Two-Stage Resource Allocation for Random Access M2M Communications in LTE Network

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***Abstract*— Deployment of massive machine-to-machine (M2M) user equipments (UEs) in the current cellular network may cause overload in the radio access network (RAN). Access class barring (ACB) is an effective solution for reducing the RAN overload. In this letter, we propose an extended random access (RA) scheme to increase access success probability of M2M UEs by efficient use of available uplink radio resources. The proposed scheme, allocates the available radio resources to the access-attempting UEs in two stages. In the first stage, the evolved node B (eNB) grants the available uplink resources to the UEs that have passed the ACB check. Then in the second stage, UEs that did not pass the ACB check utilize the remained unscheduled resources from the first stage. Simulation results show that the proposed scheme increases the number of successful requests and decreases the total service time of a traffic burst.**

***Index Terms*— Machine-to-machine communication, Access class barring, RAN overload , Random access.**

I. INTRODUCTION

Machine-to-machine (M2M) or machine-type communication (MTC) involves with a large number of user equipments (UEs) that communicate autonomously with the aim of forming a ubiquitous and automatic communication without human intervention. MTC has diversified applications such as e-health, power grid, intelligent transport system and Internet of things (IoTs) [1], [2]. The nature of massive access is a challenging problem for cellular network as a currently adopted access technology for MTC. That is when a huge number of M2M UEs try to access the network simultaneously, the radio access network (RAN) becomes overloaded [3], [4].

Several schemes are proposed for MTC RAN overload control in long term evolution (LTE) networks [3]. In 3GPP, access class barring (ACB) is considered as an efficient and practically implementable scheme. Hence, there are some recent researches which attempt to improve this scheme or adapt it according to the underlying applications. Specifically, taking into account the delay-tolerant applications, the extended access barring (EAB) mechanism controls RAN overload more efficiently compared to the ACB [1].

In this letter, we propose a two-stage random access (RA) scheme to more efficiently allocate uplink resources to UEs. In the first stage, the number of UEs which compete for uplink resources is restricted by the dynamic ACB with a computed ACB factor. Then in the second stage, UEs which were barred in the first stage are contending to exploit the unscheduled uplink resources in the first stage by passing a new ACB check. We show that the total number of successful accesses is increased by adjusting the ACB factors properly in each stage. In the rest we first present the backgrounds and system model in section II. The details and simulation results of the proposed scheme is then discussed in sections III and IV respectively.

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II. BACKGROUNDS AND SYSTEM MODEL

At the LTE system, UEs require two uplink (UL) channels to establish a connection named as physical random access channel (PRACH) and physical uplink shared channel (PUSCH). The PRACH is divided into RA slots that used for transmission of RA requests. The contention based RA procedure for uplink resources is completed by the following steps: 1) When an UE needs an access, it randomly selects one RA preamble from preambles indicated via eNB and transmits its request through the next available RA slot of the PRACH. 2) eNB sends the random access responses (RARs) through the physical downlink shared channel (PDSCH) to UEs whose preambles are decoded successfully. The RAR contains a RA preamble identifier (ID), an UL grant, a temporary cell identifier, and a time alignment (TA) command for the corresponding UEs. 3) The UEs which receive a RAR corresponding to their transmitted preambles, adjust their UL transmission times according to the TAs and send the connection setup request messages in the UL grants which are specified in the received RARs. 4) If eNB successfully receives the connection setup request in step 3, it will send the contention resolution message to the corresponding UE. UEs which do not receive this message are failed and should retry in a new RA procedure.

If one preamble is selected by more than one UE in the same RA slot the corresponding UEs transmit their third messages through the same UL grant. In this case, by ignoring the power-ramping effect, we assume that eNB is not able to decode any of these transmissions successfully and hence does not send any response to the corresponding UEs [2], [5].

We consider a scenario in which, N UEs exist in the coverage area of an eNB. Each of these UEs is activated, within the interval $[0, T_{tc}]$ according to a beta probability distribution function with $\alpha = 3$ and $\beta = 4$ [6]. T_{tc} is divided into x_{tc} cycles where according to the uplink transmission bandwidth of the cell and the framing structure of the system, each cycle contains some resource blocks (RBs). The RBs of each cycle are allocated to PRACH and PUSCH and we assume a certain amount of them are reserved for 4-step RA procedure of MTC [7]. Taking into account the estimated number of required RBs for non-M2M UEs and connected M2M UEs which have granted uplink resources, eNB determines the number of RBs that can be allocated

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for 4-step RA procedure of new activated UEs. The objective of this work is efficient utilization of PUSCH resources that are used in the RA procedure. The allocated RBs to PRACH and PUSCH are exploited for preamble transmission in step 1 and connection setup request or straight small data packet transmission in step 3 of RA procedure, respectively [8]. The number of PUSCH RBs used for transmitting the third message by an UE is called a PUSCH opportunity.

Let M and H denote the number of preambles and PUSCH opportunities constructed from available RBs for 4-step RA procedure of MTC in each cycle, respectively. Each activated UE tries to transmit its request at the beginning of each cycle and remains active until the transmission of its connection setup request or small data packet successfully. The required number of cycles to serve all UEs, i.e., the number of cycles in which all UEs in a traffic burst send their RA requests to the eNB successfully, is called total service time (TST).

It is probable that the UEs which contend in each cycle for UL resources select the same preamble and retransmit their requests in the next cycles which leads to RAN overload. To overcome this problem in the ACB scheme, each UE is allowed to select preamble according to a probability p which is called ACB factor and broadcasted by eNB. The barred or failed UEs repeat the ACB check in the next cycles [1]. This mechanism relieves the RAN overload by reducing the number of UEs participating in RA procedure. The barring factor should be adaptively adjusted according to the number of access-attempting or active UEs in each cycle.

Let N_k and p_k denote the number of active UEs and the ACB factor in the k^{th} cycle, respectively. Given that N_k is known, the expected number of preambles which are selected by only one UE in the k^{th} cycle is given by $S_k = N_k p_k \big(1 - \frac{p_k}{M}\big)^{N_k - 1}$. Note that the final number of successful requests depends on the number of available PUSCH opportunities for allocating to the selected preambles. Then, provided that eNB knows the value of N_k, the optimal ACB factor which is denoted by p_k^* is given by $p_k^* = min\{1, \frac{M}{N_k}\}$ [6].

In a real scenario, however, the number of active UEs is not available at eNB and therefore, we use the heuristic algorithm in [6] for adjusting the ACB factor in each cycle. This heuristic scheme uses this fact that the ratio of the collided to the total number of preambles will have a specific value in cycle k if p_k adjusts by the optimal value. So, it increases or decreases the ACB factor slightly in each cycle by comparing the average number of collided preambles in the previous three cycles with the expected optimal value as a threshold.

III. PROPOSED RANDOM ACCESS PROCEDURE

In each cycle and at the end of the RA procedure, we can divide preambles into three groups: 1) Successful preambles: preambles that are selected by only one UE. 2) Collided preambles: preambles that are selected by more than one UE. 3) Idle preambles: preambles that are not selected by any UE. In the k^{th} cycle each UE which passes the ACB check selects each preamble with probability $1/M$. Hence, the probability that a given preamble, named m, is selected by an UE is $\frac{p_k}{M}$ and the probability that the preamble remains idle is given by $(1 - \frac{p_k}{M})^{N_K}$. Therefore, given that N_k is known, the expected number of idle preambles, M'_k, is $M'_k = M\big(1 - \frac{p_k}{M}\big)^{N_k}$.

To maximize the uplink resource utilization in the dynamic ACB, RBs should be allocated to the PRACH and PUSCH such that the number of PUSCH opportunities, H, be equal to the sum of expected number of successful and collided preambles. By this choice the expected number of successful requests would be equal to the number of successful preambles since sufficient PUSCH resources are available for assigning to successful and collided preambles [9]. Therefore, and to be fair in comparisons, in both dynamic ACB and the proposed two-stage schemes the splitting of uplink resources to PRACH and PUSCH is done according to this principle.

The main idea of the proposed two-stage scheme against one-stage dynamic ACB is that in each cycle the number of active UEs which passed the ACB check and select preambles is more restricted in the first stage. Hence, the number of collided preambles decreases significantly which avoids wasting the PUSCH opportunities by not scheduling these opportunities for collided preambles in this stage. We should note that the decrease in the number of successful preambles in the first stage is much less than the decrease in collided preambles. Then in the second stage, we allocate these unscheduled PUSCH opportunities to active UEs which were barred in the first stage after passing a new ACB check. Using this scheme the total number of successful requests is increased compared to the one-stage dynamic ACB. The UEs which passed and those which were barred at the first stage ACB check are called primary and secondary UEs.

In the two-stage scheme, $M-1$ preambles are devoted to the primary UEs and one special preamble is assigned to the secondary UEs. At the first stage, UEs compete for non-special preambles. In the second stage, by selecting the special preamble, the secondary UEs attempt to utilize unused PUSCH opportunities which are remained from the first stage.

A. Proposed Algorithm

The proposed scheme consists of six steps as follows:

Step 1: At the beginning of each cycle, eNB broadcasts the ACB factor according to $p_k^1 = min(1, \delta p_k^*)$, where $p_k^* = \frac{M-1}{N_k}$ and δ is a parameter used for maximizing the total number of successful access requests in the two-stage scheme. By applying δ the number of access-attempting UEs in the first stage of the proposed scheme is more restricted compared to the one-stage dynamic ACB and the wasted PUSCH resources due to collisions in this stage is decreased. By proper utilizing of these resources in the second stage, the total number of successful requests is maximized.

Step 2: The active UEs perform the ACB check. The UEs which pass the ACB check select one of the non-special $M-1$ preambles randomly and send their requests to the eNB. The other active UEs select the special preamble.

Step 3: eNB detects active preambles, schedules PUSCH resources for them, and sends the corresponding RARs for all active preambles except the special preamble. If p_k^1 is equal to 1, all active UEs are belonging to the primary UEs and the procedure continues as the traditional one-stage RA procedure. If p_k^1 is less than 1, eNB determines how many unscheduled PUSCH opportunities are available and considers these opportunities for secondary UEs which had selected the special preamble. Let the number of unscheduled PUSCH opportunities be $r, r \geqslant 0$. eNB assigns r RARs to the special preamble and sends those through downlink. The preamble ID of these RARs is special preamble while the assigned PUSCH opportunity is different in each RAR.

Step 4: Each primary UE which receives a RAR on the downlink with the preamble ID similar to its selection, sends the connection setup request or its small data packet on the PUSCH opportunity indicated by RAR message.

Step 5: The secondary UEs will receive r RARs corresponding to the special preamble on the downlink. Using the broadcasted ACB factor in the first stage, these UEs know the total number of active UEs since $N_k = \frac{\delta(M-1)}{p_k^1}$. Hence each secondary UE can compute the expected number of secondary UEs, N'_k, which is given by $N'_k = N_k(1-p_k^1)$. Therefore, the optimal ACB factor for each UE in the second stage barring is given by $p_k^2 = min(1, \frac{r}{N'_k})$. Notice that eNB just broadcasts the first stage ACB factor at the beginning of each cycle and each secondary UE finds the second stage barring probability independently and contends with other UEs by randomly selecting one of the PUSCH opportunities with probability p_k^2. The secondary UEs that do not pass this check or their transmissions are collided retry in the next cycle.

Step 6: If eNB successfully received the third message transmitted in a PUSCH opportunity, it sends the contention resolution message in response to the corresponding UE. The UE's request is failed if it does not receive this response message. The proposed RA procedure is illustrated in Fig.1.

B. Analysis of the proposed scheme

Let the expected number of successful transmissions by primary UEs in the first stage and by secondary UEs in the second stage is denoted by S_k^1 and S_k^2, respectively, given that N_k is known. According to p_k^1 and p_k^2 we have:

$$S_k^1 = N_k p_k^1 (1 - \frac{p_k^1}{M-1})^{N_k - 1}, S_k^2 \quad = N'_k p_k^2 (1 - \frac{p_k^2}{H'_k})^{N'_k - 1},$$

$$\text{where} \quad p_k^2 = min\{1, \frac{H'_k}{N'_k}\},$$

$$H'_k = H - (M-1)\Big(1 - (1 - \frac{p_k^1}{M-1})^{N_k}\Big).$$

H'_k is the expected number of unused PUSCH opportunities given that N_k is known. Since the objective is maximizing the expected total number of successful transmissions in the two stages, we should select δ and hence p_k^1 such that the sum of S_k^1 and S_k^2 is maximized. By assuming $N_k \gg M$ and using $lim_{x->\infty}(1-\frac{\delta}{x})^x = e^{-\delta}$, we have:

$$S_k^1 + S_k^2 \cong (M-1)\delta e^{-\delta} + \Big(H - (M-1)(1-e^{-\delta})\Big)e^{-1}. \tag{1}$$

By taking the derivative of (1) with respect to δ, we find that the maximum total number of successes is achieved when $\delta \ = \ 1 - e^{-1}$.

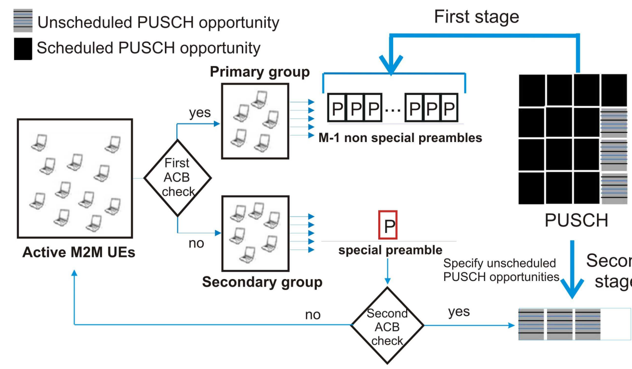

Fig. 1. Two-stage random access procedure.

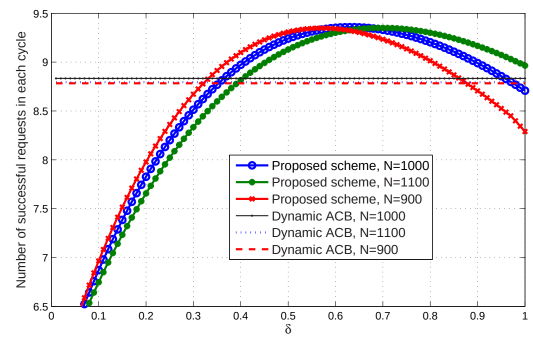

Fig. 2. The average number of successful requests for different values of δ when the number of assigned RBs for RA procedure of MTC is 21.

IV. PERFORMANCE EVALUATION

In this section, the performance of the proposed scheme is evaluated in terms of the TST and the number of successful requests in each cycle in comparison with the one-stage dynamic ACB. In each cycle, eNB estimates the value of the ACB factor by running the heuristic algorithm in [6]. We set x_{tc}=100 in all the simulations and assume 21 RBs are reserved for 4-step RA procedure of M2M communication in each cycle. Also, we assume that 24 preamble sequences are assigned to the M2M UEs in every 6 RBs, i.e., in average, each preamble requires 1/4 RB [8], [9]. Therefore, based on the mentioned principle for allocating RBs to PRACH and PUSCH, we assign 6 and 15 RBs from 21 available RBs to PRACH and PUSCH, respectively. Each RB constitutes one PUSCH opportunity. The number of access-attempting UEs is randomly drawn according to the beta distribution in each cycle. In the following, we first assume that eNB knows N_k to find the optimal ACB factor. Then, in order to show the sensitivity of the proposed scheme to fine tuning of the ACB factor we perform a simulation in which the number of access-attempting UEs is not estimated exactly. Also, we use the heuristic scheme in [6] for adjusting p_k in cycle k^{th} for both dynamic ACB and the proposed two-stage schemes in the rest of simulations.

Fig. 2 shows the analysis results for the average number of total successful requests in both schemes for three scenarios against different values of δ. In this simulation the actual number of active UEs is 1000 and the results for

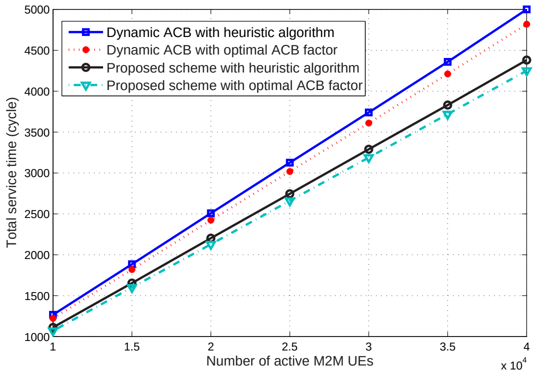

Fig. 3. The TST vs. the number of active M2M UEs when the number of assigned RBs for RA procedure of MTC is 21.

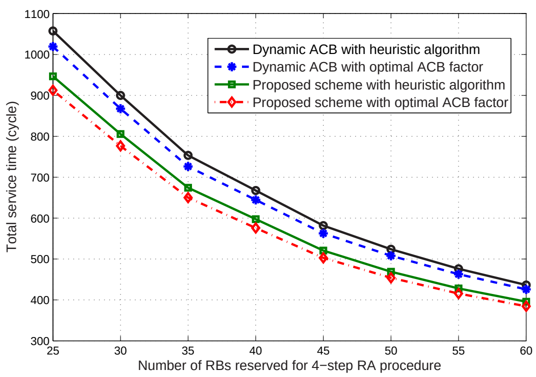

Fig. 4. The TST vs. the number of assigned RBs for RA procedure of MTC when $N = 10000$.

$N = 1000, 1100, 900$ are depicted which respectively reflects zero and plus or minus 10 percentage error in estimating the number of access-attempting UEs to adjust the ACB factor in each cycle. Using the proposed scheme and for optimal ACB factor, the average number of successful requests in each cycle is increased compared to the corresponding one-stage scheme. Also, the maximum number of successful requests for the two-stage scheme occurs when $\delta = 1 - e^{-1}$, as expected. Furthermore, Fig. 2 shows that both schemes are not much sensitive to exact tuning of the ACB factor while the two-stage scheme outperforms the one-stage ACB in these scenarios too if $\delta > 0.35$.

In Fig. 3 the TST for different number of UEs varying from 10000-40000 is depicted assuming that eNB knows the optimal value of ACB factor as well as when the estimated ACB factor obtained from the heuristic algorithm. The TST is decreased as expected since more UEs transmit their requests successfully in each cycle. In Fig. 4, assuming 10000 UEs, the TST for different number of assigned RBs for MTC varying from 25-60 is shown.

Fig. 5 shows the simulation results for the average number of successful requests in each cycle in TST interval for the two-stage and one-stage dynamic ACB schemes when the number of UEs is 10000. As expected, in average using the proposed scheme the number of successful requests is greater

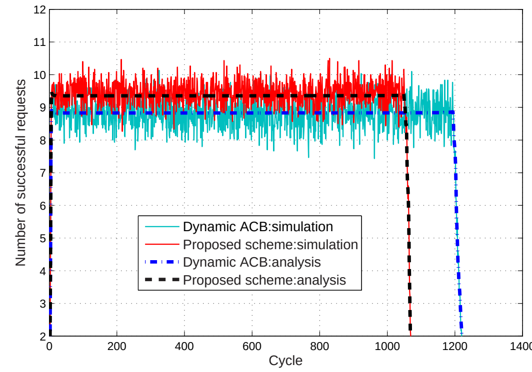

Fig. 5. The average number of successful requests in each cycle when the number of assigned RBs for RA procedure of MTC is 21 and $N = 10000$.

than the corresponding successful requests in each cycle and hence the TST is decreased.

V. CONCLUSION

We investigate the RAN overload issue in the cellular network for M2M communication and propose a new RA scheme that allocates uplink resources to the M2M UEs in two stages. In the first stage, we grant the uplink resources to the UEs that have passed the ACB check and in the second stage we utilize the unused uplink resources for UEs that did not pass the ACB check in the first stage. The results show that the proposed scheme increases the number of successful requests and reduces the TST. The proposed scheme can also be used in scenarios that some of M2M UEs have higher priority than others. In this case, we can allocate resources to high priority UEs in the first stage and then in the second stage, the low priority UEs can utilize the unused resources remained from the first stage.

REFERENCES

[1] 3GPPTS 37.868,“Study on RAN Improvements for Machine-type Communications,” v11.0.0, Sep. 2011.

[2] A. Laya, L. Alonso, and J. Alonso-Zarate,“Is the Random Access Channel of LTE and LTE-A Suitable for M2M Communications? A Survey of Alternatives,”*IEEE Commun. Surv. and Tuto.*, vol. 16 , no. 1, pp. 4-16, first quarter, 2014.

[3] F. Hussain, A. Anpalagan, and R. Vannithamby, “Medium access control techniques in M2M communication: survey and critical review,” *European Trans. Emerging Tel. Tech.* doi: 10.1002/ett.2869, 2015.

[4] T.-M. Lin,C.-H.Lee, J.-P.Cheng, and W.-T. Chen,“PRADA: Prioritized Random Access with Dynamic Access Barring for MTC in 3GPPLTE-A Networks,” *IEEE Trans. Veh. Technology,* vol. 63, no. 5, pp. 24672472, Jun. 2014.

[5] M. Gerasimenko, V. Petrov, O. Galinina, S. Andreev, and Y. Koucheryavy, “Impact of MTC on energy and delay performance of randomaccess channel in LTE-Advanced,” *IEEE Trans. Veh. Technology,*, vol. 24, no. 4, pp. 366-377, 2013.

[6] S. Duan, V. Shah-Mansouri, and V.W.S. Wong,“Dynamic access class barring for M2M communications in LTE networks,” *in Proc. of IEEE GLOBECOM,* Altlanta, GA, Dec. 2013.

[7] G. C. Madueno, C. Stefanovic and P. Popovski, “Reliable reporting for massive M2M communications with periodic resource pooling”, *IEEE Wireless Commun. Lett.*, vol. 3, no. 4, pp.429 -432 2014.

[8] S. Sesia, I. Toufik, and M. Baker, *LTE - The UMTS Long Term Evolution.* West Sussex, UK: John Wiley & Sons, Ltd, 2009.

[9] N. Zhang, G. Kang and J. Wang, “Resource allocation in a new random access for M2M communications,” *IEEE Commun. Lett.*, vol. 19, no. 5, pp. 843846, May. 2015.