Data Aggregation and Packet Bundling of Uplink Small Packets for Monitoring Applications in LTE

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Abstract—In cellular massive Machine-Type Communications (MTC), a device can transmit directly to the base station (BS) or through an aggregator (intermediate node). While direct device-BS communication has recently been in the focus of 5G/3GPP research and standardization efforts, the use of aggregators remains a less explored topic. In this paper we analyze the deployment scenarios in which aggregators can perform cellular access on behalf of multiple MTC devices. We study the effect of packet bundling at the aggregator, which alleviates overhead and resource waste when sending small packets. The aggregators give rise to a tradeoff between access congestion and resource starvation and we show that packet bundling can minimize resource starvation, especially for smaller numbers of aggregators. Under the limitations of the considered model, we investigate the optimal settings of the network parameters, in terms of number of aggregators and packet-bundle size. Our results show that, in general, data aggregation can benefit the uplink massive MTC in LTE, by reducing the signalling overhead.

I. INTRODUCTION

Machine-type communication (MTC) is growing at an impressive rate, fuelled by the widespread deployment of Internet of things (IoT) services such as smart metering, smart grids, ehealth, intelligent transport, etc. Predictions are pointing out to 18 billion IoT devices connected to wireless networks in 2022 and beyond [1]. Furthermore, a massive number of machinetype devices (MTDs) will be connected to the cellular network in regions covered by one or few Base Stations (BSs). This poses unique challenges to cellular networks that are tailored for human communication, which is typically downlinkdominated, with long session times and large packets [2]. The overhead of channel access and signalling often represents only a small fraction of the exchanged data in typical human communication. In contrast, MTC, especially for monitoring/reporting applications, is usually uplink-dominated, with short session times and short packets [2], the connections are typically set up for the time needed to transfer a few bytes of payload data, and then teared down. All this, in

the light of the massiveness of MTDs, makes the impact of the overhead significant. Third generation partnership project (3GPP), recognizing this problem, standardized three MTC technologies in release 13: extended coverage GSM (EC-GSM) for 2G networks which improves the legacy network so as to increase coverage [3]; enhanced MTC (eMTC) for LTE networks; and, finally, the narrow-band IoT (NB-IoT) technology [4] which can utilize both 4G and 2G spectrum to provide reliable and secure communication at a low cost.

1

On an architectural side, the problem of massive signalling overhead can be alleviated by adopting a 2-stage approach, in which a MTD communicates to the BS via an intermediate node, here referred to as aggregator. The aggregator covers a spatial region that is (much) smaller than the wide area covered by the BS and communicates with its associated MTDs via a capillary network, such as WiFi, Bluetooth or other short-range protocols. While the concept of aggregator assisted MTC is not new, to the best of our knowledge there is no work quantifying the reduction of signalling overhead brought about by aggregators in an LTE scenario, and taking into account the details of the radio access and radio resource control procedures. This work tries to fill this gap and details the three key factors which account for the reduction in the signalling: (1) the aggregation of multiple tiny flows into a more consistent compound flow makes it possible to keep alive the connection with the BS, thus reducing the signalling due to multiple session establishments and tear downs; (2) we enable the aggregator to perform packet bundling, i.e., aggregating multiple small packets from the MTDs into a larger packet for which the aggregator uses a single access request to the BS, thus proportionally reducing the transmission overhead; (3) the total number of access requests to the BS will be reduced, as a single aggregator acts as a proxy for multiple MTDs. The use of an aggregator is also advantageous for downlink transmission. Since the aggregator can be placed closer to the MTD than the cellular BS, the wireless communication distance can be reduced and the reliability of the downlink transmission can be increased. Furthermore the cost for managing the massive number of MTDs can be saved because the MTDs do not need to be equipped the high-cost cellular communication modem.

Traditionally, clustering through aggregators (relays) has been used for coverage improvement as well as reduced energy consumption of sensor devices [5]. The aggregator-assisted MTC is expected to spread. For example, many water meters could be connected via ISM band to aggregators, which are then connected to the BS via cellular networks. Multiple works have pointed out the negative impact of massive uplink

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transmissions on the cellular network [6]-[8]. Recently, several works considered serving uplink MTC transmissions by adopting various aggregation schemes [9]-[11]. In [9], the benefits of a clustering access scheme for MTC are described from both technical and business perspectives at a rather conceptual level. A multi-level uplink aggregation scheme is presented in [10], where the energy efficiency is analyzed using stochastic geometry. However, the model in [10] does not account for the detailed access reservation procedure used for connection establishment, such that the effect of reduced signalling overhead is not captured. Instead, [11] proposes a data aggregation scheme in which a gateway collects the MTC data within a fixed period and then forwards the aggregated data to an LTE BS. The LTE model used in [11] considers a simplified connection establishment, not taking into account that recently active aggregators do not need connection establishment, which is one of the key elements in our model and results. Furthermore, the use of fixed aggregation period introduces fixed, potentially large, latency for the MTD transmissions.

In this paper, instead, we consider a more detailed model of the dynamics of the cellular access process. Specifically, we account for the connection establishment and release procedures, and for the resource allocation in the physical channels (PRACH, PDCCH, PDSCH, and PUSCH), which we found to significantly impact on the performance of the aggregation schemes.

This setup is used to answer a number of research questions:

- What is the optimal number of aggregators for a certain density of MTDs?
- How large is the throughput increase brought by the aggregators?
- Is it possible to aggregate packets without introducing excessive latency?

The rest of the paper is organized as follows. We describe the system model for the cellular network with uplink MTC devices and aggregators in Section II. In Section III we provide the explanation about how the aggregation of massive MTC works. In Section IV we present numerical results. The conclusions are given in Section V.

II. SYSTEM MODEL

Assume a cell with M MTDs and N aggregators. In this setup each MTD transmits to its associated aggregator that, in turn, forwards the transmissions to the BS of the cell. Therefore, in this paper we investigate the trade-off between diversity gain and signalling overhead for MTC. In particular, we consider LTE as our case of study, but we note that the results shown in this paper are applicable to any other system that requires control signalling and random access to acquire transmission resources. In our study the capillary connections to the aggregators are idealized, being free of errors and offering negligible latency, which means that the obtained results should be treated as upper bounds of entire system performance. In practice, the capillary networks would introduce errors and certain latency, which depends on the technology used. In this work, however, we only focus on the

aggregating links between aggregators and BS, which have been assumed to represent a performance bottleneck.

Different aggregation scenarios are depicted in Fig. 1b. Fig. 1a depicts the case without aggregation. In this case, each MTD connects directly to the BS so that, with ideal channel access, the reliability is maximized since a failure in one of the links will not impact the rest of devices. However, in real systems, we have the problem of large signalling overhead and massive access, which can severely impact the performance of all the MTDs. From a signalling perspective, and assuming idealized capillary connection to the aggregator, the optimal solution would be to utilize a single aggregator that collects the data from all the MTDs, see Fig. 1b. In this case, however, the performance of all the MTDs can be compromised by the restrictions in the throughput of a single link and reliability issues as, e.g., deep fading periods or blockages of the link, which would impact the service of all MTDs and may lead to unacceptable degradation of the quality of service (QoS). Furthermore, such a solution would move the signalling congestion and access problems to the capillary network, which will make the assumption on idealized capillary invalid. Note that the capillary network is short-range, which would unrealistically imply that all MTDs are clustered in a spatial proximity. In any case, as we will see later, the single aggregator is not found to be the optimal solution even when we neglect these issues, considering idealized capillary network that offers short-range, low interference, high reliability, and zero latency communication. Then, the best solution it to deploy multiple aggregators, as in Fig. 1c. How to determine the optimal number of aggregators as a function of the MTDs density and packet generation rate is one of the results of our study.

A. Traffic Model

We assume that time is slotted, and in a given time slot T_s , each MTD generates traffic according to a Poisson distribution with intensity λ_{app} [packets/s]. The traffic generated in a time slot is instantaneously forwarded to the aggregators, based on a nearest neighbour rule. Therefore, the number of MTDs connected to an aggregator will determine the amount of uplink traffic for that aggregator.

Additionally, to the aforementioned temporal considerations, our traffic model also takes into account a spatial component, which is used for the association of MTDs to aggregators and for link quality evaluation. MTDs and aggregators are assumed to be uniformly deployed in the cell, following two independent Poisson point processes with parameters λ_u and λ_a [nodes/m²], respectively. As mentioned, each MTD associates to the closest aggregator. Due to the randomness in the spatial deployment, the number of MTDs served by the different aggregators is also random, and some aggregators may not be serving any active MTD, as shown in Fig. 2a. We define an aggregator as *active* if it serves at least one MTD. Based on [12], the density of active aggregators, λ'_a , can then be



Fig. 1: (a) Direct access has maximum diversity, only a single device suffers if a link has low throughput or reliability. (b) A single aggregator means minimal signalling. Transmissions are, however, limited by the throughput and reliability of a single link. (c) Having multiple aggregators is a tradeoff between diversity and minimizing signalling overhead.



(a) Example of network topology. Single LTE-BS with multiple aggregators. Each MTD is associated to the spatially closest aggregator, according to a Voronoi tessellation of the area with respect to the positions of the aggregators.



(b) Example of transmissions in aggregation and packet bundling scheme.

Fig. 2: Considered system model.

estimated as follows:

$$\begin{aligned} \lambda'_a &= \lambda_a \left(1 - \Pr[\text{no serving MTD}] \right) \\ &= \lambda_a \left(1 - \left(1 + 3.5^{-1} \lambda_u / \lambda_a \right)^{-3.5} \right). \end{aligned}$$
(1)

The average number of devices per active aggregator, in turn, is given by λ_u/λ'_a . Therefore, the packet arrival process at an active aggregator is the compound of a random number of independent Poisson generation processes and, hence, is still Poisson, with rate equal to $\lambda_u/\lambda'_a\lambda_{app}$, which accounts for the impact of spatial randomness of the nodes on the traffic.

However, this traffic model does not consider temporal or spatial correlations in the packet generation processes, which may be found in some cases, nor does it consider exception events with irregular behaviour. Nonetheless, it allows us to get insights into the performance of the system in a stationary scenario.

B. System Parameters

We consider a bandwidth of 1.4 MHz for the LTE cell, which corresponds to a Physical Random Access Channel (PRACH) of 6 resource blocks (RB) in frequency division (FD) and 1 ms in time division (TD). Every 10 subframes there is a random access opportunity (RAO). Retransmissions are allowed 4 times and the maximum number of new random access attempts per payload is 10. The RRC idle timeout is 100 ms.

C. Performance Metrics

The QoS of the aggregation scheme will be evaluated with regard to latency, outage and throughput. Furthermore the optimal throughput and the associated number of aggregators will be found. More specifically, we adopt the following definitions for the different performance indexes:

- *Latency* the period between packet generation at the MTD and successful delivery to the BS.
- *Outage* the fraction of generated packets that are not successfully received within the simulation time.
- *Throughput* the total amount of successfully transmitted data in bits divided by the sum of the latencies of each successful transmission. Note that, according to this definition, the throughput is a measure of the average bitrate experienced by each packet transmission and, hence, it is not limited by the traffic generation rate.
- *Optimal throughput* the maximum throughput that can be obtained for a given number of MTDs.
- *Optimal number of aggregators* the number of aggregators needed to obtain the optimal throughput.

III. Aggregation and Packet Bundling Scheme

In this section, we describe the proposed aggregation and packet bundling scheme in more detail.

As shown in Fig. 2b, data generated by the MTDs is first delivered to the aggregator, using another technology (which we assume orthogonal to LTE) that offers ideal capillary connection, as already described. The aggregator forwards this data to the BS using the LTE uplink channel. If the aggregator is not already connected to the BS, it needs to perform a random access procedure in order to acquire the transmission resources. To this end, the aggregator first transmits a random preamble (msg1) in a PRACH slot. The BS's reply (msg2) indicates where to send the connection request message (msg3). If the connection request is not accepted by the BS, then the aggregator repeats the random access procedure. Otherwise, the BS sends a contention resolution message (msg4) and, with some additional signalling, the connection is established and the aggregator gets assigned exclusive access to the required resource Blocks (RBs) in the uplink channel (PUSCH), which can then be used to send data. The aggregator retains a dedicated resource in PUCCH for transmission of new scheduling requests (SRs) until it is disconnected by the Radio Resource Control (RRC) after a sufficiently long idle period. Bringing this additional signalling to LTE in the PUCCH can be justified by simulations in [13], which found the PUCCH utilization to be very low. In [13] less than 0.1 % scheduling request opportunities are used for 10ms scheduling request period.

The packet bundling aims at improving the system efficiency by making a better use of the resources allocated to the node in

TABLE I: Simulation parameters

Metric	Designation	Value
Traffic distribution parameters		
Cell radius	-	1000 m
Number of MTDs	М	Variable
Number of aggregators	Ν	Variable
Packet arrival rate per MTD	λ_{app}	Variable
Packet size	-	100 bytes
PHY parameters		
EARFCN	-	DL:5900
Downlink Tx power	-	30 dBm
Uplink Tx power	-	23 dBm
MAC parameters		
Number of RACH preambles	-	54
Backoff time	-	20 subframes
Maximum RACH retransmissions	Κ	10
Random access opportunities	-	1 every 10 subframes
Fragmentation threshold	-	6 RBs ¹
System parameters		
Number of RBs per RACH slot	-	6
Simulation length	T_s	60 s
Maximum data retransmissions	L	1
Maximum number of bundled packets	В	Variable
Processing time	-	3 ms

an opportunistic manner. At the time of SR for transmission an aggregator will bundle maximum B packets in its transmission buffer to the single packet, which first triggered the SR. This mechanism is mainly triggered during the connection establishment procedure, when packets that are received by the aggregator while performing the access procedure are bundled, as for data1 and data2 in Fig. 2b. Clearly, the resource request will be dimensioned on the size of the bundled packet (data1+data2), rather than on that of the packet that has started the process (data1). However, to avoid excessive resource requests in case of massive packets arrivals during the connection establishment phase, the maximum number of packets that can be bundled together is limited to B, and the excess packets are simply buffered and sent after the connection is established. In the connected state, the aggregator immediately sends the received packets as for data3 and data4 in the figure. However, if multiple packets arrive at the aggregator during an ongoing transmission, they are bundled together.

IV. Simulation of Data Aggregation and Packet Bundling in LTE

In this section we describe the LTE simulator and the numerical results.

The term User Equipment (UE) is used in the following to describe devices connected to the BS, i.e., the aggregators when N > 0, and the MTDs when N = 0, since in absence of aggregators the MTDs are connected directly to the BS. We consider the latter case as a benchmark for the aggregation scheme.

¹If a packet cannot be transmitted in a single subframe, it is fragmented.

A. Simulation

The simulation has been developed in MATLAB, accounting for all the details of the LTE channel access procedure. More specifically, each simulation run consists in the following six steps:

- 1) Configuration of the simulation parameters.
- Random placement of the MTDs and the aggregators in the cell.
- 3) Random generation of the packet arrivals for all MTDs.
- Event-based simulation of the channel access procedure and packet transmission according to the LTE specifications.
- 5) Processing of the results and averaging over multiple repetitions of steps 2-4.
- 6) Post processing of the results and visualization.

In a two-dimensional region, MTDs and Aggregators are randomly distributed within the single cell. Therefore, each aggregator serves a different number of MTDs and the random distance between the aggregator and the base station affects the performance of the wireless transmission. We have HARQ, but the transmission power is fixed and we have thus disabled adaptive modulation as well. Table I collects the setting of the simulation parameters.

As mentioned, the simulation is event-based. Each event corresponds to the transmission of a message, which can be part of the signalling, RACH, or data transfer procedure. All messages are listed in a virtual queue and ordered according to the transmission instant. At each simulation step, the next message in the virtual queue is fetched and the corresponding event is simulated. If the event is a new packet arrival to a UE that is not connected to the BS, then the RACH procedure is simulated (assuming 6 signalling messages after msg4 to allocate resources in the PUSCH to the UE). If the procedure is successfully completed, the UE switches to the connected RRC state and starts a connection timer which is renewed upon any successful transmission. If the connection timer expires, the UE releases the resources and tears down its connection to the BS. If the event is a packet arrival at a UE that is already connected to the BS, uplink resources are requested on the PUCCH and the message will be sent to the BS using the granted PUSCH resources, if any are available. The SR on the PUCCH is implicitly handled in the simulation and the grant may take place soonest possible, at the next subframe. In case of transmission errors due to collisions during the RACH procedure, channel fluctuations, or time-outs due to resource starvation, retransmissions can be inserted in the virtual queue, as for the simulated LTE protocols.

B. Numerical results

The throughput of the system is plotted in Fig. 3a as a function of the number of aggregators, when varying the number of MTDs. We can observe that the throughput is low when the number of aggregators is very low (reduced spatial diversity) or very large (channel access contention). Note that, despite the ideal capillary network, having a single aggregator is not optimal. The reason is that the number of capillary arrivals is larger than the service rate of the LTE link. Hence,

there exists an optimal number of aggregators, larger than one, that maximizes the throughput of the system.

Fig. 3c reports the outage probability when varying the number of aggregators, for a population of M = 5000 MTDs with a packet generation rate of $\lambda_{app} = 3$ packets per minute. The different curves have been obtained by changing the number B of packets that can be bundled together during the RACH procedure. Furthermore, the curve without aggregators (N = 0) is added as benchmark. We observe that the outage rapidly raises when the number of aggregators drops below a certain threshold, because the compound arrival-rate at an aggregator exceeds its link capacity. However, packet bundling enhances the capacity of the aggregators, shifting to the left the point at which the outage increases. This capacity gain is due to the more efficient use of the RBs assigned to the aggregator. The bundling limiter, B, can be replaced with a size limit for the bundled packet to accommodate realistic machine type traffic with varying packet sizes. As the packet sizes are fixed in this work, B is a good indicator of what would be the behaviour of such a limiter.

The latency can be found in Fig. 3b where the latency is seen to be high for very low numbers of aggregators. This is due to the capacity of a single aggregator being limited. This may be alleviated to some degree by using a larger value B for the maximum packets bundled. The latency also grows as a larger number of aggregators are competing going towards the latency of the benchmark case. Thus an optimal operational point can be found.

Fig. 4 reports the optimal throughput (lines) and the corresponding optimal number of aggregators (bars) as a function of the number of MTDs, with (B = 10) and without (B = 1) packet bundling. In addition, the figure also reports the throughput (dashed line) for the baseline case with no aggregators (N = 0). We can see that, with packet bundling, the optimal number of aggregators grows more slowly with the number of MTDs compared to the case without packet bundling, thus confirming the capacity gain previously observed. It can also be noticed that the achievable optimal throughput decreases almost linearly with the number of MTDs, which agrees with the results in Fig. 3a.

The incident reports of Fig. 5 show how many times delays were reported due to each of the factors: transmission error, lack of control channel elements (CCEs) and lack of RBs. This plot indicates that the PDCCH has a relatively larger effect on the latency of the system as the number of aggregators grow, while the PUSCH has a larger impact on the performance for less aggregators.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we studied the effects of an aggregation scheme to sustain the uplink MTDs traffic in a LTE scenario. Our LTE model accounted for the details of the radio access and radio resource control procedures that, depending on the arrival rate and intensity of the traffic flows, are fundamental to fully capture the impact of traffic aggregation. We also proposed a packet bundling mechanism, which was found to further improve the capacity of the system in terms of the

6



Fig. 3: (a) Throughput as a function of the number of aggregators, $\lambda_{app} = 1$ [packet/min] and B = 10. (b) Latency as a function of the number of aggregators, with M = 5000 and $\lambda_{app} = 1$ [packet/min]. (c) Effects of packet bundling on the outage as a function of the number of aggregators, with M = 5000 and $\lambda_{app} = 3$ [packet/min].



Fig. 4: Optimal throughput and the associated number of aggregators as a function of the number of MTDs for B = 1 (red) and B = 10 (blue), $\lambda_{app} = 1$ [packet/min].

supported number of devices per aggregator and throughput of each aggregator. We evaluated the number of aggregators needed to optimize the throughput of each aggregator with and without packet bundling, under the assumption that the connection between MTDs and aggregators is obtained by means of ideal (zero latency, zero outage, infinite capacity) capillary networks.

Our results clearly show that, when evaluating schemes that involve aggregators, it is important to take into account the details of the cellular technology, such as RRC in LTE, as aggregation has a large impact on the number of access attempts and, in turn, on the signalling overhead seen at the BS. Furthermore, packet bundling turns out to be a promising strategy for aggregation in capillary cells. The evaluated packet bundling mechanism added no obligatory queueing delay at the aggregator whilst enhancing the throughput of each aggregator.



Fig. 5: Incident reports for transmission delays for M = 5000, B = 10 and $\lambda_{app} = 1$. Starvation of resources in either PDCCH or PUSCH can lead to message expiration as transmissions can not occur if either channel lacks resources.

From another perspective, we can state that packet bundling makes it possible to lower the number of aggregators required to optimally serve a given MTD density, thus reducing the overall cost of the infrastructure that includes aggregators.

Possible research directions include a thorough end-to-end performance analysis by specifying a communication model for the capillary networks. Furthermore, it is relevant to optimize resource management and packet bundling in the presence of heterogeneous MTDs with more realistic traffic-generation models. As massive MTC is one of the important use case for 5G cellular networks, the aggregator is highly effective method to bear massive MTC traffic. Design of reliable signaling schemes and low-overhead access protocol for the aggregator is essential to address the requirements for massive MTC application in 5G.

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