Massive Access Management for QoS Guarantees in 3GPP Machine-to-Machine Communications

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***Abstract*—Realizing machine-to-machine (M2M) communications requires to construct and to manage scrupulous connections (logically and physically) from devices controllers to an enormous number of devices. By leveraging existing cellular infrastructures providing higher layers connections, the most challenging task is to efficiently manage massive accesses on the air interface. Consequently, in this letter, a massive access management (MAM) is proposed, which provides the most critical guarantees of quality-of-service (QoS), for devices. By deriving sufficient conditions of QoS guarantees, we show that the proposed MAM can effectively satisfy diverse QoS requirements, thus enabling the M2M communications over 3GPP scenarios.**

***Index Terms*—M2M, LTE-Advanced, MAM, QoS guarantees.**

I. Introduction

MACHINE-to-machine (M2M) [1]–[3] had been considered as a new type of communications that empower a full mechanical automation (such as the Internet of Things and the smart grid) that may change our living styles. Enabling M2M communications in 3GPP, however, is never an easy task. One major characteristic of M2M communications is that there are multiple machine-type communications (MTC) controllers (e.g., persons, power plants or the intelligent transportation system). Each MTC controller operates an enormous number of MTC devices (e.g., meters operated by the power plant in the smart grid) [2], [3]. As a result, how to construct scrupulous connections from each MTC controller to a large number of MTC devices emerges as a critical issue. In 3GPP, it is proposed that each MTC device attaches to the existing cellular infrastructure (e.g., LTE-Advanced) [2], [3], by which, higher layers connections between the MTC controller and MTC devices are provided. The subsequent challenge thus lies in the access management on the *air interface*.

In literature, few schemes had been proposed for MTC devices to attach to the base station (BS) such as the adaptive traffic load (ATL) slotted MACA in [4], the ATL S-Aloha in [5] and the access class barring in [6]. However, these schemes are insufficient. To achieve successful M2M communications, quality-of-service (QoS) guarantees provisioning is the most important requirement. For MTC devices, some applications (e.g., data reports from meters in the smart grid or navigation signals) require *deterministic* (hard) timing constraints, and disasters occur if timing constraints are violated. For some other applications (e.g., gaming signals), *statistical* (soft) timing constraints can be acceptable. Different from applications in human-to-human communications (e.g., multimedia) that packet arrival periods typically range from 10ms to 40ms, packet arrival periods in M2M communications can range from 10ms to several minutes (*infrequent transmissions* [2]). Thus, how to effectively multiplex such massive accesses with enormously diverse QoS characteristics turns out to be the most challenging task. In this letter, we consequently propose an effective access management for MTC devices to serve urgent needs for the air interface of M2M communications.

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II. System Model

As defined by 3GPP, M2M communications are with following features [2]: (i) Each MTC device only sends or receives a small amount of data (the *small data transmissions* feature). (ii) The (LTE-Advanced) network only allows the accesses of MTC devices within an allocated access grant time interval (AGTI) (the *time controlled* feature). (iii) Multiple MTC devices can be grouped as clusters for certain management purposes (the *group based MTC* feature). Consider a multiple access management problem with a massive amount of MTC devices attaching to the LTE-Advanced BS adopting the orthogonal frequency division multiple access (OFDMA). To manage such massive accesses with QoS guarantees, an effective solution is to adopt the *group based MTC* feature to group MTC devices into M clusters (indexed by $i = 1, \ldots, M$) based on QoS characteristics and requirements. This concept is also noted by [7]. MTC devices in the same cluster are with an identical QoS characteristic and requirement. In this letter, since jitter can fully capture the timing performance of periodic traffic, jitter is adopted as the main QoS metric.

The QoS characteristic and requirement of MTC devices in the ith cluster are characterized by three parameters (γ_i,δ_i,ε_i), where γ_i is the packet arrival rate and δ_i is the maximum tolerable jitter. Jitter is defined by the difference between the time of two successive (packet) departures and the time of two successive (packet) arrivals. ε_i is the acceptable probability that the jitter violates δ_i. Typically, there is only one application running over each MTC device. For an MTC device with an application requiring a *deterministic* QoS guarantee, $\varepsilon_i = 0$. γ_i for $i = 1, \ldots, M$ is known by the BS.

Due to the *small data transmissions* feature, the BS only supports an unique packet size for all MTC devices. Within an allocated AGTI, a fixed number of time-frequency domains radio resources (known as resource blocks, RBs) are given to support the maximum L MTC devices in each cluster. Denote the number of MTC devices in the ith cluster as n_i, $n_i \leq L$ for

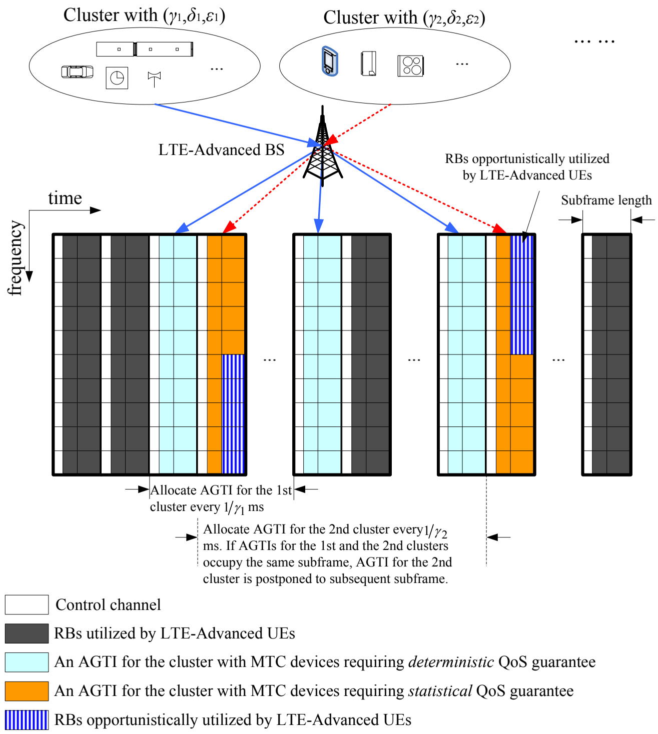

Fig. 1. The proposed massive access management.

$i = 1, \ldots, M$. A cluster with a larger γ_i has a higher priority. The priorities among clusters are sorted in the increasing order. That is, the first cluster has the highest priority.

III. Massive Access Management for MTC Devices

For clusters with MTC devices requiring *deterministic* QoS guarantees, the BS shall reserve RBs for these clusters to ensure a zero ε_i. On the other hand, to achieve an efficient RBs utilization and to satisfy certain QoS constraint of LTE-Advanced user equipments (UEs), the BS may *opportunistically* occupy RBs that have been allocated to clusters with MTC devices requiring *statistical* QoS guarantees. Such a massive access management (Fig. 1) is elaborated as follows.

Massive Access Management (MAM):

Step 1) The BS allocates an AGTI for the ith cluster every $1/\gamma_i$ ms, for $i = 1, \ldots, M$, according to the priority. Each AGTI for each cluster comprises L *allocation units*. If AGTIs for different clusters are arranged at the same subframe, the AGTI for the cluster with a lower priority is postponed to the subsequent subframe. An *allocation unit* comprises S_{MTC} RBs.

Step 2) Each MTC device in each cluster is allocated by one *allocation unit* of RBs to transmit at most one packet in the corresponding AGTI.

Step 3) The BS can allocate RBs unutilized by MTC devices in an AGTI to its UEs if $n_i < L$.

Step 4) Particularly, for clusters with MTC devices requiring *statistical* QoS guarantees, the BS can opportunistically utilize RBs (in *allocation units*) that have been allocated to MTC devices with a probability q. In this case, these RBs are marked as "unavailable" and MTC devices can not transmit packets on unavailable RBs. The availability of RBs is announced in the control channel.

In the following theorems, we provide sufficient conditions for all packets of MTC devices to satisfy their QoS constraints. Please note that each AGTI of all clusters does not overlap with each other and denote τ as the fixed length of an AGTI.

Theorem 1. *Let*

$$\delta_i^* = \tau + \sum_{k=1}^{i-1} \lceil \frac{\gamma_k}{\gamma_i} \rceil \tau, \; for \; i = 2, \ldots, M \tag{1}$$

and $\delta_i^* = \tau$ *for* $i = 1$. *If* $\delta_i^* + \tau < 1/\gamma_i$, *then the jitter of packets in the ith cluster is bounded above by* δ_i^*.

Proof: If we can show that each packet of MTC devices in the ith cluster has a maximum wait δ_i' and the packet can be delivered before the arrival of the subsequent packet,

$$\delta_i' + \tau < 1/\gamma_i, \tag{2}$$

then the jitter is not larger than δ_i'. We prove this by induction with hypotheses (i) $\delta_i' < \delta_i^*$ and (ii) $\delta_i' + \tau < 1/\gamma_i$. Consider the first cluster, the maximum wait is an AGTI τ, since the packet may arrive when the BS is serving the other cluster. Thus, $\delta_1' = \tau = \delta_1^*$. When the next AGTI comes, MTC devices of the first cluster can transmit their packets. To ensure that this is done before the next packet arrival of each MTC device, the sufficient condition is $\delta_1' + \tau < 1/\gamma_1$, which is exactly our assumption $\delta_1^* + \tau < 1/\gamma_1$. Suppose our induction hypotheses hold up to the $i-1$th cluster, we argue by contraction that $\delta_i' \le \delta_i^*$. Suppose $\delta_i' > \delta_i^*$, the BS must be serving all clusters for $k = 1, \ldots, i-1$, from time 0 to time δ_i^*. From (ii), the number of AGTIs within $(0, \delta_i^*)$ for $i-1$ clusters is at most $\sum_{k=1}^{i-1} \lceil \gamma_k \delta_i^* \rceil$. Therefore, the total amount of time that the packet in the ith cluster has to wait is bounded above by

$$\tau + \sum_{k=1}^{i-1} \lceil \gamma_k \delta_i^* \rceil \tau. \tag{3}$$

Since $\delta_i^* + \tau < 1/\gamma_i$ in (i) and $\delta_i^* < 1/\gamma_i$, (3) is bounded above by $\tau + \sum_{k=1}^{i-1} \lceil \frac{\gamma_k}{\gamma_i} \rceil \tau = \delta_i^*$, which is the definition of δ_i^*. Thus, the BS can not serve all i clusters in $(0, \delta_i^*)$. Therefore, we reach a contradiction, and $\delta_i' \le \delta_i^*$ and $\delta_i^* + \tau < 1/\gamma_i$. ■

Corollary 1. *For an MTC device (within, say the jth cluster) requiring a deterministic QoS guarantee, the QoS constraint can be satisfied if* $\delta_j^* \le \delta_j$.

Theorem 2. *For an MTC device (within, say the hth cluster) requiring a statistical QoS guarantee, the QoS constraint can be satisfied if* $\delta_h^* \le \delta_h$ *and*

$$q \le \min\{(\frac{\varepsilon_h}{1 - \frac{C_{x-1}^{n_h-1}}{C_x^{n_h}}})^{\frac{1}{x}}, 1\} \tag{4}$$

where $0 \le x \le n_h$ *is the number of allocation units of RBs allocated to MTC devices while these RBs are utilized by the BS.* C_b^a *is defined as* $C_b^a \triangleq \frac{a!}{(a-b)!b!}$.

We now devote to the proof of Theorem 2. Since the condition $\delta_h^* \le \delta_h$ is intuitive, the proof focuses on the condition (4). Since Theorem 1 and $\delta_h^* \le \delta_h$ are valid only if a packet of a MTC device can be successfully transmitted within an AGTI, the QoS constraint of an MTC device can be statistically guaranteed only if the probability that an

TABLE I
SIMULATION RESULTS OF CLUSTERS WITH MTC DEVICES UNDER THE MAM

Cluster	Characteristics (γ_i,δ_i,ε_i)[a]	Jitter bound in (1) (ms)	x	Upper bound of q in (4)	Setting of q	Max. jitter in simulation (ms)[b]	QoS violation prob. in simulation (per MTC device)
1	(0.1,2,0.1)	1	2	0.3333	0.1	0	0.00100
2	(0.05,4,0)	3	0	0	0	0	0
3	(0.05,6,0.1)	4	4	0.5956	0.1	0	0.00002
4	(0.025,12,0)	9	0	0	0	0	0
5	(0.01,50,0.05)	24	3	0.3889	0.1	1	0.00020
6	(0.01,60,0.02)	25	2	0.1491	0.1	1	0.00101
7	(0.005,80,0)	50	0	0	0	0	0
8	(0.004,100,0)	67	0	0	0	6	0
9	(0.002,150,0)	129	0	0	0	2	0
10	(0.002,200,0.05)	130	3	0.3889	0.1	2	0.00020
11	(0.001,500,0.02)	259	2	0.1491	0.1	0	0.00102
12	(0.00001,30000,0)	25951	0	0	0	0	0

[a] γ_i is in the unit of ms^{-1} and δ_i is in the unit of ms.
[b] For an MTC device requiring *statistical* QoS guarantees, if allocated RBs are utilized by the BS, this event is considered as an QoS violation and the jitter is not involved in the maximum jitter evaluations.

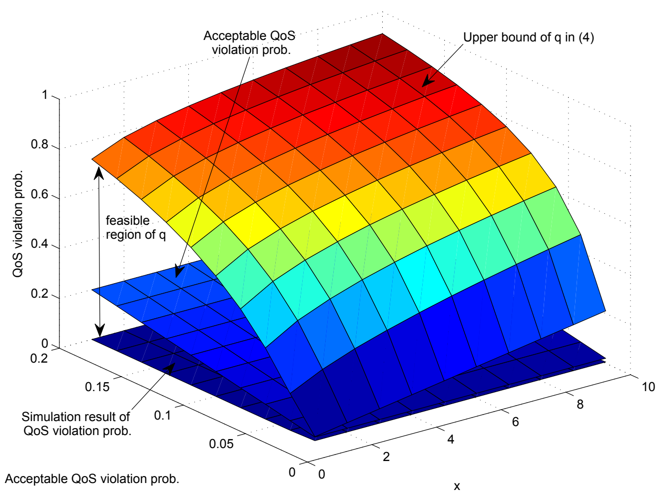

Fig. 2. Simulation results of the QoS violation probability per MTC device and the upper bound of q in (4) of the cluster with γ_i =0.1 and δ_i =2. q is set to the quarter of (4).

allocation unit of RBs allocated to the MTC device utilized by the BS does not exceed ε_h. This probability is referred as the "blocking probability". For an arbitrary MTC device among n_h, the blocking probability can be expressed as $q^x(1-\frac{C^{n_h-1}_{x-1}}{C^{n_h}_{x}})$. Therefore, $q^x(1-\frac{C^{n_h-1}_{x-1}}{C^{n_h}_{x}}) \leq \varepsilon_h$ and we can obtain (4).

These sufficient conditions serve as an effect access control in the BS to ensure that QoS constraints of admitted MTC devices can always be satisfied. Eqn. (4) also provides flexibilities to the BS to schedule LTE-Advanced UEs to achieve an efficient radio resources utilization.

IV. PERFORMANCE EVALUATIONS

In this section, we perform the experiment for the MAM by adopting the system parameters of LTE-Advanced [8]. Consider that the system bandwidth is 20M Hz and each AGTI is a subframe length (1ms) comprising 100 RBs to support 20 MTC devices in each cluster. Each MTC device occupies 5 RBs to transmit a packet of the size 1.28k bits. When 16-QAM is adopted, each RB can carry 336 bits. We consider 12 clusters and the simulation time is 100s. The packet arrival periods of clusters range from 10ms to 1.67minutes, which cover general applications in M2M communications.

Table I shows that the bound in (1) is very conservative and the jitter can be effectively guaranteed lower than the required value. It also shows that QoS violation probabilities of MTC devices requiring *statistical* QoS constraints are effectively controlled if q is controlled lower than the upper bound in (4). These results support the effectiveness on QoS guarantees of the MAM. In Fig. 2, the QoS violation probability under different x and ε_i is further evaluated. We can observe that the feasible region of q (q shall not be larger than the upper bound in (4)) is extensive. When q is set to the value less than (4), the QoS violation probability is effectively guaranteed less than ε_i, which illustrates the effectiveness of our design.

V. CONCLUSION

In this letter, we solve the most critical issue on the air interface of M2M communications to effectively provide QoS guarantees for a large amount of MTC devices with enormously diverse QoS characteristics. Such strict QoS guarantees provisioning is the key for applications of M2M communications to the smart grid or the intelligent transportation system scenarios, thus enabling the first and the last mile connections in M2M communications to serve urgent needs of the standardization progress in 3GPP.

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