On the Way to Massive Access in 5G: Challenges and Solutions for Massive Machine Communications

(Invited Paper)

Konstantinos Chatzikokolakis[1], Alexandros Kaloxylos[2], Panagiotis Spapis[2], Nancy Alonistioti[1], Chan Zhou[2], Josef Eichinger[2], and Ömer Bulakci[2(✉)]

[1] Department of Informatics and Telecommunications, National and Kapodistrian University of Athens, Athens, Greece
{kchatzi,nancy}@di.uoa.gr

[2] Huawei European Research Center, Future Wireless Technologies, Munich, Germany
{alexandros.kaloxylos,panagiotis.spapis,chan.zhou,
joseph.eichinger,oemer.bulakci}@huawei.com

Abstract. Machine Type Communication (MTC) is expected to play a significant role in fifth generation (5G) wireless and mobile communication systems. The requirements of such type of communication mainly focus on scalability (i.e., number of supported end-devices) and timing issues. Since existing cellular systems were not designed to support such vast number of devices, it is expected that they will throttle the limited network resources. In this paper, we introduce an effective solution for handling the signalling bottlenecks caused by massive machine communications in future 5G systems. The proposed approach is based on a device classification scheme using the devices' requirements and position for forming groups of devices with the same or similar device characteristics. Our scheme is analysed, and the evaluation results indicate that the proposed solution yields significant reduction in collisions compared to the standard when MTC devices attempt to access the Random Access CHannel (RACH).

Keywords: 5G · Group-based communications · Machine type communication · Massive connectivity · Random access channel

1 Introduction

According to the available predictions, the number of simple end-devices (e.g., sensors) that transmit short messages in periodic or asynchronous mode will grow considerably between 2013 and 2018, reaching 2,013 million in number, compared to 341 million reported in 2013, making thus, the need to be supported by 5G systems imperative [1]. The communication of such devices with the core network is commonly referred as Machine-to-Machine (M2M) Communication or Machine Type Communication (MTC) [2]. To efficiently support M2M communication, it is required to design new schemes that will lead to the reduction of signalling messages both in downlink and in uplink communication and avoid potential communication bottle-

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necks for a 5G operator in channels such as the random access and the paging. In this paper, we focus primarily on the uplink communication and, more specifically, on how a vast number of devices can be supported through a 5G Random Access CHannel (RACH).

Massive MTC scenarios require the development of innovative solutions so as to avoid signalling congestion in future mobile communication networks. The current design of mobile networks is tailored for human-to-human (H2H) communications (i.e., Telephony, SMS, Streaming services, etc.) [3]. In such deployments, for accessing the network, the user equipments (UEs) follow the contention-based random access procedure, which occurs in LTE networks in every Random Access Opportunity (RAO). However, such network designs are unlikely to be able to handle the MTC applications, where a large number of machines will attempt to transmit simultaneously small amounts of data.

For massive MTC, the collision rate is large for the RACH access procedure, as the number of devices is very high for a single cell; whereas, the number of the RACH preambles is very limited. For example, assuming a cell with 1000 users, 64 RACH preambles and 30ms packet arrival interval, the collision probability is almost certain (99.97%) [4]. Furthermore, the MTC network characteristics impose additional requirements for mobile networks. Specifically, deployment of large number of devices will lead to collisions that will increase the battery consumption for the MTC devices. Periodic network access may lead to increased latency and QoS degradation, and poor spectrum efficiency may occur due to allocation of resources for small data transmissions.

This paper is organized as follows. In the next section, we provide a thorough analysis of the state of the art approaches for improving the access to RACH, and we assess their suitability for 5G communication networks. In Section 3, we present a novel solution for reducing the collisions of MTC devices during the RACH access and, in Section 4, we provide evaluation results that show resiliency and robustness of the proposed solution against the demanding conditions of a 5G network. Finally, Section 5 concludes the paper.

2 State of the Art Analysis

Numerous solutions for handling the RACH procedure in wireless networks with large number of devices have been proposed in the literature. Those solutions can be classified into *pull-based* and *push-based schemes* depending on the signalling process.

The *pull-based schemes* may be further classified into several categories. In Access Class Barring (ACB) schemes [5]-[8], the UEs are categorized to access classes, and based on their access class, the UEs determine whether their RACH procedure should be delayed. Physical RACH (PRACH) resource separation between H2H and M2M schemes [9] suggest that the separation of resources can be achieved by separating either the preambles or the time-frequency RACH resources (i.e., Resource Blocks) into two groups so as to increase the PRACH slots reserved for MTC and reduce collisions. Solutions on Dynamic allocation of RACH Resources [10]-[12] suggest that base station (BS), referred to as evolved Node Bs (eNBs) in long-term evolution (LTE) networks, dynamically allocate PRACH resources based on PRACH overload and, thus, coordinating the overall procedure and reducing the failed attempts. In back-off schemes [6][8][13], the random access attempts for MTC devices and typical user terminals are treated separately using different delay schemes. Additionally, for reducing the collision rate, MTC devices could be classified further based on their delay requirements, and different back-off procedures could be applied for the various classes [6]. In addition, these solutions could be combined with other approaches (e.g., group-based random access procedure in case of collisions [13]). Other approaches focus on slotted access [4] where M2M terminals are allowed to transmit preambles in specific random access slots. In such schemes, each eNB broadcasts the random access cycle, and MTC terminals calculate random access slots based on their identity and the received random access cycle. However, preamble collision is unavoidable if several M2M devices share the same random access slot. Finally, in group (aka, cluster) based solutions MTC devices can be grouped according to QoS requirements [14] or geographical location [13][15]. In these approaches, a group head is selected to communicate with the eNB on behalf of the group. The group head receives requests from group members and relays them to the eNB.

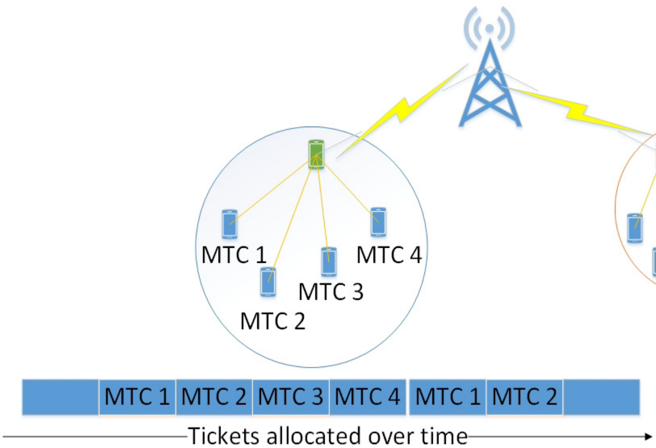
The *push-based schemes* are paging-based approaches in which the RACH procedure is triggered by the eNB rather than the UE. All MTC devices in idle mode listen to the paging message, and the devices initialize random access procedure when their IDs are included in the paging message [16].

However, the above-mentioned solutions are not targeting 5G networks and are not sufficient to fulfil the stringent requirements for future cellular communication networks. As described afore, random access resources are extremely limited for the considered number of devices, and the collisions during the random access procedure lead to unacceptable latency levels. Although some of the solutions are applied in MTC scenarios, they are only evaluated for a small number of devices ranging from tens to few hundreds, making their scalability questionable.

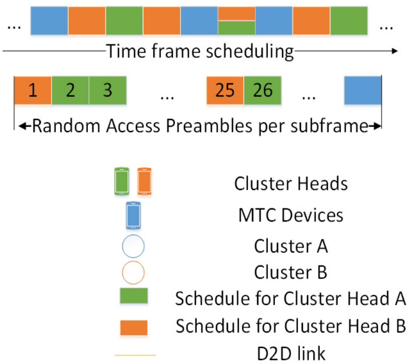
A solution that follows a form of slotted access scheme seems appropriate so as to avoid extra collisions. Furthermore, as the network environments will be much denser in the future, it is reasonable to assume that the devices can compose groups with direct communication so as to alleviate the load of the BS. Thus, the combination of clustering mechanisms, slotted access scheme, and possibly device-to-device (D2D) communication between the Cluster Members (CMs) seems as a promising solution.

3 Classification and Cluster-Based RACH Access of MTC Devices

In the previous sections, we have provided a brief analysis of the available solutions in the literature related to MTC in cellular networks, and we have argued that, in 5G communication scenarios, the existence of huge number of MTC devices will lead to signalling congestion when accessing the RACH. In this section, we provide a description of our solution. The proposed scheme aims at optimizing the random access process using:



(a)



(b)

Fig. 1. MTC RACH access scheme.

a) device classification and clustering mechanisms,
b) D2D communication inside each cluster, and,
c) an appropriate slotted access scheme for the communication of the Cluster Heads (CHs) with the network.

Figure 1 captures a conceptual view of the considered environment with huge number of MTC devices operating and attempting to access the RACH. The devices should be classified based on their communication needs and should form clusters according to their location and mobility patterns. As illustrated in Figure 1 (a) the Cluster Members will send their data to their Cluster Head with D2D links following a time-slotted scheme for intra-cluster communication. The Cluster Heads are responsible to send the aggregated data to the network. In order to do so, Cluster Heads follow the scheduling information received from the network. In Figure 1 (b) is shown that the network may decide to allocate entire subframes (or even time frames) to specific Device Classes, or multiplex Cluster Heads with different Device Class in the same subframe by providing dedicated preambles to each Device Class.

For the device classification purposes, MTC device information (i.e., transmission periodicity, data size, packet delay, device's mobility, etc.) is sent to the BS during the attach process. Then, the BS determines the Device Class (DC) for each MTC device based on the aforementioned received information. In order to do so a clustering mechanism with hierarchical splitting is followed. Firstly, the devices are split to devices that communicate periodically with the network and to the ones that communicate in an asynchronous manner. The latter class is no further split. Then all the devices that follow periodic communication with the network are further split to classes according to their periodicity (i.e., once per second, once per hour etc.). Finally, each of these groups is further split based on the communication delay requirements of the devices. Figure 2 illustrates the splitting operation that produces the DCs.

Afterwards, the BS determines the clusters of the MTC devices residing in the cell and the CH based on location and mobility information received from the MTC devices. In order to perform the geographical clustering of devices with the same Device Class, we have used the k-means clustering algorithm. K-means clustering is a well known method for cluster analysis used in data mining field that aims to partition n observations into k clusters in which each observation belongs to the cluster with the nearest mean, serving as a prototype of the cluster. Then, the BS notifies the MTC devices regarding their DC, the cluster they belong to, and the ID of their CH. Thereafter, three types of communication steps are required to realise the proposed solution.

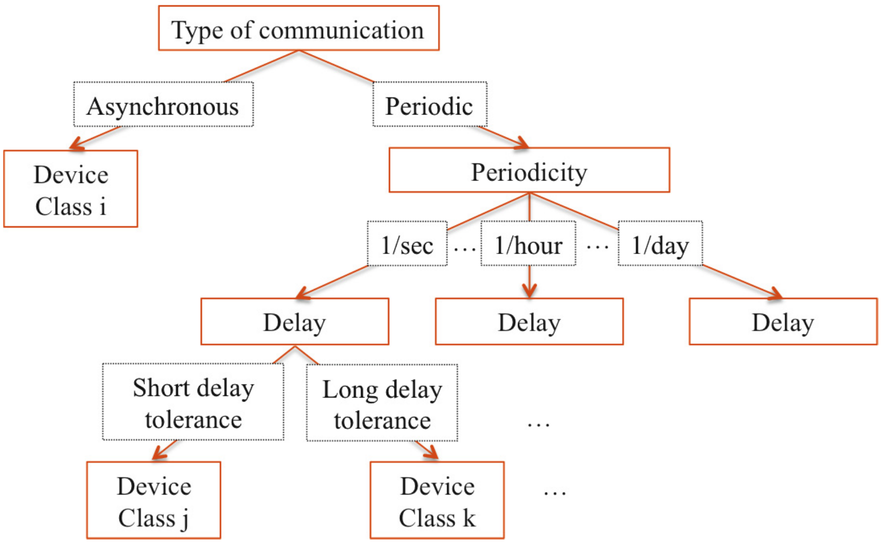


Fig. 2. Hierarchical splitting operation for Device Classes

The first type comprises a set of messages exchanged between the BS and the CHs. Firstly, the BS broadcasts RACH access scheduling information to CHs. The CHs are scheduled to be able to transmit periodically every *N* time slots with the BS. *N* may vary for different CHs depending on their DC, which determines the communication needs of the DC. Then, CHs attempt to access RACH during the specified RAOs, as scheduled. On successful communication, the CH transmits the aggregated monitoring data of its cluster to the BS. Although the CHs that transmit periodically are multiplexed and, thus, scheduled on specific time frames (specified by a periodicity factor), collision may still occur either due to having too many CHs scheduled in a frame or, due to having RACH access attempts triggered from devices with asynchronous communication. In case of collisions, the BS reschedules the CHs and broadcasts the new schedule to the CHs.

Table 1. Classification and Cluster-based RACH access algorithm

Step	Description
0	MTC devices are attached to the network and they send their device information
1	eNB determines the Device Class of the MTC devices through a clustering mechanism with hierarchical splitting
1.1	∀ MTC device perform classification based on Type of Communication and produce two classes of MTC devices; the ones with periodic transmissions and the ones with the asynchronous transmissions. Devices with asynchronous transmissions are no further classified.
1.2	∀ MTC device with periodic transmissions perform classification based on the devices periodicity and give label s to the device, s ∈ ClassLabels = {$class^1{}_1$, $class^1{}_2$, …, $class^1{}_i$,…,$class^1{}_N$)
1.3	∀ i ∈ ClassLabels, ∀ MTC device perform classification based on communication delay and add label t to the device, t ∈ $ClassLabels^2$ = {$class^2{}_1$, $class^2{}_2$, … $class^2{}_i$, … ,$class^2{}_N$). Each device has an s, t label now
2	Based on the Device Class of each device perform geographical clustering using k-means. The value of k determines the number of clusters and the maximum geographical distance between the CH and a CM.
3	eNB notifies the MTC devices regarding their DC, the cluster they belong to, and the ID of their CH. CHs also receive scheduling information for accessing the RACH
4	CH performs time-division scheduling, and broadcasts reservation token information to the CMs. D2D communication sessions with the CMs according to the produced schedule are established
5	CH performs RACH access on the RAOs defined by the network
6	Steps 2-5 are repeated so as to perform cluster merging particularly for non-stationary devices

The second type of communication comprises a set of signalling steps for intra-cluster communication between the CH and each CM. Initially, the CH produces a time-division schedule, distributes reservation token information to the CMs, and establishes D2D communication sessions with the CMs according to the produced schedule. Then, the CMs communicate with the CH according to the schedule received. In case CMs leave a cluster, they notify first the CH over specific tokens reserved by the CH for control information, and they wait for a reply from the CH. Once the device has left the cluster, the CH calculates, if necessary, a new schedule and disseminates it to the CMs.

Finally, the third type of communication is related to the operation of merging clusters. In this case, the CH needs to communicate with MTC devices that are not members of the cluster. Such operation is executed by the BS, if needed. More specifically, BS may decide merging of clusters based on their position and their mobility patterns. In that case, the BS will send a notification to the CHs to merge and indicate which device will be the new CH of the merged cluster. Table 1 summarizes the proposed mechanism steps.

4 Evaluation Results

For the assessment of the proposed scheme, we have utilized a simulation scenario comprising several machine types with various service requirements and mobility characteristics. The purpose is to assess the proposed scheme's capability to reduce the overhead of RACH due to massive deployment of MTC devices in a small geographical area. In our simulation scenario, we have assumed the deployment of 1 BS in the area, having 1 RAO per time frame (i.e., maximum 64 devices per time frame may successfully access the RACH due to 64 random access preambles available). Table 2 summarizes the simulation setup in terms of numbers of devices, traffic characteristics, and devices' mobility for a massive deployment of MTC devices in a 5G scenario, see Test Case 11 *Massive deployment of sensors and actuators* in [17]. The devices have been uniformly distributed to those characteristics.

Table 2. Requirements for MTC scenario in 5G networks.

Type	Value
Number of devices	[30.000, 300.000]
Transmission Periodicity	Periodic (1/minute, 1/hour, 1/day) or asynchronous
Data Transmission size	20, 75 or 125 bytes
Packet Delay	Small delay [5,10] msec or Larger delay [1, 5] sec
Device's Mobility	Stationary or Low mobility (i.e., <3km/h)

In the evaluated scenario, we have dropped uniformly the considered number of devices in the 387 m x 552 m grid area covered by the BS [18] and have measured the number of collisions and the collision rate of the devices over a time window of 1 hour when accessing the RACH. Figure 3 highlights the merits of our work compared to the current standard and shows significant gains regarding the collision rate. More specifically, applying our solution to the network reduces 2 times the collision rate for 30.000 devices and as the number of the devices increases we end up having up to a 2.8-time collision rate reduction for 300.000 devices.

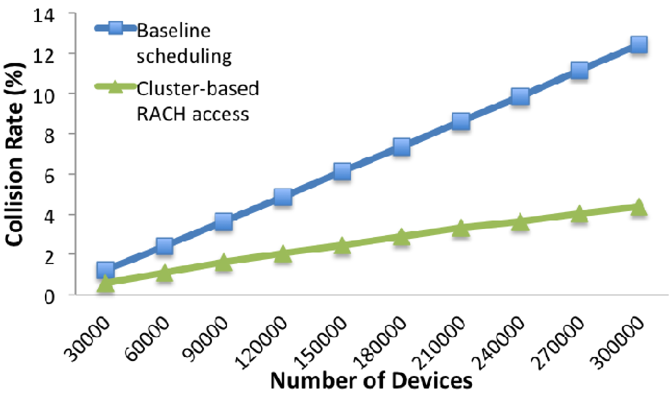


Fig. 3. Collision rate

Figure 4 highlights the benefits of our solution regarding the total number of collisions. The collisions are 4 times reduced for 30.000 devices, while this reduction reached up to 7.3 times for 300.000 devices. Overall, we observe that the developed scheme enables the deployment of a large number of devices in a small deployment area, since we take advantage of the similar traffic characteristics of co-located devices.

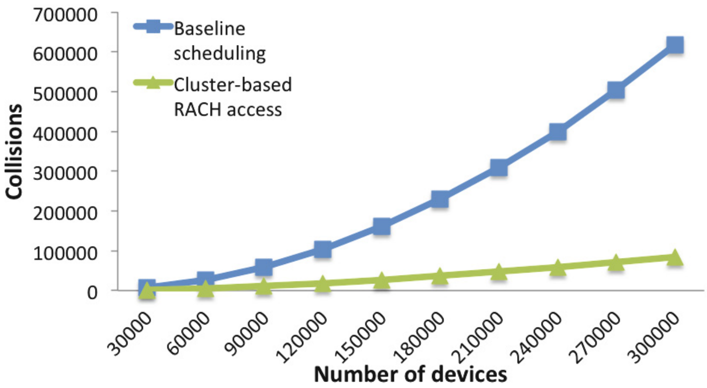


Fig. 4. Total number of collisions

5 Conclusion

The vast increase of the MTC devices that is expected for 5G networks will lead to exhaustive usage of limited network resources, such as the RACH. Additionally, such devices may have strict latency requirements and limited battery lifetime, making, thus, the collision rate of their requests a critical point that should be carefully studied. In this paper, we have assessed how currently available solutions may fail address these problems adequately and, we have presented a cluster-based solution, which exploits the traffic and mobility characteristics of each MTC device. The results show significant reduction in the collision rate and the number of collisions, and indicate the effectiveness of group-based communication schemes to address the requirements of future networks. The proposed solution is evaluated for a 5G scenario with massive deployment of sensors and actuators. In this particular scenario the considered devices are stationary or have low mobility. Although our proposed mechanism could also be applied in other scenarios by adapting the frequency of performing geographical clustering, the device classification process would be different as the communication requirements would also vary compared to the tested scenario.

Future directions for this work include formalizing the communication messages and the interfaces required to realize the proposal, and evaluating the performance under various deployment scenarios (e.g., smart grid applications and emergency scenarios). Extending the mechanism so as to support vast increase of unscheduled events (e.g., in case of emergency) would also be of interest for future work. Finally, the effect in the power/battery consumption could be considered as well, since the machines grouping and coordination seems to increase the battery durability of the sensors, due to the lower transmission power required for communicating via the cluster head.

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