Novel Pico-cell Range Expansion with Adaptive RACH Resource Allocation for Random Access of M2M Devices

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***Abstract*—In the next-generation cellular networks, Machine-to-Machine (M2M) communications, in which machine-type devices communicate with each other without user's control, is considered to create new services. In M2M communications, a large number of M2M devices distributed in a cell area may exist. So, the random access congestion problem caused by massive and simultaneous random access trials of user equipments (UEs) is one of the most important issues to be addressed. For next-generation cellular networks, an efficient random access control scheme is required to decentralize random access trials from a macro-cell to small-cells in a heterogeneous network (HetNet). So, we consider a new random access control scheme by adjusting pico-cell's coverage dynamically to improve the performance of the random access procedure in HetNets. In this paper, we propose a new Pico-Cell Range Expansion (PCRE) scheme with dynamic Random Access CHannel (RACH) resource allocation. We show that the random access efficiency and random access delay of UEs can be improved.**

Keywords–HetNets; M2M communications; random access control; cell range expansion.

I. INTRODUCTION

In the next-generation cellular networks, Machine-to-Machine (M2M) communications, which is also known as Machine-Type Communications (MTC) in the Third Generation Partnership Project (3GPP) specifications [1], is considered as a new key technology to create new services. In M2M communications, MTC Devices (MTCDs), i.e., different type of User Equipments (UEs) compared to legacy UEs for Human-to-Human (H2H) communications, communicate with each other anytime and anywhere without user's control. Because of various applications for M2M communications, e.g., metering the usage of water, electricity, and gas and road security for announcing the emergency message, a very large number of MTCDs can spread in a cell area and work simultaneously. So, one of the main issues for M2M communications is a random access congestion problem caused by the concurrent and massive random access trials of MTCDs.

In order to reduce the congestion problem, some approaches on random access controls in a Long Term Evolution (LTE) system have been discussed [2]. In [3], a preamble separation scheme which splits a set of available preambles and allocates them to MTCDs separately is introduced. A part of preambles for MTCDs are shared by M2M and H2H UEs, but the dedicated preambles are always provided to H2H UEs. And a dynamic Random Access CHannel (RACH) resource allocation scheme for dynamic traffic is proposed by Yilmaz et al. [4]. Amirijoo et al. [5] present an adaptive power control mechanism for preamble transmission according to the variation of random access loads.

However, conventional random access control schemes tend to focus on dealing with random access trials in a single cell. For the next-generation cellular network, a new random access control scheme considering the features of Heterogeneous Networks (HetNets) is required. HetNet is introduced by 3GPP to handle the growth of mobile data traffic load due to the wide spread of smart phones and tablet PCs. In a HetNet, various small-cells formed by low power network entities, such as pico-eNodeB, femto-eNodeB, and relay-eNodeB, can coexist and operate along with the conventional macro-eNodeB [6]. So, the random access loads can be spread from a macro-cell to small-cells. In particular, pico-cells can take over the random access loads of a macro-cell efficiently since they can be deployed by the operator's cell planning [7]. For an efficient random access congestion control in a HetNet, balancing random access loads between a macro-cell and small-cells is important.

As an approach for balancing random access loads in HetNets, we consider controlling the coverage area of pico-cells dynamically by utilizing Cell Rage Expansion (CRE), which has been introduced initially and discussed by 3GPP [8]. If the CRE scheme is properly applied to pico-cells, the random access congestion problem can be relieved by decentralizing the random access load of a macro-cell to pico-cells. In [9], they introduce a simple CRE scheme and show simulation results when the random access loads are offloaded from macro-cells to pico-cells depending on different bias values. Guvenc [10] analyzes the impact of capacity and fairness by applying the CRE scheme to HetNets. The CRE scheme can be realized by the power control of eNodeB. Morimoto et al. [11] proposed a power control mechanism for the CRE. The simulation results show that the throughput of the edge cell area is improved although the entire cell throughput slightly decreases. Liu et al. [12] proposed an adaptive uplink power control of pico-eNodeB to decrease the inter-cell interference where power control parameters of each pico-eNodeB can be configured according to the interference level from adjacent eNodeBs. However, their study mainly focuses on improving the cell area capacity rather than addressing the random access and the congestion problem.

In this paper, we propose a new Pico-CRE (PCRE) scheme with dynamic RACH resource allocation to improve the average random access efficiency and the average access delay of

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M2M and H2H UEs. Each pico-eNodeB measures the number of accessed UEs, and compares it with the estimated number of UEs. After the comparison, the pico-eNodeB adjusts its cell range to reduce the gap between the measured number of UEs trying to access and the estimated number of UEs tying to access, and allocates the RACH resource to cover the expected number of UEs trying to access in the expanded cell range appropriately. By the proposed scheme, the random access congestion problem can be addressed in HetNets. We show the performance improvement by our proposed scheme through simulations.

This paper is organized as follows. We describe the proposed PCRE with dynamic RACH resource allocation in Section II. In Section III, we evaluate the performance of the proposed scheme via simulations. Finally, conclusion is presented in Section IV.

II. Proposed Pico-cell Range Expansion with Dynamic RACH Resource Allocation

The congestion problem may occur when massive UEs try random access simultaneously in a network. Especially, in HetNets, the macro-eNodeB and pico-eNodeBs may utilize the same Physical Random Access CHannel (PRACH) in the same time since the macro-eNodeB and pico-eNodeBs work independently for communication services. When macro UEs are near a pico-cell and they transmit their preambles to the macro-eNodeB on the same PRACH with pico UEs, the pico-eNodeB can overhear the preambles. Although the preambles are not for the pico-eNodeB, the pico-eNodeB misunderstands that the preambles are transmitted by their pico UEs, and thus allocates unnecessary RACH resource, i.e., Random Access Opportunities (RAOs). Therefore, the performance of random access is degraded in pico-cells. So, we aim to solve the random access congestion problem by adjusting the pico-cell's range and diverting random access trials of macro UEs to pico-cells.

In a HetNet, UEs generally try to establish a Radio Resource Control (RRC) connection with the eNodeB supporting the largest Reference Signal Received Power (RSRP). The number of UEs served by a pico-cell can be limited by the relatively low transmission power of a pico-eNodeB. The adoption of an efficient CRE scheme can increase the number of UEs served by pico-cells. Fig. 1 represents an example of our proposed scheme. Since pico-eNodeBs PeNB1, PeNB3, and PeNB4 suffer from interference by macro UEs near their cells due to the shared preamble set in Fig. 1 (a), the proposed CRE scheme is applied according to the number of UEs. In order to accommodate more UEs to a pico-eNodeB, the pico-eNodeB expands the cell range by controlling the transmission power. Then pico-eNodeBs also allocate RACH resource dynamically. As shown in Fig. 1 (b), PeNB1, PeNB3, and PeNB4 allocate more RACH resource because the number of UEs, which migrate from the macro-cell to the pico-cell, is increased. For the macro-cell, less RACH resource is needed due to the reduced number of macro UEs by the proposed scheme. The proposed scheme can efficiently distribute more macro UEs near a pico-cell to the pico-cell and allocate RACH resource appropriately. The dispersion of UEs from a macro-cell to a pico-cell can solve the congestion problem in a macro-cell due to the reduction of the number of access UEs.

Now, we describe the proposed PCRE with the dynamic

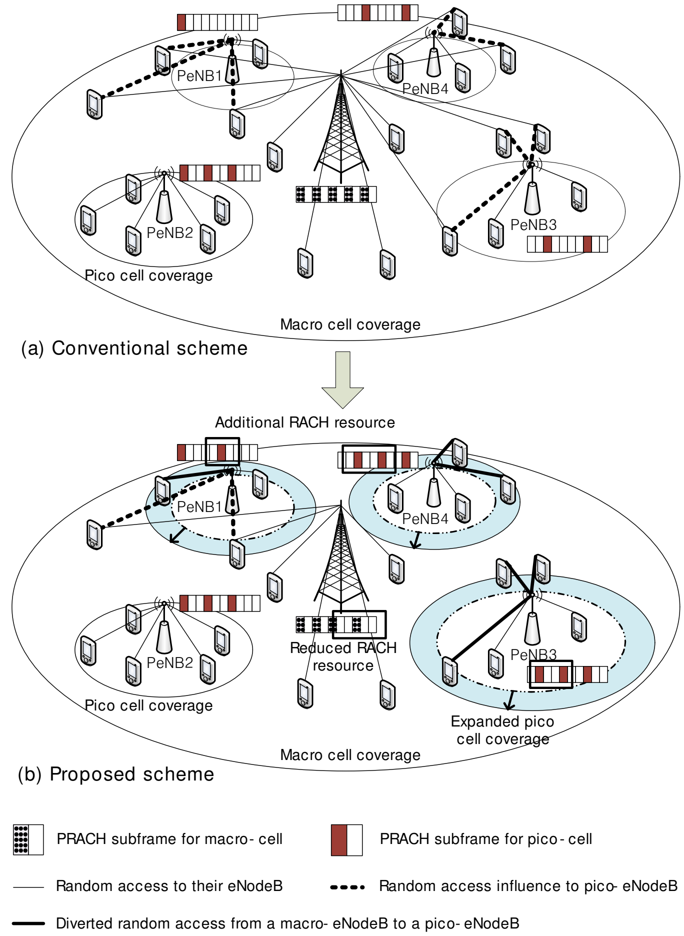

Figure 1. Random access in macro- and pico-cell networks (a) conventional scheme (b) proposed scheme.

RACH resource allocation algorithm. In our algorithm, a pico-eNodeB measures the idle RAOs in the current frame to estimate the number of UEs trying to access in the pico-cell area. Then, the pico-eNodeB calculates the estimated number of successfully accessed UEs and compares it with the measured number of successfully accessed UEs in the frame. If its gap is greater than a threshold, i.e., there are a number of macro UEs around the cell boundary, the pico-eNodeB expands its cell range to cover the macro UEs and to allocate an appropriate number of RAOs for the UEs in the expanded region.

At the ith frame, to estimate the number of UEs trying to access, the pico-eNodeB measures the number of idle RAOs ($\widetilde{L}_{idle\_pico,i}$). The probability of idle RAOs ($\hat{P}_{idle\_pico,i}$) in the ith frame can be estimated as

$$\hat{P}_{idle\_pico,i} = \frac{\widetilde{L}_{idle\_pico,i}}{L_{pico,i}}, \tag{1}$$

where $L_{pico,i}$ is the number of allocated RAOs in the ith frame. Since the probability of idle RAOs can be computed as

$$P_{idle\_pico,i} = \left(1 - \frac{1}{L_{pico,i}}\right)^{N_{PUE,i}}, \tag{2}$$

where $N_{PUE,i}$ is the number of UEs, we can get the estimated number of UEs $\hat{N}_{PUE,i}$ by letting (1) to be equal to (2) such that

$$\hat{N}_{PUE,i} = \frac{\log \hat{P}_{idle\_pico,i}}{\log\left(1 - \frac{1}{L_{pico,i}}\right)}. \tag{3}$$

From $\hat{N}_{PUE,i}$, the probability of successful RAOs $\hat{P}_{succ,i}$ in the ith frame is estimated as

$$\hat{P}_{succ,i} = \hat{N}_{PUE,i}\frac{1}{L_{pico,i}}\left(1 - \frac{1}{L_{pico,i}}\right)^{\hat{N}_{PUE,i}-1}. \tag{4}$$

Then, the pico-eNodeB estimates the number of successfully accessed UEs $\hat{N}_{succ\_pico,i}$ in the ith frame as

$$\hat{N}_{succ\_pico,i} = \hat{P}_{succ,i} \times L_{pico,i}. \tag{5}$$

In fact, the pico-eNodeB can know the actual number of successfully accessed UEs $\widetilde{N}_{succ\_pico,i}$ in the ith frame. So, by comparing $\hat{N}_{succ\_pico,i}$ with $\widetilde{N}_{succ\_pico,i}$, the pico-eNodeB recognizes the existence of macro UEs adjacent to its service coverage.

If the gap of the estimated number of successfully accessed UEs and that of the actual UEs is larger than the threshold N_{thr}, it conducts its cell range expansion to include the neighboring macro UEs. To expand its cell coverage, the pico-eNodeB should decide the amount of transmission power increment. First, the path-loss in the macro-cell $PL_{macro,i}$ and the path-loss in the pico-cell $PL_{pico,i}$ can be defined by the case model 1 in [13].

$$PL_{macro,i} = 128.1 + 37.6\log\left(d_{macro,i}[km]\right), \tag{6}$$

$$PL_{pico,i} = 140.7 + 36.7\log\left(d_{pico,i}[km]\right), \tag{7}$$

where $d_{macro,i}$ and $d_{pico,i}$ are the distance between the macro-eNodeB and a virtual UE, and the distance between the pico-eNodeB and a virtual UE, respectively. We define the RSRP (from the macro-eNodeB) at a UE as $RSRP_{macro,i}$ and the RSRP (from the pico-eNodeB) at a UE as $RSRP_{pico,i}$.

$$RSRP_{macro,i} = 10\log\left(P_{tx\_macro,i}\right) - PL_{macro,i}, \tag{8}$$

$$RSRP_{pico,i} = 10\log\left(P_{tx\_pico,i}\right) - PL_{pico,i}, \tag{9}$$

where $P_{tx\_macro,i}$ and $P_{tx\_pico,i}$ are the transmission powers of the macro- and of the pico-eNodeB, respectively.

To expand its cell range, the pico-eNodeB needs to find its current cell coverage distance $D^*_{pico,i}$. When $RSRP_{macro,i}$ and $RSRP_{pico,i}$ are equal, the pico-cell coverage distance can be obtained.

$$RSRP_{macro,i} = RSRP_{pico,i}. \tag{10}$$

However, there may be many solutions for the coverage distance. To find the shortest one, the distance $D_{mtop,i}$ between the macro-eNodeB and the pico-eNodeB is used.

$$D_{mtop,i} = \sqrt{x^2_{macro,i} + y^2_{macro,i}}, \tag{11}$$

where $(x_{macro,i}, y_{macro,i})$ is the position of the macro-eNodeB assuming the pico-eNodeB is at (0, 0). When a virtual UE is in a straight line from the macro-eNodeB to the pico-eNodeB, $D_{mtop,i}$ can be

$$D_{mtop,i} = d_{macro,i} + d_{pico,i}. \tag{12}$$

From (10) and (12), the solution $D^*_{pico,i}$ for $d_{pico,i}$ can be obtained.

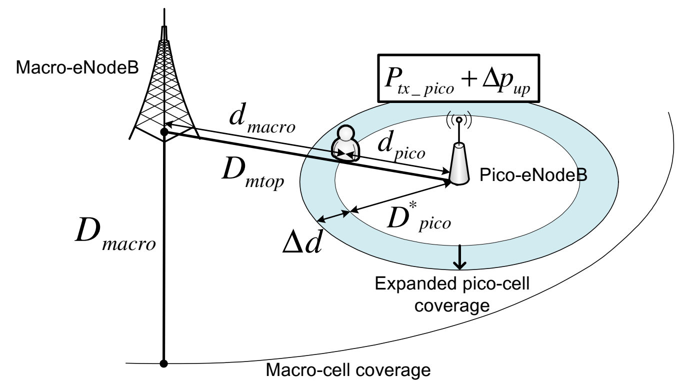

Figure 2. An example of pico-cell range expansion.

Once the pico-eNodeB obtains the its current radius $D^*_{pico,i}$, it calculates the amount of the transmission power increment $\Delta p_{up,i}$ to expand the cell range. Let $N_{TOTAL,i}$ be the maximum number of UEs served in a cell and $D_{macro,i}$ be the radius of the macro-cell. From $\hat{N}_{PUE,i}$, $N_{TOTAL,i}$, $D_{macro,i}$, $D^*_{pico,i}$, and the assumption that UEs are uniformly distributed in a cell, the additionally required pico-cell range expansion Δd_i can be calculated as

$$\hat{N}_{PUE,i} : \left(D^*_{pico,i} + \Delta d_i\right)^2 = N_{TOTAL,i} : {D_{macro,i}}^2. \tag{13}$$

After the cell range expansion, the new RSRP of a virtual pico UE at the edge area of the pico-cell on a straight line from the macro-eNodeB to the pico-eNodeB is

$$RSRP'_{pico,i} = 10\log\left(P_{tx\_pico,i} + \Delta p_{up,i}\right) - PL'_{pico,i}, \tag{14}$$

where

$$PL'_{pico,i} = 140.7 + 36.7\log\left(D^*_{pico,i} + \Delta d_i\right). \tag{15}$$

The new RSRP of the virtual pico UE (from the macro-eNodeB) is

$$RSRP'_{macro,i} = 10\log\left(P_{tx\_macro,i}\right) - PL'_{macro,i}, \tag{16}$$

where

$$PL'_{macro,i} = 128.1 + 37.6\log\left(D_{mtop,i} - \left(D^*_{pico,i} + \Delta d_i\right)\right). \tag{17}$$

For the new $RSRP'_{pico,i}$ to be the same as the new $RSRP'_{macro,i}$, the amount of transmission power increment $\Delta p_{up,i}$ can be obtained. Fig. 2 shows an example of pico-cell range expansion.

$$RSRP'_{pico,i} = RSRP'_{macro,i}. \tag{18}$$

The pico-eNodeB determines the transmission power no more than the maximum transmission power P_{max} and no less than the minimum transmission power P_{min}. So, the transmission power in the next frame for the pico-cell is updated as

$$P_{tx\_pico,i+1} = \max\left(\min\left(P_{tx\_pico,i} + \Delta p_{up,i}, P_{max}\right), P_{min}\right). \tag{19}$$

On the other hand, if the difference between the estimated number of accessed UEs and that of the measured UEs is lower than the threshold N_{thr}, it indicates that there are not

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many macro UEs contending in the pico-eNodeB. Thus, the transmission power for the next frame in the pico-cell is not updated.

In order to get the optimal number of RACH resource for dynamic RACH resource allocation of pico-cells, we use the random access efficiency of the system. We define the random access efficiency $RA_{eff,i}$ as

$$RA_{eff,i} = \hat{N}_{PUE,i}\frac{1}{L_{pico,i}}\left(1-\frac{1}{L_{pico,i}}\right)^{\hat{N}_{PUE,i}-1}. \quad (20)$$

The random access efficiency indicates the average success rate of UEs trials in a frame. The maximum random access efficiency is obtained by differentiation of (20). Then, we can get

$$L_{pico,i+1} = \hat{N}_{PUE,i}. \quad (21)$$

The dynamic RACH resource allocation phase is performed by updating the number of RAOs for the pico-cell as the estimated number of pico UEs $\hat{N}_{PUE,i}$. The number of RAOs is limited to the maximum RAOs L_{max}. Then the number of RAOs in the next frame for the pico-cell is

$$L_{pico,i+1} = \min\left(\hat{N}_{PUE,i}, L_{max}\right). \quad (22)$$

III. Performance Evaluation

In this section, we evaluate the performance of our proposed PCRE with dynamic RACH resource allocation scheme in HetNets. The parameters used in the simulations are shown in Table I. We use the simulation parameters in [13]. We consider four pico-eNodeBs and UEs are uniformly distributed in a macro-cell. In the conventional scheme, UEs randomly access to their eNodeBs with fixed RAOs. For the path-loss model, all macro- and pico-eNodeBs are outdoor, and 3GPP TR 36.814 urban macro and pico path-loss model is employed [13].

Fig. 3 and Fig. 4 show the average random access efficiency of a macro-cell and a pico-cell. In Fig. 3, as the arrival rate of UEs trying to access becomes larger, the average random access efficiency of the conventional scheme with fixed RAOs in the macro-cell slowly increases and decreases after the certain arrival rate. When the arrival rate is small, the number of RAOs is more than the number of access trials since the arrival rate is small. Then the random access efficiency increases as the arrival rate increases. After that, the random access efficiency decreases since users have insufficient number of RAOs at high arrival rate. However, the average random access efficiency of the proposed scheme in the macro-cell is almost 36%, i.e., the

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Radius of a macro cell (D_{macro})	288 m
Max. Macro-eNodeB Tx Power (P_{tx_macro})	20 W
Max. Pico-eNodeB Tx Power (P_{tx_pico})	1 W
Max. UE Tx. Power	200 mW
Arrival rate of UEs	1000 to 35000
Max. no. of preamble transmissions	10
Max. no. of HARQ transmissions	5
Max. no. of preambles	54

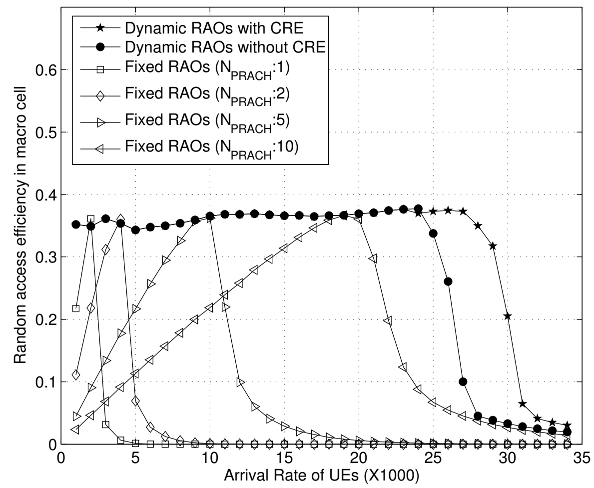

Figure 3. Average random access efficiency in a macro-cell.

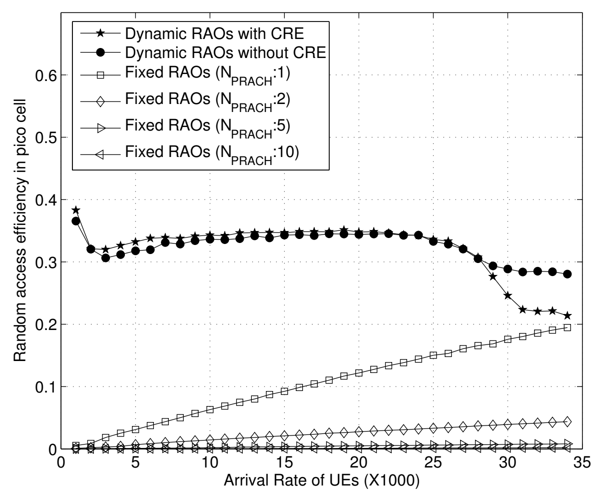

Figure 4. Average random access efficiency in a pico-cell.

maximum efficiency, since the RACH resource in the cell is allocated dynamically according to the number of UEs. After a large arrival rate, collisions may occur and the average random access efficiency decreases. When each pico-eNodeB employs the CRE scheme with dynamic RAOs, some of macro UEs near the pico-cell can access to the pico-eNodeB. Thus, when the arrival rate of UEs trying to access is large, the macro-eNodeB achieves better performance in terms of the average random access efficiency. The simulation result shows that the average random access efficiency of the proposed scheme with CRE in the macro cell is improved by 50% over that of the conventional scheme with fixed RAOs.

Fig. 4 shows the average random access efficiency of a pico-cell. In the conventional scheme without CRE, the number of UEs serviced by a pico-cell is relatively small. When many PRACH subframes for the pico-cell are assigned in a frame, there may be unused RAOs. So, the random access efficiency increases as the arrival rate of UEs increases. In the proposed

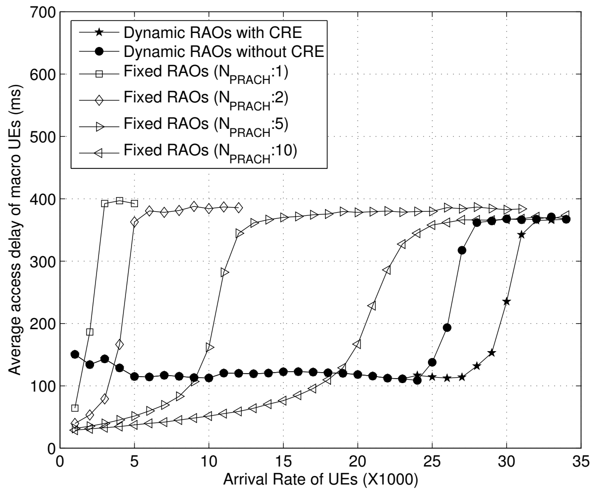

Figure 5. Average random access delay in a macro-cell.

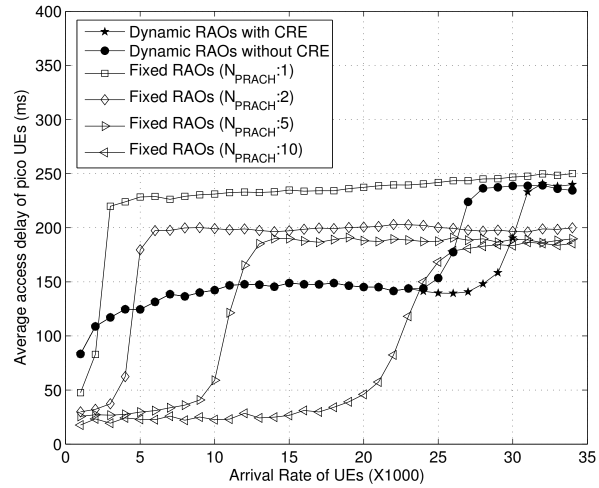

Figure 6. Average random access delay in a pico-cell.

scheme, the pico-eNodeB expands the cell range and allocates the RACH resource dynamically depending on the number of pico UEs. The average random access efficiency of the proposed scheme in the pico-cell reaches to 36%, which is similar to the average random access efficiency of a macro-cell. However, for a large arrival rate, performance may degrade since the number of macro UEs, which are allocated the same preambles with pico UEs in the near pico-cell, increases for massive UEs.

Fig. 5 and Fig. 6 show the average random access delay of UEs in a macro-cell and a pico-cell, respectively. In Fig. 5, at low arrival rate, the number of available RAOs for users may be sufficient in fixed RAOs. So, the random access delay of the conventional scheme is lower than that of the proposed scheme. As the arrival rate of UEs trying to access becomes larger, the average random access delay of the conventional scheme in the macro-cell dramatically increases. However, when the proposed scheme is applied, the average random access delay remains small for a wide range of arrival rates and starts to increase at a large arrival rate of UEs compared to the average random access delay of the conventional scheme. Collisions may occur frequently due to insufficient RAOs in the conventional scheme. However, the macro-eNodeB applying the proposed scheme allocates RAOs appropriately according to the number of macro UEs, and it results in high random access efficiency. Thus, the proposed scheme achieves better performance.

Fig. 6 shows the average random access delay of UEs in a pico-cell. For fixed RAOs, there may be unused RAOs at the low arrival rate. Then, the random access delay of the conventional scheme is lower than that of the proposed scheme. The simulation result shows that the proposed scheme with CRE can tolerate the congestion problem of UEs compared to the proposed scheme without CRE. When the arrival rate of UEs trying to access is extremely high, the average random access delay for the pico-cell may be degraded compared to that of the conventional scheme with fixed RAOs. When there are a number of UEs, PRACH subframes for the macro-cell are allocated in many of the subframes. Then pico UEs, which transmit preambles on a PRACH, can be influenced by adjacent macro UEs, which transmit the same preambles on the same PRACH as the pico UEs. Nevertheless, the average random access delay of the proposed scheme is shown to be improved in general.

IV. CONCLUSION

In this paper, we aimed at studying the performance improvement of random access in HetNets. Especially, we consider the feature of M2M communications in which a very large number of MTCDs can exist in a cell and massive MTCDs contend simultaneously. Then, the random access congestion problem can occur due to the concurrent and massive random access trials of MTCDs. To solve the problem, we have proposed the PCRE with dynamic RACH resource allocation. The proposed scheme can attract more MTCDs from a macro-cell to pico-cells by controlling the pico-cell's coverage area. The pico-eNodeBs then allocate appropriate RACH resource to cover the attracted MTCDs in the expanded cell range. We have shown that the proposed scheme can improve the average random access efficiency and the average random access delay of UEs compared to the conventional scheme with fixed random access resource via simulations.

ACKNOWLEDGMENT

This research was supported by Next-Generation Information Computing Development Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Science, ICT & Future Planning (20100020729), and was supported by Basic Science Research Program through the NRF funded by the Ministry of Education(NRF-2010-0020210).

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