Dynamic Resource Allocation for Machine-Type Communications in LTE/LTE-A with Contention-Based Access

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***Abstract*—In this paper, we propose a dynamic resource allocation method to enable efficient and low-latency machine type communications (MTC) in LTE/LTE-A with the contention based random access (CBA) scheme [9]. In the proposed method, we firstly estimate the probabilities of events caused by a CBA transmission and then calculate the latency with the measured resource unit. We increase the amount of CBA resources until the estimated latency satisfies the application QoS requirement. The simulation results demonstrate that with the proposed resource allocation method for CBA, the uplink channel access latency has been drastically reduced and that it always guarantees the latency requirements. Furthermore, the achievable latency is significantly reduced when compared to the regular scheduling and the standard random access scheme.**

***Index Terms*—LTE, MTC, resource allocation, random access, MU-MIMO.**

I. Introduction

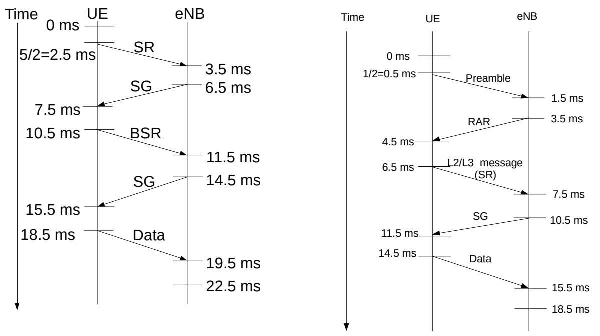
To meet the increasing demand for the broadband mobile access, the Third-Generation Partnership Project (3GPP) introduces the LTE as the next step of the current 3G mobile communication system. Among the various applications provided by LTE, MTC is one of the most promising applications due to its low cost and easy deployment [1]. At the present time, the most interesting applications from the commercial point of view are related to automated home, smart electricity, automatic water and gas meters reading. However, the M2M application space is vast and includes security, health monitoring, remote management and control, tracking and tracing, intelligent transport systems, distributed/mobile computing, gaming, industrial wireless automation, and ambient assisted living. However the current mobile communication system is mainly designed for human-to-human (H2H) communication, which is not suitable for MTC applications with different traffic characteristics and QoS requirements coupled with the potential of a rapid increase in the number of machines connected to cellular infrastructure. Therefore, some optimizations are required to accommodate MTC applications [2].

There have been numerous works considering methods to accommodate MTC in LTE. In 3GPP, a recent study item on provision of low-cost MTC devices based on LTE and a work item on system optimizations and overload control for MTC have been approved for LTE Release 11 [3]. The work in [4] proposes a user grouping method, which allocates users with similar quality of service (QoS) requirements into clusters, to address the massive access problem. In [5] an admission control algorithm with measurement-based adaptive prioritization was proposed to enable medical body area network (MBAN) applications over LTE. In [6], authors presents an network architecture design method to achieve a good tradeoff between signaling overhead and complexity for MTC over. In [7], a mobility control algorithm for MTC is proposed to reduce the co-channel interference between cells. In [8], the authors presents a resource management method for the 3GPP Evolve Packet Core (EPC) to accommodate MTC.

Besides the above work, we believe the uplink channel scheduling method should also modified due to its low spectral efficiency. Fig. 1(a) demonstrates a regular uplink scheduling procedure in LTE: (1) UE sends the scheduling request (SR) information on the PUCCH channel; (2) eNB allocates resource for that UE upon receiving its SR information; (3) UE sends buffer state report (BSR) on the allocated resource; (4) eNB allocates suitable amount of resource for the UE according to the BSR information; (5) UE sends the data packet. Assuming that the SR period is 5ms and the eNB processing time for SR, BSR and data packets is 3ms, the latency for this uplink scheduling is 22.5ms and the throughput is $10\times 8/22.5 = 3.56$Kbps provided that the packet is 10 bytes (the packet size for MTC is usually very small), which shows a very low resource utilization efficiency. One more problem for the regular uplink scheduling is that the SR period increase with the number of UEs as the maximum number of UEs which could send SR in one physical uplink control channel (PUCCH) is 36 [10]. For MTC applications, there are usually massive MTC devices in a cell. Supposing there are 2000 MTC devices in a cell and 1 PUCCH for MTC application is available in each subframe, then the SR period increases to $2000/36 = 56$ms[1], which yields a very large latency.

To address this problem, in [2] a uplink access method which uses random access channel is proposed. In this method, as shown in Fig. 1(b) a UE uses the standard random access to send SR (apply for resource from eNB) and then sends the data packet. This method saves the channel access latency

[1]In practise, the SR period should be 80ms as the SR period can only be some discrete values specified in [10]



(a) Regular scheduling (b) Standard random access

Fig. 1. Uplink channel access procedures

and improves efficiency. However, it does not work well when the collision rate is high. In [9] we proposed a contention based access (CBA) method for MTC over LTE. With our method UE send packet on the randomly selected resource which is very similar to the method in [2]. Moreover, to solve the problem of collision in our method the cell radio network identifier (C-RNTI) is sent with the data packet; the eNB employs MU-MIMO detection method to decode C-RNTIs of the collided UEs. For the successfully decoded C-RNTIs, dedicated resource is allocated for corresponding UEs for the data packet transmission. However, in [9] we did not specify the resource allocation scheme for CBA. Actually the resource allocation scheme is very crucial to CBA: allocating insufficient resource for CBA causes serve collisions and increases the channel access latency while allocating too much resource for CBA causes inefficient utilization. In this paper, we propose a resource allocation scheme for CBA. In our method, we firstly estimate the probabilities of events caused by a CBA transmission, and then estimate the latency with the given amount of CBA resource. If the estimated latency is larger than the latency requirement, we increase the amount of CBA resource until the estimated one less than the latency requirement. The simulation results show that the proposed method can find the minimum resource for CBA to comply with the latency requirement.

II. Contention based access for MTC over LTE

The contention based access (CBA) was proposed in [9] to address the inefficient uplink scheduling method for MTC over LTE. The main feature of contention based access is that UE is not assigned with dedicated resource. Instead, the resource is allocated for all or a group of UEs. A UE randomly selects its resource and sends a data packet on it. The procedure for CBA is shown in Fig. 2. First, the eNB informs UEs about the resource allocation information for CBA via the scheduling grant (SG) information which cost 0.5ms provided that the CBA resource is available in each subframe. Then, after decoding the SG information which cost 3ms, the UE selects its resource block randomly and sends the data packet [2]. The channel latency for this packet scheduling procedure is 7.5ms (not including the time waiting for the ACK information), which is much smaller than 22.5ms of the regular scheduling case.

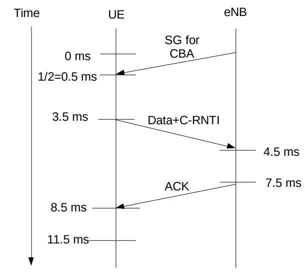


Fig. 2. Contention based access procedure

As the CBA resources are allocated for all or a group of UEs, collision happens when multiple UEs within a group select the same resource. To address the problem of collision, in our method each UE sends its identifier, C-RNTI, along with the data on the randomly selected resource. The C-RNTI is of very small size, therefore it can be transmitted with the most robust modulation and channel coding scheme (MCS) without huge overhead. MU-MIMO detection is used at the eNB side to decode packets; the highly protected C-RNTIs from different UEs might be decoded even if they are sent on the same resource. If the C-RNTI of a UE are successfully decoded while its data payload is lost, dedicated resource is allocated for that UE by eNB. With the allocated resource, the UE sends its data packet; the latency for this procedure is 15.5ms as shown in Fig.3, which is less than latency of the regular scheduling case. For the collided UEs whose C-RNTIs are not decoded, no dedicated resource (SG) is allocated by eNB; those UEs have to retransmit the packets as shown in Fig. 4. Moreover, a UE may receive a NACK when the packet is delivered with error. In this case, it also retransmits the packet using CBA, which is also shown in Fig. 4.

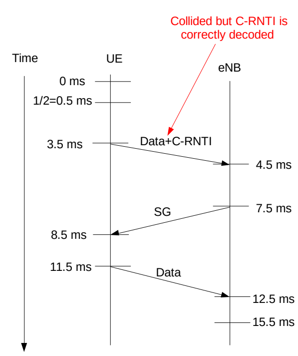


Fig. 3. Contention based access with collision detection procedure

Denoting the number of resource elements for one CBA resource unit as N_{CBA}, it contains the amount of resource elements (RE) used for control information transmission, denoted as N_{ctrl} in addition to those reserved for data N_{data}. Assuming the control information comprises 20 bits (16 bits for C-RNTI and 4 bits for MCS), the spectral efficiency of the

[2]Here we assume that the UE is uplink synchronized. Therefore, no extra synchronization is needed before sending the data packet.

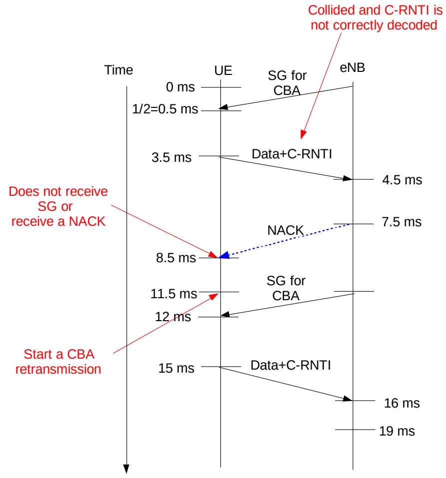


Fig. 4. Contention based access with retransmission procedure

control information is $R_c = 20/N_{ctrl}$bits/RE. Similarly, the spectral efficiency of the data is $R_d = M_{data}/N_{data}$bits/RE where M_{data} is the bit of data payload.

For one CBA transmission, we have four events: (1) neither the control information nor the data are detected, which is denoted as E_1; (2) the control information is not detected but the data is detected, which is denoted as E_2; (3) the control information is detected but the data is not detected, which is denoted as E_3; (4) both the control information and data are detected, which is denoted as E_4. In order to determine the probability of each event we take a approach based on instantaneous mutual information. This asymptotic measure yields a lower bound on the above probabilities for perfect channel state information at the receiver. To this end, the received signal on the m^{th} antenna at resource element k is

$$y_m[k] = \sum_{u=0}^{N_u-1} H_{m,u}[k]x_u[k] + Z_m[k], m = 0, \cdots, N_{\text{RX}} - 1 \quad (1)$$

where $H_{m,u}[k]$ is the channel gain for user u at antenna m, $x_u[k]$ is the transmitted signal, $Z_m[k]$ is the noise, and N_u is the random number of active users transmitted on this resource block. The normalized sum-rate for N_u contending users based on mutual information for both data and control portions is

$$I_{\text{X}} = \frac{1}{N_u N_{\text{X}}} \sum_{k=0}^{N_{\text{X}}-1} \log_2 \det \left(\mathbf{I} + \sum_{u=0}^{N_u-1} \gamma_u \mathbf{H}_u[k] \mathbf{H}_u^*[k] \right) \quad (2)$$

where X is represents either control or data, $\gamma_n, n = 0, \cdots, N_u - 1$, is the received signal-to-noise ratio (SNR) and $\mathbf{H}_i[k] = \begin{pmatrix} H_{0,n}[k] & H_{1,n}[k] & \cdots & H_{N_{\text{RX}}-1,n}[k] \end{pmatrix}^T$. The use of this expression requires the two following assumptions. Firstly, all channels can be estimated at the receiver, which requires the proper use of the cyclic shifts for channel estimation. In LTE, a maximum of 12 cyclic shifts are available on one random access resource unit (6 resource blocks) as specified in [10]. Secondly, the expression assumes Gaussian signals and that the eNB receiver uses an optimal multi-user receiver (i.e. it performs complete joint detection). These expressions can be found in [11].

Assuming there are i active UEs contending on the same CBA resource unit, the probabilities of the four events caused by one CBA transmission are:

$$P_{E_1,i} = P_{S,i} + (1 - P_{S,i})p(I_{ctrl} < R_c, I_{data} < R_d), \quad (3)$$

$$P_{E_2,i} = (1 - P_{S,i})p(I_{ctrl} < R_c, I_{data} > R_d), \quad (4)$$

$$P_{E_3,i} = (1 - p_{S,i})p(I_{ctrl} > R_c, I_{data} < R_d), \quad (5)$$

$$P_{E_4,i} = (1 - p_{S,i})p(I_{ctrl} > R_c, I_{data} > R_d), \quad (6)$$

where $P_{S,i}$ is the probability that more than one UE uses the same cyclic shift on one CBA resource unit provided that there are i contending UEs. In general, the control information is more protected than the data, i.e., $R_c < R_d$, so $P_{E_2,i} \approx 0$.

Then the expected value for the probabilities of the four events are:

$$P_1 = \sum_{i=1}^{N} P_{A,i} P_{E_1,i} \quad (7)$$

$$P_2 = \sum_{i=1}^{N} P_{A,i} P_{E_2,i} \approx 0, \quad (8)$$

$$P_3 = \sum_{i=1}^{N} P_{A,i} P_{E_3,i} \quad (9)$$

$$P_4 = \sum_{i=1}^{N} P_{A,i} P_{E_4,i} \quad (10)$$

where $P_{A,i}$ is the probability that there are i active UEs contending on one CBA resource unit; N is the total amount of UEs in a cell.

III. Resource Allocation Scheme for Contention Based Access

The main target for resource allocation is to assign the proper amount of resource such that the latency constraints are satisfied and the allocated resources are efficiently used. Accurate resource allocation for CBA is very important as it is directly connected to latency experienced by the application traffic.

To minimize the latency for the MTC traffic, the CBA resource should be available in each subfame. The resource allocation can be performed in the following steps:

1) Set the CBA resource unit
2) Initialize the amount of CBA resource unit to 1
3) Calculate the probabilities of the four events caused by a CBA transmission.
4) Calculate the latency based on the measured amount of CBA resource unit
5) If the estimated latency is larger than the latency constraint, increase the amount of resource unit by one and go back to step 3. Else end

It can be seen that as the latency decreases with amount of CBA resource unit, therefore with the above method we always find the minimum amount of CBA resource. It has to noted that here we assume that there is always enough resource. For a system which has a constraint on CBA resource, more intelligent scheduler can used to address this problem, for example a scheduler which consider the priorities between real time and non real time traffics.

A. Estimation of the probabilities of events in step 3

To estimate the probabilities of the four events caused by a CBA transmission, we drive a Semi-Markov chain model as shown in Fig. 5, where

- S_0 means that there is no packet in the UE's buffer,
- S_{2i-1}, $i \in [1, M]$, means the ith CBA transmission of the UE, where M is the transmission limit,
- S_{2i}, $i \in [1, M-1]$, means that the UE is waiting for the ACK/NACK or SG information.

The UE transfers between states as:

- When the UE is at state S_0, if a packet arrives, it transfers to states S_1 to start the first transmission; otherwise it remains at state S_0
- When the UE is at state S_{2i-1}, $i \in [1, M-1]$, it sends the packet and transfers to S_{2i}
- When the UE is at state S_{2M-1}, it sends the packet and transfers to S_0.
- When the UE is at state S_{2i} $i \in [1, M-1]$: (1) if ACK is received it transfers to state S_0; (2) if SG is received it sends the packet as shown in Fig. 3 and then transfers to state S_0; (3) if neither ACK nor SG is received at the expected time instant, it transfers to state S_{2i+1} to retransmit the packet as shown in Fig. 4.

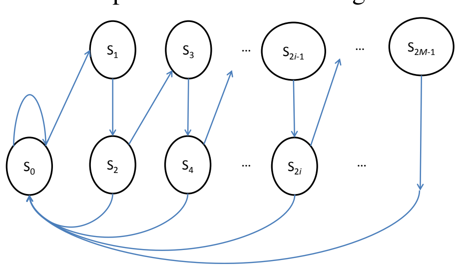


Fig. 5. Markov chain model for contention based access

Denoting $p_{i,j}$ as the state transition probability from state S_i to state S_j, $i, j \in [1, 2M-1]$, the state stationary probability of state i can be calculated as:

$$\pi_0 = \pi_0 p_{0,0} + \sum_{i=1}^{M-1} \pi_{2i} p_{(2i),0} + \pi_{(2M-1)} p_{(2M-1),0} \quad (11)$$

$$\pi_{2i-1} = \pi_{2i-2} p_{(2i-2),(2i-1)}, i \in [1, M] \quad (12)$$

$$\pi_{2i} = \pi_{2i-1} p_{(2i-1),(2i)}, i \in [1, M-1]. \quad (13)$$

With the above equations, we can get

$$\pi_i = \prod_{j=1}^{i} p_{(j-1),j} \pi_0, i \in [1, 2M-1]. \quad (14)$$

Substituting (14) into the following equation

$$\sum_{i=0}^{2M-1} \pi_i = 1, \quad (15)$$

we can get

$$\pi_0 = \frac{1}{1 + \sum_{i=1}^{2M-1} \prod_{j=1}^{i} p_{(j-1),j}}. \quad (16)$$

The state transition probability can be calculated as following. In each subframe (1ms) if a packet arrives, the UE transfers from state S_0 to state S_1. Supposing the packet arrives following a Poisson distribution with the arrival rate λ, we have $p_{0,1} = 1 - e^{-\lambda}$. When the UE is at state S_{2i-1}, after transmission it transfers to state S_{2i}, therefore $p_{(2i-1),2i} = 1$, $i \in [1, M-1]$.

When the UE is at state S_{2i}, it transfers to state S_{2i+1} if neither ACK nor SG is received, i.e., it transfers state S_{2i+1} if neither the control information nor the data are detected, therefore

$$p_{2i,(2i+1)} = P_1. \quad (17)$$

With derived transition probability, π_0 can be calculated as

$$\pi_0 = \frac{1}{1 + \sum_{i=1}^{M-1} 2(1 - e^{-\lambda}) P_1^{i-1} + (1 - e^{-\lambda}) P_1^{M-1}} \quad (18)$$

and π_i can be calculated using (12)-(13). We can see that π_i, $i \in [1, 2M-1]$, is a function of P_1.

Now let us calculate the state holding time D_i (in ms) for state S_i, $i \in [1, 2M-1]$. In state S_0 for every subframe the UE checks if a packet arrives. If so, it transfers to state S_1, therefore $D_0 = 1$.

In state S_{2i-1} as shown in Fig. 3 the UE first waits for resource allocation information for CBA and then sends the packet; finally it transfers to state S_{2i}, therefore $D_{2i-1} = 3.5$, $i \in [1, M]$.

When the US is in state S_{2i}: (1) if ACK is received it transfers to state S_0, the state holding time for this case is $11.5 - 3.5 = 8$ms as shown in Fig. 2; (2) if SG is received it sends the packet on the allocated resource as shown in Fig. 3 and then transfers to state S_0, the state holding time for this case is $11.5 - 3.5 = 8$ms; (3) if neither ACK or SG is received at the expected time instant, the UE transfers to state S_{2i+1} to start a retransmission as shown in Fig. 4, the state holding time for this case is also $11.5 - 3.5 = 8$ms. Hence, $D_{2i} = 8$, $i \in [1, M-1]$.

Denoting Q_i, $i \in [1, 2M-1]$, as the proportion of time that the UE is in state i, it can be calculated as

$$Q_i = \frac{\pi_i D_i}{\sum_{i=0}^{2M-1} \pi_i D_i}, \quad (19)$$

which is a function of P_1.

A UE trigger a CBA transmission in state S_{2i-1} and the time used for a CBA transmission is 1ms. Therefore the probability that a UE is performing a CBA transmission is

$$\tau = \sum_{i=1}^{M} Q_{2i-1} \cdot \frac{1}{D_{2i-1}}. \quad (20)$$

which is also a function of P_1.

For a UE which is performing a CBA transmission, the probability that there are i another UEs contending on the same CBA resource is

$$P_{C,i} = \sum_{j=i}^{N-1} \binom{N-1}{j} \tau^j (1-\tau)^{N-1-j} \binom{j}{i} (\frac{1}{N_{RE}})^i (1-\frac{1}{N_{RE}})^{j-i} \tag{21}$$

where $i \in [0, N-1]$, N is the total amount of UEs in a cell and N_{RE} is the amount of CBA resource unit.

Therefore, it is obvious that

$$P_{A,i} = P_{C,(i-1)}, i \in [1, N]. \tag{22}$$

which is a function of τ.

Moreover assuming the amount of UE which contends on the same CBA resource is i, for a given active UE the probability that other UE selects the same cyclic shift is

$$P_{S,i} = 1 - (\frac{11}{12})^{i-1}. \tag{23}$$

It has to be mentioned that above equation holds since the maximum available cyclic shifts in one CBA resource unit is 12. Hence, with equations (23) and (3) we can calculate $P_{E_1\_i}$ for i contending UEs.

Finally we have

$$P_1 = \sum_{i=1}^{N} P_{A,i} P_{E_1,i} \tag{24}$$

which is a function of τ.

We can see that equations (20) and (24) comprise a system of equations with two unknown P_1 and τ, which could be solved by numerical methods. Hence, we can calculate P_3 and P_4 using (9)-(10), respectively.

B. Estimation of the latency in step 4

With the results derived in last subsection, we can estimate the latency for given amount of CBA resource.

At stated in Sect II, for each CBA transmission we have four events. Here we denote the packet transmission latency for the four events as T_1, T_2, T_3, and T_4 (in ms). Hence the average latency can be calculated as:

$$T = P_1 T_1 + P_2 T_2 + P_3 T_3 + P_4 T_4. \tag{25}$$

As $P_2 \approx 0$, so the above equation can be simplified as: $T = P_1 T_1 + P_3 T_3 + P_4 T_4$.

For an unsuccessful CBA transmission where both data and control information cannot be decoded retransmission happens 11.5ms after the initial transmission as shown in Fig. 4, therefore T_1 can rewritten as $T_1 = T_5 + 11.5$, where T_5 is packet delivery latency for a new CBA transmission. Moreover, as shown in Fig. 2 and 3, we have T_3=15.5, and T_4=7.5. With the above results, we have $T = (T_5+11.5)P_1+15.5P_3+7.5P_4$.

Since $E(T) = E(T_5)$, the expected channel access latency is

$$E(T) = \frac{11.5P_1 + 15.5P_3 + 7.5P_4}{1 - P_1}. \tag{26}$$

where P_1, P_3 and P_4 are calculated in the third step.

IV. SIMULATION RESULTS

To evaluate the performance of proposed method, simulations are performed with a MATLAB based simulator. We assume that it is FDD-LTE; the SNR is set to 5 dB; transmission limit M is set to 5 and the number of receiving antennas is 2. For simplicity we have assumed a line-of-sight dominant channel model with randomized angle-of-arrival at the eNB receiver in order to model the $\mathbf{H}_i[k]$. The CBA resource unit is set to be 6 resource blocks, i.e. $6 \times 12 = 72$ subcarriers, which is same as the resource of the PRACH channel. Moreover, the packet size is assumed to be of small size, following an exponential distribution with average packet size of 100 bits.

Fig. 6 shows the resource allocation results using our proposed method with different packet arrival rates λ (packets/ms) and number of UEs when the delay constraint is 30ms. We can see that the allocated resource units non-decrease with the increase number of UEs and/or packet arrival rate. This is expected as larger number of UEs and/or higher packet arrival rate increase the packet collision rate which may require more resources to satisfy the delay constraint. For instance, when $\lambda = 1/30$ and the number of UE is 300, the CBA resource unit is one and the latency is 28ms which is very close to the threshold 30ms. Therefore, when the number of UE increases to 400, two CBA resource units are allocated which yields a latency of 18ms, and when the number of UEs reaches 600, the CBA resource unit increases to three, and the latency decreases to 18ms. Fig. 7 demonstrates the delay when using the allocated amount of resource shown in Fig. 6. It can be seen that the delay is smaller than the delay constraint 30ms, which validates our proposed method.

We also compare the channel access delay of CBA with those of two other scheduling methods: (i) regular scheduling with round-robin resource allocation, (ii) the PRACH method proposed in [2]. Firstly, we compare these three methods use same amount of resource: (1) one CBA resource unit with 6 resource blocks for CBA (referred to as CBA with fixed resource allocation in Fig. 8); (2) 6 resource blocks for regular scheduling method (referred to as regular scheduling with fixed resource allocation in Fig. 8); (3) the PRACH resource configuration index is set to 14 for the PRACH method, which also occupies 6 resource blocks in each subframe (the maximum allowed resource for PRACH in LTE); the backoff counter is 20ms. The packet arrival rate λ is 1/100 packet/ms. We can see that the latency of CBA method is always than those of PRACH and the regular scheduling method fixed resource allocation. To demonstrate that our proposed works properly with different delay requirements, here we set the latency requirement to 15ms and apply the dynamic resource allocation method proposed in this paper. With this latency requirement, the required CBA resource unit is 1 when number of UE is less than 600, while it is 2 when the number of UE is larger than 600 (referred to as CBA with dynamic resource allocation in Fig. 8). To compare fairly, when the number of UE is larger than 600, for the regular scheduling method we also allocate 12 resource blocks for it (referred to as regular scheduling with dynamic resource allocation in Fig. 8)[3]. Then, from Fig. 8 we observe that the latency of CBA with dynamic resource allocation is still smaller than that of PRACH and regular scheduling methods. Secondly, we also notice that the latency of regular scheduling with fixed and dynamic resource allocation are very close, which is because of the bottleneck of the regular scheduling, when transmitting small packets, is caused by the signaling overhead used to send SR which increases with the number of UEs as shown in Fig. 1(a). Finally, we notice that the latency of PRACH is constant among different number of UEs; the reason for this phenomenon is that the collision rate is very low for PRACH as it has 64 available preambles.

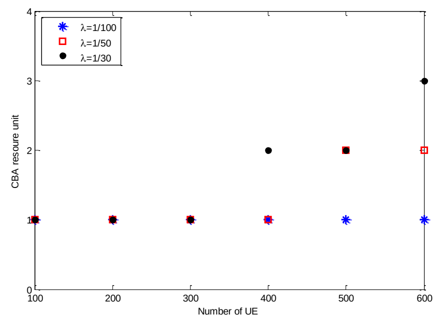


Fig. 6. CBA resource allocation for different number of UEs

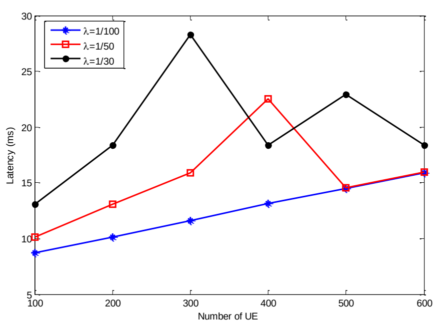


Fig. 7. Latency of CBA resource allocation method

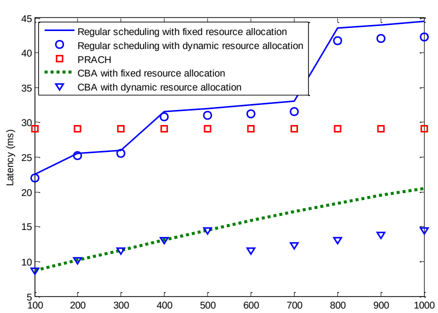


Fig. 8. Latency of different channel access method

V. Conclusion and Future Work

This paper provides a resource allocation method for contention based access. The proposed method finds the minimum needed resource for CBA by increasing the amount of resource until the estimated latency less than the latency requirement. The simulation results show that using the proposed method the latency constraint can be satisfied, which validates our method. Moreover, we find that with CBA and the proposed resource allocation method we can achieve very small channel latency, which cannot be attained by the regular scheduling and PRACH method.

Regarding the furure work, we are implementing the proposed CBA method and its resource allocation scheme in the LTE SDR implementation provided by the OpenAirInterface.org in-lab system validation platform [12] to evaluate its performance in a real LTE system. Moreover, to improve the resource utilization efficiency, the CBA resource allocation scheme should also consider the channel quality of the user and the priortity between users (e.g. real time CBA applications V.S. non real time CBA applications) as the regular scheduler. Finally, we can also use some machine learning methods to estimate the packet arrival rate when it is not constant.

[3] We cannot allocate more resource for PRACH as the PRACH resource configuration index 14 is the maximum allowed resource for PRACH in LTE.

VI. Acknowledgments

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