB because each MTC device can only access the eNB that it attaches. However, if each MTC device can not only access the eNB it attaches but also the eNB it unattaches, $\| N_m \|$ for all m are

random variables unknown by eNBs, unless the eNB selection strategy for each MTC device is given.

4. Denote $l_{n,m}$ as an indicator function that, for the n^{th} MTC device,

$$l_{n,m} = \begin{cases} 1, \text{ if the } m^{\text{th}} \text{ eNB is within } M_n \\ 0, \text{ otherwise} \end{cases} \quad (1)$$

5. Denote N'_m as the set of MTC devices that can only receive the signal from the m^{th} eNB and these MTC devices can only access the m^{th} eNB. $\| N'_m \|$ is the norm of N'_m.

In the access class barring [10], it can independently maximize the throughput of each cell by individually setting $p_m = 1/\| N_m \|$ (where p_m is the access class barring parameter of the m^{th} eNB) in each eNB, but the delay of each MTC device that attaches to the m^{th} eNB may be extremely long when there are a large number of MTC devices that attach to the m^{th} eNB [9].

IV. PROPOSED ENHANCED COOPERATIVE ACCESS CLASS BARRING AND TRAFFIC ADAPTIVE RADIO RESOURCE MANAGEMENT (ECACB+TARRM)

In the proposed ECACB, we use the number of MTC devices that attach to an eNB as a criterion to determine the probability that an MTC device may access the eNB so that we can obtain a better set of access class barring parameters **p** than CACB. It can reduce random access delay experienced by each MTC device or UE. Fig. 1 shows the architecture of an LTE-A cellular network. Some MTC devices may locate in the overlapped area of a macrocell and a picocell. These MTC devices may also access the eNB that is not attached by them. In LTE-A, the eNBs communicate with each other by an X2 interface [9].

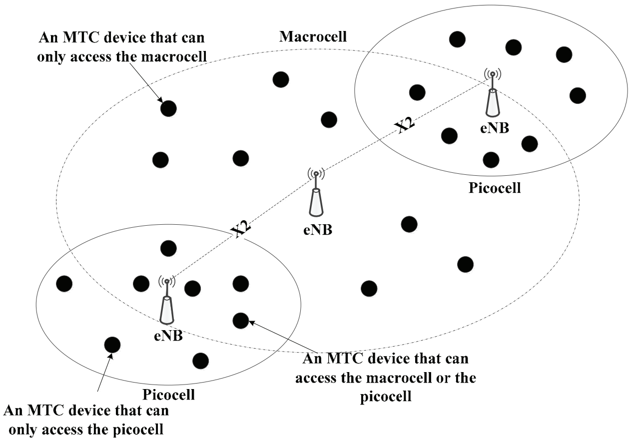

Fig. 1. Architecture of an LTE-A cellular network [9].

A. Proposed enhanced cooperative access class barring (ECACB)

In the proposed enhanced cooperative access class barring (ECACB), we want to acquire a better set of access class barring parameters $\mathbf{p} = [p_1, \dots, p_M]$ that is jointly decided by M eNBs to minimize the access delay experienced by N active MTC devices. Through cooperation among eNBs to make a joint decision of $\mathbf{p} = [p_1, \dots, p_M]$, the problem can be formulated by

$$\begin{aligned} &\min_{p_1,\dots,p_M} \ \text{balance}\left(\|N_1\|, \|N_2\|, \dots, \|N_M\|\right) \\ &\text{s.t.} \ (\text{C1.1}) \ 0 \le \mathbf{p} = [p_1, \dots, p_M] \le 1 \\ &\quad (\text{C2.2}) \ \|N_m\| p_m \le 1, \text{ for } m = 1, \dots, M \end{aligned} \quad \mathbf{(2)}$$

The eNB selection strategy is based on p_m, for $m = 1, \dots, M$. The eNB with higher p_m has a higher probability to be accessed by MTC devices. Upon receiving $p_n = \{p_i, p_j, \dots, p_k\} \subseteq \mathbf{p}$, the n^{th} MTC device adopts the following strategy to select an eNB to access.

$$\beta_n(p_i, \dots, p_k) = \left[Q_{n,i} = \frac{p_i}{\sum_{x \in M_n} p_x} \left(\frac{1}{\|A_i\| + 1} \right), \dots, Q_{n,k} = \frac{p_k}{\sum_{x \in M_n} p_x} \left(\frac{1}{\|A_k\| + 1} \right) \right], A_i \ge 0, i \in M_n \quad (3)$$

where $Q_{n,x}$ is the probability that the n^{th} MTC device selects the x^{th} eNB to access.

Note that in contrast to [9], we add the number of MTC devices that attach to an eNB as a criterion to determine the probability that an MTC device may access the eNB so as to reduce the collision probability. Given that the above strategy in (3) on the selection of an eNB by each MTC device is known by all eNBs, $\| N_m \|$ for all m can be obtained by

$$\|N_m\| = \sum_{x=1}^{M} \sum_{n \in A_x} l_{n,m} Q_{n,m} \ \text{ for } m = 1, \dots, M \quad \mathbf{(4)}$$

Finally, the better set of access class barring parameters **p** can be found by algorithm 1 and algorithm 2, proposed in [9].

We assume that MTC devices and UEs use different PRBs of a PRACH and separate preambles to perform random access with eNBs so as to reduce the congestion between them. Fig. 2 shows the access class barring procedure for each MTC device or UE. At first, an eNB broadcasts a random access control value $p \in [0,1]$. An MTC device or UE also generates a random value q which follows a uniform random number between 0 and 1 (q-unif(0,1)). If $q \le p$, the MTC device or UE is allowed to perform the random access procedure with the eNB. Otherwise, the MTC device or UE is blocked for a certain period [10]. In this paper, we assume MTC devices (UE) is blocked for 0.5ms (1ms).

B. Proposed traffic adaptive radio resource management (TARRM)

After an MTC device or a UE successfully perform random access with an eNB, the eNB needs to allocate radio resource to the MTC device or the UE. Fig. 3 shows the proposed traffic adaptive radio resource management (TARRM). In Fig. 3, we classify an MTC device into a cluster k according to its random access rate α_k and the amount of data uploaded or downloaded β_k. We use $1/(\alpha_k\beta_k)$ as the time interval to allocate PRBs to cluster k, where $\alpha_k\beta_k$ can reflect cluster k's real data arrival rate. Note that in [7], it used the packet arrival rate and delay jitter of an MTC device to classify MTC devices into different clusters. In contrast, ours can fully reflect the traffic load of MTC devices to an eNB so as to efficiently allocate radio resources to increase network throughput. This point will be verified via performance evaluation. We assume that $\alpha_1\beta_1$ of cluster 1 is larger than $\alpha_2\beta_2$ of cluster 2, so the PRB allocation frequency ($1/(\alpha_1\beta_1)$) for cluster 1 is higher than that ($1/(\alpha_2\beta_2)$) of cluster 2. We allocate PRBs to MTC devices by first come first serve (FCFS) within a cluster. Furthermore, we use the concept of cognitive radio networks such that if there are unused PRBs of UEs, the eNB can schedule MTC devices from clusters based on the allocation frequency of each cluster in the descending order to use these PRBs of UEs. Note that in LTE-A, there are 15 PRBs in a physical downlink shared channel (PDSCH) and physical uplink shared channel (PUSCH), which are used by UEs or MTCs to download and upload data traffic, and 6 PRBs in a physical random access channel (PRACH). According to a cluster's real data arrival rate to allocate PRBs and utilizing unused PRBs of UEs for MTC devices, the proposed TARRM can improve network throughput.

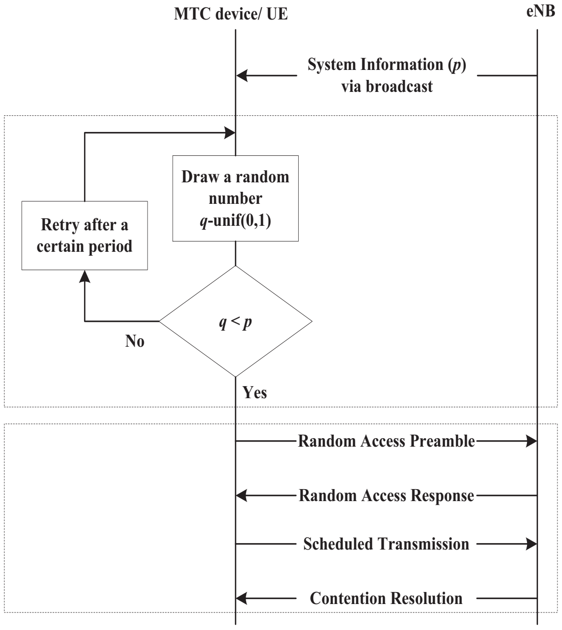

Fig. 2. Access class barring procedure for an MTC device or UE [10].

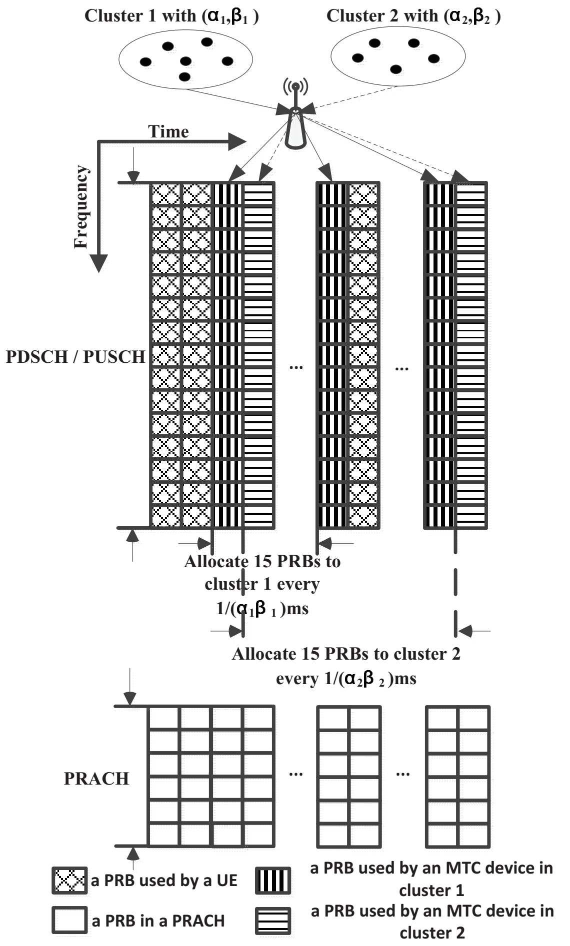

Fig. 3. The proposed traffic adaptive radio resource management (TARRM).

V. PERFORMANCE EVALUATION

In this section, we first describe simulation setup and evaluation metrics. Then, we compare the proposed ECACB with CACB [9] in terms of the *average (worst) access delay of UEs, average (worst) access delay of MTC devices, average (worst) throughput from UEs, and average (worst) throughput from MTC devices.* We also compare the proposed ECACB +TARRM with CACB [9] in terms of the *average (worst) throughput from UEs, and average (worst) throughput from MTC devices.*

A. Simulation setup and evaluation metrics

Table 2 shows related simulation parameters. First, we define the *average throughput from MTC devices* as the throughput averaged over all cells' eNBs, and the *worst throughput from MTC devices* as the lowest throughput among all cells' eNBs. Then we define the *average access delay of MTC devices* as the delay averaged over all active MTC devices, while the *worst access delay of MTC devices* as the largest access delay among all active MTC devices. The definitions of throughput and access delay of UEs are similar to those of MTC devices. Fig. 4 shows the cell layout and

MTC devices deployment percentages in each picocell and macrocell [9].

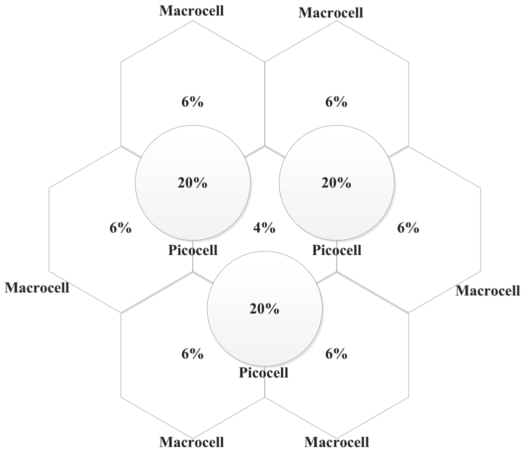

Fig. 4. Cells layout and MTC devices deployment percentages [9].

B. Comparison between proposed ECACB / ECACB+TARRM and CACB

Fig. 5 shows the average (worst) access delay of UEs. The access delay increases as the number of UEs increases. The reason is that when the number of UEs increases, collisions in a PRACH may increase. This results in the increase of access delay. The average (worst) access delay of the proposed ECACB is 33.19% (29.89%) lower than that of CACB. Fig. 6 shows the average (worst) access delay of MTC devices. The access delay increases as the number of MTC devices increases. The reason is that when the number of MTC devices increases, collisions in a PRACH may increase. This also results in the increase of access delay. The average (worst) access delay of the proposed ECACB is 12.15% (15.1%) lower than that of CACB.

Fig. 7 shows the average (worst) throughput from UEs. We observed that the throughput degrades as the number of UEs increases. This is because collisions may occur as the number of UEs increases and the number of UEs granted to uplink/downlink access may decrease. It results in degradation of the throughput. Fig. 7 also demonstrates that the proposed ECACB's average (worst) throughput from UEs is 20.93% (26.44%) higher than CACB's. The average (worst) throughput of the proposed ECACB+TARRM is 26.16% (31.42%) higher than that of CACB. Fig. 8 shows the average (worst) throughput from MTC devices. We found that the throughput degrades as the number of MTC devices increases. This is because collisions may increase as the number of MTC devices increases and the number of MTC devices granted to uplink/downlink access may decrease. It results in degradation of the throughput. Fig. 8 also demonstrates that the proposed ECACB's average (worst) throughput from MTC devices is 19.95% (12.25%) higher than CACB's. The average (worst) throughput of the proposed ECACB+TARRM is 25.11% (20.76%) higher than that of CACB.

Table 2: Simulation parameters [2][7][8][9].

Parameter	**Values**
Number of cells	7 macrocells and 3 picocells
Inter-site distance of macrocells	500m
Uplink data rate	500Mbps
Downlink data rate	1Gbps
Number of PRBs in a PDSCH / PUSCH	15
Number of PRBs in a PRACH	6
Number of PRBs for UEs in a PRACH	4
Number of PRBs for MTCs in a PRACH	2
Number of preambles for UEs	58
Number of preambles for MTCs	6
Cells layout and MTC devices deployment percentages	See Fig. 4
ϵ in [9]	0.0001
Random access rate of an MTC	0.2, 0.35, 0.5, 0.65, 1 request/s
Amount of data uploaded or downloaded for an MTC	36, 72, 108, 144, 180 bytes
Packet size	5 bytes
Random access rate of UEs	0.01 request/s
Amount of data uploaded or downloaded for UEs	500 bytes
Simulation time	600s

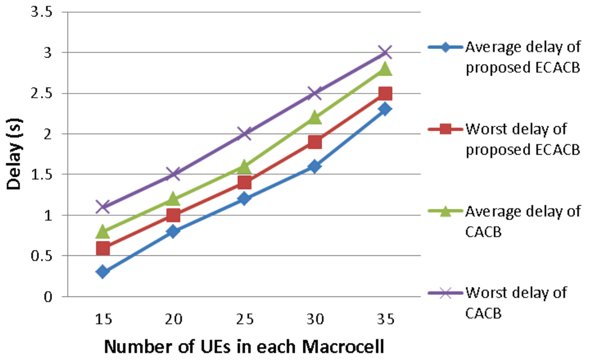

Fig. 5. Access delay of UEs.

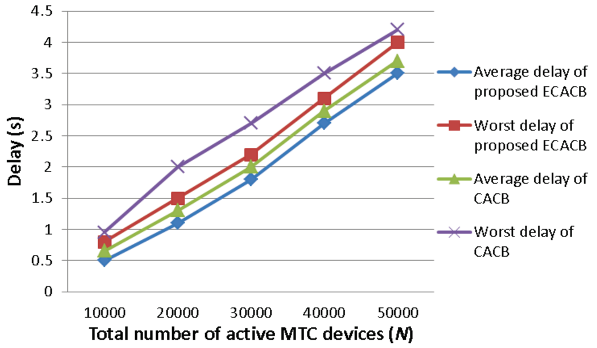

Fig. 6. Access delay of MTC devices.

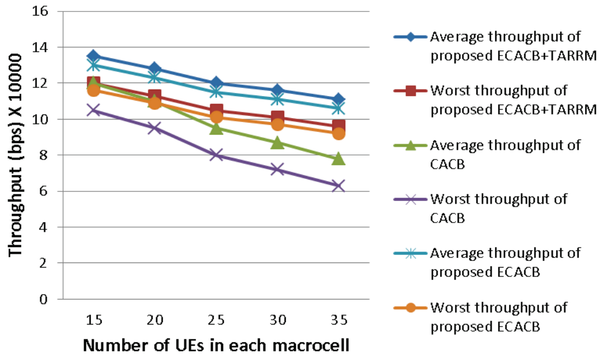

Fig. 7. Throughput from UEs.

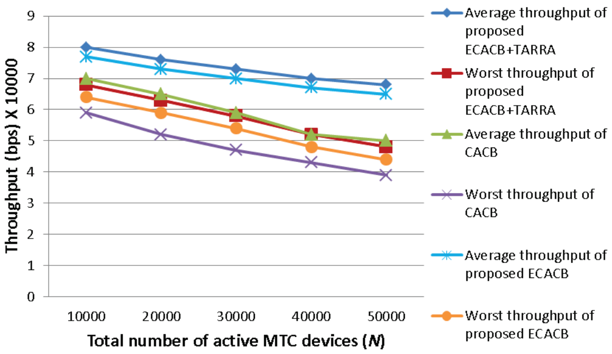

Fig. 8. Throughput from MTC devices.

VI. CONCLUSION

In this paper, we have presented enhanced cooperative access class barring (ECACB) and traffic adaptive radio resource management (TARRM) for M2M communications over LTE-A. We use the number of MTC devices that attach to an eNB as a criterion to determine the probability that an MTC device accesses an eNB. In this way, we can have a better set of access class barring parameters than CACB, which is the best available related work, so as to reduce the random access delay experienced by each MTC device or UE. After an MTC device successfully accesses an eNB, the eNB schedules radio resources for the MTC device based on the random access rate and the amount of data uploaded or downloaded by the MTC device. In addition, we use the concept of cognitive radio networks that when there are unused PRBs of UEs, an eNB can schedule MTC devices to use these PRBs of UEs. It can greatly improve network throughput. Simulation results shown that the proposed ECACB's average (worst) access delay of UEs is 33.19% (29.89%) lower than CACB's. Its average (worst) access delay of MTC devices is 12.15% (15.1%) lower than that of CACB. Its average (worst) throughput from UEs is 20.93% (26.44%) higher than that of CACB. Its average (worst) throughput from MTC devices is 19.95% (12.25%) higher than that of CACB. The proposed ECACB+TARRM's average (worst) throughput from UEs is 26.16% (31.42%) higher than CACB's. Its average (worst) throughput from MTC devices is 25.11% (20.76%) higher than that of CACB. To the best of our knowledge, no existing approach integrates access class barring with radio resource management for M2M communications over LTE-A.

ACKNOWLEDGMENTS

The supports by the National Science Council under Grants NSC99-2221-E-009-081-MY3, NSC101-2219-E-009-001, and the Ministry of Economic Affairs under Grant MoEA 100-EC-17-A-03-S1-193 are gratefully acknowledged.

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