

A Group-based Communication Scheme Based on the Location Information of MTC Devices in Cellular Networks

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Abstract—Recent standardization efforts in the 3rd Generation Partnership Project (3GPP) have made the Long Term Evolution (LTE) system a very attractive radio access technology for various types of devices and applications. However, the system has not yet been optimized to support diverse traffic profiles. In this paper, we propose a group-based communication scheme to alleviate inefficiencies in the radio access network. The proposed scheme groups multiple connections triggered by different User Equipments (UEs). For the efficient grouping of the UEs, the location information of the Machine-Type Communication (MTC) devices is utilized to identify each group. A four-phase system model is presented to analyze each segment of the connection establishment procedure in the access network. We found that the random access procedure is the main variable factor for the communication delay, and we, therefore, carefully design the procedure with details. Simulations are conducted on our LTE testbeds, and the results show that the proposed scheme is very effective in ensuring the system performance of legacy services and in utilizing radio resources within a given delay bound.

I. INTRODUCTION

In recent years, the Long Term Evolution (LTE) system has focused on accommodating various types of traffic generated by smartphones and Machine-Type Communication (MTC) devices[1] whose traffic profiles greatly differ from those of voice calls. Due to a potentially massive number of the devices[1], the concerns on signaling and protocol overheads were raised[2][3], and the access capability of eNodeB (eNB), the base station in LTE, was questioned[4][5], especially when multiple devices trigger access attempts to make connections in a short time period.

In literature and the standardization, many studies have been done to solve such problems. In [6], a time-controlled radio resource allocation scheme was suggested to guarantee quality-of-service of an enormous number of devices. In [7], a less complex, lower-cost MTC architecture was proposed to reduce the protocol overhead. However, there has been no research which exploits the location information of devices to solve the problems.

In this paper, we propose a group-based communication scheme to mitigate the congestions in eNB's access channel and reduce the signaling overheads by utilizing the location information of devices. As shown in Fig. 1, our proposed

scheme can group a number of connections that are triggered by closely located User Equipments (UEs) if a certain application of the UEs triggers a number of connections to request the same user data. One example of such applications is that a number of audiences in a concert hall may try to receive a pamphlet as they enter the hall. A firmware upgrade for closely located water meters is another good example. To efficiently group the users, we propose to deploy low-end MTC devices at the center of an area with dense user population. By separately handling those grouped connections in the network access and transmission procedures, the proposed scheme provides better resource utilization and prevents legacy UEs from experiencing severe degradations in the performance of the network access.

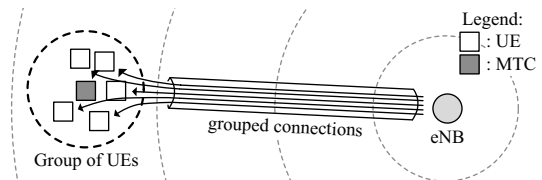


Fig. 1. The scenario: a group of UEs communicate with an eNB.

The remainder of the paper is organized as follows. In Section II, we describe a system model. In Section III, we describe the details of the proposed scheme, and the performance analysis is given in Section IV. Simulation results are shown in Section V, and the conclusion is presented in Section VI.

II. SYSTEM MODEL

In this section, we present our system model for the proposed group-based access and transmission scheme.

A. Group Model

G denotes a set of groups. G_i indicates group i . Group members can receive the same user data. If a UE wants to receive the user data of G_i , the UE can request to join G_i . $G_{i,j}$ is a subgroup j of G_i , and is an actual unit of scheduling of the user data. UEs of $G_{i,j}$ can receive the user data on the same radio resources.

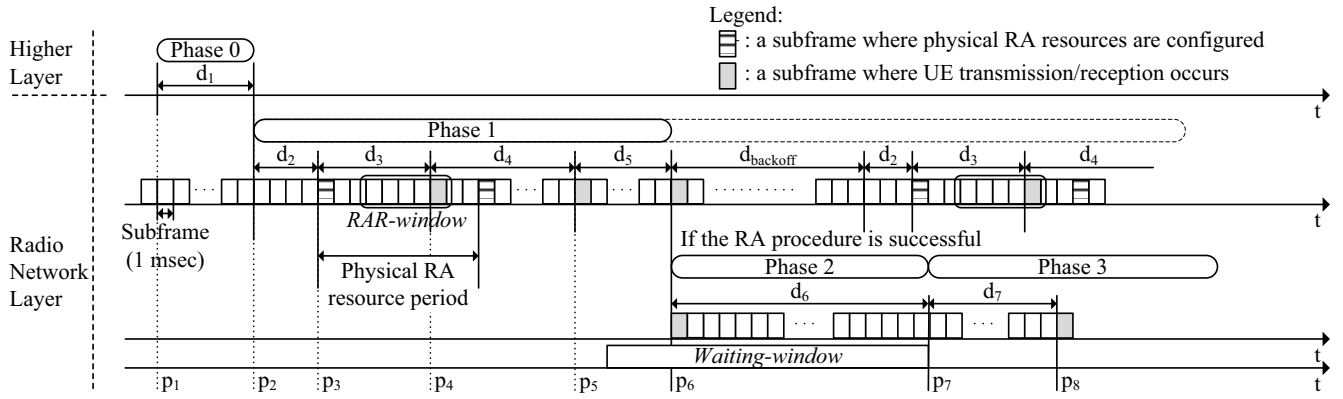


Fig. 2. Phased System Model

B. User Model

U denotes a set of users. U_i indicates users wishing to be members of G_i , and u_i indicates a user instance among U_i . $U_{i,j}$ denotes a set of UEs in a subgroup $G_{i,j}$.

C. System Model

Fig. 2 shows our system model. It consists of 4 phases. Each phase is defined based on the activities of UEs and eNB.

- Phase 0: Pre-connection establishment phase
- Phase 1: Connection establishment phase
- Phase 2: Waiting phase
- Phase 3: Group-based communication phase

In Fig. 2, p_i denotes the i -th point of a UE activity, and d_i denotes the time delay between p_i and p_{i+1} . In the following description, we assume that a user is a member of U_i .

Phase 0: During Phase 0, the user decides to connect to the application server and manipulates his device to request user data from the server (p_1). After some processing delay (d_1) in the higher layers, the application orders Radio Network Layer (RNL) to initiate a connection establishment (p_2). The application informs RNL of its intention to join G_i .

Phase 1: During Phase 1, the RNL of the UE performs the connection establishment procedure. Fig. 3 outlines the RNL connection establishment procedure. The RNL-level connection establishment is divided into two procedures: a connection establishment procedure in Radio Resource Control (RRC) layer [13] and a Random Access (RA) procedure in Medium Access Control (MAC) layer [12].

RRC layer is responsible for the connection management. To be transferred from an idle to an active radio connection status, the UE should perform the RRC connection establishment procedure. To initiate the RRC connection procedure, idle UEs wishing to initially access the network must apply the RA procedure because the LTE radio interface is a shared medium.

From the UE's perspective, the RA procedure is as follows:

- Step 1: RA Preamble (RAP) transmission (p_3)
- Step 2: RA Response (RAR) reception (p_4)
- Step 3: First scheduled uplink transmission (p_5)
- Step 4: Contention resolution message reception (p_6)

The messages exchanged in Steps 3 and 4 include RRC messages: *RRCConnectionRequest* and *RRCConnectionSetup*, denoted by message 3 and message 4, respectively.

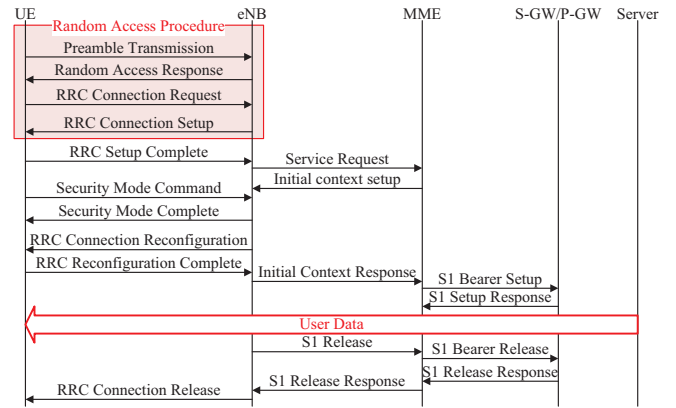


Fig. 3. RRC connection management signaling flow

Phase 2: During Phase 2, after the UE completes its connection establishment procedure, the UE waits for other UEs to join Group G_i until a sliding window expires (p_7). A new sliding window starts when the eNB receives a new request to join the group from a UE after the previous sliding window ends. UEs that arrive within the same j -th window can be grouped into the same subgroup, $G_{i,j}$.

Phase 3: During Phase 3, a group of UEs, $U_{i,j}$ of the subgroup $G_{i,j}$, simultaneously receives the user data from the server (p_8). The eNB regards the grouped UEs as a single entity, and schedules the downlink data once.

D. Delay Model

The total delay (d_{tot}) consists of several intermediate delays for analysis [8], and can be expressed as

$$d_{tot} = \sum_{i=1}^7 d_i + \sum_{k=1}^n \left(P_{BO}(k) \cdot (d_{BO,k} + d_{2,k} + \sum_{i=3}^5 d_i) \right), \quad (1)$$

where d_{BO} is the delay for which UE should back-off its subsequent reattempt when a preamble collision or a contention occurs, and d_2 is the delay for which UE waits for the next

available physical RA resources. $P_{BO}(n)$ is the probability that n -consecutive (re-)attempts are failed, and is given by

$$P_{BO}(n) = \prod_{i=1}^n P_i, \quad (2)$$

where P_i is the probability that the i -th RA attempt fails, and it depends on the network capability to accommodate the RA traffic load[9].

From the above equations, we can conclude that Phase 1 delay is a main variable factor for d_{tot} . Thus, Phase 1 should be carefully designed to bound d_{tot} in a reasonable time.

III. PROPOSED SCHEME

In this section, we describe the details of our proposed scheme. First, we propose to deploy a fixed MTC devices at the center of an area where users reach the application server. By utilizing the location information of the MTC devices, we can simplify the RNL connection establishment procedure. The rest of the scheme is largely divided into two parts: a group-based RA procedure, and a group-based communication mechanism.

A. Group-based Random Access Procedure

Fig. 4 shows the overall procedure of the proposed group-based RA procedure. The brief descriptions of the scheme are as follows:

- Group-preamble ($g_preamble$) transmission
- Multiple group-RARs (g_RAR) receptions
- Contention Resolution

1) *Group-preamble transmission*: An MTC device periodically transmits $g_preamble_i$ which has dedicated usage for G_i while U_i do not transmit their own preambles. When the eNB receives $g_preamble_i$, the eNB assembles multiple RARs and allocates them in subsequent subframes within a RAR-window, as shown in Fig. 5. Those RARs are termed as g_RAR_i s, and they contain the same RAP ID, and Timing Advance value (T_A), but different uplink grants.

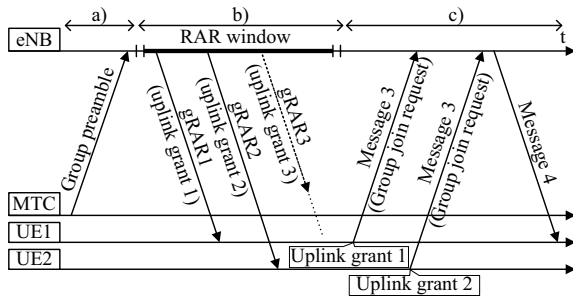


Fig. 4. The proposed group-based random access procedure.

2) *Multiple gRAR receptions*: To receive its own g_RAR_i , u_i selects a subframe within the RAR-window. u_i 's first accessible subframe index is determined by the point p_2 , as shown in the Fig. 5. Once the subframe is determined, u_i randomly selects g_RAR_i in that subframe. By receiving different g_RAR_i s, U_i can obtain different uplink grants.

For example, by pre-configuring preamble #54 as $g_preamble_i$, U_i can be uplink-synchronized by decoding the g_RAR_i message.

Utilizing the Location Information of MTC Device: The proposed scheme is feasible due to two features of RAR: 1) RAR is accessible by any UE because it is delivered over common control channel, 2) T_A in g_RAR_i is applicable to U_i .

T_A is used to compensate for the uplink timing difference of each UE, caused by the different propagation delay of each UE, and is estimated based on the preamble sent by the UE [10]. T_A normally varies as UE moves. However, the T_A for the fixed MTC device is constant, and is applicable to U_i because U_i are assumed to trigger RA procedures in the close vicinity of the device.

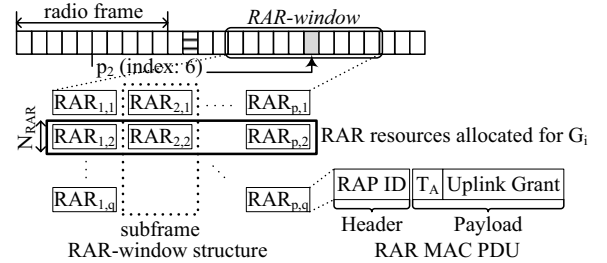


Fig. 5. RAR window structure and RAR MAC PDU.

3) *Contention Resolution*: When a contention occurs i.e. multiple UEs access the same g_RAR , the failed UEs need to backoff their subsequent attempts for a period of time, d_{BO} , that the eNB indicates.

B. Group-based Communication

To enable a group of UEs to simultaneously receive the user data, we propose a group transmission scheme and a group-joining procedure.

1) *Group Transmission*: For $U_{i,j}$ to receive user data in a multicast manner, the eNB handles $U_{i,j}$ as a single entity by assigning a single identity to $U_{i,j}$. Radio Network Temporary Identity (RNTI) is the identity which allows a UE to uniquely detect its downlink resource grant on the downlink control channel (i.e. PDCCH). Thus, if we assign Group-RNTI (G-RNTI) to a subgroup, for example, $G_RNTI_{i,j}$ to $G_{i,j}$, $U_{i,j}$ can decode a downlink grant on PDCCH with $G_RNTI_{i,j}$, and receive the data simultaneously using the same radio resources where the downlink grant indicates.

2) *Group-Joining Procedure*: To allow UEs to join a group, the message 3 in the RA procedure can be used as a request to join the group. A UE can inform the eNB of its identity and a group that the UE wishes to join by configuring values in *RRCCConnectionRequest*. Then, the UE transmits the configured message to the eNB using an uplink resource granted by the gRAR message. After receiving the message 3, the eNB responds to the requesting UE with *RRCCConnectionSetup*. In the *RRCCConnectionSetup*, the eNB can set the G-RNTI value of the group which the UE requested to join.

IV. PERFORMANCE ANALYSIS

In this section, we define parameters that affect the system performance. As generally accepted, we assume that the user arrivals are Poisson distributed.

A. Contention Probability

u_i experiences a contention if there is at least one other member of U_i accessing the same g_RAR_i . As described in the previous section, the contention probability of the proposed scheme is subject to the user arrival rate and the number of g_RAR_i s reserved for G_i , and is given by

$$P_{con} = 1 - \sum_{N_{arr}=0}^{N_{RAR}} \left\{ \left(\frac{N_{RAR} P_{N_{arr}}}{N_{RAR} \prod N_{arr}} \right) \cdot \left(\frac{e^{-\lambda t} \cdot (\lambda t)^{N_{arr}}}{(N_{arr})!} \right) \right\} \quad (3)$$

where N_{RAR} is the number of g_RAR_i reserved for G_i in a subframe, and N_{arr} is the expected number of arrivals during a time period t . λ denotes the arrival rate that includes both new arrivals, λ_{new} , and backoff re-attempts, λ_{BO} .

$$\lambda = \lambda_{new} + \lambda_{BO} \quad (4)$$

Since U_i do not transmit their own preambles, the probability P_i in (2) of the proposed scheme is equal to P_{con} .

$$P_i = P_{con}. \quad (5)$$

B. Resource Utilization

The system resource utilization depends on the length of waiting window (l_{wnd}). As we assume Poisson arrivals, the mean number of users in $U_{i,j}$ is given by

$$N_{i,j} = \alpha \lambda_i l_{wnd}, \quad 0 \leq \alpha \leq 1. \quad (6)$$

where α represents the success rate in Phase 1.

V. SIMULATION

To evaluate the performance of the proposed scheme, we perform simulations on our LTE testbed [14]-[16]. The implementation follows the 3GPP LTE specifications [10]-[13]. Regarding the parameter configurations and eNB behaviors, we follow the common assumptions that were developed by the members of 3GPP standardization working group [17][18].

A. Simulation Environments

In the simulation, a single cell environment is assumed. Table 1 shows the detailed simulation parameter set.

Except MTC devices, all other UEs are designed to have only one application-level connection establishment attempt in the life-time of the simulation. If a UE fails to successfully complete the procedure in MAC level, the result is recorded as a failure and there will not be retransmission attempts in higher layers.

The legacy traffic load indicates the rate of RA attempts that follow the legacy RA procedure, which are generated by e.g. voice calls. Since the simulation assumes 54 preambles, an average of $18.9 (= 0.35 \times 54)$ RA attempts are expected at every RA opportunity in the case of high load situation.

TABLE I
SIMULATION PARAMETER SET

Parameters	Value
System bandwidth	10MHz
The number of UEs applying the legacy RA scheme (legacy UEs)	5000
Traffic arrival model for legacy UEs	Poisson
Traffic load for legacy UEs (new arrivals/RA opportunity/preamble)	0.05, 0.15, 0.35
The number of groups	10
The number of U in each group	500
Traffic arrival model for U	Poisson
Mean arrival rate for U (arrivals/s)	250
Physical RA resource subframe Index	1
Physical RA resource allocation periodicity	10 msec
Total number of preambles	54
Maximum number of preamble (re-)transmissions	10
Random access response window size	10 subframes
RAR reserved for each group in subframe (N_{RAR})	1
Backoff indicator	10, 20, 40 ms
the length of waiting window (l_{wnd})	100 ms

To reflect the impact of the physical layer, a limited model in [17] is applied. The model takes into account important channel conditions such as path-loss and fast fading.

B. Performance Metrics and Results

1) *Performance Comparison of Legacy and Group-based RA procedure:* We first evaluate the performance of legacy UEs generating VoIP services in the legacy RA procedure. To show that the proposed scheme is effective in ensuring the eNB's access capability, we assess the RA procedure under various traffic loads with diverse metrics: collision probability, the average number of preamble transmissions, and RA delay. The collision probability is the ratio of the number of collision occurrences to the total number of preamble transmission attempts. The RA delay is defined as the time delay from the first preamble transmission attempt to the successful reception of the contention resolution message (i.e. $d_3 + d_4 + d_5$.)

TABLE II
PERFORMANCE COMPARISON OF TWO RA PROCEDURES

traffic load	low(0.05)		medium(0.15)		high(0.35)	
	legacy	group	legacy	group	legacy	group
average delay (msec)	122.23	119.71	126.59	121.47	197.32	133.71
collision probability	0.129	0.096	0.235	0.175	0.569	0.398
average # of preamble transmissions	1.150	1.060	1.310	1.210	2.2245	1.690

Table 2 shows the RA performance of the legacy UEs when the legacy and the group-based RA procedures are applied to the U , respectively. In the case of low and medium traffic loads, the results show little difference. In the high traffic load case, however, 6% of UEs fail to establish connections to eNB

with the legacy procedure.

Figs. 6 and 7 show the CDF graphs of the access delay of legacy UEs and that of U , respectively. Both graphs also show the difference of the performance when the group-based RA scheme is applied to U and when the conventional scheme is applied to U . Fig. 6 shows that 95% of the UEs can successfully complete the RA procedure within 200 msec when the group-based RA scheme is applied to the U , while almost 40% of the UEs' access delay exceed 200 msec with the conventional approach.

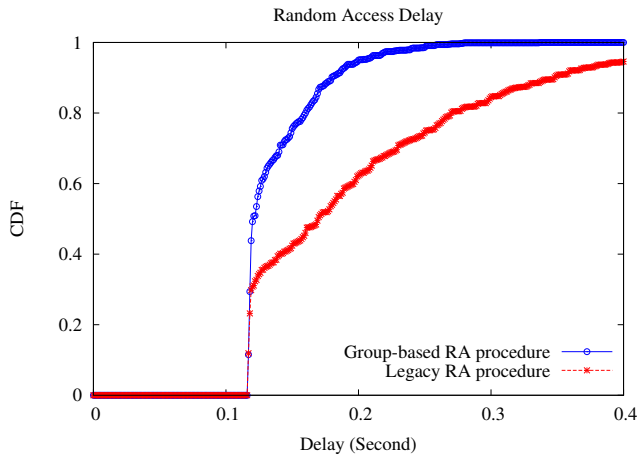


Fig. 6. Random access delay for legacy UEs in high-load (0.35).

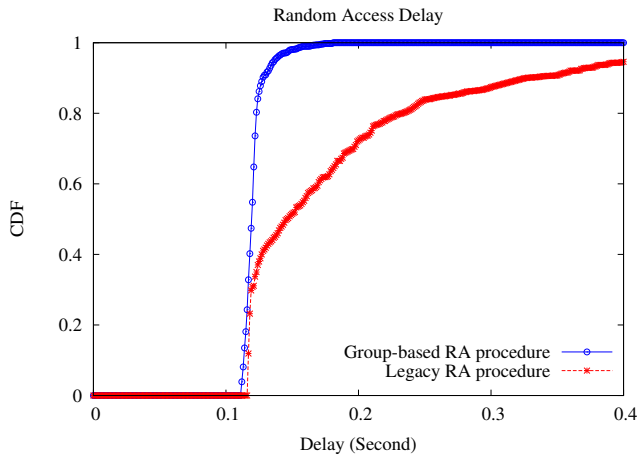


Fig. 7. Random access delay for U in high-load (0.35).

2) *System utilization*: In LTE, the packet delay budget (PDB) for best-effort manner communications is set to 300 msec [19]. In the simulation, we attempt many parameter configurations to roughly bound the d_{tot} within the PDB under a given traffic load. While satisfying the delay requirement, we examine the system resource utilization under the timing constraints.

To examine the system utilization, we evaluate the radio resource utilization. For the evaluation, we compare the number of radio resource blocks (N_{RB}) that are used to transmit

user data between the legacy unicast scheme and the proposed group transmission scheme.

$$Util. = \frac{N_{RB}(\text{the proposed scheme used})}{N_{RB}(\text{the legacy scheme used})} = 37.2 \quad (7)$$

As shown in (7), the proposed scheme uses 62.8% less radio resources for the same number of UEs than those of the legacy unicast approach.

VI. CONCLUSION

In this paper, we presented a group-based communication scheme in 3GPP LTE network, and compared the performance of the proposed scheme with that of the conventional LTE mechanisms. Our group-based scheme utilizes the common features and the location information of the devices, and improves the efficiency of the system by utilizing the current LTE connection establishment procedure, particularly the RA procedure. The simulation results clearly show enhancements in the random access performance in the high traffic load case. Future work will be extended to investigating a more intelligent scheme to spread the traffic[20] for batch arrivals, which may negatively affect the performance of the current system.

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