Dynamic Allocation of Random Access Opportunity for Machine-Type Communication in LTE-Advanced

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Abstract

With the rapid growth of machine-type communications (MTC) devices, the radio access network (RAN) will be overloaded when a large number of MTC devices try to access the radio networks in a short time. In this paper, a combination of a dynamic resource allocation and a random access check mechanism is proposed to solve the overload problems for MTC in LTE-Advanced. An analytical model is presented with the derivation of three metrics, the collision probability, the success probability, and the idle probability to evaluate the method. Simulation and analysis results show the superior performance of the method we proposed to solve the RAN overload problem.

Keywords: Machine type communication; RAN overload; LTE-Advanced; Access check; Dynamic resource allocation

1. Introduction

Machine-type Communication (MTC), also known as machine-to-machine (M2M) communication over existing cellular networks without human interposition [1], usually involves a lot of MTC devices. These devices can help to support a large amount of applications such as smart grid, e-health, road security, domestics and consumer electronic devices. However, the massive MTC devices access of a radio network may result in intolerable delays, packet loss. What's more, the H2H communication services will be unavailable to the present human-to-human (H2H) communication services [2]. Therefore, proper overload control mechanisms are needed to make the network available and to guarantee the quality under heavy MTC load [3].

TR 37.868 is a technical document which summarizes the state-of-the-art standard activities of MTC in 3GPP [4]. It also concludes the output of the study item on radio access network (RAN) improvements for MTC. The aims of the study item are to investigate the traffic characteristics of different MTC applications and to define new traffic models. Up to now, RAN overload control should be improved firstly. Massive MTC devices contend for the Random-Access Channel (RACH) simultaneously will cause high random-access collision probabilities. To avoid this, RAN overload control is necessary [5, 6]. Some solutions have been discussed such as Access Class Barring (ACB) schemes, separate RACH resources for MTC, RACH resources dynamic allocation, slotted access and MTC specific backoff, and these solutions can be used to tackle the RAN overload problem. Extended Access Barring (EAB) is evolved from ACB and is a scheme that could control the potential access attempts, and therefore it may be considered as a baseline solution to RAN overload in the future. The basic idea of EAB is that the MTC devices, which belong to certain access classes indicated by the system-broadcasting

information, are unable to access the network when EAB is activated. However, the enabling mechanism and practical barring procedures for EAB still needs some improvement.

In order to evaluate the performance of RAN overload control schemes, some performance metrics have been defined in 3GPP TR 37.868. Collision probability, access success probability and statistics of access delay are three of the performance metrics. The collision probability is the first performance metric. It is defined in Section 6.3 of TR 37.868 that collision probability is the ratio of the number of Random Access Opportunity (RAO) when two or more MTC devices send a random-access attempt using the same preamble to the overall number of RAOs in the period [7, 8]. The access success probability is the second performance metric. It is defined as the probability to complete the random access procedure successfully within the maximum number of preamble transmission. The statistics of access delay is the third performance metric. It is known as the Cumulative Distribution Function (CDF) of the delay for each random access procedure between the first RA attempt and the completion of the random access procedure, for the successfully accessed MTC devices [9].

Another important performance metric is idle probability. It is also used to evaluate the performance of RAN overload control schemes. The idle probability is the ratio between the number of RAOs with no MTC in it and the overall number of RAOs. That is to say there are some of RAOs in the idle state. Or in other words, there are some RAOs used for neither M2M nor H2H. Therefore, the utilization of radio access resource should be an important metric for evaluating the performance of RAN overload control. If the idle probability is higher, the utilization probability is lower; and vice versa. Therefore, a high level of resource utilization in resource-constrained radio access context should be guaranteed when we are designing overload control scheme.

In this paper, a new scheme is presented to solve RAN overload problem. The scheme we proposed has a superior performance compared with other schemes. This paper is organized as follows: In section 2, we describe the detailed mechanism of the scheme. In section 3, an analytical model is presented to estimate the performance of the scheme. In section 4, we compare the performance of the overload control scheme we proposed with slotted access scheme. And then, we summarize our conclusions and future works in section 5.

2. System Model

A new scheme for RAN overload control will be presented in this section. There are two mechanisms in the new scheme. One is Access Check, another is dynamic resource allocated of RAOs.

2.1. Access Check

How to design a mechanism for handling the random-access (RA) load, generated by a large number of M2M in a short time should be considered seriously in M2M communication network.

In the whole process of RA, a MTC device shall go through a preliminary stage, called Access Check, as depicted in Fig.1, which shows whether the MTC device access to the network is prevented or not by Access Check. The procedure of Access Check is based on the received system information and its random-number generation. It can be found in Fig.1 that System Information (SI) determines the value of Access Check Factor. A random number from a uniform distribution (0, 1) shall be drawn to an MTC device. The MTC is able to perform RA if the random number drawn on the MTC is smaller than Access Check Factor; otherwise, the MTC is forbidden .If the RA of MTC devices is forbidden, these MTC devices shall backoff and wait for a period of time. After that, MTC will restart a RA procedure if it can pass the stage of Access Check.
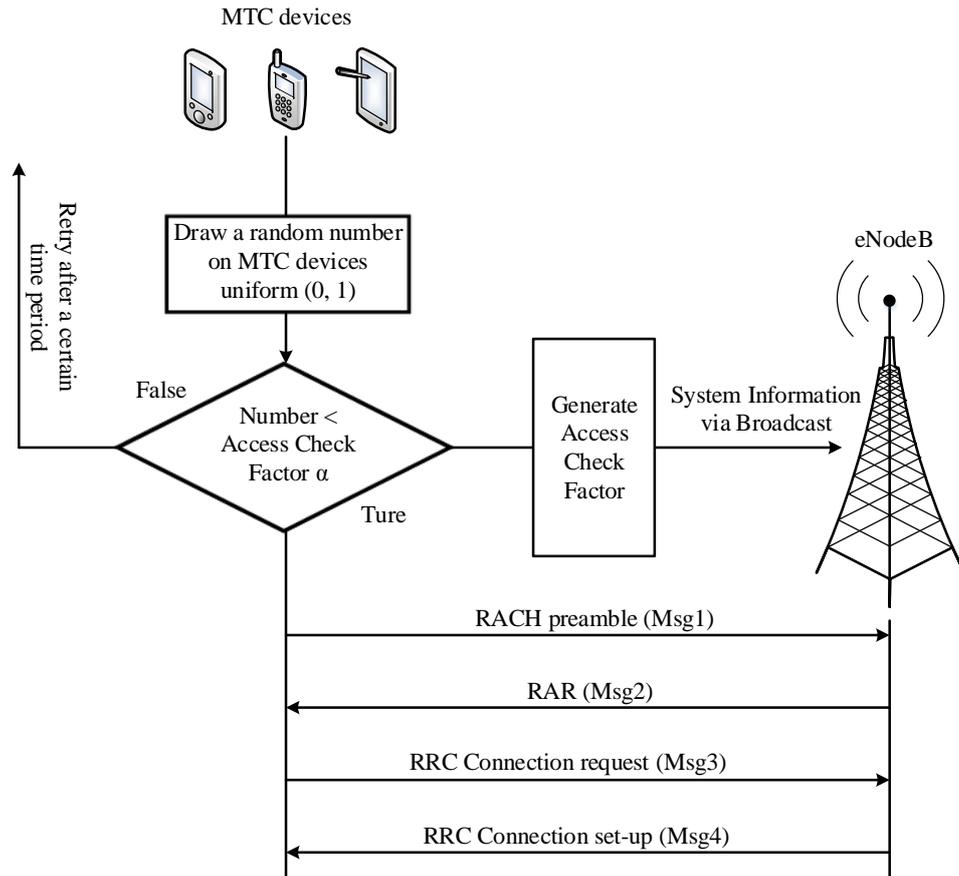
Figure 1. The Procedure of Access Check

Before data transmission, MTC devices get attention of an eNodeB through the random access channel (RACH) by using the random access procedure defined in 3GPP LTE-Advanced [10]. The amount of currently available radio resource can decide the eNodeB and the opportunity to continue to release some of the RACH. The MTC device then uses these RACH opportunity of radio resources to the eNodeB by the four steps are also shown in Fig. 1. The first step for a UE is to transmit a message called Msg1, which contains one of the 64 random access preambles generated by a Zadoff-Chu sequence for allowing those simultaneously transmitted Msg1 to be decoded by eNodeB [11]. Then, the UE waits to receive the random access response (RAR) within the RA response window. After successful decoding of Msg1, eNodeB replies an RAR containing an RA-preamble identifier or a backoff Indicator subheader called Msg2 at the second step. If the RAR contains a RA-preamble that matches the one it transmitted in Msg1, the UE then conveys Msg3 with a UE identifier to eNodeB. After receiving Msg3, eNodeB replies Msg4 to confirm that the connection is successfully established and ends the RA procedure.

Let γ be the random-access intensity of random-access network, it means that there are γ random-access attempts per second and cell. It is assumed that there are a large number of devices in the cell which is valid for this scenario. Moreover, it is also assumed that the arrival of RACH requests is uniformly distributed over time. Let α be the value of access check factor. If α is smaller, it means that there are fewer MTC devices allowed to access the network. The system can determine the size of the access intensity according to the current network load conditions to avoid network congestion. The mechanism of Access Check has changed the random-access intensity from γ to $\alpha\gamma$. It means that random-access intensity can be controlled by access check procedure.
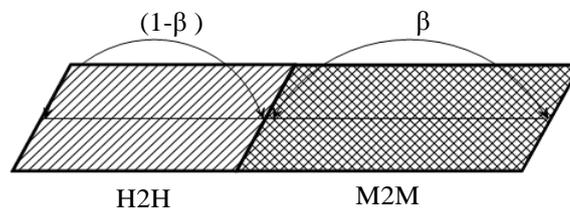
2.2. Dynamic Allocation of RAOs

In LTE, RACH resource is determined in terms of RAOs [12], as illustrated in Fig. 2. Let m , n , and k be the number of random access slots in one second; the number of random access frequency bands in each random-access slot; and the number of random-access preamble signatures per random access slot. The total number of RAOs per second, L , is given by

$$L = m \times n \times k$$

(1)
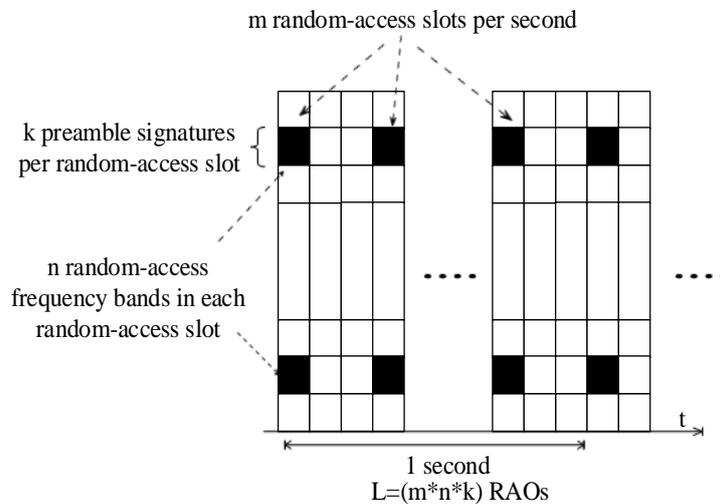
Figure. 2. Random Access Opportunity (RAOs)

For improving the utilization of RAOs, one mechanism is design to control the quantity of RAOs for M2M communication. As shown in Fig. 3, the overall RAOs is divided into two parts. β is dedicatedly allocated to M2M communication; the rest of RAOs, $(1 - \beta)$, is dedicatedly allocated to H2H communication. The range of β is (0, 1). The value of β is determined by Radio Access Network (RAN) resource allocation strategies. A different resource allocation strategy, the value of β is different. β is larger, the more access resource allocated to the M2M, and vice versa. Resource allocation strategies are required to guarantee network availability and quality of H2H services under heavy M2M load.

Figure. 3. Dynamic Allocation of RAOs

The mechanism can used to control the quantity of RAOs provided to M2M. The allocation of RAOs will be more flexible to adapt to different M2M communication load situation. After using the mechanism, the total number of RAOs per second for M2M communication is changed from L to βL .

3. Analytical Model

In this section, an analytical model is presented to estimate the performance of the scheme we proposed in section 2. There are three important performance metrics for evaluating performance have been defined in the section 6.3 TR 37.868.

In Sec.6.3 of TR 37.868, the collision probability is defined as the ratio between the number of occurrences when two or more MTC devices send a random-access attempt using exactly the same preamble and the overall number of opportunities in the period. According to this definition, the collision probability can be derived as the ratio of total number of collided RAOs observed in T seconds and total number of RAOs provided in T seconds. That is, the collision probability of an RAO, $p_{c,RAO}$, is given by

$$p_{c,RAO} = \frac{\#\ of\ collided\ RAOs\ in\ T\ sec}{\#\ of\ RAOs\ in\ T\ sec} \tag{2}$$

The access success probability is defined as the probability to successfully complete the random access procedure within the maximum number of preamble transmission. According to the definition, the success probability of an RAO, $p_{s,RAO}$ is the ratio of total number of successful RAOs observed in T second and total number of RAOs provided in T second. According to the definition the $p_{s,RAO}$ is given by

$$p_{s,RAO} = \frac{\#\ of\ successful\ RAOs\ in\ T\ sec}{\#\ of\ RAOs\ in\ T\ sec} \tag{3}$$

The idle probability of an RAO, $p_{i,RAO}$ is the probability that no one arrives in an RAO. It is given by

$$p_{i,RAO} = \frac{\#\ of\ idle\ RAOs\ in\ T\ sec}{\#\ of\ RAOs\ in\ T\ sec} \tag{4}$$

According to section 2, adopt the proposed scheme, $\alpha\gamma$ is the random-access intensity, βL is the number of RAOs for M2M communication. It is assumed that the arrival of random-access requests is uniformly distributed over time. For Poisson arrival with rate $\alpha\gamma/\beta L$. The equation (2), (3), and (4) can be rewritten as

$$p_{c,RAO} = 1 - \frac{\alpha\gamma}{\beta}\exp\left(-\alpha\gamma/\beta L\right) - \exp\left(-\alpha\gamma/\beta L\right) \tag{5}$$

$$p_{s,RAO} = \frac{\alpha\gamma}{\beta}\exp\left(-\alpha\gamma/\beta L\right) \tag{6}$$

$$p_{i,RAO} = \exp\left(-\alpha\gamma/\beta L\right) \tag{7}$$

$$p_{c,RAO} + p_{s,RAO} + p_{i,RAO} = 1 \tag{8}$$

We also noted that the sum of the collision probability, the success probability, and the idle probability of RAOs is equal to one. It is meaning that the resources of radio access are used or happened conflict or be wasted.

The analysis model can be used to estimate the performance of the new scheme for RAN overload control. It can be found from equation (5), (6), and (7), the collision probability, the success probability, and the idle probability determined by the random-access intensity, γ, generated by MTC devices and the number of RAOs, L, provided by RAN. In other words, the performance metrics equation proposed in (5), (6), and (7) is a function of RAOs and random-access intensity. In the next section, it will be seen that the

performance can be controlled by changing the random-access intensity and the number of RAOs available to M2M.
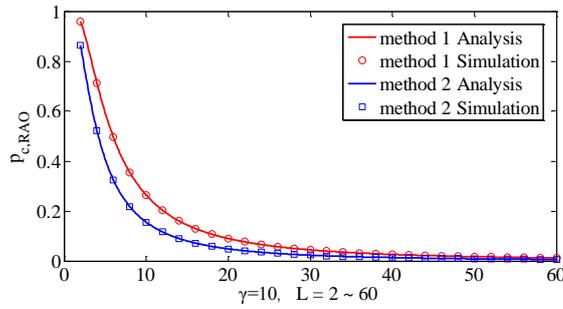
4. Simulation and Numerical Results

In this section, we present the simulation set up, the simulation results, and the analysis results. The simulation and analysis results, which show the superior performance of our proposed scheme for solving the RAN overload.

Table 1. Simulation Parameters for RACH Capacity for LTE

| Parameter	Value
Cell bandwidth	10 MHz
PRACH Configuration Index	6
Total number of preambles	54
Maximum number of preamble transmission	10
Number of UL grants per RAR	3
Number of CCEs allocated for PDCCH	16
Number of CCEs per PDCCH	4
Ra-Response Window Size	5 subframes
Mac-Contention Resolution Timer	48 subframes
Backoff Indicator	20ms
HARQ retransmission probability for Msg3 and Msg4	10%
Maximum number of HARQ TX for Msg3 and Msg4	5

Table 1 summarizes the basic LTE simulation parameters as defined by TR 37.868. All random-access attempts are assumed to be initiated by MTC devices with no back ground noise caused by H2H. For LTE, if two or more MTC devices select the same RAO at the same time, it is assumed that eNodeB will not be able to decode any of the preambles; hence, the eNodeB will not send the Msg2 (RAR). MTC devices will only detect a collision if Msg2 is not received in the response window. Successful completion of one random access procedure means the successful reception of Msg4. The idle means that no one MTC arrives in a Random-access opportunity.

Used with the new scheme comparison is slotted access scheme, called method 1. In the method, the access slots are defined for MTC devices and each MTC device only accesses at its dedicated access slot. It may be the most efficient access method, has the least impact to the legacy system with minimal enhancement required on the existing system [13, 14]. The proposed overload control scheme, called method 2. Using the method of numerical analysis and simulation, comparing the performance of the two kinds of overload control schemes based on collision probability, success probability, and idle probability. After that, we will analyze the simulation results. In the following figures, the horizontal axis is the number of RAOs provided to random-access; the longitudinal axis is random-access intensity. The number of RAOs for M2M is gradually increases from 2 to 60. Symbols and lines are used to represent the simulation and analytical results, respectively. The red line and blue line are used to represent the method 1 and method 2, respectively.
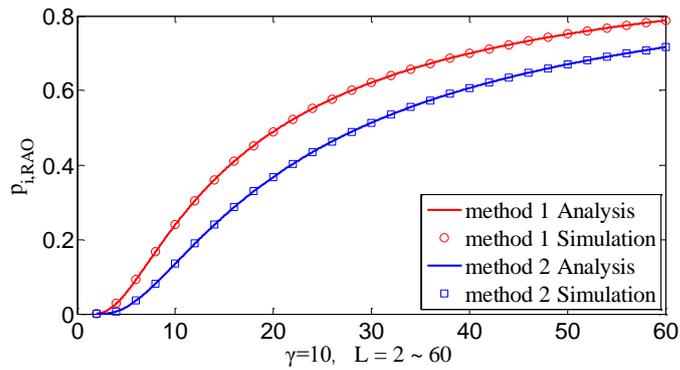
Figure 4. Simulation and Analysis Results of $p_{c,RAO}$

Fig.4 demonstrates the simulation and analytical results of about method 1 and method 2, respectively. From the figure, it is clear that the numerical analytical results are consistent with the simulation results. It shows that the collision probability of method 2 is lower than method 1. With the increase of L, the collision probability, $p_{c,RAO}$, is gradually decreased, because that the more RAOs are provided to M2M, the collision probability is smaller. It is mean that the more RAOs provided to M2M can reduce the collision probability.
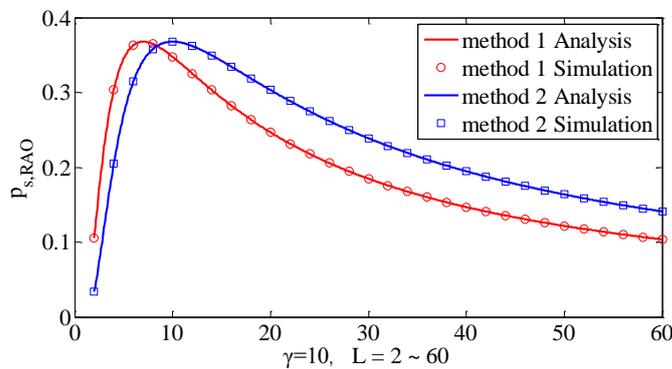
**Figure 5. Simulation and Analysis Results of** $p_{s,RAO}$

Fig.5 shows the simulation and analytical results of $p_{s,RAO}$ about method 1 and method 2, respectively. Simulation results shows that $p_{s,RAO}$ is first increased and then decreased by increasing L. The maximum value of $p_{s,RAO}$ occurs when L is equal to γ. It is because that offering more RAOs results in more success access attempts and thus, a higher $p_{s,RAO}$, in overload situation ($\gamma > L$). However, further increasing may decrease the $p_{s,RAO}$, because most of RAOs are wasted in underused situation ($\gamma < L$). In the whole, the $p_{s,RAO}$ of method 2 is higher than method 1.

**Figure 6. Simulation and Analysis Results of** $p_{i,RAO}$

Fig. 6 shows the simulation and analytical results of $p_{i,RAO}$ about method 1 and method 2, respectively. Simulation results show that idle probability of method 2 is lower than method 1. In other words; the utilization probability of RAOs about method 2 is higher than method 1. Hence, it also shows that Equation (7) can accurately estimate the simulation results. It is future found that increasing L will result in a higher $p_{i,RAO}$, because more RAOs are not used.

Overall, the proposed feature has shown to be a good solution to controlling overload caused by MTC. In the following figures, the red, blue, and black lines are used to represent the collision probability $p_{c,RAO}$, the success probability $p_{s,RAO}$ and the idle probability $p_{i,RAO}$ of method 2, respectively.
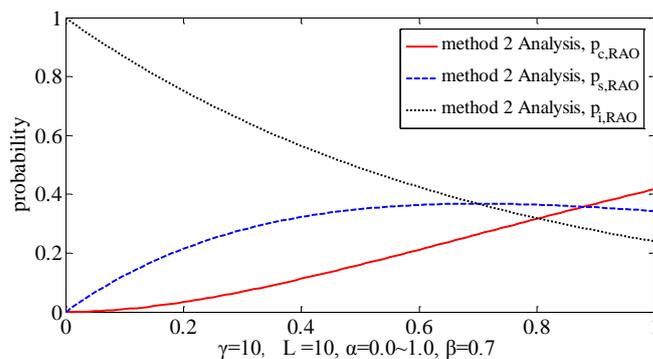
Figure 7. Analysis Results of $p_{c,RAO}$ **,** $p_{c,RAO}$ **,** $p_{i,RAO}$ **for** $\gamma = 10$ **,** $L = 10$ **,** $\alpha = 0 \sim 1$

The change of α will have an impact on the performance of method 2. The value of α for random-access intensity is gradually increases from 0 to 1 are shown in Fig.7. With the increase of α, the collision probability, $p_{c,RAO}$, is gradually increased, because that the more MTC devices attempt to access the to the network. $p_{s,RAO}$ is first increased and then decreased by increasing α. And then, it is future found that increasing α will result in a lower $p_{i,RAO}$, because more RAOs are used.
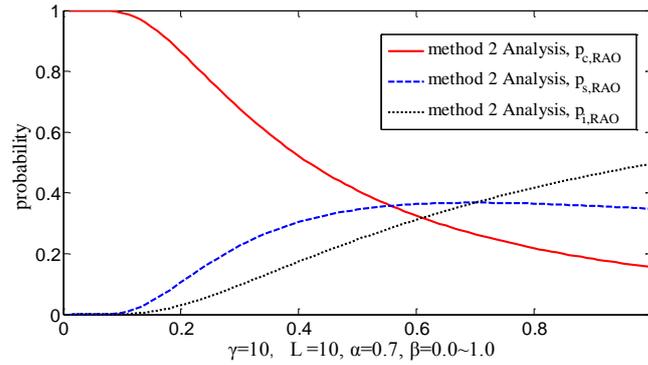
Figure 8. Analysis Results of $p_{c,RAO}$, $p_{s,RAO}$, $p_{i,RAO}$ **for** $\gamma = 10$, $L = 10$, $\beta = 0 \sim 1$

Similar to the Fig. 7, the value of β for M2M is gradually increases from 0 to 1 are shown in Fig. 8. The change of β also have an impact on the performance of method 2. With the increase of β, the collision probability, $p_{c,RAO}$, is gradually decreased, because that offering more RAOs for MTC devices random access to the network. Analysis results shows that $p_{s,RAO}$ is first increased and then decreased by increasing β. It is possible to observe that the maximum value of $p_{s,RAO}$ occurs when α is equal to β. It is means that the number of RAOs provided by network is exactly equal to the number of MTC access attempts. At this point, the success probability of RAOs is highest. It is future found that increasing β will result in a higher $p_{i,RAO}$, because more RAOs not be used.

5. Conclusions and Future Works

In this paper, the RAN overload issue had been addressed. A novel scheme has been proposed for RAN overload control. The scheme can dynamically adjust the random-access intensity and the number of RAOs to M2M communication. An analytical model is presented to derive the collision probability, the success probability, and the idle probability of RAOs based on the scheme we proposed. Simulation and analytical results show that the new scheme has superior performance for RAN overload control compared with slotted access scheme.

It should also be noted that the analytical model presented in this paper is valid only if the MTC traffic follows a Poisson process with constant arrival rate. The performance metric of the collision probability, the success probability, and the utilization probability is derived based on the steady-state behavior of the network. However, the Poisson process assumption is applied to H2H services but may not be applicable for bursty MTC traffic [15]. Normally, the RAN overload may be resulted from unexpected heavy MTC traffic generated in a short period of time, which has been specified in 3GPP TR 37.868. Therefore, an important future work is to develop a proper analytical model to investigate the transient behavior of the random access system triggered by the bursty MTC traffic with non-Poisson arrivals. At the same time, the proposed model is able to achieve high access success probability, low collision probability, and low idle probability in all different types of services while maintain reasonably low access delay.

Acknowledgment

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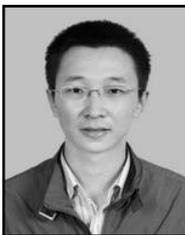
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