Contention based access for machine-type communications over LTE

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***Abstract*—To enable the efficient and low latency machine-type communications (MTC) over long term evolution (LTE), a contention based access (CBA) method is proposed. With CBA, UEs transmit packets on the randomly selected resource without having any UE specific scheduled resources. To address the problem of collision caused by CBA in high traffic load, eNB exploits the MU-MIMO detection technique to decode radio network temporary identifier (RNTI) of the collided UEs and use this information to perform a regular scheduling in subsequent subframe. The latter is also exploited on the data portion to increase the probability of receiving the packet on the first transmission, even in the case of contention. Detailed low layer signaling enhancement to implement this CBA technique in current LTE specification (Rel. 10) is also presented. Simulation results demonstrate that CBA can significantly outperform the existing uplink channel access methods.**

***Index Terms*—MTC, scheduling, MU-MIMO, LTE.**

I. Introduction

In one of the recent studies for LTE Release 11 related to radio access improvement for machine-type commmunications (MTC), overhead and latency reduction are identified as the first priority [1].

Among the various applications provided by LTE, machine-type communications, for example: alarms and event detection sensing [8], is one of the most promising applications due to its low cost and easy deployment [2]. However, the regular mobile networks are designed for human-to-human (H2H) communications, targeting the voice/multimedia transmissions with a continuous flow of packets, which are not suitable for MTC with different traffic characteristics and quality of service (QoS) requirements [3]. Therefore, there have been some literatures considering different methods to enable efficient MTC over LTE system. Reference [4] presents a method to provide QoS guarantees to facilitate MTC applications over LTE. In [3], authors propose an architecture design method for MTC over LTE. Mobility managementfor MTC with LTE is proposed in [5]. Reference [6] analyzes the main latency bottlenecks for several real-time MTC applications over LTE. Besides the above work, we believe that a new efficient scheduling method should be designed for MTC since the legacy scheduling method in LTE is not suitable for MTC.

Fig. 1 shows the scheduling consecutive signaling steps when a UE is in RRC connected mode and synchronized in uplink for LTE FDD frame format (also applicable to LTE TDD). Firstly, the UE waits for the PUCCH channel on which it sends the scheduling request (SR) information with the period of 5ms. The period of SR is configurable, ranging from 1ms to 80ms [10], and increases with the number of UEs in a cell. Afterward, the eNB sends the scheduling grant (SG) information, which is carried on PDSCH with downlink control information (DCI) format 0, to allocate resource. Then UE decodes the received SG and transmit the buffer state report (BSR) on the allocated resource. The eNB allocates the corresponding resources based on the received BSR information and sends the SG information to UE. Finally, the UE sends the data frame on the allocated resources. The latency for this uplink channel access is 22.5ms in the best case. If transmission error happens, the latency will be increased. It should be mentioned that the eNB processing time for the SR, BSR and data frames are assumed to be 3ms, which is actually implementation dependent.

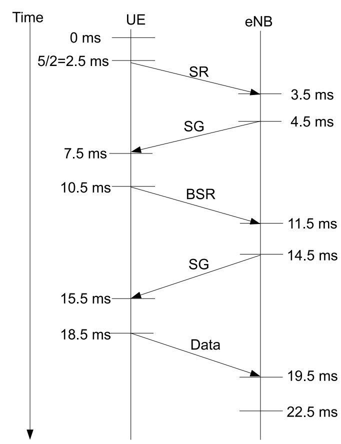

Fig. 1. Uplink scheduling in LTE

Supposing the data size is 10 bytes, the throughput for this uplink transmission procedure is 10×8/22.5=3.56 Kbps, which is not efficient in the view of resource consumption. Moreover, in a high load traffic cell the UE has to wait longer time to send the SR or be scheduled by the eNB due to the increased load, which increases the latency of the uplink access. Therefore, the regular uplink scheduling may not be suitable for delay-sensitive MTC applications due to the large channel access delay and inefficient resource utilization [8]. Another issue regarding latency is the addition power consumption in UE while it waits for scheduling. This is sub-optimal for very low duty-cycle applications.

In [1], UEs use the random-access procedure to get specific resources for data transmissions as shown in Fig. 2. The results show that with this method the latency can be greatly reduced compared to the regular scheduling method. However, as random-access procedure should be performed before data transmission, some redundant latency is still introduced. Therefore, the proposed method may still not be very efficient in delay-sensitive MTC application, which motives us to design a new uplink channel access method to further reduce the latency.

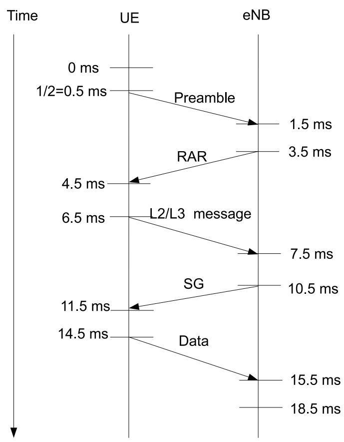

Fig. 2. Uplink channel access method

In the proposed method, UEs are not allocated with specific resources, but rather with a pool of resources where they randomly select for the data transmission. The collision may happen if more than two UEs use the same resource. In this case, dedicated resources are allocated for data retransmissions provided that RNTI of the collided UEs can be correctly decoded based on the MU-MIMO detection technique. The latency gain is therefore achieved by bypassing the SR, BSR, and preamble procedures used in above mentioned methods.

The rest of paper is organized as follows. Section 2 provides the basic idea of the proposed CBA method. In Section 3, detailed low layer signaling enhancement to implement CBA technique in current LTE specification (Rel. 10) is presented. Section 4 analyzes the performance of the proposed method. Finally, Section 5 provides concluding remarks and future directions.

II. Basic idea for the contention based access

To provide a low latency uplink channel access for MTC over LTE, a new resource allocation method, called contention based access (CBA), is proposed. The main feature of CBA is that the eNB does not allocate resources for a specific UE. Instead, the resource allocated by the eNB is applicable to all or a group of UEs and any UE which has data to transmit randomly uses resource blocks among the available resource. The schematic view for contention based uplink access is shown in Fig. 3. First, the UE receives the resource allocation information which indicates the resource allocated for CBA; it costs 0.5 ms assuming the CBA resource is available in each subframe. Then, after decoding the resource allocation information which costs 3 ms, the UE sends the frame on the randomly selected resource. The latency for this whole procedure is 7.5 ms for the best case, which is much smaller than that of the regular scheduling case.

As the CBA resources are not UE specific but rather allocated for all or a group of UEs, collisions may happen

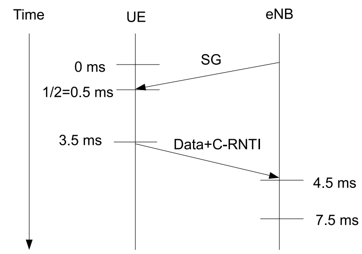

Fig. 3. Contention based uplink access

when multiple UEs select the same resource. In a network with sporadic traffic, the collision probability is very low, which means most transmissions are free of collision and therefore CBA method outperforms the regular scheduling method in view of latency. However, in a dense network the collision probability is very high, which means lots of retransmission are needed and hence the latency is increased. For example supposing the total available resource block in a subframe is 50, the collision probability is 0.06 if 3 UEs transmit in the subframe, while the collision probability increases to 0.99 if 20 UEs transmit in the subframe.

To solve the above problem, the following method is used. Each UE sends its identifier, C-radio network temporary identifier (C-RNTI), along with the data on the randomly selected resource. Since the C-RNTI is of very small size, therefore it can be transmitted with the most robust modulation and channel coding scheme (MCS) without introducing huge overhead. By the use of MU-MIMO detection, these highly protected C-RNTIs might be successfully decoded even if they are sent on the same time-frequency resource. Upon the successfully decoding for the collided C-RNTIs, the eNB triggers regular scheduling for the corresponding UEs. Therefore, the overall latency for this whole scheduling procedure is still not larger than that of the regular scheduling as illustrated in Fig. 4.

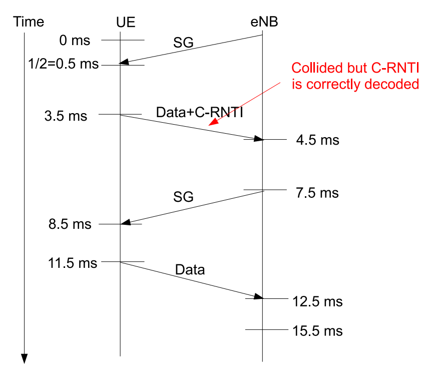

Fig. 4. CBA with successful collision detection

Herein, we have introduced the basic idea of the contention based access. To adapt to the contention based access, the following enhancements related to the LTE specification should be added.

III. Enhancements to the LTE specification

A. Enhancements to the RRC signaling related to 3GPP TS 36.331

1) Signaling to inform UEs about the cyclic shift : The reference signals or pilot signals from UEs are generated from the same base sequence, for example Zadoff-Chu sequence [9], with cyclic shifts. As the Zadoff-Chu sequence has the property that the different cyclic shifted versions of the same sequence are orthogonal to each other, therefore reference signals sent on the same time-frequency resource can be successfully decoded provided that different cyclic shifts are used. With the correct decoded reference signals, the channel state information (CSI) of UEs can thus be estimated. Therefore, the eNB can perform the MU-MIMO detection such that the C-RNTIs of the collided UEs might be detected.

To implement this mechanism, the cyclic shifts used by UEs are allocated by eNB through the RRC signaling. The UE specific physical channel configuration is defined in the PhysicalConfigDedicated information element with the ASN.1 notation in [10]. A new field called pusch-CBAConfigDedicated has to be added to the PhysicalConfigDedicated element with the following sub-fields: betaOffset_CBA_Index and cShift.

2) Signaling to inform UEs about the CBA-RNTI : The CBA-RNTI, which is used by a UE to decode the resource allocated information for CBA, is allocated by eNB during the RRC connection reconfiguration procedure for the data radio bearer (DRB) establishment. To implement this procedure, the CBA-RNTI has be added to the RadioResourceConfigDedicated information element as defined in [10]. It should be mentioned that the CBA-RNTI is not UE specific. Instead, all UEs or a group of UEs have a common CBA-RNTI configured by RRC signaling.

B. Enhancement to the PHY signaling related to the 3GPP TS 36.212

1) Signaling to inform UEs about the CBA resource allocation : For the regular scheduling operation, DCI is sent by eNB to inform UEs about the resource allocation[1]; the DCI is attached by a 16-bit CRC, where the CRC parity bits are scrambled with the C-RNTI such that UEs can identify the UE-specific allocated resource. To adapt to the resource allocation for CBA, a new DCI format, DCI format 0A, is defined. The DCI format 0A is used to inform UEs about the resource allocated to CBA. The content of DCI format 0A is shown in TABLE I, where N_{RB}^{UL} is number of resource block in the uplink. The CRC for DCI format 0A is scrambled with a new defined radio network temporary identifier CBA-RNTI. With the CBA-RNTI, the UE decodes the DCI format 0A to locate the resource allocated for CBA. As the resource allocation is not UE specific, multiple UEs may select the same resource, which causes collisions.

2) Signaling to inform eNB about the selected MCS: With CBA, UEs are not informed the MCS used for uplink transmission by eNB. Instead, UEs determine the MCS independently. Therefore, the UE should inform the eNB about the selected MCS so that the uplink frame can be properly decoded. To inform the eNB about the selected MCS, the following method is proposed.

[1]DCI format 0 is used for uplink resource allocation, while DCI format 1/1A/1B/1C/1D and 2/2A is used for downlink [11].

TABLE I
FIELD OF DCI FORMAT 0A

Information	Type Number of Bits	Purpose
Hopping flag	1	Indicates whether PUSCH frequency hopping is performed
Resource block assignment	$\log_2 N_{RB}^{UL}(N_{RB}^{UL}+1)$	Indicates assigned resource blocks

A new type of uplink control information (UCI) information, uplink MCS, is defined. The uplink MCS is mixed with C-RNTI to form a new element, which is referred to as beta channel quality indicator (CQI), and transmitted on physical uplink shared channel (PUSCH) as shown in Fig. 5.

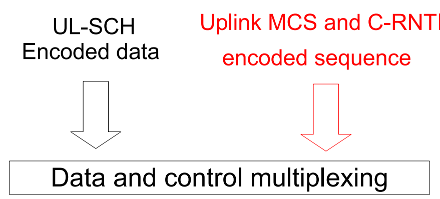

Fig. 5. Multiplexing of data and control information on PUSCH

C. Enhancement to the PHY procedures related to the 3GPP TS 36.213

1) UE procedure to locate the resource allocated for CBA: With the allocated CBA-RNTI which is obtained during the RRC connection reconfiguration procedure procedures, a UE can locate the resource allocated for CBA by decoding the DCI format 0A information.

2) UE hybrid ARQ (HARQ) procedure for CBA : UEs should find the ACK/NACK information after sending the data frame such that a new transmission or a retransmission can be properly performed. To adapt to CBA, the method to locate the ACK/NACK information is described as follows.

To locate the ACK information, the method is the same as the one specified in [11]. The physical HARQ indicator channel (PHICH) index is implicitly associated with the index of the lowest uplink resource block and the cyclic shift used for corresponding contention-based access. Therefore, UEs which successfully send frames can find the corresponding ACK information without extra signaling. The details for this method can found in [11].

As for an unsuccessful transmission, it is natural to think locating the NACK information on PHICH with the same method as ACK. However, a more efficient NACK signaling method, which also carries the scheduling information, is employed. In this method, as introduced in Sect.II, the C-RNTI is sent by the UE in the data frame with low order of MCS. Though the data frame may not successfully transmitted, which is be caused by wireless channel error or collision, the C-RNTI might be correctly decoded with MU-MIMO detection. For these unsuccessful UEs with successfully decoded C-RNTI, the eNB triggers regular scheduling by sending the DCI format 0 (not DCI format 0A). In the DCI format 0 the new data indicator (NDI) field is set to 0 to represent the NACK information. Hence once a UE which employs CBA receiving the DCI format 0 with NDI 0, it infers that the last transmissions is unsuccessful and starts retransmission on the dedicated resource indicated by DCI format 0. For the FDD system, the UE starts the retransmission three subframes later after receiving the DCI with format 0 as shown in Fig. 4. Besides that, there are still some UEs whose C-RNTIs cannot be successfully decoded. For these UEs, which do not receive the DCI information with format 0 at the expected time, new retransmissions with CBA are performed as shown in Fig. 6.

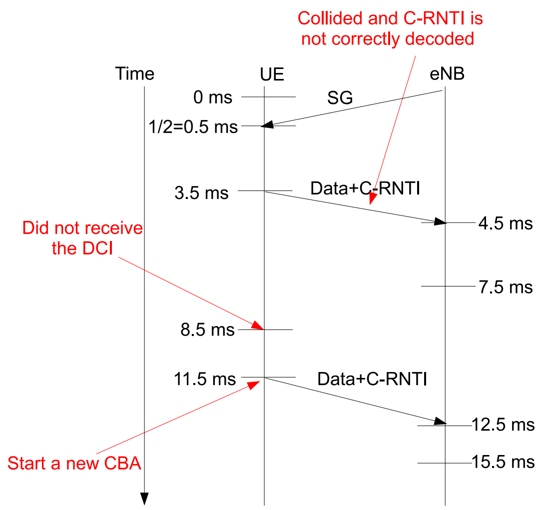

Fig. 6. CBA with unsuccessful collision detection

IV. Performance Analysis

Let us denote the total number of resource elements allocated for one CBA transmission as N_{RACH}. This contains the amount of resource elements used for control information transmission, denoted as N_{ctrl} in addition to those reserved for data N_{data}, i.e., $N_{RACH} = N_{ctrl} + N_{data}$. Therefore, The spectral efficiency of the control information is $R_c = 20/N_{ctrl}\text{bits/RE}$ under the assumption that the control information comprises 20 bits (16 bits for C-RNTI and 4 bits for MCS). Similarly, the spectral efficiency of the data is $R_d = M_{data}/N_{data}\text{bits/RE}$ where M_{data} is the bit of data payload.

For each contention based access transmission, we have the following 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 and (4) both the control information and data are detected, which is denoted as E_4. In order determine the probability of each event we take a an 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 $H_{m,n}[k]$ 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 computed as

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

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 $\mathbf{H}_i[k] = \left(H_{0,n}[k] \quad H_{1,n}[k] \quad \cdots \quad H_{N_{\text{RX}}-1,n}[k]\right)^T$. The use of this expression requires the two following assumptions. Firstly, all channels can be estimated at the receiver irrespective of the number of contending users. This has to make proper use of the cyclic shifts to guarantee contention-free access for channel estimation. In practice, for loaded cells with only CBA access, this will require association of UEs to orthogonal CBA resources (in time/frequency) and on a particular CBA resource a maximum of 12 contenting UEs can be accommodated. 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 [12].

Under these assumptions, the probability for events are: $\Pr(E_1) = \Pr(I_{ctrl} < R_c, I_{data} < R_d)$, $\Pr(E_2) = \Pr(I_{ctrl} < R_c, I_{data} > R_d)$, $\Pr(E_3) = \Pr(I_{ctrl} > R_c, I_{data} < R_d)$, and $\Pr(E_4) = \Pr(I_{ctrl} > R_c, I_{data} > R_d)$. In general, the control information is more protected than the data, i.e., $R_c < R_d$, so $\Pr(E_2) \approx 0$. The probability for a packet being delivered only after n transmissions is

$$p_0(n) = \begin{cases} \Pr(E_4) & n = 1 \\ \Pr(E_1)^{(n-2)} \Pr(E_3) + \Pr(E_1)^{(n-1)} \Pr(E_4) & n \in (2, M) \end{cases} \quad (3)$$

where M is transmission limit. The average latency is then

$$T = \sum_{n=1}^{M} T_n p_0(n) \quad (4)$$

where T_n is the time for a packet delivered with n transmissions.

To evaluate the performance of the proposed CBA method, the CBA is compared with two other methods: (i) regular scheduling with round-robin PUCCH allocations for scheduling requests, (ii) the method proposed in [1] where the PRACH is configured with index 14 such that the PRACH with 64 preambles is available in each subframe (largest amount of resources [10]). Regarding CBA method, the DCI with format 0A is transmitted in each subframe, therefore CBA can be performed in every subframe. Furthermore, perfect power control is assumed yielding $\gamma_0 = \gamma_1 = ... = \gamma_{N_u} = \gamma$. The packet arrives uniformly over a period of 100 ms, which is similar to the traffic model used in [1]. Moreover, the packet size is assumed to be of small size, following exponential distribution with average packet size of 200 bits.

The results obtained from simulations using the regular scheduling method and the RACH methods are compared with analytical results obtained with (4) in Fig. 7. The SNR γ is set to 5dB, 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 $\mathbf{H}_i[k]$. It can be seen that the latency with CBA is much lower than that of regular scheduling and RACH method, which also implies the throughput of our methods is higher than the other two methods. Moreover, it is found that the performance of CBA depends on the rate of control information R_c. When the number of user is 750, R_c=0.2 achieves the lowest latency of 6.1ms. While when the number of user is 1250, R_c=0.15 achieves the best latency of 10.3ms. Therefore, R_c should be carefully configured, and is a topic for future research. A careful optimization of R_c is likely to be more important for larger packet sizes.

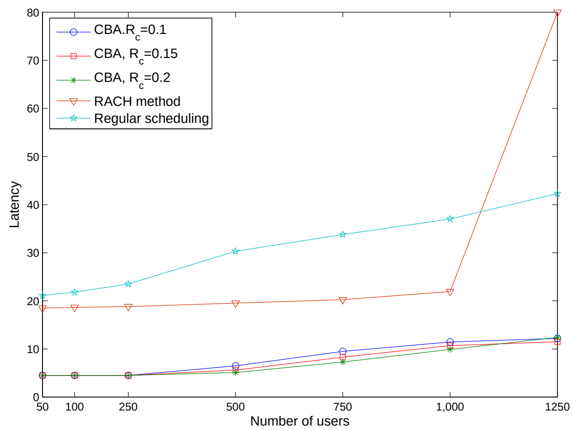

Fig. 7. Latency vs. network load

We also investigate the effect of number of receiving antenna on the performance of CBA (The SNR γ is 5dB, and R_c=0.15). As shown in Fig. 8, it demonstrates the latencies under different number of antennas are almost the same when number of users is 50 and 250. However, when the number of user increases, using more antenna attains lower latency. This is feasible because when the number of user is large, the interference is very serve which causes lots of retransmissions and hence increases the latency. While with more antennas, the channel capacity is increased and hence retransmission is reduced.

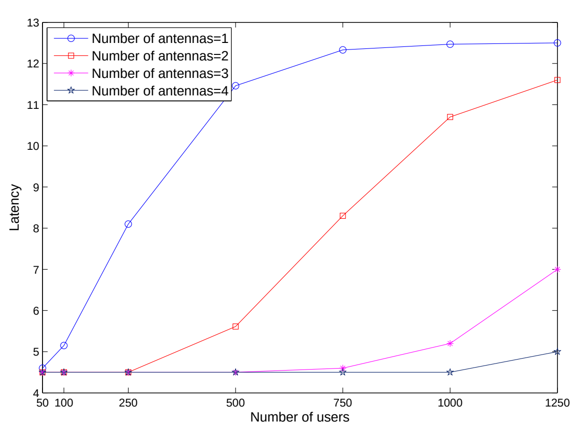

Fig. 8. Effect of number of antennas on the performance of CBA

V. Conclusion

This paper proposes a new contention based uplink channel access for MTC over LTE. With CBA, UEs select resource randomly without indications from eNB, which saves signaling overhead and hence the latency can be reduced. To address the problem of collision, a control header with higher protection combined with MU-MIMO detection at the eNB allows for the identification the collided UEs and their transport format so that it could allocate specific contention-free resources in subsequent subframes. The performance of the proposed method is compared with the regular scheduling method and RACH method and current results show that the CBA method can significantly reduce latency. Moreover, it is also found that the performance of CBA depends on the coding rate of control information and the number of receiving antennas.

VI. Acknowledgments

The research leading to these results has received funding from the European Commission under the Seventh Framework Programme (FP7/2007-2013)/ ERC grant agreement no. 248993 (LOLA).

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