Success Rate Maximization with Code-Expanded Random Access for M2M Communication

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Abstract— Many researchers expect that Internet of Things (IoT) era will arrive. As a result huge amount of machine-to-machine (M2M) devices will appear. However, current LTE system is not suitable for this massive amount of M2M devices. Preamble is a kind of resource that is used for random access of devices. The problem is that while expected number of M2M devices in the future is so large, the number of preamble is restricted to 64. What is worse, 64 preambles cannot be used for M2M communications because some of them are reserved for (human-to-human) H2H communications. Among studies to solve this kind of problem, code-expansion can be a powerful method. In this paper, we propose an optimization problem for efficient use of code-expanded. Code-expansion is investigated to maximize the success probability of random access while satisfying the code utility ratio and the access delay threshold. Our simulation shows that the length of a virtual frame which is equal to two is enough to cover up to 120,000 devices for 10seconds.

Keywords— Random access, Success rate, Code-expanded, Preamble, M2M communications

I. INTRODUCTION

In recent years, number of machines for machine-to-machine (M2M) communications has been increased on cellular networks which is designed for human-to-human (H2H) communications. According to this increase of M2M communications, changes of conventional sight on M2M communications have appeared [1], [2]. There are some big differences between conventional human-to-human communications and machine-to-machine communications. While requirements of traditional H2H communications are higher bit rate and lower transmission time, the important requirement of M2M communications are huge amount of transmissions and lower bit rate.

The primary issue in M2M communications is to adjust cellular networks to cover Machine-Type Communications (MTC) traffic features efficiently, concretely the traffic load generated by huge amount of simultaneous low data transmissions. The problem occurs from the Random Access Channel (RACH), which is the transport-layer channel. It is designed to manage the devices that are trying to access base station.

The random access procedure occurs by a device when it wants to make a data connection with the base station. It is for the synchronization with the base station after a long unconnected time or when the connected base station is changed due to handover.

The random access procedure is divided as contention-free and contention-based depending on the purpose. Contention-free random access procedure is used for control of delay-sensitive access requests with high success requirements. The process is fully managed by base station that controls the access requests of devices to minimize collision and access time. Therefore, it is not impacted by M2M communications so much. In contrast, the contention-based random access procedure is more impacted by M2M communications.

The RACH consists of a sequence of time-frequency resources, which is called Random Access (RA) slots. Devices can try access requests by transmitting preamble by RA slots. The time-frequency resources on which the preamble is transmitted is called the Physical Random Access Channel (PRACH) as illustrated in [4].

In each LTE cell, total 64 types of preambles are exist which are made by Zadoff-Chu sequence. Some preambles are allocated for contention-free random access, and the rest preambles are allocated for contention-based random access. The procedure of contention-based random access is explained in [4].

3GPP suggests that the random access procedure is a main challenging issue for M2M communications because the massive access requests by machine-type devices can overload the PRACH, which yields an increase of the collision probability, access delay and failure rate [5].

Code-expanded random access is a new way of random access scheme different from the current 3GPP method. While the base station decodes the received preambles from one subframe in current scheme, a group of successive subframes for preamble transmission are grouped together as a virtual frame (see Fig. 2 in [6]). Each device chooses a codeword that are composed of a randomly selected preamble in every subframe in the virtual frame. In this way, the number of resources for preamble transmission increased, so the number of collisions is decreased.

II. RELATED WORK

Large amount of Machine-Type devices in a cell can create huge amounts of traffic and yield intensive network load. 3GPP LTE release LTE-A system, and it contains RAN overload management methods [7]. Access Class Barring (ACB) assigns different access classes to every device, then control the number of devices that try random access according to their assigned class. One way to separate RACH resources is to allocate for H2H devices and M2M devices. According to the number of random access trial of M2M devices and H2H devices, the base station can dynamically allocate RACH resources. A M2M communication backoff scheme is also another way to control the number of random access trial.

In [8], spatial group based random access scheme is proposed. The authors assume that collision does not occur if the distance between the devices that select same preamble is far enough. According to this principle, cell area can be divided into several sectors, and the same preamble sets can be allocated into different sectors that are far away enough.

Instead of allocating more preambles on M2M communications, increasing the number of PRACH can be another way to deal with massive access. An optimization problem to determine how many random access opportunities (RAOs) should be allocated according to the number of devices trying random access is proposed in [9]. RAO is the product of the number of PRACH that can be used for random access per cell in an LTE frame, and the number of preambles. The authors define random access efficiency as how many M2M devices can be accessed successfully, and takes it as objective function. The authors also calculates the average access delay and takes it as a constraint.

Resource management scheme by clustering is proposed in [10]. The authors cluster M2M devices according to the QoS characteristics. To alleviate inefficiency in RANs, communication scheme based on grouping is proposed in [11]. The authors group several connections triggered by different M2M devices. The base station is assumed to know all the location information of M2M devices, and by the communication scheme, random access performances in massive access trial is improved. In [12], by grouping and coordinator selection of M2M devices, access management is processed. Then, it determines the number of groups minimizing the energy consumption.

The remainder of this paper is organized as follows. Section 3 discusses the troubles of code-expaned model and our problem description. Section 4 provides a success ratio maximization problem with codeword idle ratio and access delay constraints. In Section 5, we solve the optimization problem to get the required number of preambles and the length of a virtual frame and evaluate the performance. Finally, Section 6 concludes the paper.

III. Design of Code-Expand

As mentioned above, by utilizing code-expanded random access, we can increase the number of codeword and decrease the collision probability. To increase the number of codewords, the number of preambles to be used and length of a virtual frame should be increased. However, the number of preambles is restricted. Length of a virtual frame is directly associated with access time of a device. Even though QoS of M2M communication does not directly influence Human's satisfaction, access time requirement should be met. Therefore, length of a virtual frame should be investigated.

A. *Troubles of code-expanded*

Let's suppose the number of codewords is much bigger than the number of devices that are attempting to access to the base station. For specific, suppose that the number of preamble for M2M communication M=10, the length of a virtual frame L=4, and the number of devices N=1,000. Then, the number of codewords (CW) made by ten preambles and four subframes is 14,640 by Equation (1).

$$CW = (M+1)^L - 1 \quad (1)$$

The number of devices is far less than the number of codewords. In this case, even though all 1,000 devices successfully access with no collision, 13,640 codewords are not used. It is waste of resource, and such large number of codewords is not necessary.

If smaller number of preambles are used for M2M communication, more preamble can be used for H2H communications, then the QoS of H2H communications will be increased. By decreasing the number of codewords that are not selected, the number of phantom codewords can be reduced, and as a result, we can reduce the waste of resources for data transmission.

Therefore, it is necessary to decrease the number of codewords that are not used. Because of this, codeword idle ratio (P_{idle}) is considered.

$$P_{idle} = \frac{\text{number of codewords that are not selected by any device}}{\text{total number of codewords}} \quad (2)$$

B. *Success rate maximization*

In the topic of random access procedure, Success rate is a very important performance metric. That is because ultimate goal of random access procedure is to connect M2M devices as many as possible satisfying the access time requirement. Many researchers expect that Internet of Things (IoT) era will be realized in the future, and huge amount of M2M devices will appear. The problem is that, since the number of preamble is restricted, as the number of devices increases, access collision probability will also be increased. Collided devices try random access at next opportunity and if the number of preamble is not enough, these kinds of backlogged devices will be piled continuously. Then, collision probability will be increased, and this becomes a vicious cycle.

Since code-expanded is a scheme to solve this problem, success rate ($S_{A_{req}}$) to satisfy access time requirement is considered as a performance metric and defined as

$$S_{A_{req}} = \frac{\text{number of succeeded devices until access time requirement}}{\text{total number of attempting devices}} \quad (3)$$

Setting success rate as the objective function, codeword idle ratio and a virtual frame length are set as two constraints. The first constraint C1 is related to the code utility.

$$C1: P_{idle} \leq P_{req}$$

The second constraint C2 is related to the access delay due to the length of a virtual frame.

$$C2: \text{Length of a virtual frame} \leq A_{req}$$

If the length of a virtual frame is longer than the time requirement (A_{req}), it is impossible to meet the access delay requirement.

All the variables in the paper are summarized as in Table I.

TABLE I VARIABLES AND THEIR DEFINITIONS

Variable	Definition
M	Number of preambles for M2M communications
L	Length of a virtual frame
CW	Number of codewords
P_{idle}	Ratio of codewords that are not selected by any device
P_{req}	Threshold of P_{idle}
T	Time length of a frame
A_{req}	Access time requirement of devices
$P_{collision}$	Collision probability
λ	Arrival rate of a device
λ_T	Number of devices in steady state
N	Number of new arrivals in a frame
T_{limit}	Counter limit of a virtual frame to satisfy the access time requirement
$S_{A_{req}}$	Ratio of succeeded devices within the access time requirement
$F_{best,n}$	Best fitness value until n_{th} generation
M_{max}	Expected maximum number of preamble for M2M communications

IV. Proposed Optimization Problem

Our ultimate goal is to maximize the success rate of random access while guaranteeing the codeword idle ratio requirement and the average access time requirement for the M2M communications. The problem is formulated as follows:

$$\begin{aligned} &\text{argmax } S_{A_{req}} \\ &\text{s. t. } P_{idle} \leq P_{req} \\ &L \cdot T \leq A_{req} \\ &M, L \geq 0, \text{ integer} \end{aligned} \tag{4}$$

Note that both $S_{A_{req}}$ and P_{idle} are nonlinear function of M and L which leads the problem to integer nonlinear programming. By solving this problem we can get optimal number of preambles (M^*) and optimal length of virtual frame (L^*) satisfying two constraints.

A. Success rate to satisfy access time requirement

To get the success rate, we should calculate the collision probability in a virtual frame first. If more than one devices transmit the same codeword on the same virtual frame in the first step of the random access procedure, they get the equivalent uplink grant and time alignment (TA) value in random access response in the second step. Next, they send their desired data packets by the same uplink resource, and it induces a collision. If a collision occurs, base station does not transmit a contention resolution in the fourth step. Hence, the devices eventually perceive the collision and they try the random access at the next opportunity.

According to [13], collision probability ($P_{collision}$) can be defined as

$$P_{collision} = \frac{\text{number of collided devices}}{\text{total number of attempting devices}} \tag{5}$$

Let $P_{collision}$ and $\lambda_T[i]$ respectively represent the collision probability and total random access arrival rate in the i-th virtual frame. Then,

$$\lambda_T[i] = \lambda \cdot T + P_{collision} \cdot \lambda_T[i-1] \tag{6}$$

λ denote the random access arrival rate of devices, T denotes the period of subframe for preamble transmission, and $P_{collision} \cdot \lambda_T[i-1]$ denotes the reattempted random access arrival rate from the previous virtual frame due to collisions. In steady state, we can drop the slot index i, then λ_T is expressed as

$$\lambda_T = \frac{\lambda \cdot T}{1 - P_{collision}} \tag{7}$$

Collision probability can be calculated by

$P_{collision}$ = 1 - Pr[no node select a given codeword] - Pr[one node select a given codeword] (8)

Let X be a random variable that denotes the number of devices that select a codeword. Then the probability that a given codeword is selected by k devices among N can be represented as

$$\Pr[X = k] = \binom{N}{k} \cdot \left(\frac{1}{CW}\right)^k \cdot \left(1 - \frac{1}{CW}\right)^{N-k} \tag{9}$$

Here, $N = \lambda_T$, so (8) can be represented as

$$P_{collision} = 1 - \Pr[X = 0] - \Pr[X = 1]$$

$$P_{collision} = 1 - \left(1 - \frac{1}{CW}\right)^{\lambda_T} - \frac{\lambda_T}{CW} \cdot \left(1 - \frac{1}{CW}\right)^{\lambda_T - 1} \tag{10}$$

From (7) and (10) we have

$$P_{collision} = 1 - e^{W[\ln(1-\frac{1}{CW})]\lambda_T} \quad (11)\ [8]$$

$W(.)$ is a Lambert W function. By using collision probability, we can calculate the success rate. First it is assumed that at every random access procedure, there are new N devices that are trying to access base station.

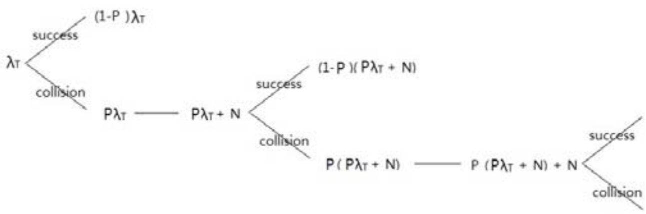

Fig. 1 Arrival of Devices in the system

Figure 1 illustrates the device arrival in the system. We assume that the system is in steady state as in (6), and there are initially λ_T devices in the system. Then, the number of devices that fail to access the base station at first random access is $\lambda_T P_{collision}$. The number of devices that fail to access the base station at second random access among initial λ_T is $\lambda_T P^2_{collision}$. On the same principle, the number of devices that fail to access the base station at n-th random access among initial λ_T is $\lambda_T P^n_{collision}$.

Counter limit of a random access of a device to satisfy the access time requirement can be calculated as the access time requirement over the time length of a virtual frame. If we let T_{limit} be a counter limit to satisfy the access time requirement and A_{req} be an access time requirement, T_{limit} can be written as

$$T_{limit} = \left\lfloor \frac{Access\ time\ requirement}{time\ length\ of\ a\ virtual\ frame} \right\rfloor = \left\lfloor \frac{A_{req}}{LT} \right\rfloor \quad (12)$$

Then, ratio of devices that succeed to access the base station within the access time requirement among initial λ_T devices can be written as

$$S_{A_{req}} = 1 - \frac{\lambda_T \cdot (P_{collision})^{T_{limit}}}{\lambda_T} = 1 - (P_{collision})^{T_{limit}} \quad (13)$$

B. Codeword idle ratio

As mentioned, if the number of devices is far less than the number of codewords, a lot of codewords are not in use, which is a waste of resource. To deal with this codeword utility problem, the number of codewords should be managed according to the random access arrival rate of devices.

Let P_{idle} denote the codeword idle ratio. Then P_{idle} can be represented as

$$P_{idle} = \frac{number\ of\ codewords\ that\ are\ not\ selected}{total\ number\ of\ codewords} \quad (14)$$

The number of codewords that are not selected by devices can be represented as

$$\text{Number of codeword in use} = (\Pr[X = 0]) \cdot CW \quad (15)$$

where CW denotes the total number of codewords. From (14) and (15) we have

$$P_{idle} = \frac{(\Pr[X = 0]) \cdot CW}{CW} = \Pr[X = 0] = \left(1 - \frac{1}{CW}\right)^N = \left(1 - \frac{1}{(M+1)^L - 1}\right)^N \quad (16)$$

Lemma 1. When the length of a virtual frame L is fixed, the maximum number of preamble M_{max} that satisfies the codeword idle ratio of (4) is given by

$$M \le \sqrt[L]{1 + \frac{1}{1 - \sqrt[N]{P_{req}}}} - 1 = M_{max} \quad (17)$$

(Proof) Clear from (4) and (16).

We can also expect the length of a virtual frame. During the process of random access we have three kinds of codewords; codewords that are not selected by any device, codewords that are selected by only one device, and codewords that are selected by more than one device.

Lemma 2. If λ_T devices succeed the random access, then the codeword idle ratio of (4) is given by

$$\frac{CW - \lambda_T}{CW} \le P_{req} \quad (18)$$

(Proof) Clear from (4) and (14).

Theorem 1. The number of codewords that satisfies the success of λ_T devices and the codeword idle ratio P_{req} is given by

$$(M+1)^L - 1 \le \frac{\lambda_T}{1 - P_{req}} \quad (19)$$

(Proof) Clear from (1) and (18).

From (19) we can expect the maximum length L_{max} of a virtual frame that guarantees the success of all λ_T devices, when the number of preambles M for the M2M communication is given.

V. Genetic Algorithm for the Code-Expanded Random Access

In this section, we employ Genetic Algorithm to solve the proposed optimization problem. The proposed success rate maximization problem is a nonlinear integer programming model which is difficult to get the optimal solution due to its combinational nature and potential existence of multiple local maxima in the search space. Genetic Algorithms (GAs) are powerful tools [14] for solving such nonlinear integer programming problems. Table II lists the values of simulation parameters. Pre_{max} is the maximum number of preamble available for M2M communications.

Table Ⅱ. Parameters used in Simulation

Variable	Value
P_{req}	0.3, 0.5
T	10 ms
A_{req}	22ms, 60ms
λ	10,000 ~ 120,000 devices/10sec
Pre_{max}	30

A. Genetic Algorithm

We solve the proposed optimization problem with the Genetic Algorithm. Since the ultimate goal is to get the optimal number of preambles for M2M communications and the optimal length of a virtual frame, we set the chromosome as (X_1, X_2), where X_1 represents the number of preambles and X_2 represents the length of a virtual frame.

Since the goal of the optimization is to maximize the success rate, we set the fitness function (F) as success rate. If constraints are not satisfied, penalty values are added. Fitness function is given as follow:

$$F = S_{A_{req}} - \alpha \cdot \max(0, P_{idle} - P_{req}) - \beta \cdot \max(0, LT - A_{req}) \quad (20)$$

α and β are penalties of the first and the second constraint respectively. In our experiment α=10 and β=1.

Population size is set to 500. Binary tournament selection is employed with elitist model which keeps the generation best. Uniform crossover is performed with crossover rate 0.5. Mutation rate is set to 0.01 to prevent premature convergence. The GA is stopped when the improvement of the best is less than 0.1%.

B. Performance evaluations

Figure 2 shows the optimal number of preamble and optimal length of a virtual frame for various numbers of devices. The number of preambles for M2M communication increases as the number of devices increases to the maximum available value 30. After that, when the number of codewords is not enough to maximize the success rate, then the length of a virtual frame is increased and the number of preamble decreases. In the right figure of Figure 2 shows the length of a virtual frame. Note from (19) that the maximum length of a virtual frame is two with the simulation data in Table II. The access delay is satisfied for both A_{req} =22ms and 60ms as we expected. We see that even though the access delay is 60ms, the maximum length is two. This is because if the length of a virtual frame is larger than two, then the number of codewords becomes too large which violate the codeword idle ratio.

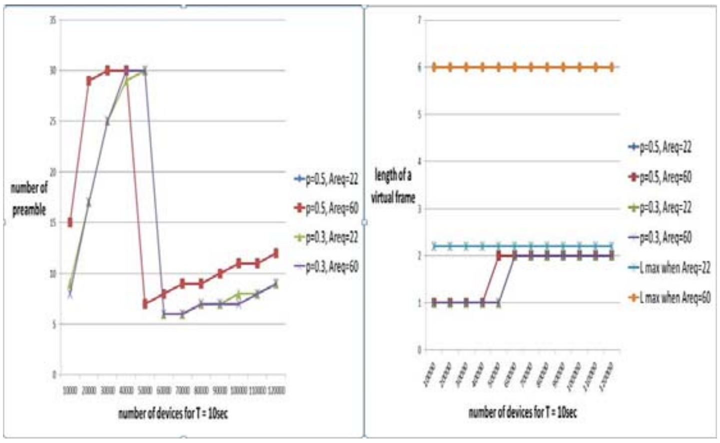

Fig. 2 Optimal number of preamble (left) and Optimal length of a virtual frame (right)

Figure 3 shows the increase of codewords by increasing the length of a virtual frame. It is clear that more codewords are required as the codeword idle ratio becomes higher.

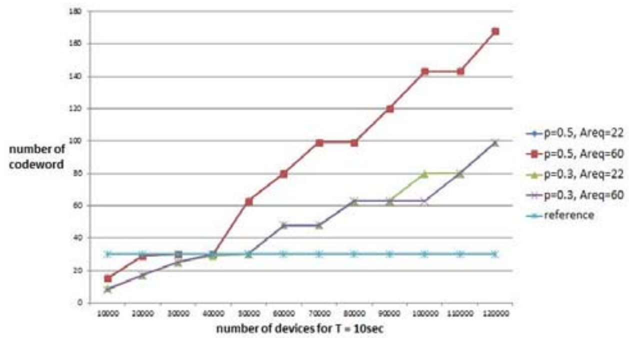

Fig. 3 The number of Codeword

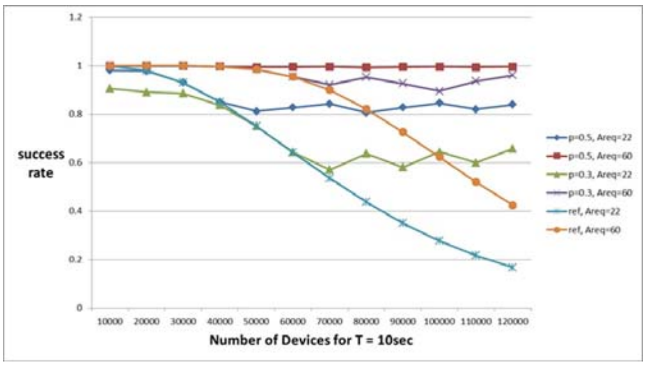

Fig. 4 Success rate to satisfy the access time requirement

Figure 4 shows the success rate of random access. Note that the success rate of reference model decreases continuously as the number of devices increase. The success rate of code-expanded model does not decrease below 0.55. In the figure the success rate of tight access delay is lower than the loose one. Also, the success rate of lower ratio of idle codewords is lower than of higher ratio.

VI. CONCLUSION

In this paper, we have analyzed the code-expansion with a virtual frame for M2M communication. An optimization problem is proposed which maximizes the success rate of random access under the codeword idle ratio and access delay constraints. A Genetic algorithm is employed to get the required number of preambles and the length of a virtual frame. Experiment shows that the code-expanded model presents much higher success rate than the reference model as the number of devices increases. Our simulation illustrates that the length of a virtual frame which is equal to two is enough to cover up to 120,000 devices for 10seconds.

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