

# Resource usage of LTE networks for machine-to-Machine group communications: Modeling and analysis<sup>☆</sup>

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## ABSTRACT

Machine nodes (MNs) such as monitoring devices and utility devices can be handled with machine-to-machine (M2M) group communications in commercial 3GPP LTE networks. However, the current LTE networks are designed for human-oriented communication, i.e., human-to-human (H2H) communication, as a main service. Hence, the M2M group communications may utilize a limited amount of radio resource in the LTE networks so that they do not degrade the quality-of-services (QoS) of the H2H communications. Under the resource limitation, the MNs in the M2M communication group may suffer resource contentions when they simultaneously send uplink data packets to a base station (BS). In this paper, we first mathematically model the overall procedure of the M2M group communications. Then, we also optimize the system parameters for the M2M group communications to maximize resource utilization of the LTE networks and minimize the packet transmission delay, while satisfying the resource constraint.

## 1. Introduction

Machine-to-machine (M2M) communications is a novel network communicating machine nodes (MNs) without human intervention. MNs are typically physical devices, vehicles, home appliances, sensors, etc. An MN collects data and transmits collected data to a machine server. Since there are a massive number of MNs in a network, some MNs may transmit data at the same time. When the MNs individually are operated, there is a high possibility of network overload. Hence, the MNs such as monitoring devices or utility devices can be handled as a group in cellular networks by an operator and these use cases are called M2M group communications. For an example, if the group size of the MNs is  $M$ , then the  $M$  MNs simultaneously transmit their uplink data to a machine server.

The third generation partnership project (3GPP) has considered various M2M group communications over mobile cellular networks. Especially, the long-term evolution (LTE) networks are expected to play an important role for M2M group communications as next generation mobile networks[1]. However, the LTE network are originally designed for human-oriented services. Moreover, since human-to-human (H2H) communication is a main service in LTE networks, MNs need to utilize a very limited amount of radio resource without quality degradation for H2H service.

When an M2M group consisting of  $M$  MNs simultaneously reports uplink data packets with a length of  $L_{\text{data}}$  as shown in Fig. 1, some MNs may suffer contentions to utilize the limited LTE network resources.  $M$  MNs perform a 7-step M2M group communication procedure which is composed of a 4-step random access (RA) procedure, a data bearer connection setup, and uplink data transmission procedure. They use network resources allocated in physical random access channel (PRACH), physical downlink control channel

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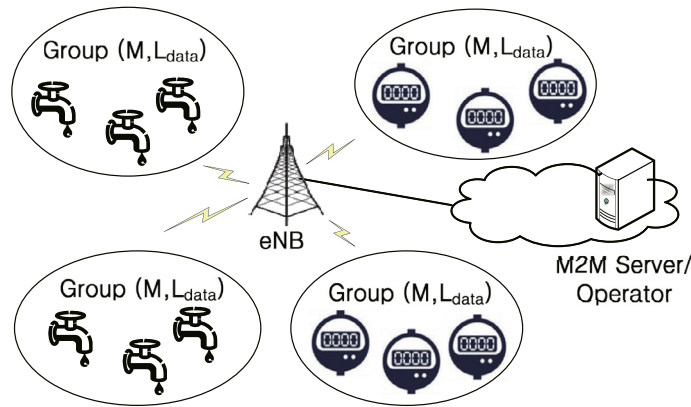


Fig. 1. A use case of M2M group communications .

(PDCCH), physical downlink shared channel (PDSCH), and physical uplink shared channel (PUSCH) during the 7-step M2M group communication procedure.  $M$  MNs simultaneously request RA preambles in step 1. As the number of RA preambles requested in step 1 increases, the number of response messages of step 2 increases. If network resource is insufficient in step 2, an eNB cannot send messages of step 2 to MNs. When MNs do not receive the messages of step 2, MNs go to step 1 again. The number of messages of step 3 is requested as many as the number of messages of step 2. If the collision RA preamble occurs, an eNB cannot send messages of step 4 to collided MNs. Even if RA preambles do not collide, an eNB cannot send messages of step 4 to MNs due to the shortage of network resource. MNs not receiving the message of step 4 are operated in the same manner as the preamble collision and MNs go to step 1 again. If MNs do not receive messages of steps 2 and 4 from the eNB due to lack of resources, MN should go back to the step 1. After completing steps 1 through 4, data bearer connection is established through steps 5 and 6. If MNs do not receive messages of step 6, repeat step 5 again. Step 7 is uplink data transmission and MNs re-transmit uplink data at step 7 until the data transmission is completed. 7 steps are closely related. If MNs do not receive response messages from the eNB due to lack of resources, resource waste will occur because MN should go back to the first step or the previous step again.

Thus far, many studies focused on improving the performance of the 4-step RA procedure out of a 7-step M2M group communication procedure. In step 1, most solutions have been proposed such as access class barring (ACB), large contention backoff window size, and load balancing for limiting the number of simultaneously attempting MNs. Li *et al.* [2] proposed an optimal scheme to dynamically adjust the ACB factor and the number of RACH resources for M2M group communications according to service quality. Hu *et al.* [3] showed that two ACB algorithms were proposed to efficiently resolve the congestion problem in large-scale M2M group communications in LTE systems. Chen *et al.* [4] proposed a dynamic backoff indicator assignment algorithm to solve a serious access delay problem in a group paging environment. Arouk *et al.* [5] proposed a group paging mechanism controlling RA opportunity, and improved access delay and successful access probabilities. Cheng *et al.* [6] classified different types of random access network (RAN)-level contention resolution mechanism and showed RAN/core network resources are insufficient to meet the needs of all users and MNs. In [7,8], the authors introduced analytical models reflecting the M2M group communication. In the study fields from step 2 to step 4, several researchers investigated the effect of a group size of  $M$  on the PDCCH and PUSCH. Yang *et al.* [9] showed that a congestion problem on the PDCCH used in steps 2 and 4 might be very serious in some applications, and they proposed a PDCCH bundling transmission scheme. Osti *et al.* [10] showed that PDCCH resource severely constrains the group size performing the 4-step RA procedure simultaneously. They estimated the upper limit of the group size that can be served by an eNB and determined the size of PDCCH resource to satisfy a given traffic demand. Andrade *et al.* [11] showed that the impact of M2M traffic on human communication service in terms of PDCCH resource used in step 2. Yilmax *et al.* [12] [13] analyzed the PUSCH resource used in step 3 according to the group size. In addition, they showed that the number of preambles for RA and the resource usage of PUSCH are closely correlated.

The existing studies considered a few steps out of the 7-step M2M group communication procedure. However, in this paper, we consider the 7-step RA procedure where  $M$  MNs in an M2M group simultaneously transmit their uplink data to a machine server. For analysis of the 7-step M2M group communication procedure, we develop a semi-analytical simulator: the results of preamble collision probability in step 1 are obtained using an analytical model, and then the output is applied to both of the system simulator and the analytical model. The main contributions of this paper are as follows: it is the first analytical model reflecting the M2M group communication. Moreover, we show the network resource used in all steps, and find the optimal system parameters of random access response window and additional delay window for the M2M group with  $(M, L_{data})$  satisfying given resource constraints. This paper is organized as follows. In Section 2, we describe the 7-step M2M group communication procedure in LTE networks. In Section 3, we mathematically model and analyze the M2M group communication procedure in terms of resource utilization. In Section 4, we evaluate the system performance and optimize the system parameters of random access response window and additional delay window satisfying given resource constraints. Finally, we draw conclusion in Section 5.

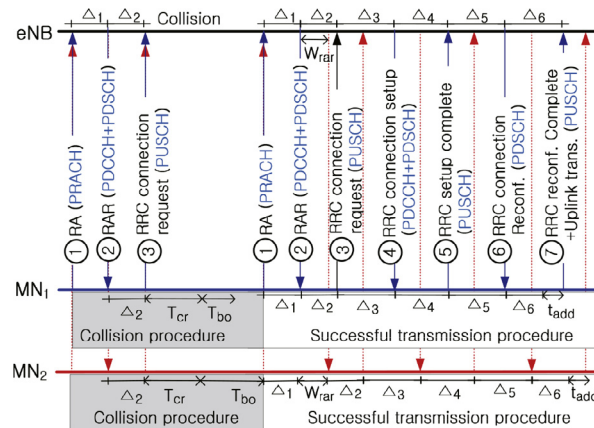


Fig. 2. A 7-step M2M group communication procedure.

Table 1  
Notation I.

Notation	Description	Notation	Description
$M$	The number of MNs in a group.	$L_{\text{data}}$	The length of a packet to transmit.
$W_{\text{rar}}$	The random access response window.	$T_{\text{cr}}$	The contention resolution time (48ms).
$W_{\text{bo}}$	Backoff window size (21ms).	$T_{\text{ra}}$	The repetition cycle of RA slot.
$T_{\text{add}}$	The additional delay window.	$R$	The number of RA preambles (54).
$M_p$	The number of MNs transmitting RA preambles at the $p$ -th RA slot	$M_p[n]$	The number of MNs transmitting preambles $n$ times at the $p$ -th RA slot
$N_t$	The maximum number of preamble transmissions	$\omega_b$	the probability that the collided MNs retransmit preambles after $b$ RA slots
$t_{\text{min}}$ ( $t_{\text{max}}$ )	The minimum (maximum) waiting time to retransmit a preamble	$p_{\text{min}}$ ( $p_{\text{max}}$ )	The minimum (maximum) number of RA indexes to retransmit a preamble

## 2. 7-Step M2M group communication procedure in LTE networks

All  $M$  MNs in a group generate data about utility information, and simultaneously report uplink data packets with a data length of  $L_{\text{data}}$  to an eNB as shown in Fig. 1. When  $M$  MNs start an M2M group communication procedure, they perform either a *collision procedure* due to preamble collision or a *successful transmission procedure*, as shown in Fig. 2. Since the successful transmission procedure is composed of 7 steps, it is called a 7-step M2M group communication procedure. Table 1 shows the notations used in this paper. The further details are described in the following subsections.

### 2.1. Collision procedure

In **step 1**, an MN randomly selects a preamble for RA and transmits the selected preamble to an eNB through the PRACH. In **step 2**, the eNB responds a random access response (RAR) message to the received preamble after  $\Delta_1$  subframes, where  $\Delta_i$  is the processing time<sup>1</sup> at the step  $i$ . The RAR message which contains the information about the received preamble index, uplink resource grant, and timing advance is sent through PDCCH and PDSCH during the random access response window ( $W_{\text{rar}}$ ). In **step 3**, the MN sends an RRC connection request message on the resource indicated by the RAR message through PUSCH after  $\Delta_2$  subframes from receiving the RAR message. If more than two MNs selected the same preamble, then the eNB can not decode the RRC connection request messages from two MNs and it does not send an RRC connection setup message. When the MN does not receive an RRC connection setup message after the contention resolution time ( $T_{\text{cr}}$ ), it recognizes the previous preamble transmission as a failure and restarts random backoff. The MN retransmits a random preamble through the PRACH after the backoff window time ( $T_{\text{bo}}$ ) which is randomly determined by a uniform distribution with backoff window size ( $W_{\text{bo}}$ ).

### 2.2. Successful transmission procedure

If a single MN selects a specific preamble in **step 1**, the eNB responds an RAR message to the received preamble in **step 2**. Fig. 2

<sup>1</sup>  $\Delta_1$  = propagation delay (1ms) + processing time required by the eNB to detect the preambles (3ms),  $\Delta_2$  = processing delay by the MN to decode scheduling information (5ms),  $\Delta_3$  = processing time by the eNB (4ms),  $\Delta_4$  = processing time by the MN (12ms),  $\Delta_5$  = processing delay in the eNB (4ms), and  $\Delta_6$  = processing delay by the MN (16ms) from Table 16.2.1-1 of TR 36. 912 V10.0.0

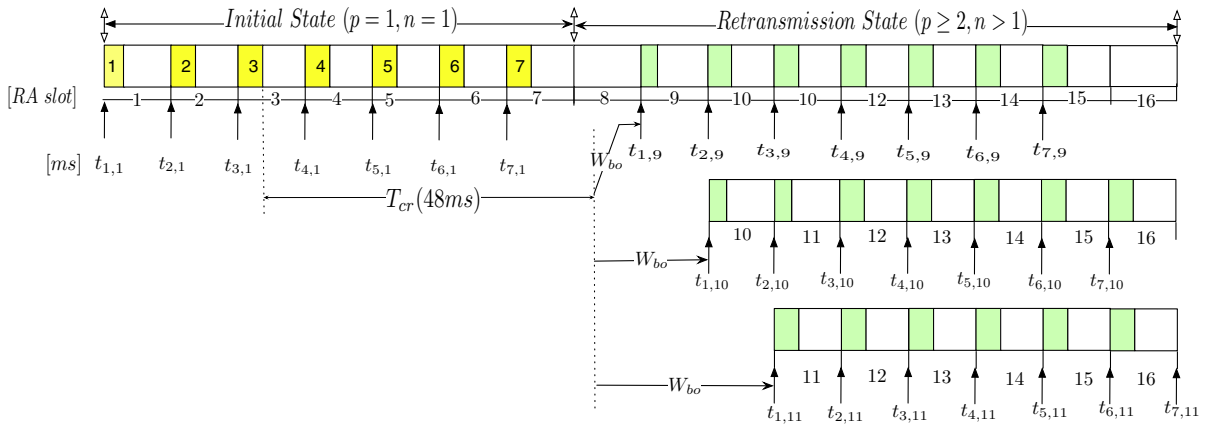


Fig. 3. Timing of initial state ( $p = 1$ ) and retransmission state ( $p \in \mathbb{S}'_2$ ) in a 7-step M2M group communication procedure.

shows the example that  $MN_1$  receives the RAR message at the beginning of  $W_{rar}$  period and  $MN_2$  receives the RAR message at the end of  $W_{rar}$  period. In **step 3**, the eNB can decode the RRC connection request message of the MN. In **step 4**, the eNB sends an RRC connection setup message as a response of step 3 through PDCCH and PDSCH after  $\Delta_3$  subframes. In **step 5**, an RRC connection is established between the MN and the eNB when the MN sends an RRC connection setup complete message through PUSCH after  $\Delta_4$  subframes. In **step 6** and **step 7**, a data radio bearer between the MN and the eNB is established through an RRC connection reconfiguration message and an RRC reconfiguration complete message after  $\Delta_5$  plus  $\Delta_6$  subframes. In **step 7**, the MN transmits an uplink data packet with length of  $L_{data}$  as long as the additional delay window ( $t_{add}$ ) is permitted.

### 3. Mathematical modeling and analysis

We model the process that a group with  $M$  MNs performs step 1 in the first PRACH. Some of  $M$  MNs go to the collision procedure in Section 2.1 while the others go to the successful transmission procedure in Section 2.2. The retransmission is performed until there is no MN in the collision process. Namely, we calculate the amount of spent time and used resources until all  $M$  MNs in the group succeed in transmission. We focus on a group with  $M$  MNs and analyze the network resource of PDCCH, PDSCH, and PUSCH used in the 7-step M2M group communication by a group.

#### 3.1. Timing of 7 steps

Frame structure of LTE network consists of 10 subframes in one radio frame. The PRACH configuration index defines which subframe has PRACH within a radio frame as specified in Table 5.7.1–2 of 3GPP TS 36.211. The cycle of PRACH,  $T_{ra}$ , is the interval between the current PRACH and the next PRACH. PRACH existing every  $T_{ra}$  interval are numbered into RA slots. In this paper, PRACH is used as the RA slot. We assume that PRACH Configuration Index is 3. It means MNs are allowed to PRACH only at subframe number 1 of every radio frame, i.e.,  $T_{ra}$  is 10ms. The start time of the next RA slot is converted to the unit of ms when the index of the current RA slot is multiplied by  $T_{ra}$ , i.e., the start time of the  $p$ -th RA slot is  $(p - 1)T_{ra}$  ms.

Fig. 3 depicts time table of messages where the time-axes present the two units of RA slot and ms. The left of Fig. 3 represents the process of MNs that succeeded in the first RA attempt. In contrast, the right of Fig. 3 is the process of retransmission that the failed MNs in step 3 of the first RA attempt. The collided MN selects one of the three lines at the retransmission state by  $W_{bo}$ . Numbers of 1 through 7 on the box indicate the step index. Since the elapsed time of each step may be different, the length of box is different. The elapsed time of step 1 is time of PRACH, i.e., sub-frame number 1. Each elapsed time from step 2 to step 6 is determined by  $W_{rar}$ . The elapsed time for step 7 is determined by the length of uplink packet. Detailed time calculations are described below.

Let  $p$  be the index of RA slot, let  $n$  be the number of transmissions, and let  $i$  be the index of step. If collided MNs can transmit preambles until reaching the maximum number of preamble transmissions,  $N_p$ . All MNs start at the initial state ( $p = 1$ ) and collided MNs of all MNs retransmit preambles at the retransmission state ( $p \geq 2$ ;  $p \in \mathbb{S}'_1$ ). Let  $t_{i,p}$  be the start time of step  $i$  in the unit of ms. When step 1 starts at the  $p$ -th RA slot, then the start time of step 2,  $t_{2,p}$ , is calculated as from  $(p - 1)T_{ra} + \Delta_1 + 1$  to  $(p - 1)T_{ra} + \Delta_1 + W_{rar}$ . When step 2 is performed at the end of  $W_{rar}$ , the remaining steps reactively are deferred for  $W_{rar}$ . The time of step  $i$  for  $3 \leq i \leq 7$  is expressed as  $t_{i,p} = t_{2,p} + \sum_{m=2}^{i-1} \Delta_m$  ms. Time of  $t_{i,p}$  can be converted into the  $s$ -th subframe in the  $k$ -th RA slot where there are from 0 to 9 subframes in one radio frame. Therefore,  $t_{i,p}$  is expressed as follows:

$$t_{i,p} = (\text{the } k_{i,p}\text{-th RA slot, the } s_{i,p}\text{-th subframe number}), \quad (1)$$

where  $0 \leq s \leq 9$ ,  $k_{i,p} = \lceil t_{i,p}/T_{ra} \rceil$ , and  $s_{i,p} = (t_{i,p} - 1 - (k_{i,p} - 1)T_{ra})$ .

### 3.2. Calculation of the number of MNs transmitting preambles at step 1

Let  $R$  be the number of preambles for M2M group communications, then  $M$  MNs randomly select one of  $R$  preambles for step 1. Let  $M_p$  be the number of MNs transmitting preambles at the  $p$ -th RA slot. Since  $M$  MNs in a group simultaneously transmit their preambles at the initial state,  $p = 1$ ,  $M_1$  is expressed as  $M$ . The collided MNs retransmit preambles until reaching the maximum number of preamble transmissions,  $N_t$ . Let  $M_p[n]$  be the number of MNs transmitting the preambles  $n$  times at the  $p$ -th RA slot,  $1 \leq n \leq N_t$ . At the retransmission state,  $p \geq 2$ ,  $M_p[n]$  is the total number of MNs transmitting RA preambles  $n$  times at the  $p$ -th RA slot when the collided MNs retransmit preambles. It is expressed as follows:

$$M_p = \sum_{n=2}^{N_t} M_p[n]. \quad (2)$$

When  $M_p$  MNs randomly select one of  $R$  preambles, the probability that  $m$  MNs select the same preamble is expressed as follows:

$$\mathbb{P}_{m,M_p} = \binom{M_p}{m} \left(\frac{1}{R}\right)^m \left(1 - \frac{1}{R}\right)^{M_p-m}. \quad (3)$$

If more than or equal to two MNs select the same preamble, a collision procedure occurs with probability

$$\mathbb{P}_c(M_p) = 1 - \mathbb{P}_{0,M_p} - \mathbb{P}_{1,M_p}. \quad (4)$$

The collided MNs retransmit preambles at the RA slot right after  $T_{cr}$  plus  $T_{bo}$  ms. The period of the collision procedure,  $t_{coll}$ , is expressed as  $t_{min} \leq t_{coll} \leq t_{max}$  where  $t_{min} = \Delta_1 + W_{far} + \Delta_2 + T_{cr} + 1$  and  $t_{max} = \Delta_1 + W_{far} + \Delta_2 + T_{cr} + W_{bo}$ . The collided MNs retransmit preambles at the RA slot in the range of  $[p_{min}, p_{max}]$  where  $p_{min} = \lceil t_{min}/T_{ra} \rceil$  and  $p_{max} = \lceil t_{max}/T_{ra} \rceil$ .

When a preamble collision occurs at MNs retransmitting RA preambles  $(n-1)$  times at the  $(p-b)$ -th RA slot, the collided MNs retransmit RA preambles  $n$  times at the  $p$ -th RA slot after  $b$  RA slots. Therefore, the number of MNs transmitting RA preambles  $n$  times at the  $p$ -th RA slot, i.e.,  $M_p[n]$  is expressed as follows:

$$M_p[n] = \sum_{b=1}^{p_{max}} M_{p-b}[n-1] \mathbb{P}_c(M_{p-b}[n-1]) \omega_b, \quad (5)$$

where  $p \geq 2$  and  $2 \leq n \leq k$ . The first term,  $M_{p-b}[n-1]$ , presents the number of MNs transmitting RA preambles  $(n-1)$  times at the  $(p-b)$ -th RA slot; the second term,  $\mathbb{P}_c(M_{p-b}[n-1])$ , presents the collision probability for  $M_{p-b}[n-1]$  MNs; the product of the first term and the second term means the number of preamble-collided MNs  $(n-1)$  times at the  $(p-b)$ -th RA slot. The third term,  $\omega_b$ , presents the probability that the collided MNs retransmit preambles after  $b$  RA slots. The collided MNs retransmit preambles after  $b$  RA slot for  $b \in [p_{min}, p_{max}]$ . Therefore, the probability of  $\omega_b$  is determined by the ratio of a specific RA slot to the length of  $W_{bo}$ . Thus,  $\omega_b$  is expressed as follows:

$$\omega_b = \begin{cases} (p_{min} T_{ra} - t_{min})/W_{bo}, & b = p_{min}, \\ T_{ra}/W_{bo}, & p_{min} < b < p_{max}, \\ \{t_{max} - (p_{max} - 1)T_{ra}\}/W_{bo}, & b = p_{max}, \\ 0, & \text{otherwise.} \end{cases} \quad (6)$$

The set of RA slot indexes where there are MNs transmitting preambles,  $\mathbb{S}$ , is expressed as follows:

$$\mathbb{S} = \{p | M_p > 0, \forall p\}. \quad (7)$$

The set of RA slot indexes which are larger than  $k$ ,  $\mathbb{S}'_k$ , is expressed as follows:

$$\mathbb{S}'_k = \{p | p \geq k+1, p \in \mathbb{S}\}. \quad (8)$$

Therefore,  $p$  is equal to 1 at the initial state while there exists  $p \in \mathbb{S}'_1$  at the retransmission state.

### 3.3. Calculation of resource usage from step 2 to step 7

In LTE downlink, scheduling information and unicast messages are sent through PDCCH and PDSCH, respectively. In addition, MNs obtain the cell identity and frame timing through synchronization signal (SS), and broadcasting system information through physical broadcast channel (PBCH). On the other hand, in LTE uplink, MNs initiate contact with eNB through RACH and transmit uplink data through PUSCH. The eNB transmits control information such as channel quality indication, hybrid-automated repeat request feedback, and scheduling request through physical uplink control channel (PUCCH), and decoding PUSCH signals through demodulation reference signal (DMRS).

Since the resources allocated by SS, PBCH and PRACH are sparse, we here do not consider these resources. We focus on PUSCH, PDCCH, and PDSCH which are used during the 7-step M2M group communication procedure. PDCCH is allocated to MNs in terms of control channel elements (CCEs) while PDSCH and PUSCH are allocated in terms of resource block groups (RBGs). A CCE consists of 36 resource elements (REs) where 1 RE = 1 subcarrier  $\times$  1 symbol. An RBG is a pair of consecutive resource blocks (RBs) over a subframe.

Let  $x$  denote the channel information, then  $x \in \mathbb{X}$  and  $\mathbb{X} = \{\text{pdccch}, \text{pdsch}, \text{pusch}\}$ . The total number of REs per subframe is calculated by the product of the total number of subcarriers in frequency domain (the number of RBs  $\times$  12 subcarriers) and the number of symbols per subframe in time domain (14 symbols). Therefore, we let  $N_x^{\text{tot}}$  denote the total number of REs of channel  $x$  per subframe, and it is expressed as follows:

$$N_x^{\text{tot}} = \begin{cases} N_{\text{rb}} \times 12 \times n_{\text{pdccch}}, & x = \text{pdccch}, \\ N_{\text{rb}} \times 12 \times (14 - n_{\text{pdccch}}), & x = \text{pdsch}, \\ (N_{\text{rb}} - n_{\text{pucch}}) \times 12 \times (14 - n_{\text{dmrs}}), & x = \text{pusch}, \end{cases} \quad (9)$$

where  $N_{\text{rb}}$  denotes the total number of RBs,  $n_{\text{pdccch}}$  denotes the number of symbols of PDCCH per subframe,  $n_{\text{dmrs}}$  denotes the number of symbols of DMRS per subframe, and  $n_{\text{pucch}}$  denotes the number of RBs used in PUCCH. For example, the FDD LTE system with each uplink/downlink of 5MHz bandwidth has a configuration:  $N_{\text{rb}} = 25$ ,  $n_{\text{pdccch}} = 3$ ,  $n_{\text{dmrs}} = 2$ , and  $n_{\text{pucch}} = 4$ .

We calculate the number of required messages at step  $i$  and the number of required REs of channel  $x$  at step  $i$ . Let  $N_{i,p}^{\text{msg}}$  be the number of required messages at step  $i$  by MNs performing step 1 at the  $p$ -th RA slot. The messages of steps 2 and 3 are generated as many as the number of preambles used by MNs at the step 1 while the messages of the remaining steps are generated for successful MNs from step 4 to step 7 as shown in Section 2. Since the number of MNs performing step 1 at the  $p$ -th RA slot is  $M_p$ ,  $N_{i,p}^{\text{msg}}$  is expressed as follows:

$$N_{i,p}^{\text{msg}} = \begin{cases} R(1 - \mathbb{P}_{0,M_p}), & 2 \leq i \leq 3, \\ RP_{1,M_p}, & 4 \leq i \leq 7. \end{cases} \quad (10)$$

Since step 2 is performed over  $W_{\text{rar}}$  subframes, MNs can receive RAR messages of the step 2 during  $W_{\text{rar}}$ . If the period of  $W_{\text{rar}}$  is short, MNs can not receive RAR messages due to the shortage of resource. If  $W_{\text{rar}}$  increases, the following steps are performed over several RA slots. The size of resource at every step is determined by  $W_{\text{rar}}$ . Step  $i$  is performed over  $n_i$  RA slots where  $n_i \in \{1, \dots, \lceil W_{\text{rar}}/T_{\text{ra}} \rceil + 1\}$ . Since the range of  $W_{\text{rar}}$  is [1ms, 10ms],  $n_i$  become 1 or 2, i.e.,  $n_i \in \{1, 2\}$ .

When step 1 starts at the  $p$ -th RA slot, the remaining step  $i$  after step 1 is performed at the  $k$ -th RA slot. The relation of the  $k$ -th RA slot and the  $p$ -th RA slot is that  $k$  is equal to or greater than  $p$ . Let  $\chi_{i,p,k}$  be the probability that step  $i$  is performed at the  $k$ -th RA slot when step 1 starts at the  $p$ -th RA slot. If  $n_i$  is 1, step  $i$  is performed at the  $k$ -th RA slot. If  $n_i$  is 2, step  $i$  is performed at the  $k$ -th RA slot and the  $(k+1)$ -th RA slot. When the  $k$ -th RA slot is to be the  $k_i$ -th RA slot from Eq. (1), step  $i$  is executed at  $k_i$ -th RA slot. Therefore, the probability  $\chi_{i,p,k}$  is expressed as follows:

$$\chi_{i,p,k} = \begin{cases} 1, & n_i = 1, k = k_{i,p}, \\ (W_{\text{rar}} - s_{i,p})/W_{\text{rar}}, & n_i = 2, k = k_{i,p}, \\ 1 - (W_{\text{rar}} - s_{i,p})/W_{\text{rar}}, & n_i = 2, k = k_{i,p} + 1, \\ 0, & \text{otherwise.} \end{cases} \quad (11)$$

Using Eqs. (10) and (11), the number of required messages of the step  $i$  at the  $k$ -th RA slot when MNs performing step 1 at the  $p$ -th RA slot,  $N_{i,p,k}^{\text{msg}}$ , is expressed as follows:

$$N_{i,p,k}^{\text{msg}} = \chi_{i,p,k} N_{i,p}^{\text{msg}}, \quad p \leq k, p \in \mathbb{S}'_k. \quad (12)$$

Next, we find the number of REs of channel  $x$  required at step  $i$  for  $2 \leq i \leq 7$ ,  $N_{x,i}^{\text{re}}$ , is expressed as follows<sup>2</sup>:

$$N_{x,i}^{\text{re}} = \lceil 8L_i^{\text{msg}} / (cN_m N_x^{\text{rbg}}) \rceil N_x^{\text{rbg}}, \quad (13)$$

where  $L_i^{\text{msg}}$  represents the message length of the step  $i$  which is measured in bytes,  $c$  represents a coding rate of 1/2,  $N_m$  represents the modulation order, and  $N_x^{\text{rbg}}$  represents the number of REs per RBG on the channel  $x$ .

The total available number of REs of channel  $x$  during the  $k$ -th RA is expressed as follows:

$$C(x, k) = \sum_{p \in \mathbb{S}'_k} \sum_{i=2}^7 \chi_{i,p,k} \underbrace{W_{\text{rar}} N_x^{\text{tot}}}_{\substack{\text{the total available number} \\ \text{of REs during each step.}}} \quad (14)$$

Since M2M and H2H communication coexist in a network, MNs can be allocated only some of a total resource. Let  $\alpha$  be the ratio of allocated resources to the total resources. We allocate  $\alpha$  of total resources to M2M group communications for  $\alpha \leq 1$ . Using Eqs. (9) and (11), the total allocated number of REs of channel  $x$  for MNs during the  $k$ -th RA is expressed as follows:

$$R_{\text{allo}}(x, k, \alpha) = \alpha C(x, k). \quad (15)$$

Using Eq. (13), the resource usage of channel  $x$  at the  $k$ -th RA slot,  $R_{\text{used}}(x, k)$ , is measured in the number of REs and it is expressed as follows:

<sup>2</sup> In detail,  $L_2^{\text{msg}} = L_3^{\text{msg}} = 7$  bytes,  $L_4^{\text{msg}} = 38$  bytes,  $L_5^{\text{msg}} = 22$  bytes,  $L_6^{\text{msg}} = 61$  bytes,  $L_7^{\text{msg}} = (12 + L_{\text{data}})$  bytes from Table 6.3.1.2-1 in 3GPP TR 37.869 V12.0.0.0.  $m = \{2, 4, 6\}$ ,  $N_{\text{pdsch}}^{\text{rbg}} = 12 \times (14 - n_{\text{pdccch}})$ , and  $N_{\text{pusch}}^{\text{rbg}} = 12 \times (14 - n_{\text{dmrs}})$ .

$$R_{\text{used}}(x, k) = \sum_{p \in \mathbb{S} \setminus \mathbb{S}_{k'}} \sum_{i=2}^7 N_{x,i}^{\text{re}} N_{i,p,k}^{\text{msg}} \quad (16)$$

Consequently, the resource utilization presents the ratio of the used resources to the allocated resources, and resource utilization of channel  $x$  at the  $k$ -th RA slot is expressed as follows:

$$U(x, k, \alpha) = \frac{R_{\text{used}}(x, k)}{R_{\text{allo}}(x, k, \alpha)} = \frac{R_{\text{used}}(x, k)}{\alpha C(x, k)}. \quad (17)$$

As  $L_{\text{data}}$  increases, the usage of resource of PUSCH increases. To solve the lack of PUSCH resource, we propose to set additional delay window for uplink data transmission at step 7. The end time of step 7 is replaced by  $t_{7,p} + t_{\text{add}}$ . From Eqs. (15) ~ (17), the resource utilization decreases as the values of  $W_{\text{rar}}$  and  $t_{\text{add}}$  increase. Moreover, the delay increases as the values of  $W_{\text{rar}}$  and  $t_{\text{add}}$  increase. Since, resource utilization is determined by  $\alpha$ ,  $R$ ,  $M$ ,  $W_{\text{rar}}$ ,  $t_{\text{add}}$ , and  $L_{\text{data}}$ , maximizing resource utilization means minimizing the delay by the relation of resource utilization and delay. Therefore, we should maximize resource utilization in order to minimize delay.

We set a constraint that  $U(x, k, \alpha)$  is always less than or equal to 1 to prevent networks overloading. To optimize system parameters with simultaneously satisfying minimizing delay and maximizing the resource utilization under given resource constraints, we formulate an optimization problem under given input variables of  $M$  and  $L_{\text{data}}$ , and given resource constraints  $\alpha$  as follows:

$$\begin{aligned} (W_{\text{rar}}^*, t_{\text{add}}^*) = & \arg \max_{(W_{\text{rar}}, t_{\text{add}})} U(x, k, \alpha) \\ \text{subject to } & U(x, k, \alpha) \leq 1, \forall x, k, \alpha. \end{aligned} \quad (18)$$

We solve the optimization problem through a exhaustive search for all possible sets of  $(W_{\text{rar}}^*, t_{\text{add}}^*)$  and given  $\alpha$  and  $M$ . Given the value of  $\alpha$ ,  $M$ , and  $L_{\text{data}}$ , the optimal parameter sets are found as shown in Table 2.

#### 4. Performance evaluation

The LTE network is assumed to have the following configuration:  $R = 54$ ,  $T_{\text{ra}} = 10$  ms,  $M = \{5, 10, 20\}$ ,  $W_{\text{rar}} = \{5, \dots, 10\}$  ms,  $L_{\text{data}} = \{100, 500\}$  bytes, and  $t_{\text{add}} = \{0, \dots, 5\}$  ms.

##### 4.1. The effect of $M$ and $W_{\text{rar}}$ on resource usage

Fig. 4 shows the resource utilization of channel PDCCH, PDSCH, and PUSCH when all resources are allocated M2M group communications, i.e.,  $\alpha = 1$ . Each of  $M$  MNs transmits a data packet of  $L_{\text{data}} = 100$  bytes for varying  $M$  and  $W_{\text{rar}}$ . As  $W_{\text{rar}}$  increases, the resource utilization of all channel resources decreases. Inversely, as  $M$  increases, the resource utilization of all channel resources increases. Adjusting  $W_{\text{rar}}$  is effective on controlling the resource utilization of all channel resources when the usage of network resource is limited. Therefore, since an increase in  $W_{\text{rar}}$  increases the capacity of all channel resource, the resource utilization decreases.

##### 4.2. The Effect of $t_{\text{add}}$ and $L_{\text{data}}$ on Resource Usage

Fig. 5 shows the resource utilization of PUSCH when all resources are allocated M2M group communications, i.e.,  $\alpha = 1$ .  $M$  is 20 and  $L_{\text{data}}$  and  $t_{\text{add}}$  are varied. As the length of an uplink data packet of  $L_{\text{data}}$  increases, the resource utilization of PUSCH increases. Since  $L_{\text{data}}$  is subject to additional delay window,  $t_{\text{add}}$  and  $L_{\text{data}}$  directly affect the resource utilization of PUSCH. Therefore, as the  $W_{\text{rar}}$  value and  $t_{\text{add}}$  increases, the resource utilization of PUSCH decreases. When  $t_{\text{add}}$  is extended to 5ms at  $W_{\text{rar}} = 5$ ms, packets with 500 bytes are supported with 55% of the amount of PUSCH resource.

##### 4.3. Maximizing resource utilization under a limited resource allocation

From Eq. (18), we find optimal system parameters for two cases: case A ( $M = 20$ ,  $L_{\text{data}} = 100$  bytes) and case B ( $M = 5$ ,  $L_{\text{data}} = 500$  bytes). In a conventional network,  $W_{\text{rar}}$  and  $t_{\text{add}}$  are configured to 5 ms and 0 ms, respectively. To support uplink packets transmission under resource constraints by  $\alpha$ ,  $W_{\text{rar}}$  and  $t_{\text{add}}$  are adjusted. Table 2 shows the optimal set of  $(W_{\text{rar}}^*, t_{\text{add}}^*)$  while satisfying  $\alpha = \{0.1, 0.2, 0.3, 0.4\}$ .

**Table 2**  
The Optimal system parameters of  $(W_{\text{rar}}^*, t_{\text{add}}^*)$ .

Case ID ( $M$ , $L_{\text{data}}$ )	$\alpha$			
	0.1	0.2	0.3	0.4
Case A (20, 100bytes)	(9,1)	(7,2)	(5,0)	(5,0)
Case B (5, 500bytes)	(8,2)	(6,1)	(5,1)	(5,0)

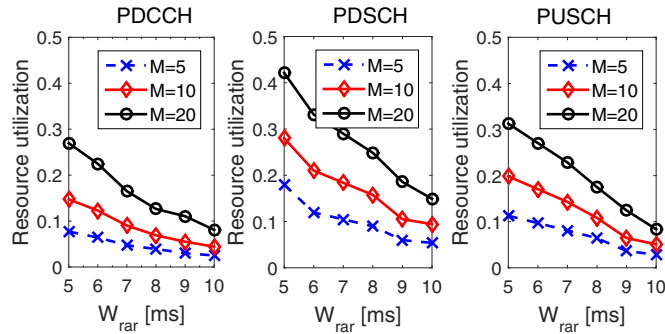


Fig. 4. Resource utilization ( $U$ ) of PDCCH, PDSCH, and PUSCH for  $\alpha = 1$  and varying  $M$  and  $W_{\text{rar}}$  when  $M$  MNs transmit an uplink data packet of  $L_{\text{data}} = 100$  bytes.

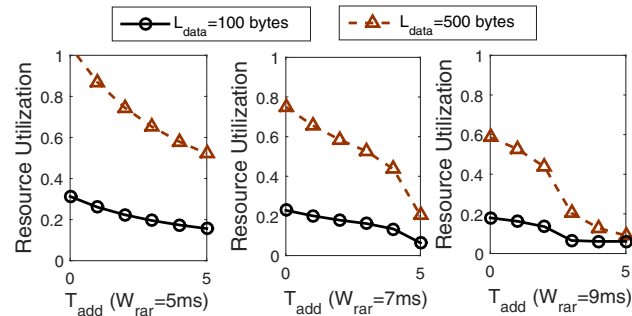


Fig. 5. Resource utilization ( $U$ ) of PUSCH for  $\alpha = 1$  and varying  $L_{\text{data}}$ ,  $t_{\text{add}}$ , and  $W_{\text{rar}}$ .

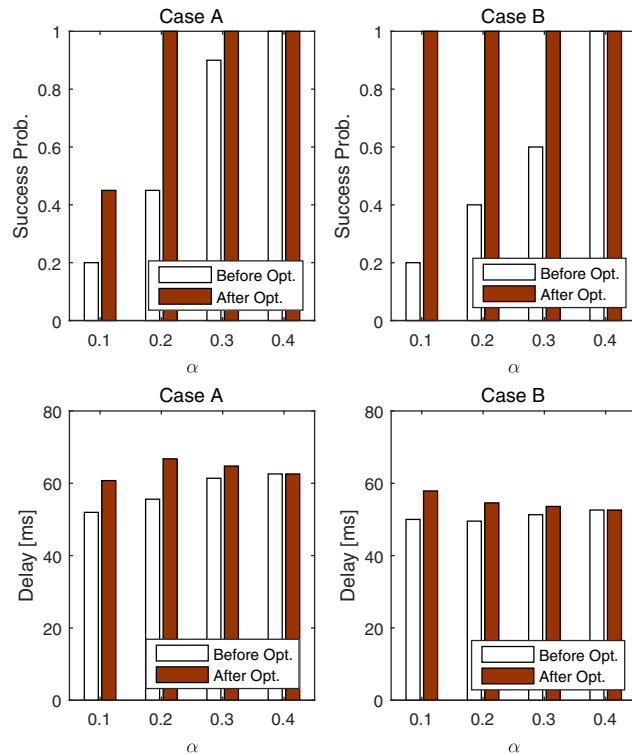


Fig. 6. Success probability and delay of case A and case B while satisfying  $\alpha$  before and after optimization .

Fig. 6 shows the success probability and delay for cases A and B while satisfying  $\alpha$  before and after optimization. Before optimization, the success probability of case B is lower than that of case A and the delay performance of case A is longer than that of case B. It implies that the length of an uplink packet seriously affects resource constraints and the number of MNs seriously affects the delay. Since the delay is calculated for MNs performing successful transmissions, delay increases as the success probability increases. After optimization, the success probabilities are given as 1 except the case A with  $\alpha=0.1$  while the delay is increased through optimization of  $(W_{\text{rar}}^*, t_{\text{add}}^*)$ .

## 5. Conclusion

With the development of internet of things technology, the number of machine nodes is explosively increasing. The usage of network resource rapidly is increased by excessive access requests of machine nodes. Therefore, the resource usage by machine nodes is limited not to exceed a certain level so as not to affect the human-to-human service. 3GPP specified various schemes such as access class barring, large contention backoff window size, and load balancing for limiting the number of simultaneously attempting machine nodes. It is meaningful to analyze how much network resources are used for a machine-to-machine group communication.

In this paper, we considered a machine-to-machine group communication that  $M$  machine nodes in a group simultaneously transmit their uplink data to a machine server. First, we modeled the machine-to-machine group communication as the 7-step machine-to-machine group communication procedure which is composed of a 4-step random access procedure, a data bearer connection, and uplink data transmission. Next, we calculated the amount of required network resource until all machine nodes in a group complete uplink data transmission. Since messages from step 2 to step 6 should be transmitted within the period of  $W_{\text{rar}}$ , controlling of  $W_{\text{rar}}$  is effective at the steps 2 to 6 to satisfy a given resource threshold. As the length of uplink data  $L_{\text{data}}$  increases, the lack of resource of physical uplink shared channel increases. To solve the lack of resource of physical uplink shared channel, we propose to set  $t_{\text{add}}$  for uplink data transmission at step 7 to satisfy a given resource threshold. We showed the effect of system parameters:  $W_{\text{rar}}$  and  $t_{\text{add}}$  on network resource and found optimal system parameters of  $W_{\text{rar}}$  and  $t_{\text{add}}$  for case A and case B while satisfying given resource constraints in order to maximize resource utilization under a limited resource allocation.

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## Supplementary material

Supplementary material associated with this article can be found, in the online version, at [10.1016/j.compeleceng.2018.07.031](https://doi.org/10.1016/j.compeleceng.2018.07.031)

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