Joint Access Class Barring and Timing Advance Model for Machine-Type Communications

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***Abstract*—The existing wireless cellular networks can provide machine-to-machine (M2M) service to machine-type communication (MTC) devices deployed in large coverage areas. However, the current Long Term Evolution (LTE) cellular networks designed for human users may not be able to handle a large number of bursty random access requests from MTC devices. In this paper, we propose to jointly use access class barring (ACB) and timing advance (TA) command to reduce the random access overload. In our proposed scheme, the expected number of MTC devices served in one random access slot is determined by the coverage of the base station, total number of devices to be served, the number of preambles, and ACB parameter. By choosing the optimal ACB parameter, we can maximize the number of MTC devices being served in each random access slot. The total number of random access slots required by an LTE base station to serve all MTC devices can be minimized. Simulation results show that in typical LTE cellular networks, our proposed scheme can reduce at least a half of the total slots required by the base station to serve all MTC devices.**

I. Introduction

Machine-to-machine (M2M) communication system involves a large number of machine-type communication (MTC) devices, which can communicate with the remote server or other MTC devices in a peer-to-peer manner. M2M is leading us to the Internet of Things. Its applications include smart metering, remote security sensing, health care monitoring, remote control, and fleet tracking. It is expected that 24 to 50 billion MTC devices will be deployed in the next decade [1].

Since the potential M2M applications usually require seamless coverage over a large area, one approach to provide M2M services is via the existing cellular networks. Meanwhile, the 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) cellular networks can allow MTC devices to connect to remote servers or devices in other network domains [2]. However, the LTE systems, which are designed for human-to-human (H2H) communications, may not be optimal to carry M2M traffic. M2M communications differ from H2H communications in several aspects [2]. The size of the data produced or consumed by an MTC device is much smaller than that in H2H traffic. Bursty random access requests from MTC devices may be sent to the base station or the evolved node B (eNB) when neighbouring MTC devices used for sensing detect an event together. The number of MTC devices can be larger than the number of human users. The channel resource contention, which seldom happens in H2H communications, will occur in M2M context. This kind of channel resource contention is called *random access overload* [3].

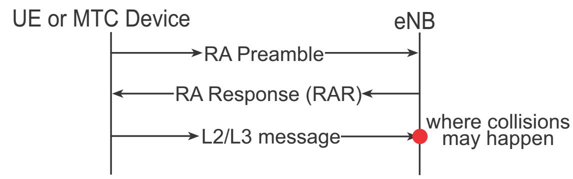

Fig. 1. Random access process in LTE systems.

We now describe how the random access overload can impact the LTE networks. Fig. 1 shows the first three steps for random access in LTE systems. These steps are the same for both user equipment (UE) and MTC device. Random access is available to UE periodically via random access slots. At the beginning of a random access slot, a UE selects a random access preamble and sends it to the eNB. The eNB sends a *random access response* (RAR) to acknowledge the request. The RAR contains (a) a number to identify the current random access slot, (b) the index of the preamble selected by the UE being acknowledged, (c) the timing advance command T_A [4][5], and (d) the resource allocation information. The information in (a) and (b) is used to address an RAR to its target UE. The information in (c) and (d) is used to synchronize the UE to eNB and help the UE to schedule its L2/L3 message in Step 3. Some UEs may send an identical preamble via the same random access slot, and they will receive the same RAR. When this happens, not only the target UE but also other UEs will send their L2/L3 messages over the same wireless channel. This may cause collisions at the eNB. Compared to H2H, the probability of collisions increases in the M2M random access overload scenario. Thus, random access overload may reduce the performance of LTE systems.

Different schemes have been proposed to address the random access overload in LTE networks. MTC devices can be grouped with some MTC gateway devices [6][7]. Each gateway device can aggregate several short packets, and then send them together in an energy-efficient manner [8]. The work in [9] proposed the *massive access management* to satisfy the quality of service requirements. Access class barring (ACB) is proposed in [10] by tuning an ACB parameter b ($0 \leq b \leq 1$). When an MTC device wants to connect to the eNB, it generates a random number over $[0,1]$ uniformly and joins the random access contention only if the generated value is less than b. The work in [11] proposes to control the ACB parameters on multiple eNBs to serve MTC devices efficiently. A random access protocol for stationary MTC devices is proposed in [12]. The T_A in an RAR represents the propagation delay from its receiver to the eNB. Thus, for a given stationary MTC device, the T_A does not change over time. When an MTC device receives an RAR message, it compares the T_A in the RAR to the T_A that it obtained in previous random access slots. It sends the L2/L3 message only if the two T_A are the same. However, T_A is quantized and takes only the index values as multiples of $16T_s$, where T_s is the *basic time unit* in LTE systems [5], so the T_A may be same for two MTC devices if the difference between their propagation delays is less than $16T_s = 0.52$ μs. Thus, simply comparing the values of T_A will have less effect in reducing the random access overload when the density of MTC devices increases.

In this paper, we propose to use both ACB and T_A to reduce random access overload for stationary MTC devices in LTE networks. In our problem formulation, we aim to maximize the expected number of MTC devices being served in each random access slot. We show that, for an LTE base station with a given coverage radius, when we have the total number of MTC devices and the number of preambles, the expected number of devices served in a slot can be presented as a non-closed-form function of the ACB parameter. Given the complexity of the problem, we use a numerical approach to obtain the solutions. Our analytical results are validated via simulations. Results also show that compared to the schemes using either ACB or T_A only, the proposed scheme can save at least 50% of total random access slots required to serve all MTC devices in typical LTE systems.

The rest of the paper is organized as follows. In Section II, we introduce our system model, formulate the problem, and also present the numerical solution. Simulation results are presented in Section III. Conclusion is given in Section IV.

II. System Model and Problem Formulation

We consider the system where the MTC devices connect to an eNB in the LTE networks. The radius of the coverage of the eNB is R. N stationary MTC devices requiring access are uniformly distributed within the cell. We assume these MTC devices had received the timing advance command T_A [4] in their previous communications with eNB. After sending a preamble in a random access slot, an MTC device sends its L2/L3 message only if the same T_A is received in an RAR. Since T_A is quantized, we assume that two MTC devices have the same T_A if the difference of their distance to eNB is smaller than d.

Consider three MTC devices n_1, n_2, and n_3 in Fig. 2 as an example. Assume that n_1, n_2, and n_3 receive the same RAR whose target device is n_1. Since the difference between n_1 and n_3 to eNB is greater than d, n_3 will not send its L2/L3 message. However, n_1 and n_2 will send their L2/L3 messages simultaneously and will cause collision.

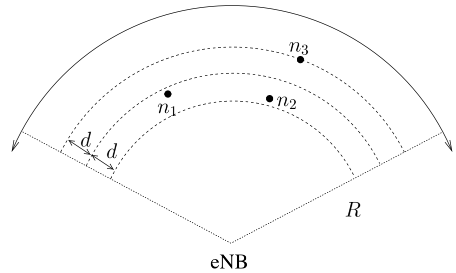

Fig. 2. Coverage area of a base station (eNB) and three MTC devices n_1, n_2, and n_3. n_1 and n_3 cached different values of T_A since the difference from n_1 and n_3 to eNB is greater than d. Thus, even if n_3 receives n_1's RAR, it will not cause collision with n_1.

The MTC devices are uniformly distributed, so the probability density function that a particular MTC device has a distance r to the eNB is given by $2r/R^2$, for $0 < r < R$. Consider an MTC device u which has distance r from the eNB, the probability that another specific MTC device has the same T_A as u is given by

$$p(r) = \begin{cases} \frac{2}{R^2}\int_0^{r+d}\gamma \,\mathrm{d}\gamma = \left(\frac{r+d}{R}\right)^2, & \text{if } 0 \le r < d, \\ \frac{2}{R^2}\int_{r-d}^{r+d}\gamma \,\mathrm{d}\gamma = \frac{4rd}{R^2}, & \text{if } d \le r \le R-d, \\ \frac{2}{R^2}\int_{r-d}^{R}\gamma \,\mathrm{d}\gamma = 1-\left(\frac{r-d}{R}\right)^2, & \text{if } R-d < r \le R. \end{cases} \tag{1}$$

For MTC device u, we denote $I_u = 1$ as the event that u passes ACB, and $I_u = 0$ otherwise. If the ACB parameter in the current random access slot is b, we have the probability $\mathbb{P}(I_u = 1) = b$. Let Y_u denote the random variable which represents the number of additional MTC devices that also pass the ACB. Y_u follows a binomial distribution $\mathcal{B}(N-1, b)$. We use $R_u = r$ to represent the event that u has distance r from the eNB. The conditional probability that there are i additional MTC devices which pass the ACB and contend the access of eNB with u is given by

$$\begin{aligned} &\mathbb{P}(Y_u = i, I_u = 1 \mid R_u = r) \\ =\ &\mathbb{P}(Y_u = i, I_u = 1) \\ =\ &\binom{N-1}{i}(1-b)^{N-1-i}\, b^{i+1},\ i = 0, 1, \ldots, N-1. \end{aligned} \tag{2}$$

Note that the random variables I_u and Y_u are both independent of u's position. Consider there are m preambles in total. Let $J_u = j$ denote the event that MTC device u selects preamble j from m preambles in a uniform manner. We denote random variable L_u to represent the number of other MTC devices that pass the ACB and choose the preamble j as well. We have

$$\begin{aligned} &\mathbb{P}(L_u = k, J_u = j \mid Y_u = i, I_u = 1, R_u = r) \\ =\ &\frac{1}{m}\binom{i}{k}\left(\frac{1}{m}\right)^k\left(1-\frac{1}{m}\right)^{i-k},\quad \begin{array}{l} k = 0, 1, \ldots, i, \\ j = 1, 2, \ldots, m. \end{array} \end{aligned} \tag{3}$$

Given $L_u = k$, $J_u = j$, $Y_u = i$, $I_u = 1$, and $R_u = r$, MTC device u succeeds in random access if the following two conditions are satisfied: a) u is chosen as the target device of the RAR from all $k+1$ devices that selected the preamble j, and b) none of other k devices has the same T_A as u. Therefore, if we denote $S_u = 1$ as the event that MTC device u succeeds in random access, the conditional probability of $S_u = 1$ is given by

$$\begin{aligned} &\mathbb{P}\left(S_u = 1 \mid L_u = k, J_u = j, Y_u = i, I_u = 1, R_u = r\right) \\ &= \frac{\left(1 - p\left(r\right)\right)^k}{k+1}. \end{aligned} \tag{4}$$

From (3) and (4), we have

$$\begin{aligned} &\mathbb{P}\left(S_u = 1, L_u = k, J_u = j \mid Y_u = i, I_u = 1, R_u = r\right) \\ &= \mathbb{P}\left(S_u = 1 \mid L_u = k, J_u = j, Y_u = i, I_u = 1, R_u = r\right) \\ &\quad \times \mathbb{P}\left(L_u = k, J_u = j \mid Y_u = i, I_u = 1, R_u = r\right) \\ &= \frac{1}{m\left(k+1\right)} \left(1 - \frac{1}{m}\right)^i \binom{i}{k} \left(\frac{1 - p\left(r\right)}{m-1}\right)^k. \end{aligned} \tag{5}$$

Thus, for $i = 0, 1, \ldots, N-1$, and $0 < r < R$, we obtain

$$\begin{aligned} &\mathbb{P}\left(S_u = 1 \mid I_u = 1, Y_u = i, R_u = r\right) \\ &= \sum_{j=1}^{m} \sum_{k=0}^{i} \mathbb{P}\left(S_u = 1, L_u = k, J_u = j \mid Y_u = i, I_u = 1, R_u = r\right) \\ &= \left(1 - \frac{1}{m}\right)^i \sum_{j=1}^{m} \frac{1}{m} \sum_{k=0}^{i} \frac{1}{k+1} \binom{i}{k} \left(\frac{1 - p\left(r\right)}{m-1}\right)^k \\ &= \left(1 - \frac{1}{m}\right)^i \frac{\left(1 + \phi\left(r\right)\right)^{i+1} - 1}{\phi\left(r\right)\left(i+1\right)}, \end{aligned} \tag{6}$$

where $\phi\left(r\right) = \frac{1 - p(r)}{m-1}$, and we use $\sum_{k=0}^{i} \frac{\phi(r)^{k+1}}{k+1} \binom{i}{k} = \frac{(1+\phi(r))^{i+1} - 1}{i+1}$ in the last step. From (2) and (6), we have

$$\begin{aligned} &\mathbb{P}\left(S_u = 1, I_u = 1 \mid R_u = r\right) \\ &= \sum_{i=0}^{N-1} \mathbb{P}\left(S_u = 1, I_u = 1, Y_u = i \mid R_u = r\right) \\ &= \sum_{i=0}^{N-1} \binom{N-1}{i} (1-b)^{N-1-i} b^{i+1} \left(\frac{m-1}{m}\right)^i \frac{(1+\phi\left(r\right))^{i+1} - 1}{\phi\left(r\right)(i+1)} \\ &= \frac{m\left(1-b\right)^N}{\phi\left(r\right)\left(m-1\right)} \\ &\quad \times \sum_{i=0}^{N-1} \frac{\left(1 + \phi\left(r\right)\right)^{i+1} - 1}{i+1} \binom{N-1}{i} \left(\frac{b\left(m-1\right)}{\left(1-b\right)m}\right)^{i+1}. \end{aligned} \tag{7}$$

Since $N\binom{N-1}{i} = \left(i+1\right)\binom{N}{i+1}$, equation (7) becomes

$$\begin{aligned} &\mathbb{P}\left(S_u = 1, I_u = 1 \mid R_u = r\right) \\ &= \frac{m\left(1-b\right)^N}{\phi\left(r\right)N\left(m-1\right)} \\ &\quad \times \sum_{i=0}^{N-1} \left(\left(1 + \phi\left(r\right)\right)^{i+1} - 1\right) \binom{N}{i+1} \left(\frac{b\left(m-1\right)}{\left(1-b\right)m}\right)^{i+1}. \end{aligned} \tag{8}$$

We further have

$$\begin{aligned} &\sum_{i=0}^{N-1} \left(1 + \phi\left(r\right)\right)^{i+1} \binom{N}{i+1} \left(\frac{b\left(m-1\right)}{\left(1-b\right)m}\right)^{i+1} \\ &= \left(1 + \frac{\left(1 + \phi\left(r\right)\right)b\left(m-1\right)}{\left(1-b\right)m}\right)^N - 1, \end{aligned} \tag{9}$$

and

$$\sum_{i=0}^{N-1} \binom{N}{i+1} \left(\frac{b\left(m-1\right)}{\left(1-b\right)m}\right)^{i+1} = \left(1 + \frac{b\left(m-1\right)}{\left(1-b\right)m}\right)^N - 1. \tag{10}$$

Equation (8) becomes

$$\begin{aligned} &\mathbb{P}\left(S_u = 1, I_u = 1 \mid R_u = r\right) \\ &= \frac{m\left(1-b\right)^N}{\phi\left(r\right)N\left(m-1\right)} \\ &\quad \times \left(\left(1 + \frac{(1+\phi\left(r\right))b(m-1)}{\left(1-b\right)m}\right)^N - \left(1 + \frac{b(m-1)}{\left(1-b\right)m}\right)^N\right). \end{aligned} \tag{11}$$

By substituting $\phi\left(r\right) = \frac{1-p(r)}{m-1}$ into (11), we obtain

$$\begin{aligned} &\mathbb{P}\left(S_u = 1, I_u = 1 \mid R_u = r\right) \\ &= \frac{m}{N(1-p\left(r\right))} \left(\left(1 - \frac{b}{m} p\left(r\right)\right)^N - \left(1 - \frac{b}{m}\right)^N\right). \end{aligned} \tag{12}$$

Since MTC device u at distance r which does not pass the ACB will not succeed in the random access slot, we have $\mathbb{P}\left(S_u = 1, I_u = 0 \mid R_u = r\right) = 0$. Thus, we have

$$\begin{aligned} \mathbb{P}\left(S_u = 1 \mid R_u = r\right) &= \sum_{\ell=0}^{1} \mathbb{P}\left(S_u = 1, I_u = \ell \mid R_u = r\right) \\ &= \mathbb{P}\left(S_u = 1, I_u = 1 \mid R_u = r\right). \end{aligned} \tag{13}$$

Note that all MTC devices are uniformly distributed in the coverage area, so we have

$$\begin{aligned} &\mathbb{P}\left(S_u = 1\right) \\ &= \frac{2m}{R^2 N} \int_0^R \frac{\left(1 - \frac{b}{m} p\left(r\right)\right)^N - \left(1 - \frac{b}{m}\right)^N}{1 - p\left(r\right)} r \, \mathrm{d}r. \end{aligned} \tag{14}$$

That is, when the ACB parameter b is given for N devices that are requiring access in the current random access slot, equation (14) gives the probability that an arbitrary MTC device succeeds in this random access slot with the coverage radius R and preamble number m. Let random variable Z denote the number of MTC devices that succeed in a random access. We have $Z \sim \mathcal{B}(N, \mathbb{P}\left(S_u = 1\right))$. The expectation of Z is given by

$$\mathbb{E}\left[Z\right] = \frac{2m}{R^2} \int_0^R \frac{\left(1 - \frac{b}{m} p\left(r\right)\right)^N - \left(1 - \frac{b}{m}\right)^N}{1 - p\left(r\right)} r \, \mathrm{d}r. \tag{15}$$

Note that equation (15) is for one random access slot. In bursty requests scenario, eNB needs to serve multiple MTC devices in a number of consecutive random access slots. To minimize the total slots required to serve all MTC devices in LTE systems, we need to find the optimal b that maximizes $\mathbb{E}[Z]$ in each random access slot. After substituting the piecewise function $p(r)$ given in (1) into (15), (15) can be written as the summation of the following three functions of b

$$\zeta(b) = 2m\int_0^d \frac{\left(1-\frac{(r+d)^2 b}{mR^2}\right)^N - \left(1-\frac{b}{m}\right)^N}{R^2-(r+d)^2} r\ \mathrm{d}r, \quad (16)$$

$$\xi(b) = 2m\int_d^{R-d} \frac{\left(1-\frac{4dbr}{mR^2}\right)^N - \left(1-\frac{b}{m}\right)^N}{R^2-4dr} r\ \mathrm{d}r, \quad (17)$$

$$\psi(b) = 2m\int_{R-d}^{R} \frac{\left(1-\frac{R^2 b-(r-d)^2 b}{mR^2}\right)^N - \left(1-\frac{b}{m}\right)^N}{(r-d)^2} r\ \mathrm{d}r. \quad (18)$$

Therefore, the optimization problem can be formulated as

$$\begin{aligned} &\underset{b}{\text{maximize}} \quad \zeta(b)+\xi(b)+\psi(b) \\ &\text{subject to} \quad 0 \le b \le 1. \end{aligned} \quad (19)$$

However, we cannot obtain any one of (16)-(18) in a closed-form function of b. Thus, it is difficult to determine the theoretical solution to the problem (19). To solve the problem, we propose to find the optimal solution numerically instead. The values of (16)-(18) for a given b can be evaluated by the numerical integrals. From the analytical results shown in Fig. 3, we observe that when b varies from 0 to 1, there exists an optimal ACB parameter $b^\star$ which maximizes the expected number of MTC devices served in a random access slot. This feature is quite similar to that of the throughput in multichannel slotted Aloha [13]. The main reason lies in the fact that the preambles are the limited resources in our model and each preamble plays a similar role as a wireless channel in the multichannel slotted Aloha protocol. Meanwhile, the collision probability in the preamble contention can be reduced by comparing the T_A in RAR for stationary MTC devices. Since numerical integrals can be used to evaluate the objective function, the solution $b^\star$ to problem (19) can be determined numerically.

III. Performance Evaluation

In this section, we first validate the analytical results via simulations, including the expected number of successful MTC devices and the probability that an arbitrary MTC device succeeds in a random access slot contention. We then show that, by using the optimal ACB parameter determined in Section II for each random access slot, the total number of slots required in the proposed scheme can be reduced. We also show that, comparing to the other schemes which used either ACB or T_A only, our proposed scheme that used both ACB and T_A requires the minimum number of random access slots to serve all MTC devices in random access overload scenario.

A. Model Validation

To simulate the expectation of the number of MTC devices served in a random access slot, we deploy different number of MTC devices uniformly in the cellular service area with

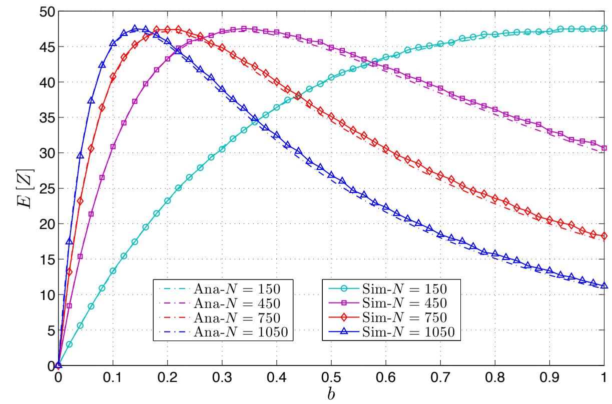

Fig. 3. Analytical and simulation results of $\mathbb{E}[Z]$.

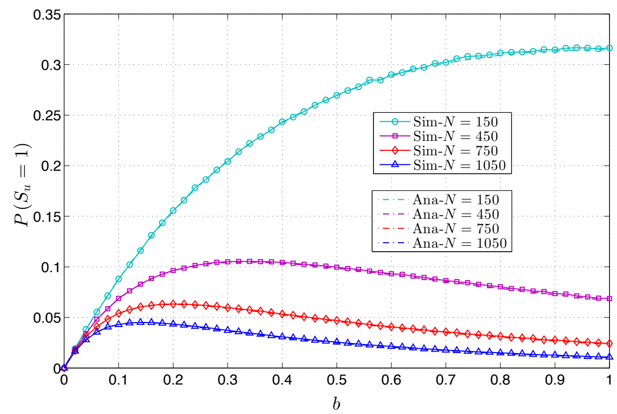

Fig. 4. Analytical and simulation results of $\mathbb{P}(S_u = 1)$.

radius $R = 1.5$ km. Consider the effect of quantization, we have $d = 16T_s c/2 = 78$ m [5], where $T_s = 3.072 \times 10^{-7}$ s is the *basic time unit* [14], and $c = 3 \times 10^8$ m/s is the speed of light. In the simulation, we first consider the ACB check on each MTC device with a parameter b, and then let the MTC devices which passed the ACB check contend for $m = 64$ preambles [14]. We check each preamble and increase the count of successfully served MTC devices when one of following two cases happens: 1) the preamble is selected by exactly one MTC device; 2) the preamble is chosen by many MTC devices, and for a target device selected randomly within these devices, its T_A value is different from others. We run the simulation 5×10^3 times and determine the average of successfully served MTC devices. Our simulation results compared to the analytical results are presented in Fig. 3. With similar parameters and approaches, we simulate the probability that an arbitrary device succeeds in a random access slot. The simulation results and the corresponding analytical results are presented in Fig. 4. From Figs. 3-4, we can see that our simulation results and analytical results closely match.

B. Effect of Optimal ACB parameters

For the scheme that applied both T_A and ACB to relieve the random access overload, we run simulations over consecutive

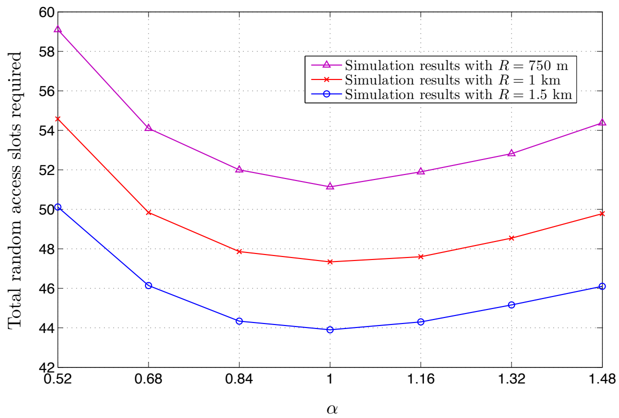

Fig. 5. Performance optimality with optimal solutions. ($N_0 = 2000$)

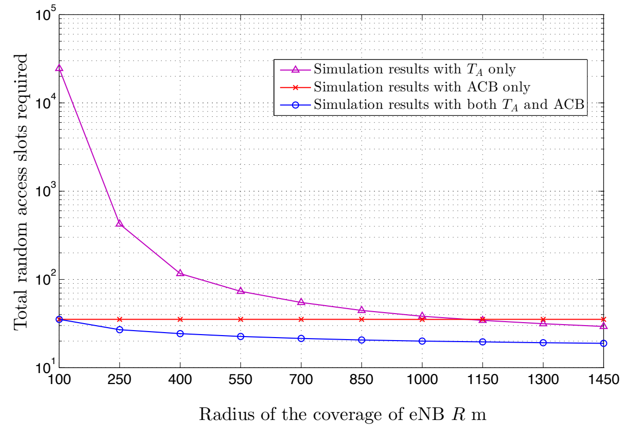

Fig. 6. Total random access slots required versus the radius of coverage of eNB R. ($N_0 = 800$)

random access slots and count how many random access slots are required to serve all MTC devices. Let N_0 denote the total number of MTC devices that need to be served at the beginning of a simulation run. Every device within the N_0 initial backlog needs to be served exactly once in one simulation. The MTC device that has not yet been served keeps on checking ACB in each slot and trying to access the eNB until it is successfully served. The optimal ACB parameter $b^\star$ determined in Section II is used in each random access slot of our simulation. We would like to show that using the optimal ACB parameters can obtain a better performance in reducing the total number of random access slots than using other ACB parameters.

To show the optimality, we introduce a parameter α and let α vary from 0.52 to 1.48 with the step size 0.16. During the simulations, we apply $b = \min\{1, \alpha b^\star\}$ as the ACB parameter used in each random access slot. Note that when $\alpha = 1$, we have $b = b^\star$. We run simulations 100 times, and we count the total random access slots required to serve all N_0 initial backlog in each simulation run. The average results with various coverage radius of eNB are presented in Fig. 5 when $N_0 = 2000$. We observe that using the optimal ACB parameters $b^\star$ for the proposed scheme obtains the best performance in reducing the total number of random access slots to serve all N_0 MTC devices.

C. Performance Comparison

In this section, we compare the performance among the following three schemes in term of total random access slots required to serve all MTC devices: (a) the scheme with T_A only, (b) the scheme with ACB only, and (c) the proposed scheme with both ACB and T_A. We also present how the parameters in LTE networks affect the performance of above three schemes. We assume there are N_0 MTC devices at the beginning of a simulation, and each device within the initial backlog N_0 needs to be served exactly once. To simulate the scheme which only used T_A, we let all MTC devices contend together in every slot by keeping $b = 1$. To obtain the best performance of the scheme where only ACB is used, we refer to the work in [15] and use its optimal ACB parameter m/N in every slot. Unless stated otherwise, we choose $m = 64$.

We first compare the total random access slots required by the schemes to handle the initial backlog with $N_0 = 800$ devices in LTE networks. The average result of 200 simulations is shown in Fig. 6. We find that the scheme that used both T_A and ACB consumes the least total slots to serve all MTC devices. Both schemes that applied T_A have better performance when the eNB has a larger radius of coverage because fewer MTC devices have the same T_A in sparse networks and collision probability decreases. We observe that the total slots required by the scheme which only used ACB is a constant. This is because without using T_A, the maximum number of MTC devices which can be served per slot is a constant as long as the preamble number in the network is given. So the total slots required by this scheme maintains a constant for the same N_0. This also explains why in a dense network, using both T_A and ACB obtains much better performance than using T_A only. We also notice that just using T_A in sparse networks may take fewer slots than only using ACB. The reason is that the number of MTC devices may be so small that the optimal ACB parameter becomes 1 and loses its functionality, but meanwhile, comparing T_A still works and reduces the collision probability. Last but not least, the proposed scheme that used both T_A and ACB requires more slots when the cellular's coverage becomes smaller, and eventually, it needs the same number of random access slots to serve all MTC devices as the scheme that used ACB only. This phenomenon is caused by that when the N_0 MTC devices are located in a smaller coverage of eNB, the density of MTC devices increases and more MTC devices have the same T_A value. Thus, the scheme that only used ACB is in fact a special case of the proposed scheme when the radius of the LTE network is small enough and all MTC devices share the identical T_A.

We then present how the number of initial MTC devices backlog N_0 affects the number of random access slots required by the three schemes. With the radius of coverage of the eNB $R = 1$ km, our simulation results are presented in Fig. 7. The

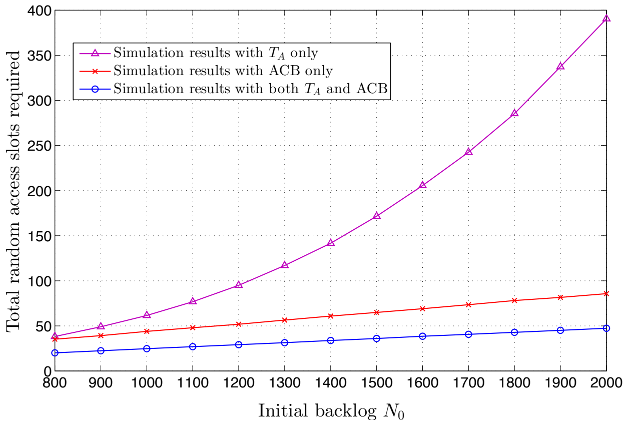

Fig. 7. Total random access slots required versus initial backlog N_0. ($R = 1$ km)

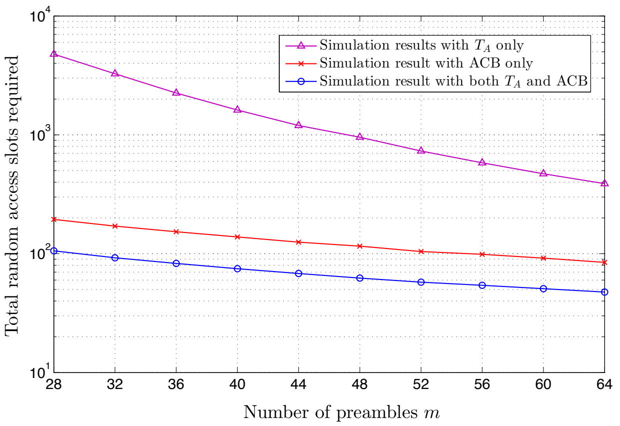

Fig. 8. Total random access slots required versus preamble number m. ($N_0 = 2000$, $R = 1$ km)

linear relationship between total slots and N_0 can be found in the two schemes that used ACB. For the scheme which used T_A only, the required total slots increase faster than the other two schemes. This is because when N_0 is larger, more MTC devices contend together with a higher collision probability in the beginning of a simulation. Thus, rather than a linear relation, this scheme requires even more slots to clear up all requests. Our proposed scheme that used both T_A and ACB takes the least total slots in all scenarios, and it almost reduces at least half of total number of slots required by other two schemes.

We present the simulation results with different preambles in Fig. 8 when $R = 1$ km and $N_0 = 2000$. For all of the three schemes being tested, the total number of slots required grows exponentially when fewer preambles are available. In particular, for the scheme that used T_A only, the total number of slots required is an order of magnitude higher than that required by the other two schemes. From Fig. 8, we also observe that the proposed scheme requires fewer total slots to clear up all MTC devices' requests, and the other schemes will consume at least twice the random access slots to serve all of them in all scenarios being tested.

IV. Conclusion

In this paper, we proposed to jointly apply the ACB and compare the T_A information in RARs to relieve the contentions of random access overload in M2M communications. We determined the probability that an arbitrary MTC device succeeds in a random access slot in the proposed scheme. We found that, with a given coverage radius of the LTE base station, when the total number of devices and the number of preambles are provided, there exists an optimal ACB parameter which maximizes the expected number of devices served in the current random access slot. We obtained the optimal ACB parameter by numerical approach. By simulations, we showed that using the optimal ACB parameter we determined for each random access slot provides a good performance in reducing the total number of random access slots required to serve all MTC devices. When we compared the performance of the proposed scheme to the other two schemes that used either T_A or ACB only, we found that jointly using T_A and ACB can save at least 50% of the total random access slots required by a typical LTE base station to serve all MTC devices.

References

[1] Ericsson, "More than 50 billion connected devices," Feb. 2011. [Online]. Available: http://www.ericsson.com/res/docs/whitepapers/wp-50-billions.pdf

[2] 3GPP TS 22.368 V12.2.0, "Service requirements for machine-type communications (MTC)," Mar. 2013.

[3] J.-P. Cheng, C. han Lee, and T.-M. Lin, "Prioritized random access with dynamic access barring for RAN overload in 3GPP LTE-A networks," in *IEEE GLOBECOM Workshops (GC Wkshps)*, Houston, TX, Dec. 2011, pp. 368–372.

[4] 3GPP TS 36.321 V11.3.0, "Evolved universal terrestrial radio access (E-UTRA) medium access control (MAC) protocol specification," Jun. 2013.

[5] 3GPP TS 36.213 V11.3.0, "Evolved universal terrestrial radio access (E-UTRA) physical layer procedures," Jun. 2013.

[6] C.-Y. Tu, C.-Y. Ho, and C.-Y. Huang, "Energy-efficient algorithms and evaluations for massive access management in cellular based machine to machine communications," in *Proc. of IEEE Vehicular Technology Conference (VTC-Fall)*, San Francisco, CA, Sep. 2011.

[7] 3GPP TR 22.888 V12.0.0, "Study on enhancements for machine-type communications (MTC)," Mar. 2013.

[8] H.-L. Fu, H.-C. Chen, P. Lin, and Y. Fang, "Energy-efficient reporting mechanisms for multi-type real-time monitoring in machine-to-machine communications networks," in *Proc. of IEEE International Conference on Computer Communications (INFOCOM)*, Orlando, FL, Mar. 2012.

[9] S.-Y. Lien and K.-C. Chen, "Massive access management for QoS guarantees in 3GPP machine-to-machine communications," *IEEE Communications Letters*, vol. 15, no. 3, pp. 311–313, 2011.

[10] 3GPP TR 37.868 V11.0.0, "Study on RAN improvements for machine-type communications," Sep. 2011.

[11] S.-Y. Lien, T.-H. Liau, C.-Y. Kao, and K.-C. Chen, "Cooperative access class barring for machine-to-machine communications," *IEEE Trans. on Wireless Communications*, vol. 11, no. 1, pp. 27–32, Jan. 2012.

[12] K. S. Ko, M. J. Kim, K. Y. Bae, D. K. Sung, J. H. Kim, and J. Y. Ahn, "A novel random access for fixed-location machine-to-machine communications in OFDMA based systems," *IEEE Communications Letters*, vol. 16, no. 9, pp. 1428–1431, Sep. 2012.

[13] Y.-J. Choi, S. Park, and S. Bahk, "Multichannel random access in OFDMA wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 3, pp. 603–613, 2006.

[14] 3GPP TS 36.211 V11.3.0, "Evolved universal terrestrial radio access (E-UTRA) physical channels and modulation," Jun. 2013.

[15] S. Duan and V.W.S. Wong, "Dynamic access class barring for M2M communications in LTE networks," in *Proc. of IEEE Global Communications Conference (GLOBECOM)*, Altlanta, GA, Dec. 2013.