A Novel Random Access for Fixed-Location Machine-to-Machine Communications in OFDMA Based Systems

Kab Seok Ko, Min Jeong Kim, Kuk Yeol Bae, Dan Keun Sung, Jae Heung Kim, and Jae Young Ahn

***Abstract*—Machine-to-machine (M2M) communications typically exhibit features such as a large number of devices, low data-rates, small-sized packets, and low or no mobility, while human-to-human (H2H) communications typically support a small number of users, high data-rates, large-sized packets, and high mobility. To support M2M communications in future cellular systems, one of the most challenging problems is to resolve a collision problem in random access because of access attempts from a large number of devices. For a large class of fixed-location M2M services such as smart metering and remote sensing, each machine device has fixed uplink timing alignment (TA) due to a fixed distance between the machine device and its eNodeB. We propose a novel random access scheme based on its fixed TA information for M2M communications at a large number of fixed-location machine devices in future orthogonal frequency division multiple access (OFDMA)-based cellular systems like Long Term Evolution (LTE) system. The proposed random access scheme yields significantly lower collision probability, shorter access delay, and higher energy-efficiency, compared with the conventional random access scheme.**

***Index Terms*—M2M, LTE, random access, timing alignment.**

I. INTRODUCTION

ACCORDING to the estimation of the wireless world research forum (WWRF), up to 7 trillion wireless devices will be connected to various networks for serving 7 billion people in the future [1]. In a case of smart metering, for example, the number of smart meters is expected to be approximately 35,000/sector in a cell with a radius of 2 km under urban (London) scenario [2]. This extremely large number of machines/sensors may cause an addressing problem and may cause a shortage problem in limited radio resources. To support machine-to-machine (M2M) communications in future orthogonal frequency division multiple access (OFDMA)-based cellular networks, several standardization bodies (e.g. IEEE 802.16 and 3GPP) [2], [3] have studied M2M communications and specify features and requirements of M2M communications, which typically exhibit a variety of characteristics: low/no mobility, a large number of devices, etc., which are quite different from those of human-to-human (H2H) communications. There are many challenges in efficiently accommodating M2M communications which will be an important part of future cellular networks.

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K. S. Ko, M. J. Kim, K. Y. Bae, and D. K. Sung are with the Department of Electrical Engineering, KAIST, Korea (e-mail: {ksko, mjkim, kybae}@cnr.kaist.ac.kr; dksung@ee.kaist.ac.kr).

J. H. Kim and J. Y. Ahn are with the Telecomm. Research Lab., Electronics and Telecommunications Research Institute, Korea (e-mail: {kimjh, jyahn}@etri.re.kr).

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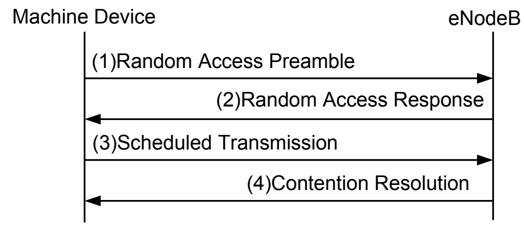

Fig. 1. Random access procedure in LTE system.

The concept of M2M communication has already existed in sensor networks in small area networks. In sensor networks, sensors monitor physical or environmental conditions and transmit the sensing data to a server through multi-hop relaying. Utilizing sensor networks is a possible solution to support M2M communications in a limited range [4]. However, we consider cellular systems as an alternative approach for some reasons, such as reliable wide-area two-way communication, security, mobility, quality of service (QoS) and the cost of installing and maintaining new communication systems. In this paper, we consider an OFDMA-based cellular system to accommodate M2M services.

There have been studies in cellular systems to support M2M communications. A massive access management scheme considering QoS constraints was proposed for a large number of machine devices [5]. To reduce total energy consumption in M2M systems, a joint massive access control and resource allocation scheme was proposed [6]. In standardization activities such as IEEE 802.16p, new protocols have been proposed to support devices with low/no mobility to reduce a large amount of overhead related to mobility management [7]. A contribution in 3GPP [8] shows that both machine devices and mobile users may suffer from severe collisions at the random access (RA) which is used for the following purposes: network entry/reentry, handover, scheduling request, and uplink timing synchronization.

In contrast to mobile devices, fixed-location machine devices have a fixed uplink timing alignment value which is considered in the RA procedure. We focus on a large class of fixed-location M2M services such as smart metering and remote sensing. In this letter, we propose a novel random access scheme based on fixed timing alignment (TA) information at a large number of fixed-location machine devices to reduce collision probability, lower average access delay, and achieve energy-efficiency.

II. RANDOM ACCESS (RA) IN OFDMA-BASED SYSTEM

Fig. 1 shows an example of the current RA procedure for M2M communications in LTE [9]. In the first step, a machine

TABLE I
BACKOFF PARAMETER (BP) VALUES

Index	BP value (ms)	Index	BP value (ms)	Index	BP value (ms)
0	0	6	80	12	960
1	10	7	120	13	Reserved
2	20	8	160	14	Reserved
3	30	9	240	15	Reserved
4	40	10	320		
5	60	11	480		

device randomly selects one preamble among M orthogonal preambles and transmits the preamble on RA slot. In the second step, when the eNodeB receives the preambles from machine devices, it detects which preamble is transmitted, and obtains a TA value of the detected preamble, and then broadcasts an RA response for the detected preamble. The response includes a preamble identifier, uplink grant, and TA information. Each machine device uses the preamble identifier to identify the destination of the response. In the third step, the machine device adjusts uplink transmission time for synchronization according to the received TA information and transmits a scheduled message on the assigned uplink resource. Once the message is transmitted, the machine device starts a contention resolution (CR) timer to check for an access collision. In the last, if the eNodeB successfully decodes the scheduled message, it transmits a CR message to the corresponding machine device. Before the CR timer expires, if each machine device successfully receives the CR message, then it successfully completes the RA. Otherwise, it regards the previous RA attempt as a collision. Then, it needs to reattempt an RA after performing a backoff mechanism until successful transmission or the maximum number of retransmissions.

In the LTE system, a backoff parameter (BP) value is initially set to 0 ms to reduce the connection set-up delay. If a machine device receives an RA response which contains a Backoff Indicator (BI), it can set the BP value as indicated by the BI and selects a random backoff time according to a uniform distribution between 0 and the BP value. Table I shows a BP value in the LTE system as an example [9].

A. Collision Probability

We assume that eNodeB can perfectly detect each preamble among multiple preambles in this paper. Since a preamble is a kind of sequence in physical layer, eNodeB may not figure out the exact number of machine devices which transmitted the same preamble. If more than one device simultaneously transmit the same preamble on the same RA slot, they would receive the same uplink grant and TA information, and transmit their scheduled messages on the same uplink resource, and, finally, they experience a collision. In other words, if machine devices happen to select the same preamble on the same RA slot, they cause a collision of their scheduled messages. Then, the probability that a given machine device selecting one preamble among M preambles experiences a collision with other machine device(s) among $(k-1)$ machine device(s) on a single RA slot is expressed as $P_c^{ue}(M,k) = 1-(1-\frac{1}{M})^{k-1}$. An increase in the number of machine devices in a cell causes to increase this collision probability.

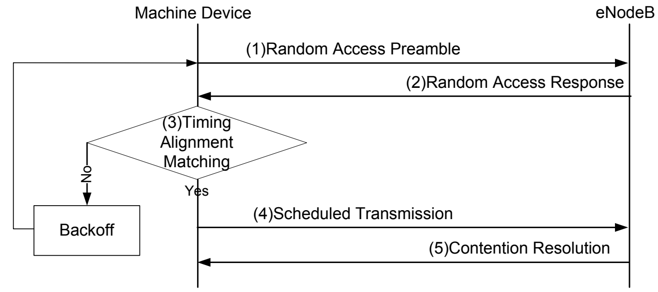

Fig. 2. Proposed random access procedure.

III. PROPOSED RANDOM ACCESS SCHEME

We assume that the TA value between each fixed-location machine device and eNodeB is fixed and unchanged. In the conventional RA scheme, fixed-location machine devices do not utilize the unchanged, fixed TA information during the RA procedure. On the other hand, in our proposed system, if a fixed-location machine device receives an RA response which has a different TA value from its own TA value, it does not transmit a subsequent scheduled message, and, thus, the fixed-location machine device does not cause to collide with other devices. If it receives the same TA value as its own TA value, it has a high probability to successfully transmit a scheduled message to eNodeB. Based on this fact, we propose a novel RA scheme based on the fixed TA information in order to significantly reduce the collision probability and access delay for a large number of fixed-location machine devices.

During the initial access to a serving eNodeB, machine devices use the conventional RA and we assume they acquire and store their TA values (T_{stored}). Since then, it is assumed that they use this proposed RA scheme utilizing their own fixed TA values unless the serving eNodeB is updated.

A. Proposed Random Access Procedure

Fig. 2 shows the proposed RA procedure with 5 steps. The first and second steps are the same as those of the conventional RA procedure. In the third step, a machine device which receives an RA response compares the TA value in the response with its own TA value. If it does not match, it performs a retransmission procedure by selecting a random backoff value and waiting for the backoff time. If the received TA value matches with its own TA value, it continues to perform a scheduled transmission in the fourth step. These fourth and fifth steps correspond to the third and fourth steps of the conventional RA procedure, respectively.

The proposed scheme enables the fixed-location machine devices to predetermine whether they can advance to the next step for scheduled transmission with a higher probability of no collisions. In the proposed scheme, the fixed-location machine devices can predetermine the possible occurrence of collisions in the first two steps before a contention resolution step in contrast with the conventional scheme. This proposed scheme can significantly reduce the collision probability as well as access delay through the TA matching.

B. Timing Alignment Matching

Due to measurement or estimation errors at eNodeB for every RA procedure, each fixed-location machine device needs a TA matching mechanism in the proposed scheme. T_{curr} denotes the TA value in the current RA response. Let ϵ be the margin of TA error. The TA matching results are expressed as follows:

$$\begin{cases} \text{matched}, & \text{if } T_{curr} \in [T_{stored} - \epsilon, T_{stored} + \epsilon] \\ \text{mismatched}, & \text{otherwise.} \end{cases} \tag{1}$$

As the ϵ value becomes larger, more machine devices are likely to belong to the acceptable TA range. However, it may result in an increase in the collision probability.

C. Collision Analysis, Access Delay, and Energy Efficiency

Suppose $k+1$ machine devices including one tagged device select their own preambles and attempt random accesses on a single RA slot. We calculate the probability that a tagged machine device experiences a collision with other machine device(s) among k devices. We assume the tagged fixed-location machine device o has a TA value of $T_o = 2r_o/c$, where r_o is the distance between the tagged device and eNodeB, and c is the light speed. Let $f(r)$ be the probability density function that there exists a fixed-location machine device at distance $(r, r+dr)$ from eNodeB.

If the tagged machine device is located according to the $f(r)$ distribution, the collision probability of the tagged machine device is expressed as

$$P_c^{'ue} = \int_0^R f(r)(1-(1-\frac{P(r)}{M})^k)dr. \tag{2}$$

where $P(r)=\int_{r-\epsilon c/2}^{r+\epsilon c/2} f(r)dr$ is the probability that there exists one machine device which attempts random access on the same RA slot within a range of $(r-\epsilon c/2, r+\epsilon c/2)$.

In the proposed scheme, the collision probability is reduced due to the factor $P(r)$. In other words, a tagged machine device experiences a collision when at least one of other machine devices located in $(r-\epsilon c/2, r+\epsilon c/2)$ selects the same preamble as the tagged device on the same RA slot, while in the conventional scheme, a tagged machine device may collide with any other machine devices selecting the same preamble on the same RA slot in the entire cell area.

In a uniformly distributed case of $f(r)=2r/R^2$, the collision probability is expressed as

$$P_c^{'ue} = 1 - \frac{2}{R^2}\Big\{ \int_{R-\frac{\epsilon c}{2}}^{R} r(1-\frac{(R^2-(r-\frac{\epsilon c}{2})^2)}{MR^2})^k dr + \int_0^{\frac{\epsilon c}{2}} r(1-\frac{(r+\frac{\epsilon c}{2})^2}{MR^2})^k dr + \int_{\frac{\epsilon c}{2}}^{R-\frac{\epsilon c}{2}} r(1-\frac{4r\frac{\epsilon c}{2}}{MR^2})^k dr \Big\}. \tag{3}$$

Fig. 3 shows the collision probability of both the proposed and conventional schemes for varying the number of RA attempts from machine devices on a single RA slot when $M = 5$ and 20, $\epsilon = 0.52$ μs[1], and $R = 2$ km. The collision probability of the proposed scheme is reduced to approximately 1/10 of that of the conventional scheme.

We compare the access delay of the proposed scheme with that of the conventional scheme, where the access delay is defined as the time duration of an RA attempt to successful completion of the RA procedure. We perform simulations using a process-oriented discrete-event simulation package (CSIM). We assume the location of machine devices follows a uniform distribution within a cell radius of 2 km and the RA inter-arrival time follows an exponential distribution. We set a linear backoff mechanism. We evaluate the access delay when the number of machine devices is set to 30,000, the number of allocated RA slots is one sub-frame (1 ms) within a radio-frame of 10 ms, $M = 5$ and 20, $\epsilon = 0.52$ μs, and the initial backoff parameter value is set to 20 ms.

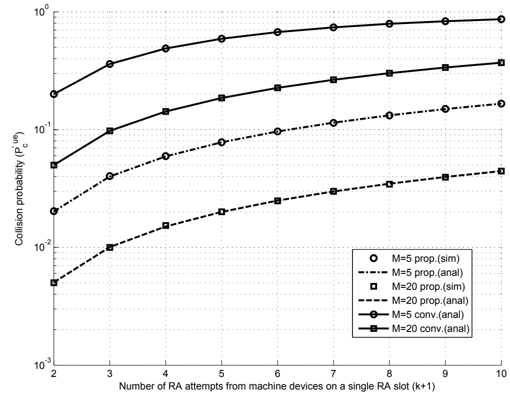

Fig. 3. Collision probability.

Fig. 4 shows the access delay of both the proposed and conventional schemes for the above setting. Shorter inter-arrival time of RA attempts results in longer access delay due to an increase in the collision probability. In particular, if the inter-arrival time is set to 4 minutes and M is 5, then the access delay of both the proposed and conventional schemes is 16 ms and 43 ms, respectively. As the inter-arrival time becomes shorter, the proposed scheme yields significantly lower access delay than the conventional scheme.

Fig. 5 shows the performance of the access delay. From Fig. 5, we can observe that the proposed scheme can support a much larger number of machine devices than the conventional scheme to achieve the same access delay.

Taking into account the number of transmissions of preambles and scheduled messages until successful transmission, we can relatively compare the energy efficiency. The simulation study shows that the average number of transmissions of the proposed and conventional schemes is 2.3 and 3.0, respectively, when the RA inter-arrival time is set to 4 minutes and the number of preambles is set to 5. Thus, the proposed scheme yields higher energy-efficiency than the conventional scheme.

D. Impact of Errors

We investigate the impact of ϵ on the performance of the proposed scheme. In a simulation, we set the RA inter-arrival time to 5 minutes and the other parameters to the same values for the above access delay performance. Fig. 6 shows the performance of the access delay when the ϵ value varies. The conventional scheme is independent of ϵ and, thus, sets to a reference value. As the ϵ value increases, the access delay of the proposed scheme also increases and, finally, converges to that of the conventional scheme. Each machine device may

[1] Since we assume the TA value is fixed, we choose this value which represent a resolution unit in timing alignment value in LTE system.

TABLE II
NUMBER OF MACHINE DEVICES PER GROUP AND COLLISION PROBABILITY PER GROUP

Group number	1	2	3	4	5	6	7	8	9	10	11	12	13
Number of machine devices	164	543	895	1253	1574	1913	2428	2808	3051	3532	3790	4263	3786
Collision probability (x*0.0001)	14	51	188	188	137	378	374	509	806	574	700	1003	697

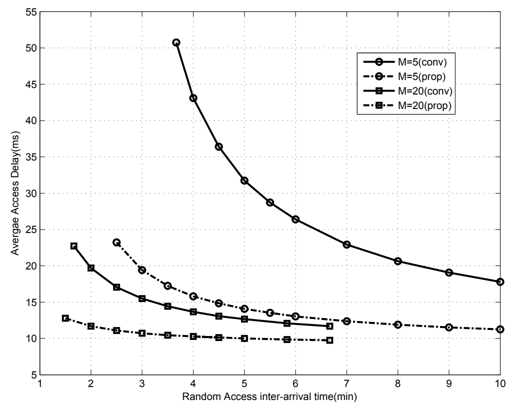

Fig. 4. Access delay.

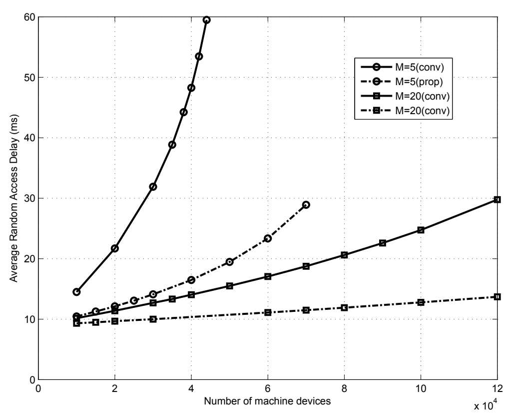

Fig. 5. Impact of the number of machine devices on the access delay of the proposed scheme and the conventional scheme.

collide with the others in a cell when the ϵ value is larger than 6.67 μs.

E. Unfairness Problem

In the proposed scheme, there may exist an unfairness problem depending on the distribution of machine devices. In a uniformly distributed case, as the distance from the eNodeB increases, the number of machine devices with the same TA also increases. Thus, the group which is the nearest to the eNodeB has a lower collision probability than the group which is the farthest from the eNodeB. Table II shows the number of machine devices per group and the corresponding collision probability when the RA inter-arrival time is set to 5 minutes. The collision probability of Group 1 is much lower than that of Group 12 because of a difference in the number of machine devices. However, the collision probability of Group 12 is still lower than that of the conventional scheme (0.2548). The proposed scheme yields much lower collision probabilities than the conventional scheme despite this unfairness problem.

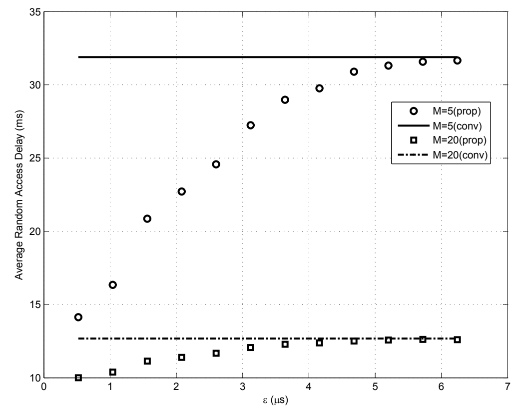

Fig. 6. Impact of ϵ on the access delay of the proposed scheme.

IV. CONCLUSION

In this letter, utilizing the fact that the timing alignment information for fixed-location machine devices is fixed when machine devices perform an RA procedure, we proposed a new RA scheme for fixed-location machine devices. We evaluated the performance of the proposed scheme in terms of the collision probability, access delay, and the average number of transmissions. The proposed scheme yields much lower collision probability, shorter access delay, and higher energy-efficiency than the conventional scheme.

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