Packet aggregation for Machine Type Communications in LTE with Random Access Channel

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***Abstract*—A packet aggregation method is proposed in this paper to lower the packet collision rate when the random access channel is used for machine type communications (MTC) uplink channel access in LTE. With the proposed packet aggregation method, a UE triggers random access when the aggregated packets in the buffer reaches the given threshold. However, this method reduces the packet collision rate at the expense of an extra latency which is used to aggregate certain amount of packets. Therefore, the tradeoff should carefully be selected between packet loss rate reduction and extra channel access latency. In this paper, we derive the packet loss rate and channel access latency as functions of amount of aggregated packets using a Semi-Markov chain model. With the derived results, the optimal amount of aggregated packets which satisfies the packet loss requirement and keeps the latency as small as possible can be found, which is verified through simulations.**

***Index Terms*—LTE, MTC, random access, packet aggregation**

I. Introduction

Among the various applications provided by LTE, MTC is one of the most promising applications due to its low cost and easy deployment [1]. It is predicted the MTC promises huge market growth with expected 50 billion connected devices by 2020 [2]. However, it is challenging to cohabitate MTC with the conventional voice and Internet traffic. This is because the current LTE/LTE-A system are primarily designed for a continuous flow of information, at least in terms of the timescales needed to send several IP packets (often large for user plane data), which makes the signaling overhead manageable. While the analysis of emerging M2M application scenarios such as smart metering/monitoring, e-health, and e-vehicle has revealed that in majority of cases, the MTC traffic has the following specific features [3]:

- low mobility
- Short and small number of packets
- Uplink-dominant packets
- massive UEs in a cell
- low cost for mass-market acceptance
- power constraint

which is different from the regular voice and Internet traffic significantly. Therefore for MTC applications, further optimizations and cost reduction are needed to lower the signaling overhead and optimize the system performance.

There have been various methods proposed to study MTC applications in LTE. The subscription control and network congestion control mechanism is discussed in [4], and a new solution based on bulk signaling handling is proposed. In [5] they studied the RAN-level contention resolution methods and introduced the current development of the core network overload control mechanism in LTE. Ref. [6] examines the LTE uplink coverage and capacity for machine type communications. Ref. [7] investigates the collision probability of random access method used for MTC application and provides a model to derive the collision probability, the success probability, and the idle probabilities of UE. Ref. [8] provides a resource management scheme for M2M using customization and grouping and introduces a cached based resource reservation and event notification mechanism. Ref. [9] presents a prioritized random access scheme to efficiently solve the RAN overload problem and provide quality-of-service (QoS) for different classes of MTC devices in LTE-A networks. Ref. [10] reviews the features of MTC services in LTE and provides architectural enhancements, various resource allocation schemes and their utilities.

Besides the above work, new uplink channel access method is proposed to accommodate MTC application in LTE. As specified in [11], *random access channel (RACH) is used for MTC uplink access*. With RACH a UE sends selected preamble to request resource from eNB, which saves signaling overhead of the regular uplink scheduling method. There have been some works which try to optimize the performance for MTC application with RACH. It was proposed in [12] that a prioritized random access scheme is used to provides QoS for different classes of MTC applications. [13] presents a resource allocation scheme for spatial multi-group random access in LTE. In this paper we provide a packet aggregation method to reduce the collision rate of the RACH method.

It is known that with RACH the resource for uplink access is not UE specific, therefore the collision rate is very high when there are massive UEs in a cell. For example, supposing the number of UE in a cell is 1000; the packet arrival interval is 30ms and the available number of preamble is 64; then collision probability is 99.97%, which indicates that most packets cannot be sent. To solve this problem, we propose a packet aggregation method. With our method, a UE will not start a transmission for every arrived packet. Instead, it triggers a transmission until the number of packets in the buffer reaches a certain threshold. If we set the packet aggregation threshold to 5 in the previous example, then the collision probability is reduced to 0.21 which is much lower than the original one. However, our method reduces packet (preamble) collision rate at the expense of extra channel access latency which is used to aggregate some amount of packets (in the previous example a UE has to wait for 150ms before triggering a transmission). And we can image that the collision rate becomes even smaller if we use larger packet aggregation threshold and hence introduce larger latency. Therefore, a good tradeoff should be made between collision rate reduce and extra channel access latency increase. In our work, we derive the packet loss rate and overall channel access latency as functions of amount of aggregated packet using a Semi-Markov chain model. With the derived results, the optimal amount of aggregated packets can be selected such that the packet loss rate requirement is satisfied while the channel access latency is kept as small as possible. One typical application of our proposed method is for MTC gateway, where packets generated by multiple applications are aggregated and delivered by one transmission.

The rest of paper is organized as follows. Section 2 provides the overview of the random access mechanism in LTE. In section 3, a packet aggregation scheme for MTC application in LTE using RACH is presented. Section 4 provides the simulation results of the proposed method. Finally, section 5 gives the conclusion and future works.

II. RANDOM ACCESS MECHANISM OF LTE

The random access mechanism is specified in [14], which contains two types of random access procedure: contention free random access and contention based random access. With contention free random access dedicated preambles are allocated for UEs, which is critical for cases where low latency is required, for example handover between cells [15]. The contention based random access is used for UE's state transition from RRC_IDLE to RRC_CONNECTED, recovering from radio link failure, uplink synchronization, sending scheduling request (SR) to apply resource from eNB (it is used for MTC uplink access as specified in [3]), etc. The procedure for contention based random access is shown in Fig. 1:

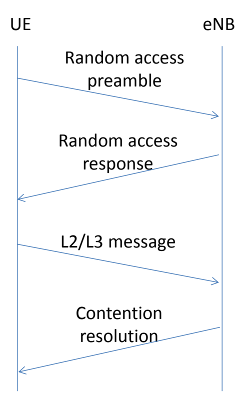

Fig. 1. Contention based random access in LTE

1) random access preamble transmission;
2) random access response reception;
3) L2/L3 message transmission;
4) contention resolution reception.

A. random access preamble transmission

A UE select one of the $64 - N_c$ random access preambles randomly, where N_c is the number of preambles reserved for contention free random access. In LTE, Zadoff-Chu (ZC) sequences [16] is employed for uplink random access preamble transmission due to its low peak-to-average power ration (PAPR) which is important for power limited uplink transmission of UE. Denoting the ZC sequence of odd-length N_{ZC} as $a_q(n)$, where $q \in [1, N_{ZC} - 1]$ is the ZC sequence root index, $n \in [0, N_{ZC} - 1]$, $l = 0$ in LTE for simplicity [15], it has ideal cyclic autocorrelation property which can be given by

$$r_{qq}(\sigma) = \sum_{n=0}^{N_{ZC-1}} a_q(n) a_q^*(n+\sigma) = \delta(\sigma) \quad (1)$$

where σ is the shift between two sequences. The random access preambles are obtained from a ZC sequence with different cyclic shifts. Specifically the number of preambles per ZC sequences is

$$N_p = \lfloor \frac{N_{ZC}}{N_{CS}} \rfloor \quad (2)$$

where N_{CS} is the cyclic shift size. In FDD-LTE, N_{ZC} and N_{CS} is 839 and 13 respectively, and therefore the number of available preambles per ZC sequence is 64 (including preambles for contention based and contention free random access).

To inform eNB about the packet size of L2/L3 message, the preambles used for contention based access are divided into two subgroups: Random Access Preambles group A and Random Access Preambles B. A UE whose L2/L3 message size is larger than the *messageSizeGroupA* which is configured by eNB selects a preamble from Random Access Preambles B; otherwise it uses preambles in Random Access Preambles group A [14].

B. random access response reception

After sending the random access preamble, a UE decodes the physical dedicated control channel (PDCCH) with random access-radio network temporary identifier (RA-RNTI) in the random access response window to receive the random access response (RAR) message. The RA-RNTI is computed as:

$$RA - RNTI = 1 + t_{id} + 10 * f_{id} \quad (3)$$

where t_{id} is the index of the first subframe of the specified physical random access channel (PRACH) ($0 \leq t_{id} < 10$), and f_{id} is the index of the specified PRACH within that subframe, in ascending order of frequency domain ($0 \leq f_{id} < 6$). The random access response window starts at the subframe that contains the end of the preamble transmission plus three subframes and has length *ra-ResponseWindowSize* subframes which is configure by eNB [14].

The RAR message includes the identity of the detected preamble (random access preamble identifier), uplink channel synchronization information, resource allocation information for the subsequent L2/L3 message transmission, backoff indicator which instructs UEs to backoff for certain time before starting the next random access (the backoff time is uniformly selected over a period configured by eNB), temporary C-RNTI, etc [15].

A UE identifies its RAR through the random access preamble identifier which corresponds to the random access preamble transmitted in the first step. Therefore, for UEs which select same preamble in step 1 they are allocated with the same resource in this stage. If the UE does not receive a RAR after the random access response window, it starts a new preamble transmission.

C. L2/L3 message transmission

In this step, UEs send the actual message for this random access procedure, which includes: RRC connection request, handover request, etc. It has to be noted that for MTC applications, the UE sends scheduling request (SR) to apply resource for data packet transmission.

Collision happens in this stage if UEs select same preamble in the first stage. To help eNB to identify collision, the temporary C-RNTI which is allocated in stage 2 and either C-RNTI (for RRC_CONNECTED UE) or the 48-bit UE identity should be transmitted along with the L2/L3 message. It has to be noted that the C-RNTI and UE identity is unique.

D. contention resolution reception

eNB acknowledges the successfully decoded L2/L3 message through contention resolution message. The contention resolution message is addressed to either the C-RNTI or the temporary C-RNTI of the decoded L2/L3 message (the UE identity should be included in L2/L3 message in the latter case). Therefore by decoding the contention resolution message a UE can infer whether the previous L2/L3 message delivery is successful or not. For a failed packet delivery, a new random access is triggered.

III. PACKET AGGREGATION SCHEME FOR MTC IN LTE WITH RACH

To reduce the collision rate of the random access, we propose a packet aggregation method. In our method, a UE does not send a preamble until the buffered packet reaches the given aggregation threshold. However, it can be seen that this method reduces the packet collision rate with extra time used to accumulate some amount of packets. In this section we provide a Semi-Markov chain to analyze the random access procedure with packet aggregation. With the proposed Semi-Markov model, we derive the overall latency and packet loss rate as functions of number of aggregated packets and then find the optimal number of aggregated packets which satisfies the packet loss rate requirement and keeps the latency as small as possible.

The Semi-Markov chain model is shown in Fig. 2, where

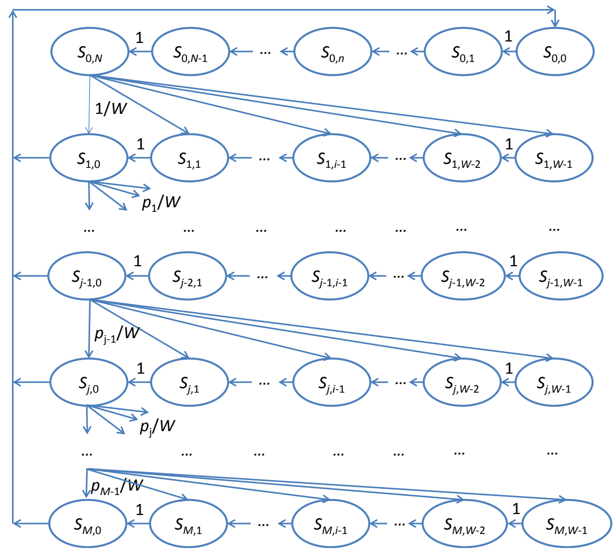

Fig. 2. Semi Markov chain model for random access with packet aggregation

- state $S_{0,n}$,$n \in [1, N]$ means the random access is not started and there are n packets in the UE's buffer where N is the packet aggregation threshold;
- state $S_{j,i}$, $j \in [1, M], i \in [0, W-1]$ means that the packet aggregation threshold has bee reached; the backoff counter is i and the random access has been performed for $j-1$ times where M is the transmission limit and W is the maximum backoff counter size.

A UE transfers between states as follows:

1) When the UE is at state $S_{0,n}$,$n \in [1, N-1]$, for each arrived packet it transfers to state $S_{0,n+1}$.
2) When the UE is at state $S_{0,N}$ it selects a random number i which is uniformly distributed over $[0, W-1]$ and then transfers to state $S_{1,i}$.
3) When the UE is at state $S_{j,i}$, $j \in [1, M], i \in [1, W-1]$ it decrease its backoff counter by 1 after one subframe and transfers to state $S_{j,i-1}$.
4) When the UE is at state $S_{j,0}$, $j \in [1, M-1]$ it starts a random access as introduced in Sect.II when the random access channel is available. If the UE is allocated with some resource after the random access (the random access is successful), it sends the aggregated packet and transfers to state $S_{0,0}$; otherwise it increases the transmission counter by 1; set the backoff counter to i which is uniformly distributed over $[0, M-1]$ and transfers to state $S_{j+1,i}$.
5) When the UE is at state $S_{M,0}$, it performs the random access as introduced in Sect.II. If the random access is successful it sends the aggregated packet on the allocated resource and transfers to state $S_{0,0}$; otherwise it drops the aggregated packet and transfers to state $S_{0,0}$.

Denoting p_i, $i \in [1, M-1]$, as the failed probability of the ith preamble transmission, the state transition probability from

$S_{j,0}, j \in [1, M-1]$ to $S_{j+1,i}$ can be calculated by

$$p' = p_i/W. \quad (4)$$

A failed random access can be caused by wireless channel error or collision, therefore we have

$$p_i = p_c + p'_i - p'_i p_c \quad (5)$$

where p_c is the collision probability and p'_i is the error probability caused by wireless channel for the ith preamble transmission.

Denoting $\pi_{j,i}$ as the stationary probability of state $S_{j,i}$, we have

$$\pi_{0,n} = \pi_{0,0}, n \in [1, N]. \quad (6)$$

$$\pi_{1,i} = \pi_{0,N} \cdot 1/W + \pi_{1,i+1}, i \in [0, W-2]. \quad (7)$$

$$\pi_{j,i} = \pi_{j-1,0} \cdot p_{j-1}/W + \pi_{j,i+1}, j \in [2, M], i \in [0, W-2]. \quad (8)$$

$$\pi_{1,W-1} = \pi_{0,N} \cdot 1/W. \quad (9)$$

$$\pi_{j,W-1} = \pi_{j-1,0} \cdot p_{j-1}/W, j \in [2, M]. \quad (10)$$

With the above equations we can get

$$\pi_{1,0} = \pi_{0,N} \quad (11)$$

$$\pi_{1,i} = \frac{W-i}{W} \cdot \pi_{0,N} = \frac{W-i}{W} \cdot \pi_{1,0}, i \in [1, W-1]. \quad (12)$$

$$\pi_{j,0} = p_{j-1} \cdot \pi_{j-1,0}, j \in [2, M] \quad (13)$$

$$\pi_{j,i} = \frac{W-i}{W} p_{j-1} \cdot \pi_{j-1,0} = \frac{W-i}{W} \cdot \pi_{j,0}, j \in [2, M], i \in [1, W-1]. \quad (14)$$

As the sum of all state stationary probabilities is one, we have

$$\begin{aligned} 1 &= \sum_{n=0}^{N} \pi_{0,n} + \sum_{j=1}^{M} \sum_{i=0}^{W-1} \pi_{j,i} \quad (15) \\ &= \pi_{0,0}(N+1) + \sum_{j=1}^{M} \pi_{j,0} \sum_{i=0}^{W-1} \frac{W-i}{W} \\ &= \pi_{0,0}(N+1) + \sum_{j=1}^{M} \pi_{j,0} \frac{W+1}{2} \\ &= \pi_{0,0}(N+1) + \frac{W+1}{2} \sum_{j=1}^{M} \prod_{i=0}^{j-1} p_i \cdot \pi_{0,N} \\ &= \pi_{0,0}[(N+1) + \frac{W+1}{2} \sum_{j=1}^{M} \prod_{i=0}^{j-1} p_i] \end{aligned}$$

where p_0=1.

Therefore,

$$\pi_{0,0} = 1/[N + 1 + \frac{W+1}{2} \sum_{j=1}^{M} \prod_{i=0}^{j-1} p_i] \quad (16)$$

which is a function of p_c.

Then the stationary probability $\pi_{j,0}, j \in [1, M]$ is given by

$$\pi_{j,0} = \prod_{i=0}^{j-1} p_i \cdot \pi_{0,N} = \prod_{i=0}^{j-1} p_i \cdot \pi_{0,0} \quad (17)$$

which is also a function of p_c.

Now let us calculate the state holding time for this Semi-Markov chain model.

It is obvious that the state holding time for $S_{0,N}$ and $S_{j,i}$, $j \in [1, M], i \in [1, W-1]$ is 1 ms.

Assuming the packet arrives following Poisson distribution with arrival rate λ, then the average state holding time for state $S_{0,n}, n \in [0, N-1]$ is $1/\lambda$.

When the UE is at state $S_{j,0}, j \in [1, M]$, after sending preamble there will be three results

1) the preamble is delivered with wireless channel error of probability p'_j at the ith transmission. The state holding time in this case is $T_{rach}/2 + T_E$, where T_{rach} is the period of the random access channel and T_E is the duration that starts from the time that the UE sends a preamble and ends at the time instant which is the end of the random access response window as described in Sect.II.
2) the preamble is transmitted without error but with collision. The probability for this case is $(1 - p'_j)p_c$, where p_c is the collision probability. The state holding time in this case is $T_{rach}/2 + T_C$ where T_C is the duration that starts from the time that the UE sends a preamble and ends at the time that a UE do not find its identity in the contention resolution message.
3) the preamble is successfully transmitted with probability $(1 - p'_j)(1 - p_c)$. The state holding time in this case is $T_{rach}/2 + T_S$ where T_S is the duration that starts from the time that the UE sends a preamble and ends at the time that the sends the data packet.

Hence the expected state holding time for state $S_{j,0}, j \in [1, M]$, is

$$\begin{aligned} h_j = &p'_j(T_{rach}/2 + T_E) + (1 - p'_j)p_c(T_{rach}/2 + T_C) \quad (18) \\ &+ (1 - p'_j)(1 - p_c)(T_{rach}/2 + T_S). \end{aligned}$$

With the above results,the proportion of time that a UE is at $S_{j,0}, j \in [1, M]$ is

$$P_j = \frac{\pi_{j,0} \cdot h_j}{T}. \quad (19)$$

where

$$T = \pi_{0,N} + \sum_{n=0}^{N-1} \pi_{0,n} \cdot \frac{1}{\lambda} + \sum_{j=1}^{M} \sum_{i=1}^{W-1} \pi_{j,i} + \sum_{j=1}^{M} \pi_{j,0} \cdot h_j. \quad (20)$$

A UE triggers a random access in state $S_{j,0}, j \in [1, M]$, and the time used to transmit a preamble is 1ms. Therefore the probability that a UE trigger a random access is

$$\tau = \sum_{j=1}^{M} \frac{1}{h_j} P_j. \quad (21)$$

which is a function of p_c as P_j and h_j are the functions of p_c.

Moreover, supposing the amount of preamble allocated for contention based random access is N_C, and the amount of MTC device in the cell is N_M, then collision probability p_c is calculated by

$$p_c = \sum_{i=1}^{N_M} \binom{N_M}{i} \tau^i (1-\tau)^{N_M - i} (1 - (1 - \frac{1}{N_C})^{i-1}). \quad (22)$$

which is a function of τ.

It can be seen that equations (21) and (22) comprise a non-linear system, which could be solved by numerical methods. Therefore, we can get the collision probability p_c.

A failed random access can be caused by wireless channel error or collision as described above, hence the duration for a failed random access at the ith try is

$$T'_i = \frac{p'_i}{p'_i + (1-p'_i)p_c} T_E + \frac{(1-p'_i)p_c}{p'_i + (1-p'_i)p_c} T_C. \quad (23)$$

Therefore, channel access latency if the aggregated packet is successfully delivered at ith try is

$$T_1 = T_S + W/2. \quad (24)$$

$$T_i = \sum_{j=1}^{i-1} [T'_j + W/2] + T_S + W/2, i > 2. \quad (25)$$

Then the expected time used to deliver an aggregated packet is

$$d' = (1-p_1)T_1 + \sum_{i=2}^{M} \prod_{j=1}^{i-1} p_j (1-p_i) T_i \quad (26)$$

where $p_i = p'_i + (1-p'_i)p_c$ is the failed probability of a random access at the ith try.

With the above results, the overall latency: time to accumulate packets plus time to deliver the aggregated packet is

$$d = \frac{N-1}{\lambda} + d' \quad (27)$$

where the $\frac{N-1}{\lambda}$ is the time needed to aggregate N packets.

The optimal amount of aggregated packet N can be found by

$$\begin{aligned} \arg\min_{N} \quad & d \\ \text{subject to} \quad & \prod_{i=1}^{M} p_i < \alpha, \\ & N < N_{max}. \end{aligned} \quad (28)$$

where α is the packet loss rate threshold, and N_{max} is the maximum allowed amount of aggregated packets which is determined by buffer size. As we do not have a closed form of d, therefore this optimization problem cannot be solved by any specific optimization method. Instead, we use exhaustive search to solve this problem.

IV. Simulation Results

To evaluate the performance of proposed method, simulations are performed with a MATLAB based simulator. The transmission limit M is set to be 5; the packet loss rate threshold α is 0.1; the maximum allowed amount of aggregated packets N_{max} is 50 the packet size follows an exponential distribution with average packet size of 100 bits. The wireless channel error rate for the ith preamble transmission is $1/e^i$ as that used in [11]. The amount of preamble used for contention based access N_C is 20, the backoff window size $W = 20$ ms. T_E is 8.5 ms; T_C is 14.5 ms and T_S is 18.5 ms. And we assume all the preamble are used in Random Access Preambles group A (the L2/L3 message, SR, is of small size in our case). The period of rach access $T_{rach} = 1ms$, i.e., the random access channel is available in each subframe.

Fig. 3 shows the amount of aggregated packet under different number of UEs and packet arrival rate λ (packets/ms) when using our proposed method. It can be seen that the amount of aggregated packet non-decreases with the increase of packet arrival rate or number of UE. This is reasonable since the collision rate increases with packet arrival rate or number of UE. If the collision rate is larger than the given threshold, aggregating more packets is needed to lower it. Otherwise, the amount of aggregated packet may not be increased. For instance, when λ=1/10 and the number of UE is 2500, the amount of aggregated packet is 1 and the packet drop rate is 0.08 which is very close to the threshold 0.1. Therefore, when the number of UE increases to 3000, the amount of aggregated packets increase to 2, which yields a packet drop rate of 0.02. After that, the amount of aggregated packets remain 2 when the number of UE increases to 4000 as the packet drop rate is always less than the threshold.

Fig. 4 demonstrates the packet loss rate when using the packet aggregation results shown in Fig. 3. It can be seen that with our method the packet loss rate is lower than the packet loss rate threshold (0.1), which validates our method. In contrast, without packet aggregation the packet loss rate is very high when $\lambda = 1/5$ or $1/10$ and the number of UE is larger than 2500, which indicates that our proposed packet aggregation method is crucial to optimize the performance for MTC applications in LTE. It has to be noted that as the amount of aggregated packet is 1 when $\lambda = 1/30$ (shown in Fig. 3), therefore with or without the proposed packet aggregation method yields the same packet loss rate. Fig. 5 shows the channel access latency using the packet aggregation results shown in Fig. 3[1]. We can see that the latencies are still kept at a low level, which is acceptable for most MTC applications.

V. Conclusion and Future Work

Random access is used for machine type communication uplink channel access in LTE. However, it suffers from high collision rate in dense networks. To address this problem, a

[1]The latencies of method which does not use the packet aggregation are not shown in this figure since without packet aggregation a large proportion of packets are dropped when $\lambda = 1/5$ or $1/10$ and the number of UE is larger than 2500.

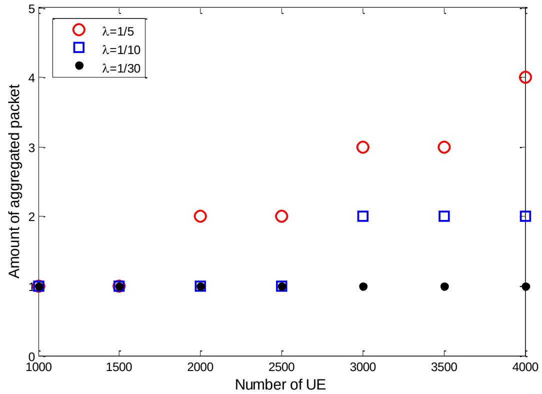

Fig. 3. Amount of aggregated packet

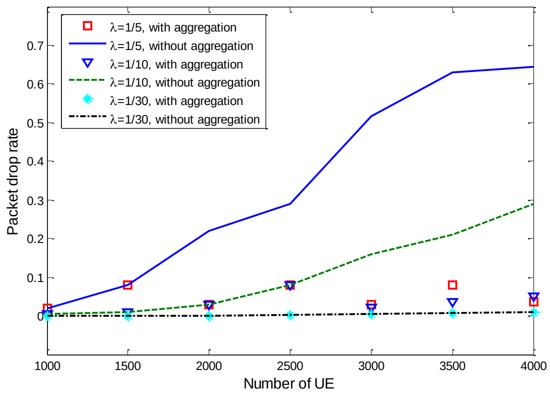

Fig. 4. Packet loss rate

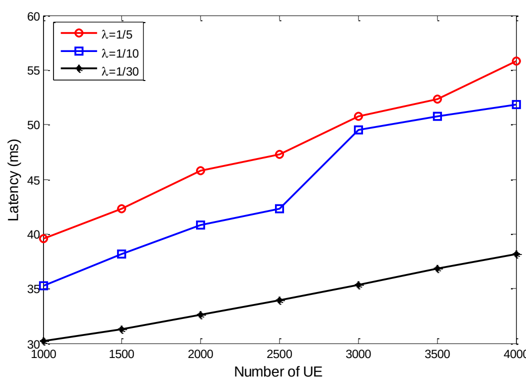

Fig. 5. Latency

packet aggregation method is proposed in this paper. With the proposed method, a UE does not start a random access until the aggregated packets in the buffer reaches the given threshold. However, this method introduces extra channel access latency which is used to accumulate certain amount of packets. We propose a Semi-Markov chain method to analyze the random access procedure with packet aggregation and derive the packet loss rate and channel access latency as functions of amount of aggregated packets. Therefore, the optimal amount of aggregated packet which satisfies the packet loss requirement while keeping the latency as small as possible can be found. The simulation results shows that proposed method set the amount of aggregated packet properly and the packet drop rate is greatly reduced compared to that of the method without packet aggregation.

Regarding the future work, in this paper we adjust the number of aggregated packets to satisfy the packet drop rate requirement at the expense of extra latency. Though the channel access latency with packet aggregation is not very large (it is acceptable for most MTC application with flexible delay requirement), it may not be desirable for some real-time MTC applications. Therefore, for these MTC applications with short and strict latency requirement, the number of aggregated packets should be set such that the delay constraint is satisfied while the packet drop rate is reduced as much as possible.

VI. ACKNOWLEDGMENTS

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