Cooperative Access Class Barring for Machine-to-Machine Communications

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***Abstract*—Supporting trillions of devices is the critical challenge in machine-to-machine (M2M) communications, which results in severe congestions in random access channels of cellular systems that have been recognized as promising scenarios enabling M2M communications. 3GPP thus developed the access class barring (ACB) for individual stabilization in each base station (BS). However, without cooperations among BSs, devices within dense areas suffer severe access delays. To facilitate devices escaping from continuous congestions, we propose the cooperative ACB for global stabilization and access load sharing to eliminate substantial defects in the ordinary ACB, thus significantly improving access delays.**

***Index Terms*—M2M communications, 3GPP LTE-Advanced, cooperative ACB, random access.**

I. Introduction

MACHINE-to-machine (M2M) [1]–[3] had been considered as a new type of communications that empowers a full mechanical automation (such as the Internet of Things and the smart grid) [4]–[6] that may change our living styles. Enabling M2M communications, however, is never an easy task. M2M communications are distinct from sensor networks [7] where each device is either a sensor or the network decision maker (the sink), thus only connections from each sensor to the sink are required. To satisfy the needs of a full mechanical automation, each device may play multiple roles among the sensor, the decision maker and the action executor [4]–[6]. Therefore, the ultimate goal of M2M communications is to provide scrupulous connections among all machine-type communications (MTC) devices. In 3GPP [2], [3] and IEEE 802.16p [8], it is proposed that each MTC device attaches to the existing cellular infrastructure (e.g., LTE-Advanced or IEEE WiMAX2.0), by which, higher layers connections among MTC devices are provided. However, the subsequent challenge lies in the access control on the *air interface* [9], [10].

Supporting a massive number of MTC devices has been considered as an essential requirement in M2M communications, which had been recognized as one of major differences from human-to-human communications. In 3GPP, the first step to establish an air interface connection is performing random access at the random access channel (RACH). Random access is typically performed to deliver requests to the base station (BS) in a contention manner when the MTC device turns on or requires radio resources for data transmissions. In successful M2M communications, a massive number of MTC devices shall be supported. The most critical and open challenge obstructing the development of M2M communications is an effective medium access scheme to prevent access congestions at the RACH of the cellular infrastructure. To alleviate congestions, few schemes such as multiple access collision avoidance (MACA) based solutions [11], [12] have been proposed for MTC devices. However, these schemes are effective for the contention based data delivery and they are infeasible for the cellular networks that contention is only adopted for the requests delivery while data is transmitted in a scheduling basis. In LTE-Advanced, a network coordinated random access stabilization scheme known as the access class barring (ACB) is adopted [13], [14]. In the RACH, the purpose of the stabilization is to control the expected number of simultaneous accesses to a common RACH radio resource to be one. The stabilization thus maximizes the throughput and enhances the delay performance of requests delivery via the RACH. In the ACB, when the random access procedure is initialed, the BS broadcasts an ACB parameter $p \in [0, 1]$ to MTC devices. Each active MTC device (the MTC device attempting to send a request to the BS) also draws a random number $q \in [0, 1]$. If $q \leq p$, then the active MTC device proceeds to the random access procedure; otherwise, the active MTC device is barred for a barring time duration. Therefore, the BS can control the congestion (stabilize the system to maximize the throughput) by controlling p. In existing cellular networks, each MTC device shall attach to one BS. In LTE-Advanced, each MTC device can only send requests (access) to the BS that the MTC device attached to. Therefore, in the ordinary ACB, each BS individually determines the ACB parameter p for the individual stabilization in each "cell" (formed by an BS). However, if a severe congestion occurs in a cell, the BS may set its p to an extremely low value, which results in an unacceptable access delay experienced by MTC devices. As a result, in the ordinary ACB, delay is by no means to be improved.

The state-of-the-art cellular systems, such as LTE-Advanced, are with a heterogeneous multi-tier network architecture [15]. That is, in additional to conventional Macrocells, there are picocells underlaying the Macrocell to enhance the received signal strength and alleviate the burden of the Macrocell. As a result, an MTC device may locate within overlapped coverage areas of multiple cells (the Macrocell and the picocell) as shown in Fig. 1. If such an MTC device

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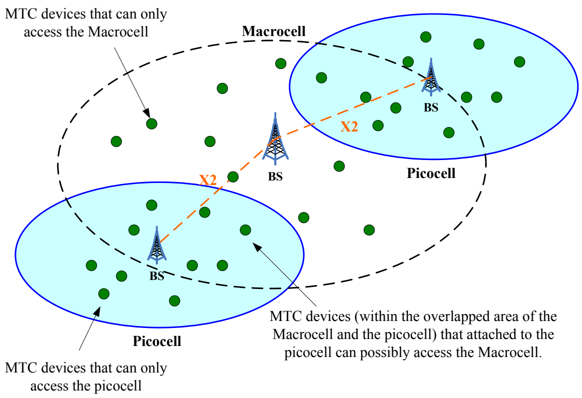

Fig. 1. In state-of-the-art cellular systems, an MTC device may locate within the overlapped coverage area of multiple "cells". If these MTC devices can access the BS not attached by the MTC device, the access delay can be alleviated. In LTE-Advanced, there is an X2 interface among BSs. By leveraging this interface, BSs can cooperate with each other to perform the cooperative ACB.

can possibly access the BS with an eased congestion, the access delay experienced by the MTC device can be alleviated. For this purpose, all ACB parameters p in each BS shall be jointly decided by all BSs, rather than individually decided in each BS, to jointly achieve stabilizations and the access load sharing among BSs. Through the interface among BSs (such as the X2 interface in LTE-Advanced), direct communications and thus cooperations among BSs are available. In this letter, we consequently propose the cooperative ACB, where all ACB parameters of all BSs are jointly optimized based on levels of congestions in each BS to substantially enhance the performance of the ordinary ACB.

II. Problem Formulation

Consider the random access of M2M communications in LTE-Advanced with M BSs indexed by $m = 1, \ldots, M$ and N active MTC devices indexed by $n = 1, \ldots, N$. Distinct from the ordinary ACB that each MTC device can only access the BS attached by the MTC device, in this letter, we propose that an MTC device is able to access the BS unattached by the MTC device when the MTC device locates within the overlapped coverage area of multiple BSs. To formulate such a random access problem, we adopt following notations.

(i) Denote A_m as the set of MTC devices attaching to the mth BS and $\|A_m\|$ as the norm of A_m, $\sum_{m=1}^{M} \|A_m\| = N$. When cooperations of BSs are available, A_m for all m are known by all BSs.

(ii) Denote M_n as the set of BSs that the nth MTC device can possibly access. The nth MTC device selects one BS from M_n to proceed to the random access. In LTE-Advanced, the BS can request the MTC device to perform the exploration of surrounding BSs, and report the exploration result. Thus, M_n for all n are available for all BSs. However, M_n for $n = 1, \ldots, N$, $n \neq j$ are unknown by the jth MTC device for $j = 1, \ldots, N$.

(iii) Denote N_m as the set of MTC devices that access the mth BS. In the ordinary ACB, $\|N_m\|$ for all m are known by each BS. However, if each MTC device can access the BS unattached by the MTC device, $\|N_m\|$ for all m are random variables unknown by BSs, unless the BS selection strategy of each MTC device is given.

(iv) Denote $\mathbf{1}_{n,m}$ as an indicator function that, for the nth MTC device,

$$\mathbf{1}_{n,m} = \begin{cases} 1, & \text{if the } m\text{th BS is within } M_n, \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

(v) Denote $N_m^{'}$ as the set of MTC devices that can only receive the signal from the mth BS and these MTC devices can only access the mth BS. $\|N_m^{'}\|$ is the norm of $N_m^{'}$.

In the ordinary ACB, although the throughput of each cell can be individually maximized by individually setting $p_m = \frac{1}{\|N_m\|}$ (where p_m is the ACB parameter of the the mth BS) in each BS, the delay experienced by an MTC device attached to the mth BS may be unacceptable when p_m requires to be set to an extremely small value under a large $\|N_m\|$. Such an unfavorable performance can not be improved in the ordinary ACB. In this letter, our objective is to provide an optimum control of a set of ACB parameters $\mathbf{p} = [p_1, \ldots, p_M]$ jointly decided by M BSs to minimize the largest access delay experienced among N active MTC devices. Such an objective can be achieved by minimize the maximum number of accesses among M BSs (or cells). Through cooperations among BSs to make a joint decision of $\mathbf{p} = [p_1, \ldots, p_M]$, the problem can be formulated by

$$\begin{aligned} &\min_{p_1,\ldots,p_M} \max(\|N_1\|, \|N_2\|, \ldots, \|N_M\|) \\ &\text{s.t. (C1.1) } 0 \preceq \mathbf{p} = [p_1, \ldots, p_M] \preceq 1, \\ &\quad\quad \text{(C1.2) } \|N_m\| p_m \leq 1, \text{ for } m = 1, \ldots, M. \end{aligned} \quad (2)$$

The objective function in (2) minimizes the number of accesses to the BS with the severest congestion (that is, with the maximum number of accesses) under the constraint of the feasibility of the selected $\mathbf{p}$ in (C1.1) and the constraint of stability in each BS in (C1.2) (the expected number of aggregated accesses of MTC devices to the mth BS shall not exceed 1). From the perspective of engineering, the stabilization constraint (C1.2) can be further relaxed to

$$\|N_m\| p_m \leq 1 + \delta, \text{ for } m = 1, \ldots, M \quad (3)$$

and the performance can still approach to the optimum if δ is sufficiently small. However, in (2), when each MTC is able to access the BS unattached by the MTC device according to our proposition, $\|N_m\|$ for all m are random variables and are unknown by BSs. As a result, the problem in (2) is unsolvable. To obtain $\|N_m\|$ for all m, BSs shall be aware of the strategy adopted by each MTC device on the selection of the BS, under any given $\mathbf{p}$. Then, BSs can optimize the number of accesses of MTC devices by controlling $\mathbf{p}$. For this purpose, we shall first determine the strategy on the selection of BS for each MTC device. In the following section, we thus propose the BS selection strategy for each MTC device. In this letter, all MTC devices are homogeneous, that is, no priority among MTC devices.

III. The BS Selection Strategy for Each MTC Device

Consider that a set of ACB parameters $\tilde{\mathbf{p}}_n = \{p_i, p_j, \ldots, p_k\} \subseteq \mathbf{p}$, where $\|\tilde{\mathbf{p}}_n\| = \|M_n\|$, is received by the nth MTC device. Denote $Q_{n,x}$ as the probability that the nth MTC device selects the xth BS to access. Since there is no priority among MTC devices, no MTC device can make the decision priori to the decision makings of other MTC devices. Thus, all MTC devices shall adopt the same strategy. In the following, constraints for the nth MTC device on the selection of one BS from M_n is provided.

Proposition 1. *Generally considering $p_i \geq p_j \geq \ldots \geq p_k$ (otherwise, these probabilities can be resorted), the strategy adopted by the nth MTC device shall satisfy that*

$$\beta_n(p_i, p_j, \ldots, p_k) = [Q_{n,i}, Q_{n,j}, \ldots, Q_{n,k}],$$
$$\text{where } Q_{n,i} \geq Q_{n,j} \geq \ldots \geq Q_{n,k} \text{ and } \sum_{x \in M_n} Q_{n,x} = 1. \quad (4)$$

Proof: We first consider the case of $\tilde{\mathbf{p}}_n$ with only two elements, say p_i and p_j, and $p_i > p_j$. Since all MTC devices receiving p_i and p_j adopt the same strategy and the MTC realizes that there are MTC devices adopting the same strategy with it (although the MTC device does not know the number of MTC devices adopting the same strategy with it), if the MTC device adopts the strategy with $Q_{n,i} < Q_{n,j}$, the jth BS with severe congestions suffers even severer congestions since all MTC devices receiving p_i and p_j attempt to access the jth BS, while the slight congestion of the ith BS is even eased. Therefore, adopting $Q_{n,i} < Q_{n,j}$ may not improve the access delay of the MTC device, especially when the number of MTC devices adopting the same strategy is unknown by the MTC device. Thus, the MTC device tends to change its strategy. On the other hand, if $Q_{n,i} > Q_{n,j}$ is adopted, the MTC devices can not choose a better strategy to further improve its performance (since the number of MTC devices adopting the same strategy is unknown by the MTC device). Thus, the MTC device may stay on adopting this strategy. If $p_i = p_j$, the consequence of selecting the ith BS and the jth BS are equivalent. Thus, $Q_{n,i} = Q_{n,j}$ is adopted. Therefore, if $p_i \geq p_j$, the MTC device shall adopt $Q_{n,i} \geq Q_{n,j}$. This result can be extended to the case of $\tilde{\mathbf{p}}_n$ with an arbitrary number of elements by pairwise arguments among all elements. ■

Proposition 2. *If $p_i \geq p_j \geq \ldots \geq p_k > 0$, then the nth MTC device shall adopt a mixed strategy of*

$$\beta_n(p_i, p_j, \ldots, p_k) = [Q_{n,i}, Q_{n,j}, \ldots, Q_{n,k}], \text{ where}$$
$$Q_{n,i} \geq Q_{n,j} \geq \ldots \geq Q_{n,k} > 0 \text{ and } \sum_{x \in M_n} Q_{n,x} = 1 \quad (5)$$

Proof: We had proven that if $p_i \geq p_j \geq \ldots \geq p_k$ are received by the MTC device, then the MTC device shall adopt the strategy with $Q_{n,i} \geq Q_{n,j} \geq \ldots \geq Q_{n,k}$. Here, we focus on the proof of the mixed strategy. The two elements case of $\tilde{\mathbf{p}}_n$ is also adopted in this proof. If $p_i > p_j$ and $Q_{n,i} > Q_{n,j}$ while $Q_{n,j} = 0$, then $Q_{n,i} = 1$ for the MTC device and other MTC devices receiving $p_i > p_j$ (that is, the pure strategy). If the pure strategy is adopted, although congestions in the jth BS can be relaxed, congestions in the ith may be extremely worse. Thus, the MTC device and other MTC devices tend to change their strategies. Thus, $Q_{n,i} > Q_{n,j} > 0$ shall be adopted, which suggests a mixed strategy. ■

Proposition 1 and Proposition 2 suggest that, if each MTC device can possibly access the BS unattached by the MTC device, the performance of the MTC device can be potentially improved. To satisfy these constraints, the general form of the strategy for each MTC device shall be as follows.

Proposition 3. *Upon receiving $\tilde{\mathbf{p}}_n = \{p_i, p_j, \ldots, p_k\} \subseteq \mathbf{p}$, the nth MTC device adopts the strategy*

$$\beta_n(p_i, p_j, \ldots, p_k) = [\frac{p_i}{\sum_{x \in M_n} p_x} + \theta_i, \frac{p_j}{\sum_{x \in M_n} p_x} + \theta_j, \ldots, \frac{p_k}{\sum_{x \in M_n} p_x} + \theta_k], \sum_{x \in M_n} \theta_x = 0. \quad (6)$$

Since strategies satisfying the general form of (6) are equivalent, we can specify the strategy as

$$\beta_n(p_i, p_j, \ldots, p_k) = [Q_{n,i} = \frac{p_i}{\sum_{x \in M_n} p_x}, Q_{n,j} = \frac{p_j}{\sum_{x \in M_n} p_x}, \ldots, Q_{n,k} = \frac{p_k}{\sum_{x \in M_n} p_x}]. \quad (7)$$

After providing the strategy of each MTC device, BSs thus can control $\mathbf{p}$ to jointly achieve the stabilization and the access load sharing "globally" among all BSs. In the following section, we consequently propose the cooperative ACB to optimize the jointly decided $\mathbf{p}$.

IV. Cooperative Access Class Barring

Given that the strategy on the selection of the BS in each MTC device in (7) is known by BSs, $\|N_m\|$ for all m can be obtained by

$$\|N_m\| = \sum_{x=1}^{M} \sum_{n \in A_x} \mathbf{1}_{n,m} Q_{n,m} \text{ for } m = 1, \ldots, M. \quad (8)$$

Thus, $\|N_m\|$ is no longer unknown by BSs. With the facilitation of (8), the problem (2) can be written by

$$\begin{aligned} &\min_{p_1, \ldots, p_M} \max(\sum_{x=1}^{M} \sum_{n \in A_x} \mathbf{1}_{n,1} Q_{n,1}, \ldots, \sum_{x=1}^{M} \sum_{n \in A_x} \mathbf{1}_{n,M} Q_{n,M}) \\ &\text{s.t. (C2.1) } 0 \preceq \mathbf{p} = [p_1, \ldots, p_M] \preceq 1, \\ &\text{(C2.2) } \begin{cases} \sum_{x=1}^{M} \sum_{n \in A_x} \mathbf{1}_{n,1} Q_{n,1} p_1 \leq 1 + \delta \\ \sum_{x=1}^{M} \sum_{n \in A_x} \mathbf{1}_{n,2} Q_{n,2} p_2 \leq 1 + \delta \\ \vdots \\ \sum_{x=1}^{M} \sum_{n \in A_x} \mathbf{1}_{n,M} Q_{n,M} p_M \leq 1 + \delta \end{cases} \end{aligned} \quad (9)$$

However, the problem in (9) is not in specific forms (e.g., convex), which makes this problem intractable and a closed-form expression of the optimum solution may not be analytically available. To solve (9), we propose an iterative method composed of two algorithms to obtain the optimum control of $\mathbf{p}$. To ensure the convergence to the optimum, Algorithm 1 is proposed to obtain $\|N_1^*\|, \|N_2^*\|, \ldots, \|N_M^*\|$ under a given deployment of BSs and MTC devices such that differences among $\|N_1^*\|, \|N_2^*\|, \ldots, \|N_M^*\|$ are minimized. It is exactly the objective of (9) without regarding (C2.1) and (C2.2). $\|N_1^*\|, \|N_2^*\|, \ldots, \|N_M^*\|$ serve as the initiation of iterations in Algorithm 2. We will show that this initiation ensures the convergence.

The complexity of Algorithm 1 is $\mathcal{O}(nm \log m)$. At this moment, the optimum $\mathbf{p}$ is still unknown. Algorithm 2 thus devotes to obtain the $\mathbf{p}$ such that the corresponding $\|N_1\|, \|N_2\|, \ldots, \|N_M\|$ approach to the optimum while (C2.1) and (C2.2) are satisfied, by iterations.

Algorithm 1 THE PROCEDURE OF OBTAINING $\|N_1^*\|, \|N_2^*\|, \ldots, \|N_M^*\|$.

1: Set $\|N_m^*\| = \|N_m^{'}\|$ for all m.
2: Find the BS(s) with the minimum $\|N_m^*\|$, $m' = \arg\min\{\|N_1^*\|, \|N_2^*\|, \ldots, \|N_M^*\|\}$. Find the BS(s) with the second minimum $\|N_m^*\|$, $m'' = \arg_{m'' \neq m'} \min\{\|N_1^*\|, \|N_2^*\|, \ldots, \|N_M^*\|\}$. Denote $L_{m'}$ as the number of MTC devices that $n \notin N_{m'}^{'}$ and $m' \in M_n$ for all possible m'.
3: **if** $L_{m'} = 0$ **then**
4: Move $\|N_{m'}^*\|$ to the output queue and this BS is not considered in subsequent operations.
5: Go to "Row 2".
6: **end if**
7: **if** $L_{m'} \leq \sum_{m'}(\|N_{m''}^*\| - \|N_{m'}^*\|)$ for all possible m' **then**
8: Set $\|N_{m'}^*\| = \|N_{m''}^*\|$ for all m'.
9: Set $L_{m'} = L_{m'} - \sum_{m'}(\|N_{m''}^*\| - \|N_{m'}^*\|)$.
10: **else**
11: Equally allocate $L_{m'}$ to all possible m'.
12: Set $L_{m'} = 0$.
13: Move $\|N_{m'}^*\|$ to the output queue and this BS(s) is not considered in subsequent operations.
14: **end if**
15: Go to "Row 2" until all $\|N_1^*\|, \|N_2^*\|, \ldots, \|N_M^*\|$ are within the output queue.
16: **Output:** $\|N_1^*\|, \|N_2^*\|, \ldots, \|N_M^*\|$

Algorithm 2 THE PROCEDURE OF THE CONTROL OF **p**

1: **Input:** $\|N_1^*\|, \|N_2^*\|, \ldots, \|N_M^*\|$ from Algorithm 1
2: Set $p_m = \frac{1}{\|N_m^*\|}$ for all m.
3: Set $\|\hat{N_m}\| = \sum_{x=1}^{M}\sum_{n \in A_x} \mathbf{1}_{n,m} Q_{n,m}$ for all m.
4: **while** $|\|\hat{N_1}\| - \|N_1^*\|| > \epsilon$ or $|\|\hat{N_2}\| - \|N_2^*\|| > \epsilon$ or $\ldots$ or $|\|\hat{N_M}\| - \|N_M^*\|| > \epsilon$ **do**
5: Set $\|N_m^*\| = \|\hat{N_m}\|$ for all m.
6: Set $p_m = \frac{1}{\|N_m^*\|}$ for all m.
7: Set $\|\hat{N_m}\| = \sum_{x=1}^{M}\sum_{n \in A_x} \mathbf{1}_{n,m} Q_{n,m}$ for all m.
8: **end while**
9: **Output:** $p_1, p_2, \ldots, p_M$

In Algorithm 2, iterations stop when the difference of results between two successive iterations is not larger than ϵ. That is, $|\|\hat{N_m}\| - \|N_m^*\|| \leq \epsilon$ for all m in "Row 4" of Algorithm 2. We will show, in the next section, that the number of iterations is acceptable, even though ϵ is set to an extreme small value 10^{-4}. In the following, we devote to the proof of the convergence in Algorithm 2 and the optimality of **p** obtained by Algorithm 2. We consider the two BSs case and such a case can be easily extended to the M BSs case. We first prove the convergence of Algorithm 2. Denote $\|N_1^{(t)}\|$ and $\|N_2^{(t)}\|$ as the expected numbers of MTC devices that may access the first BS and the second BS after the tth iteration. Therefore,

$$\|N_1^{(t+1)}\| = \|N_1^{'}\| + (\|N_1^{(t)}\| - \|N_1^{'}\|) \cdot \frac{1/(\|N_1^{(t-1)}\| + \varepsilon)}{(1/(\|N_1^{(t-1)}\| + \varepsilon)) + (1/(\|N_2^{(t-1)}\| - \varepsilon))}, \tag{10}$$

$$\text{or } \|N_1^{(t+1)}\| = \|N_1^{'}\| + (\|N_1^{(t)}\| - \|N_1^{'}\|) \cdot \frac{1/(\|N_1^{(t-1)}\| - \varepsilon)}{(1/(\|N_1^{(t-1)}\| - \varepsilon)) + (1/(\|N_2^{(t-1)}\| + \varepsilon))} \tag{11}$$

where $\|N_1^{(t-1)}\| \pm \varepsilon = \|N_1^{(t)}\|$, $\varepsilon \geq 0$ is the difference between $\|N_1^{(t-1)}\|$ and $\|N_1^{(t)}\|$. According to the *contraction mapping theorem* [16], it is known that $\|N_1^{(t)}\|$ converges to a fixed value when $t \to \infty$ if

$$\frac{1/(\|N_1^{(t-1)}\| + \varepsilon)}{(1/(\|N_1^{(t-1)}\| + \varepsilon)) + (1/(\|N_2^{(t-1)}\| - \varepsilon))} = \frac{\|N_2^{(t-1)}\| - \varepsilon}{\|N_1^{(t-1)}\| + \|N_2^{(t-1)}\|} < 1, \tag{12}$$

$$\text{or } \frac{1/(\|N_1^{(t-1)}\| - \varepsilon)}{(1/(\|N_1^{(t-1)}\| - \varepsilon)) + (1/(\|N_2^{(t-1)}\| + \varepsilon))} = \frac{\|N_2^{(t-1)}\| + \varepsilon}{\|N_1^{(t-1)}\| + \|N_2^{(t-1)}\|} < 1. \tag{13}$$

Therefore, ε is required to be less than $\|N_1^{(t-1)}\|$ and the inequality $|\ \|N_1^{(1)}\| - \|N_1^{(0)}\|\ | < \|N_1^{(0)}\|$ shall be achieved. Similar to (10) and (11), it is known that $|\ \|N_2^{(1)}\| - \|N_2^{(0)}\|\ | < \|N_2^{(0)}\|$ also shall be achieved. Since the initial input of Algorithm 2 ($\|N_1^{(0)}\|$ and $\|N_2^{(0)}\|$) is the output of Algorithm 1, which achieves the most balanced sharing of numbers of accesses to the first BS and to the second BS under the given deployment of BSs and MTC devices, $|\ \|N_1^{(1)}\| - \|N_1^{(0)}\|\ | < \|N_1^{(0)}\|$ and $|\ \|N_2^{(1)}\| - \|N_2^{(0)}\|\ | < \|N_2^{(0)}\|$ can be achieved by adopting such an initiation. From (10) and (11), it is also known that $\varepsilon < \|N_1^{(t-1)}\|$ (and $\varepsilon < \|N_2^{(t-1)}\|$) is valid after the tth iteration for any t (ε decreases after each iteration). We thus complete the proof of the convergence. Such a convergence to a fixed value also suggests the optimality of **p** by Algorithm 2. In Algorithm 2, the initial input is the ideally optimum performance without regrading (C2.1) and (C2.2). Then, a **p** is decided for the stabilization. Such **p** consequently results in a new $\|N_m\|$ for all m. Since iterations proceed until the stop rule is met, if there exists $\mathbf{p}'$, $\mathbf{p}' \neq \mathbf{p}$, resulting in a better performance than that of **p**, then $\mathbf{p}'$ can not satisfy (C2.2), which suggests the optimality of **p**.

Please note that if a small ε can be achieved, it is known that $\frac{1}{\|N_m^{(t)}\|}(\|N_m^{(t)}\| + \varepsilon) = 1 + \frac{\varepsilon}{\|N_m^{(t)}\|} = 1 + \delta$. Therefore, $\delta < \varepsilon$. Since $\varepsilon \leq \epsilon$, we have $\delta < \epsilon$. As a result, δ in (C2.2) can also be acceptable.

V. SIMULATION RESULTS

To evaluate the performance of the proposed cooperative ACB, we adopt simulation parameters for LTE MTC devices [17] that had been agreed by 3GPP. In this simulation, seven Macrocells and three picocells are considered. A typical deployment of these Macrocells and picocells is depicted in Fig. 2. Since the purpose of the picocell is to be deployed at the hot spot to share traffic load of the Macrocell, in this simulation, the coverage of each of three picocells is deployed by 20% among total N MTC devices. This setting of the non-uniform deployment of MTC devices to all cells particularly highlights the general purpose of picocells deployments in 3GPP. Details of simulation parameters are listed in Table I.

In this evaluation, we particularly focus on two classes of performance metrics: (i) the average (access) delay and the

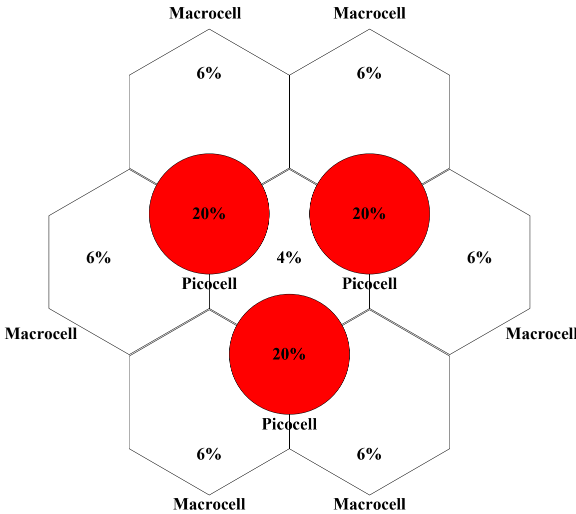

Fig. 2. Cells layout for simulations. Seven hexagonal-grid Macrocells with wrap-around and three picocells deployed at the boundary of the central Macrocell with wrap-around are considered. Each picocell is deployed by 20% of MTC devices among N. These MTC devices attach to the BS of the picocell. Each Macrocell (except the central) is deployed by 6% of MTC devices among N. These MTC devices attach to BSs of corresponding Macrocells. 4% of MTC devices among N are deployed to and attach to the central Macrocell.

TABLE I
SYSTEM PARAMETERS AND ASSUMPTIONS FOR SIMULATIONS

Parameters	Values/assumptions
Total number of active MTC devices (N)	10000, 20000, 30000, 40000 and 50000
Number of cells	Seven Macrocells and three picocells
Cells layout (as shown in Fig. 2.)	Seven hexagonal-grid Macrocells with wrap-around. Three picocells are deployed at the boundary of the central Macrocell with wrap-around.
Inter-site distance of Macrocells	500m
MTC devices deployment (Fig. 2)	Each picocell is deployed by 20% of MTC devices among N. These MTC devices attach to the BS of the picocell. Each Macrocell (except the central) is deployed by 6% of MTC devices among N. These MTC devices attach to BSs of corresponding Macrocells. 4% of MTC devices among N aredeployed to and attach to the central Macrocell.
Number of preambles	1 preamble[a]
The period of RACH	5ms
The downlink TX power of the BS in the Macrocell	46 dBm
The downlink TX power of the BS in each picocell	30 dBm

[a] In this simulation, we particularly adopt only one preamble for the random access, to limit the random access resource to the time domain, rather than the preamble domain.

average throughput, and (ii) the worst (access) delay and the worst case throughput, where (i) is interested by the system operator while (ii) is interested by MTC devices users. We first evaluate the performance of the average (access) delay and the worst (access) delay experienced by MTC devices in Fig. 3. The average delay is the delay performance averaged over all N MTC devices, while the worst case delay is the largest delay among N MTC devices. We can observe from Fig. 3 that

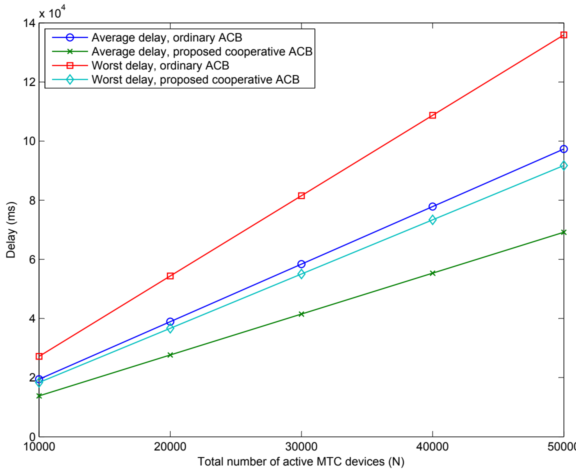

Fig. 3. The average delay and the worst case delay experienced by MTC devices under the ordinary ACB and the proposed cooperative ACB ($\epsilon = 10^{-4}$).

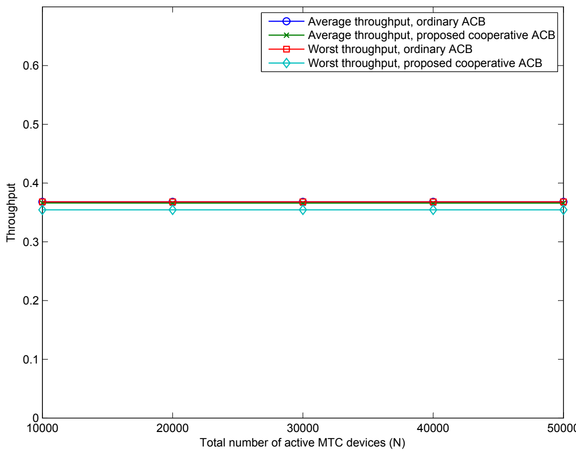

Fig. 4. The average throughput and the worst case throughput under the ordinary ACB and the proposed cooperative ACB ($\epsilon = 10^{-4}$).

around 30% improvement can be achieved by the proposed cooperative ACB as compared with the ordinary ACB, both in the average delay and the worst case delay performance. Such improvement is due to that MTC devices can access the BS not attached by MTC devices. These results suggest the effectiveness of the cooperative ACB on the control of $\mathbf{p}$ to balance loadings of accesses among BSs.

We next evaluate the performance of the average throughput and the worst case throughput. The average throughput is averaged over all cells, while the worst case throughput is the lowest throughput among all cells. Distinct from the ordinary ACB, in additional to the stabilization, $\mathbf{p}$ determined by the proposed cooperative ACB shall also guide MTC devices to access appropriate BSs for the access load sharing. As a result, there could be throughput degradations in the cooperative ACB. Therefore, we shall evaluate whether such throughput degradation in the cooperative ACB can be acceptable. Fig. 4 shows that, the degradation on the average throughput under the cooperative ACB is very trifling as compared with that under the ordinary ACB. On the other hand, the worst case throughput under the cooperative ACB is only 0.01 lower than the worst case throughput under the ordinary ACB. These

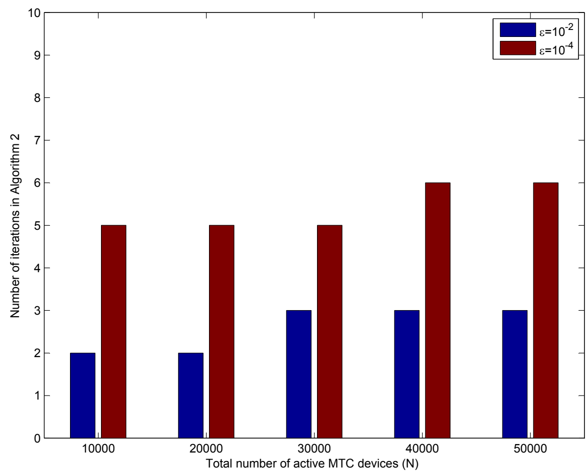

Fig. 5. Number of iterations in Algorithm 2 when $\epsilon = 10^{-2}$ and $\epsilon = 10^{-4}$.

results suggest that the cooperative ACB can significantly improve the access delay with trifling throughput degradations.

Finally, we can observe from Fig. 5 that, 5 to 6 iterations in Algorithm 2 are sufficient even though ϵ is set to 10^{-4}. Thus, the computational complexity of the cooperative ACB is acceptable in practice.

VI. Conclusion

In this paper, we resolve the most critical issue of M2M communications in the 3GPP scenario by proposing the cooperative ACB to globally control congestions among BSs. By only utilizing the ordinary ACB parameters $\mathbf{p}$, the cooperative ACB yields no impacts on the system architecture of LTE-Advanced, thus it can be smoothly applied to LTE-Advanced. Simulation results show that the cooperative ACB can effectively improve the access delay that is by no means to be improved in the ordinary ACB. Yielding limited complexities, the cooperative ACB thus enables the first mile connections in M2M communications.

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