Virtual Bearer Management for Efficient MTC Radio and Backhaul Sharing in LTE Networks

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***Abstract*— The increasing adoption of Machine Type Communication (MTC) applications using the Long Term Evolution (LTE) brings new challenges for the traditional bearer allocation and network management. MTC devices are high in number, each requiring an individual bearer for a short data transmission; an inefficient process considering the signaling and management effort to the duration of the actual bearer use. This paper introduces the notion of a virtual bearer that can be shared among a number of MTC devices with similar Quality of Service (QoS) characteristics. The virtual bearer support at the MTC device side is based on the paradigm of Network Function Virtualization (NFV) and can migrate from one MTC device to another eliminating the need for individual device bearer establishment for both the radio and backhaul. The use of virtual bearers is enhanced by considering additionally MTC device-to-device (D2D) connectivity allowing devices without direct access to the network to use the virtual bearer via other devices, which act as gateways. Gateway devices may also be re-located dynamically based on NFV principles. In this way, a finer control is achieved on prioritizing certain services and providing load balancing. Our simulation results demonstrate the benefits of our proposed scheme compared to conventional approaches wherein MTC devices use individual bearers to send data in response to a trigger or according to a predetermined schedule.**

I. INTRODUCTION

3GPP Long Term Evolution (LTE) aims at providing high speed broadband connectivity enhancing the network capacity and service quality. Among the different services supported by LTE, new evolving ones that take advantage of the LTE ubiquitous coverage involve machine communications without human intervention. Such communication paradigm introduces new requirements, which are different from conventional human communication because of the plurality of MTC devices and the need to transmit small data at infrequent periods. 3GPP has already specified the network architectures for supporting such MTC devices and services, while is currently exploring ways to optimize the network usage for supporting large number of MTC devices [1][2][3].

In particular, it is estimated that a large number of MTC devices are affiliated with a single MTC service wherein a single MTC server is allied with a number of MTC devices. Such MTC server and devices are connected through a packet switched network owned by a mobile network operator via an Access Point Name (APN) using the SGi interface. Typically, if there are n numbers of MTC users who owns m numbers of MTC devices, $(n * m)$ number of devices need to transmit small data, and for each individual transmission the radio and S1 bearer needs to be re-established when moving from ECM_IDLE to ECM_CONNECTED state per device (ECM - EPS Connection Management).

When many MTC devices send small amounts of data, the Radio Resource Control (RRC) connection setup, radio bearer setup and S1 bearer setup generate more signaling than the size of the actual data payload that needs to be transmitted. Such a process may easily cause congestion considering the associated signaling in combination with the high number of MTC devices, which may try to access the network almost at the same time in an attempt to either attach to the network or to activate/modify/deactivate a Packet Data Network (PDN) connection. More details regarding such use cases are given in 3GPP TS 22.368 [4]. In fact, it would be beneficial to minimize the Non-Access Stratum (NAS) signaling, S1 and radio bearer re-establishment procedures [3].

To achieve such signaling reduction, this paper introduces the concept of virtual bearer; i.e. a bearer, which is initially established following the conventional paradigm but then shared by a specified set of MTC devices simply by shifting its parameters from one device to another following the NFV paradigm [5]. Hence, a group of MTC devices do not need to individually establish a radio and backhaul bearer, reducing in this way the otherwise associated signaling. To enhance the use and vicinity of such a virtual bearer, MTC D2D (Device-to-Device) communications as introduced in [6] is also considered. In such a case, a certain MTC device that currently uses the shared virtual bearer can act as a gateway that relays traffic on behalf of other MTC devices, which have connectivity only via a D2D communication means. Gateway devices may also be virtualized in the sense that the corresponding gateway functionality may dynamically be migrated among the set of MTC devices, which share the virtual bearer following again the NFV paradigm.

A simple example that demonstrates the main concepts and usage of our proposed scheme is illustrated in Fig. 1, considering MTC services provided within the Operator premises and via the Internet. Each base station, or in the 3GPP's terminology evolved Node B (eNB), may support a range of different MTC groups and MTC individual devices and schedule them according to their QoS demands , mobility features, or other device-specific requirements. Every MTC group shares the same bearer, which is used by one device at a time that acts as a gateway, holding the Gateway Virtual

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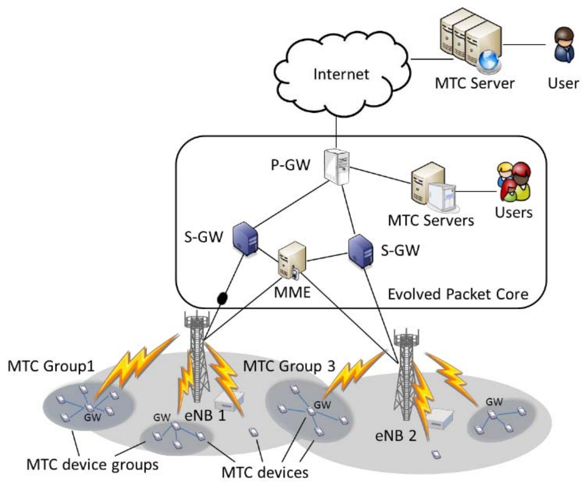

Fig. 1. Simple use case scenario of the proposed mechanism.

Machine (GVM) and providing connectivity for other devices via a D2D communication network. The way in which groups are formed may serve coverage extension purposes, e.g. MTC group 1 in Fig. 1 connects devices without LTE coverage. Additionally, MTC groups could serve load balancing or service prioritization by associating specific devices towards a less loaded eNB, e.g. MTC group 3 connects selected devices in eNB 1 coverage to eNB 2. Effectively, this would increase flexibility permitting selected MTC devices to divert the associated traffic towards neighboring eNBs beyond their coverage range.

Such decision could also be complemented considering the backhaul load as well as the load corresponding with the associated Serving-Gateway (S-GW). Hence, connecting MTC devices with eNBs beyond their coverage could reduce potential congestion in the Radio Access Network (RAN) and the Evolved Packet Core (EPC) providing also service prioritization by associating a certain group of devices with a less loaded eNB that can serve them faster. Finally, the use of D2D communications could also prove beneficial to conserve battery of devices that are within critical need of power, mainly due to shorter transmission distance.

The remaining of this paper is organized as follows. Section II presents some related work. Section III introduces our proposed virtual bearer scheme and elaborates D2D extensions via the use of gateway MTC devices. The simulation, analytical study, and result analysis are presented in Section IV. Finally, Section V provides the conclusions and some further research directions.

II. Related Work

The increasing growth of cellular-based MTC services, as forecasted in [7], which is accompanied with an increase in MTC devices deployment could potentially generate a huge amount of data and signaling traffic, creating congestion for the radio and core networks [3][8]. The problem of congestion in cellular networks caused by the operation of MTC devices has been widely studied with the most common solutions concentrating on Random Access Channel (RACH) overload control [8][9] and uplink scheduling of MTC devices [10]. In 3GPP, a first set of solutions that deal with small data optimization are explored in [1]. Admission control policies based on congestion awareness, as described in [11], may further enhance congestion control by selectively restricting access for particular MTC devices according to a probability which reflects the level of network congestion.

To support efficient access for a large number of MTC devices with diverse characteristics in terms of QoS, prioritization, transmission times and mobility features, several schemes introduced grouping or clustering. MTC devices within the same group share identical QoS characteristic and/or other device requirements, e.g. mobility. The objective of grouping is to simplify the resource management allocation, which is performed on a cluster basis and not for individual MTC devices. A QoS-specific MTC grouping scheme is analyzed in [8], considering the tradeoff between resource management simplification, by creating large groups, and MTC service performance, taking into account device transmission delay requirements and group prioritization. Another approach that considers a similar MTC grouping with the purpose of overload control is described in [12] taking into account the use of the 3GPP data offloading techniques via femtocell access.

Besides resource allocation, grouping may also be used to compact MTC data related to a group of devices that share common information, i.e. identical subscriber features, by creating a profile ID for the group as introduced in [13]. In this way, the actual amount of data exchanged between LTE nodes is reduced, while the option of dynamic grouping based on overload conditions allows finer network control of MTC traffic. An alternative solution that combines MTC-IWF (MTC Interworking Function) to reduce signaling related to triggering MTC devices with low mobility features without involving the Mobility Management Entity (MME) and dynamic grouping of MTC devices sharing redundant information elements by creating a profile group ID is proposed in [14], grouping together devices with common Information Elements, e.g., subscription features.

Our proposed scheme also employs dynamic grouping, but unlike prior art solutions, it uses dynamic grouping for bearer sharing along the RAN and core network. MTC groups are formed based on QoS and transmission times assuming low mobility features, similarly to [14], while MTC devices utilize D2D communications, similarly to [15], also adopting the concept of MTC gateway, which relays data on behalf of other devices. Unlike other approaches, we also explore the impact of gateway relocation shifting the gateway functionality from one MTC device to another, in order to accommodate the requirements of dynamic grouping, while providing load balancing and traffic prioritization avoiding congestion. In 3GPP, bearer sharing is not an entirely new concept. Bearer sharing is employed for broadcasting and multicasting, i.e. Multimedia Broadcast/Multicast Service (MBMS) bearer [16], where devices share radio and core network resources to transmit and receive the same data at the same time. In our proposed scheme, the shared bearer is used for virtualizing the MTC group so that the network would treat it as a single entity, allowing devices within the same group to utilize the shared bearer sequentially, transmitting and receiving different data.

III. Virtual Bearer Principles and Mechanisms

The envisioned network architecture consists of a 3GPP LTE network, wherein D2D communications are enabled among MTC devices using Wireless Local Area Network (WLAN) or LTE-direct (currently studied in [6]). The shared virtual bearer stretches along the Radio, S1 and S5/S8 interfaces enabling a single MTC device, out of the group, which holds the Gateway Virtual Machine (GVM) function, to transmit and receive data. MTC devices that form a group share the same subscription, with similar transmission or reception timing demands. Besides device service characteristics, MTC groups are formed considering devices' geographical locations, in combination with RAN and EPC congestion level information, accounted as the expected buffer length at eNB and S-GW. The GVM-enabled MTC device is preferably a device with low mobility features, within the coverage of an eNB, which is selected to carry the group's traffic, while also being capable to provide D2D connectivity to other group devices beyond the coverage of the selected eNB. eNBs are selected to carry a predetermined groups' traffic based-on the expected buffer length, with the objective to provide load balancing and service prioritization.

MTC groups can be preconfigured in the Home Subscriber Server (HSS) if the traffic produced is deterministic or it can be dynamically arranged to reflect altering usage demands, a more common scenario [13][14]. A centralized management entity, e.g. the Self-Organized Network (SON) server [17], which keeps track of the network performance, may assist such a process provided that it cooperates with the corresponding MTC Server. MTC group specific information is eventually supplied to MME at time when each MTC device attaches to the network together with the corresponding subscription information. MME may then suggest which MTC device should operate GVM first or even the entire sequence of MTC devices that need to exchange the GVM functionality.

GVM is the network function that enables virtualization, making a MTC group to be treated as a single device. GVM can migrate from one MTC device to another within the same group, eliminating the need for an individual device bearer. It contains all the bearer related information including Radio, RRC, and Packet Data Convergence Protocol (PDCP) state, as well as all MTC group specific data including Radio Network Temporary Identities (RNTI), group keys, group IMSI (International Mobile Subscriber Identity), group TMSI (Temporary Mobile Subscriber Identity), group IP address, group ID etc.

When GVM migrates from one MTC device to another, the timing advance value, i.e. the time duration a signal needs to reach the eNB, may need to be adjusted since the locations of MTC devices are expected to be different. The GVM receiving

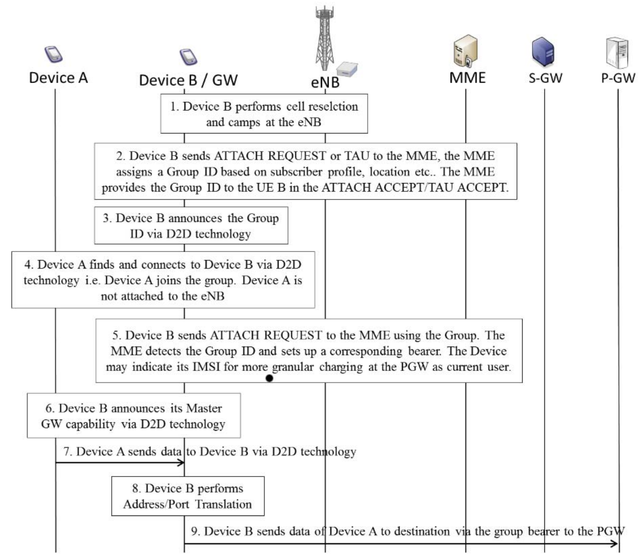

Fig. 2. Establishing and advertising the GVM-enabled device.

device needs to inform the associated eNB about changing the group RNTI in order to enable only the device hosting GVM to decode the DCI (Downlink Control Information). Downlink data is then DCI masked with RNTI, i.e. only the GVM-enabled device can read the DCI and can perform the corresponding mapping of downlink packets towards the appropriate MTC device of the group, which is connected via D2D communications. It should be noted that for sharing radio bearer, not the same security context is used by all devices in the network; instead a group key is allocated only to certain devices, which are authorized to join specified groups. Considering the security for direct device communications, it is assumed that it is handled by the specific D2D technology.

In the following, we elaborate in detail the two fundamental processes of our proposed scheme including (i) the establishment and advertisement of the GVM-enabled MTC device and (ii) the migration of the GVM functionality from one device to another. Fig. 2 shows the call flow for establishing and advertising the GVM-enabled device and for providing connectivity to group members via D2D communications. Initially all MTC devices within the LTE coverage attach to the network to be authenticated and then the MME provides them with the appropriate MTC grouping information.

In Fig. 2, device B initially performs a cell reselection, camps on eNB and then sends, to the associated MME, an ATTACH REQUEST or Tracking Area Update (TAU), in case it is already attached to the network and just moved into a new cell. MME, in turn, assembles the corresponding group information (e.g., group IMSI, group ID, group Key, and group TMSI) based on subscription profile and provides such group information to device B in the reply message, i.e. ATTACH ACCEPT/TAU ACCEPT. MME may also provide, in the same message, a list of how GVM should be exchanged among the group devices. Device B then configures GVM and announces/broadcasts the group ID via the D2D connectivity towards other group devices in order to get informed. The device that holds GVM, i.e. device B, also sends an ATTACH REQUEST to MME using the group IMSI as identity. MME detects the group IMSI and sets up a bearer that reflects the QoS requirements of the corresponding group, while the Packet Data Network-Gateway (P-GW) assigns an IP address for the group IMSI. The device identity, e.g. IMSI should also be included for more granular charging at P-GW.

Once GVM is configured, device B announces its active gateway capability, i.e. hosting the GVM, via the D2D network. Hence, all other group devices would become aware of the GMV device, which currently transmits or receives data via the shared bearer. Other group devices, outside the coverage of eNB, can then use such GMV-enabled device to connect to the network via direct device communications provided that they include their identity, e.g. IMSI, IMEI, or ICSI within the communication process. For instance, in Fig. 2, device A can send data towards the LTE network via device B, which, in turn, performs address/port translation for device A and propagates its data to the final destination via the shared bearer to P-GW. In addition, device B also collects charging records, which are provided to the application server before releasing the GVM to another device.

The transfer of GVM from one MTC group device to another is illustrated in Fig. 3, wherein both devices A and B belong to the same MTC group and are already authenticated camping at the same eNB. Assuming that device B, which is hosting the GVM has just completed transmitting or receiving data, we describe the process of transferring such GVM to the next MTC device, i.e., device A. If information regarding the next device that needs to use the shared bearer is already provided to MME, it would inform device B, which transfers the GVM directly to the corresponding MTC device, i.e. to device A, as indicated in Step 6 in Fig. 3, skipping Steps 3, 4 and 5.

Otherwise, when the next device that needs to host GVM is not known to MME, a discovery process is triggered by the device that currently holds GVM, i.e. device B in Fig. 3, which announces via the D2D network that it can release GVM. Devices within the group that need to use the shared bearer respond to such an announcement, optionally indicating the urgency of using the shared bearer. The GVM-enabled device would examine such requests and then transfer GVM to the appropriate device. Alternatively, when a device needs to send data, it informs the current GVM-enabled device, which keeps a record of that in order to decide later where to transfer the GVM functionality. In Fig. 3, device A requests the GVM, which is transferred from device B. The GVM transfer includes the Evolved Packet System (EPS) bearer context, the Signaling Radio Bearer (SRB), Data Radio Bearer (DRB), APN, IP address, PDCP state, RRC state, etc. Such information may also be signed by device B so that MME can check that device A correctly received GVM.

Device A configures the GVM and then announces itself as a gateway device hosting GVM via the D2D network. Hence, other devices that use only the D2D network would know

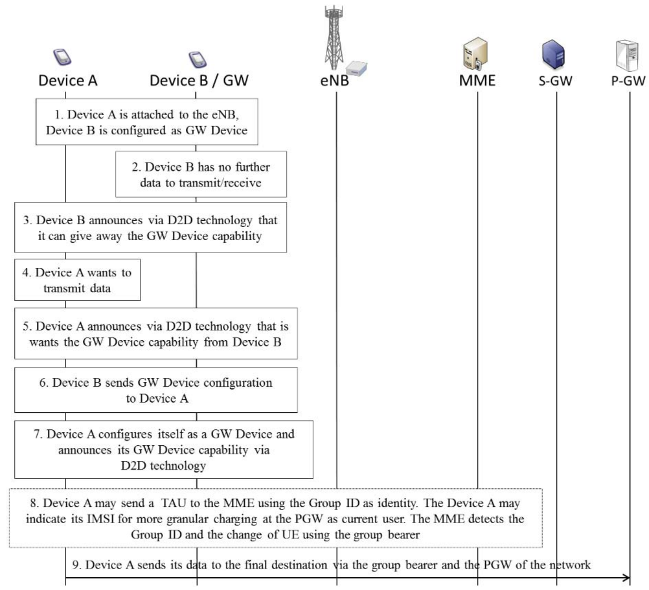

Fig. 3. GVM migration.

about the location of the new gateway. The actual configuration of GVM in device A may be carried out in one of the following two ways. Device A informs eNB about the GVM reception and eNB, in turn, changes the group RNTI in order to enable only such a device to decode DCI. Alternatively, device A sends a TAU message to MME using the group ID, optionally including the signature of device B to let MME know that it received GVM from device B. MME, in turn, reads the group ID and updates its records regarding the GVM-enabled device. Eventually, device A can transmit and receive data, also on behalf of other devices using the shared bearer.

In case the shared bearer is not in use or becomes no longer needed by another group device, eNB may release such radio and S1 bearer after a predetermined idle period. The current device hosting GVM realizes when the shared bearer is released and announces this via the D2D network. This means that the next MTC device that needs to use the shared bearer has to first perform a service request to re-activate the shared radio and S1 bearer.

IV. Result Analysis

Following the description of the proposed MTC-oriented virtual bearer mechanism, this section first analyzes the signaling savings from its usage before demonstrating via a simulation study its potential in avoiding congestion. Fig. 4 shows a call flow of the messages that are needed in order to establish the radio and S1 bearers to enable an MTC device to transmit or receive data.

In particular, five RRC messages need to be exchanged before the MTC device can send uplink data. Considering the signaling plane of the core network, another five messages are needed. The same applies for the bearer release, which includes a release request with acknowledgement for RRC protocol layer, and five core network messages exchanged between MME, eNB and S-GW. Therefore, setting up and

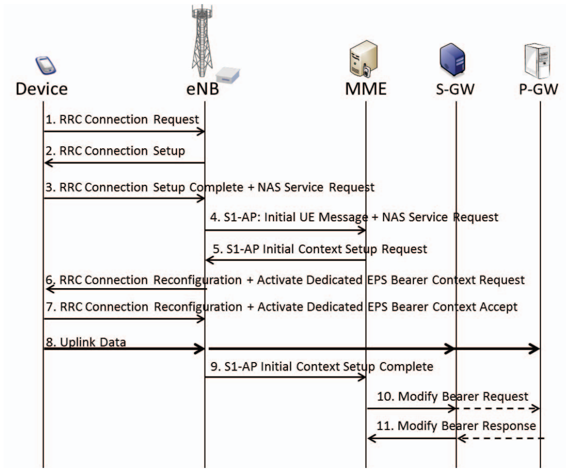

Fig. 4. Setup of radio and S1 bearers.

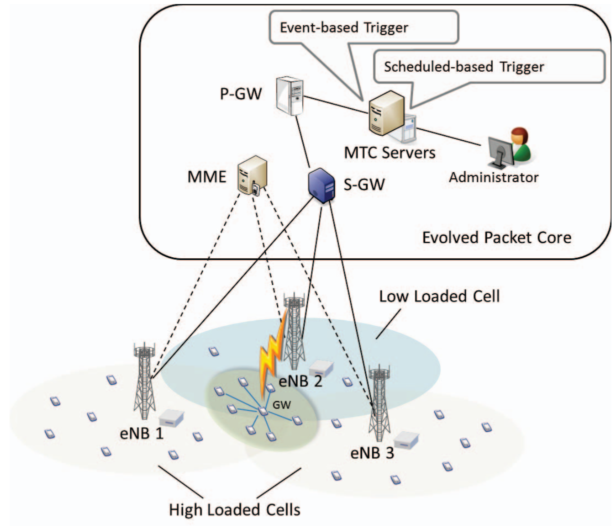

Fig. 5. Simulation topology.

releasing a bearer for an MTC device is costly considering the signaling needed versus the actual amount of user plane data. Such a problem escalates considering a high number of MTC devices, for instance 1000 MTC devices would produce 11,000 signaling messages just to set up their bearers before sending or receiving any actual data. The proposed mechanism shares a single radio and S1 bearer among a group of devices reducing the signaling for bearer establishment to eleven messages per MTC group. The bearer is then shared among the group devices moving the GVM function from one device to another using the D2D network, so that there is no significant cost in signaling on the LTE interface.

Simulations were carried out using the NS-3 LENA model [18], with the objective to demonstrate the performance benefits of the proposed grouping-based approach compared to conventional device triggering schemes including:

- Event-based triggering wherein a set of MTC devices attempt to transmit data towards the MTC server at the same time, once a certain event occurs.
- Scheduled triggering wherein the MTC server allocates random times, according to a uniform distribution, for MTC devices to transmit data.

Our proposed grouping approach, i.e. the D2D enabled MTC gateway-based grouping, adopts scheduled triggering for the MTC devices of each group, which also includes information regarding the MTC device grouping and network point of attachment.

For the simulation, we considered the network topology illustrated in Fig. 5, which consists of three eNBs positioned closely in order to create overlapping regions at the edge of the cells. All network topology links were simulated with a capacity of 10Mbps. The buffer sizes at eNBs and S/P-GWs are set to 100 and 200 packets, respectively. Our goal is to create a traffic scenario wherein neighboring cells experience diverse traffic patterns at certain time instances. To achieve this, we alter the MTC traffic associated with eNB 1 and eNB 3 by varying the active MTC devices within the coverage of each eNB within the range of $\{10, 20, 30, 40, 50\}$, while at the same time we keep a constant low load at eNB2, by allocating 10 active MTC devices. MTC devices, once triggered, respond with five packets. The size of each packet is 1024 Bytes. For the scheduled triggering approach, we considered a random uniform distribution within the interval [0, 25ms).

Our analysis focuses on the performance of the mentioned event-based, scheduled triggering-based and the proposed D2D-enabled MTC gateway-based grouping approach considering the average packet loss and the average uplink delay of the entire MTC device population. Fig. 6 illustrates the average uplink loss, in where it is clear that our group-based approach outperforms other conventional schemes introducing a packet loss only up to approximately 1%. In the event-based approach, the average packet loss increases dramatically once the number of MTC devices and associated data surpass the capacities of eNBs and S/P-GW, creating severe congestion. When a large number of MTC devices transmit data at the same time, we also noted inter-device interference, as an additional performance deration parameter.

The scheduled triggering-based approach ensures that MTC devices avoid transmitting data at the same time, reducing and avoiding packet losses, particularly when a reasonable grant and access-forbidden time intervals are assigned. In principle, there is a tradeoff between delay and loss on configuring such time interval, which also depends on the number of different MTC groups. However, when the number of MTC devices is large, exceeding 80, the loss becomes noticeable as demonstrated in Fig. 6. Our proposed D2D-enabled MTC gateway-based grouping scheme reduces packet losses even in the presence of a large number of MTC devices, provided that a neighboring cell can accommodate their extra traffic and that a D2D connectivity can be used to transfer MTC traffic towards the selected neighboring cells.

In Fig. 7, the uplink delay is plotted for different MTC traffic loads. From the figure, it is evident that simultaneous triggering of MTC devices, i.e. the event-based approach, could only be efficient for network arrangements or applications

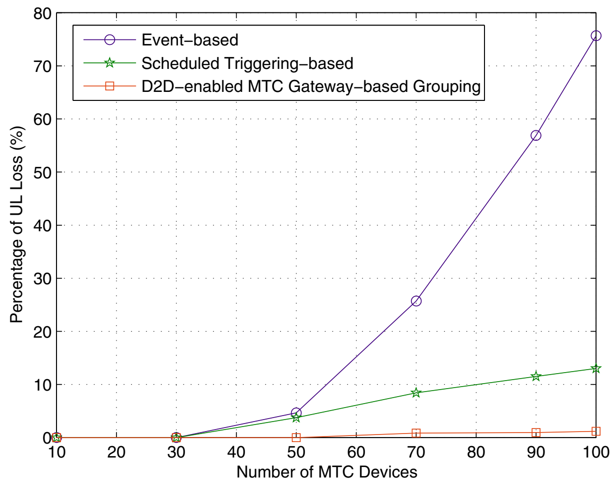

Fig. 6. Uplink loss percentage.

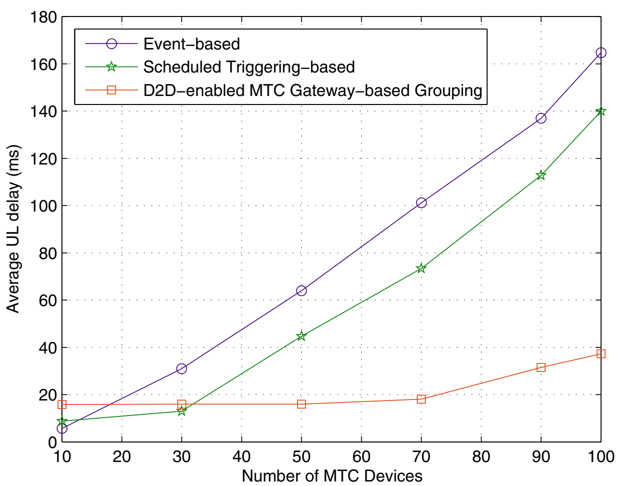

Fig. 7. Uplink delay.

that involve a small number of MTC devices. The scheduled triggering-based approach introduces delays slightly longer than in the case of the event-based one when the MTC load is low. This is mainly due to the fact that devices are triggered at different times, randomly selected from within a specified time interval. Such a time interval defines a tradeoff between delay and loss. Once MTC traffic increases, the scheduled triggering-based approach clearly outperforms the event-based one, shortening delays by 30% on average.

The proposed D2D-enabled MTC gateway-based grouping scheme introduces the longest delay when the network operates under low MTC load. This is mainly attributable to the use of more links as a consequence of D2D communications. However, in case of high MTC loads, our proposed solution outperforms the two other approaches introducing the shortest delay. This good performance is mainly due to the features of D2D enabled grouping that can divert MTC traffic towards less loaded eNBs, ultimately avoiding congestion.

V. CONCLUSIONS

This paper introduced the concept of virtual bearer based on the NFV concept, which is shared among a specified group of MTC devices that have common QoS requirements. Such bearer is established once and then used within the MTC device group by transferring the state parameter from one device to another for the duration of the entire group communication. In this way, a significant amount of bearer related signaling can be avoided enhancing the connectivity efficiency of MTC applications. Furthermore, we elaborated the contribution of D2D connectivity in enhancing the use of the virtual bearer and showed through a simulation study its benefits in providing reduced packet loss and end-to-end delay for particular applications. An MTC service analysis to quantify prioritization should be encountered in a further study focusing on the tradeoff between delay and signaling overhead.

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