Scheduling M2M Traffic over LTE Uplink of a dense Small Cells Network

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***Abstract*—We present an approach to schedule Long Term Evolution (LTE) uplink (UL) Machine to Machine (M2M) traffic in a densely deployed heterogeneous network, over the lamp posts of a big boulevard for smart city applications. The small cells operate with frequency reuse 1 and Inter-Cell Interference (ICI) is a critical issue to manage. We consider a Release 9 3rd Generation Partnership Project (3GPP) compliant scenario, where Single Carrier Frequency Division Multiple Access (SC-FDMA) is selected as the multiple access scheme, which requires that all Resource Block (RB)s allocated to a single user have to be contiguous in frequency within each time slot. This adjacency constraint limits the flexibility of the Frequency-Domain Packet Scheduling (FDPS) and Inter-Cell Interference Coordination (ICIC), when trying to maximize the scheduling objectives, and this is sufficient to make the problem NP-hard. We aim to solve an optimization problem, taking into account criteria such as the maximization of the overall throughput, the minimization of the radio resource usage, and the minimization of ICI. This can be modelled through a Mixed Integer Linear Programming (MILP) and solved through a heuristic implementable in the standards. We present simulation results in a 3GPP compliant network simulator, which support the effectivity of our algorithm, for different M2M applications, with respect to state of the art approaches.**

I. Introduction

Recent studies proposed by e.g. Cisco [1] predict that from 2013 to 2018 the traffic in mobile networks will grow by a factor of 10. This will be due to the increment in traditional Human to Human (H2H) traffic and to Machine Type Communications (MTC). Cellular networks are expected to provide ubiquitous coverage to this heterogenous eco-system, and at low deployment cost. This is why significant effort has been lately devoted in standardization to the M2M paradigm. The 3rd Generation Partnership Project (3GPP) has formed several MTC-related study items working on M2M enhancements for future releases [2]. IEEE has initiated the 802.16p and 802.16.1b projects dealing with M2M amendments on Mobile Wimax standard [3]. ETSI has been working on defining M2M functional architecture and interface specifications through an M2M Technical Committee [4].

The advent of MTC will generate a need for capacity increase, which can only be satisfied by the fundamental rethink of the radio access network, where heterogeneous small cells, like Radio Remote Head (RRH)s, femto, pico, micro, coexist with traditional macrocells in the same area, with an extremely high equipment density. In this densely deployed 5G networks, neighbouring base stations operate on the same channel due to the scarcity of spectrum resources. Managing dense networks with frequency reuse 1 is tremendously complex. Radio resource management decisions, at one base station, have significant impact at the interference level on neighbouring base stations, and vice versa, due to the high frequency reuse and to the broadcast nature of wireless communication. Left unmanaged, this interference significantly degrades capacity.

In this paper we focus on a densely deployed network, where neighbouring base stations operate on the same channel, providing service to a urban scenario in a near future smart city. We focus on a big boulevard, equipped with a dense small cell deployment co-located with the lamp posts of the street, able to support both Human to Human (H2H) and M2M traffic. M2M traffic generated by most services/applications is bi-directional, which means that the network must be designed to support great amounts of uplink traffic. Furthermore, different applications have different requirements in terms of throughput, maximum tolerable packet loss rate, maximum delay, etc., which requires the implementation of intelligent scheduling algorithms to meet the requirements of all the applications.

The Long Term Evolution (LTE) scheduling functionality, located at the base station, within the LTE Medium Access Control (MAC) layer, plays a crucial role, as it manages the limited radio resources at the access level, in a way that optimizes the system performances in terms of a variety of criteria. The bandwidth is organized onto separable groups of sub-carriers, denoted as Resource Block (RB)s, which are the minimum scheduling resolution in the time-frequency domain. The scheduling functionality performs the RB-to-User Equipment (UE) assignment in each Transmission Time Interval (TTI), handling shared radio resources among neighbour base stations. Decisions are based on scheduling policies, taking into account network conditions, wireless channel quality and the Quality of Service (QoS) experienced by users at service level, etc. Considerable work has been devoted in literature to scheduling downlink traffic in densely deployed heterogeneous networks through Inter-Cell Interference Coordination (ICIC) approaches [5]. The study of the uplink, even if has been approached in traditional macrocell scenarios [6], is much less explored in dense networks where the component of interference plays a disruptive role.

Scheduling LTE's uplink requires making considerations in terms of UE limited power budget, satisfaction of QoS requirements, and enhancement of throughput versus fairness trade-off, but not only. Differently from the downlink, where LTE adopts Orthogonal Frequency Division Multiple Access (OFDMA), the LTE's uplink uses a pre-coded version of Orthogonal Frequency Division Modulation (OFDM), called Single Carrier Frequency Division Multiple Access (SC-FDMA), to solve the undesirable high Peak to Average Power Ratio (PAPR) of OFDM, which would increase the cost of the UE terminal and drain the battery faster. However, the advantage of low power requirements is largely realized when resource contiguity is enforced in the RB allocations made to a single UE in the uplink. This contiguous constraint is sufficient to make the UL LTE problem NP-hard. We propose then a heuristic algorithm which provides a solution to a Mixed Integer Linear Programming (MILP) problem, modeling the scheduling of M2M traffic over the uplink of a densely deployed, interference limited network. The algorithm aims at maximizing the overall throughput, while minimizing radio resource usage and the Intercell Interference (ICI). Simulation results carried out in a 3GPP compliant network simulator, Network Simulator 3 (NS3) LTE-EPC Network Simulator (LENA) [7], show the promising performances of our scheme for different M2M applications and with respect to state of the art approaches.

The rest of the paper is organized as follows. Section II presents the proposed high level cellular architecture to serve M2M traffic for the smart city applications. Section III presents the uplink scheduling algorithm. Section IV discusses meaningful simulation results. Finally, Section V summarizes the main conclusions.

II. Proposed Architecture

In this paper we focus on a smart city scenario where M2M traffic is served by a 3GPP LTE small cell network, deployed on the lamp posts of a big street. The high level scenario is depicted in Figure 1. The architecture that we are

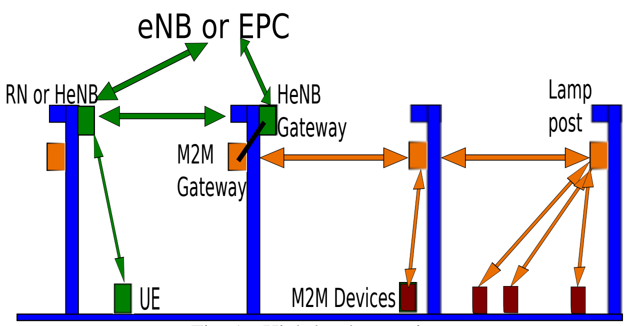

Fig. 1. High level scenario.

going to consider includes M2M devices connected directly or via M2M gateways to the Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) architecture. The evolved Node B (eNB)s in E-UTRAN are connected to the Evolved Packet Core (EPC) via Serving Gateway (S-GW)s. The Packet data network Gateway (P-GW) acts as the gateway to the core network and provides connectivity to the IP backbone. The IP backbone provides connectivity among M2M devices, UEs, servers and users. The Evolved Packet System (EPS) including E-UTRAN and EPC form the M2M and the cellular access network. Besides getting access to E-UTRAN through an eNB, the machines can also get access through small cells, such as a Relay Node (RN) or a Home evolved Node B (HeNB). RNs are connected to the EPC via the Donor EPC, while HeNBs are directly connected to the S-GW, or through gateway. The aggregated M2M and H2H traffic collected by the small cells can be routed to a LTE gateway, then to an eNB and, finally, to EPC. In the rest of the paper we refer to the RNs or HeNBs generically as Small Cell (SC).

III. Scheduler

The first challenge to tackle in the scenario is to efficiently allocate radio resources in order to manage and control the interference that the different small cells can cause to each other in the densely deployed urban scenario. In opportunistic scheduling for LTE, two techniques are used to schedule the UEs: Time Domain Packet Scheduling (TDPS) and Frequency-Domain Packet Scheduling (FDPS). The former is used for long-term scheduling, i.e. the scheduler decides which are the UEs that need to transmit data in the next TTIs. This approach is very relevant to guarantee the QoS in terms of delays. FDPS is used in short term scheduling. Once the TDPS selects the priority UEs, FDPS schedules them at TTI level.

We aim at designing the multi-user resource assignment that distributes the m RBs among the n users, focusing on a FDPS scheduling model. Each user j generates a demand of traffic d_j, and we aim at satisfying it by maximizing the overall throughput. We assume the coherence time of the channel to be larger than a TTI, so that channel conditions are constant over a TTI. We impose the condition of contiguous RB allocation to the same user. The number of assigned RBs per user is flexible and spans between 0 and m.

The scheduling is carried out taking into account information transmitted by the user in the Uplink (UL) over the Signalling Radio Bearers (SRB): Scheduling Requests (SR), to distinguish active users with data in buffers, from idle users; Buffer Status Reports (BSR), to inform the Base Station (BS) about the amount of data needed to be transmitted; Power Headroom Reports (PHR), to inform the BS about the available power at the user for the scheduling; Sounding Reference Signal (SRS), used to provide information on the UL channel quality; Channel Quality Indicator (CQI), to measure the channel quality between UE and eNB.

A. Problem Formulation

In order to take into account the high level of interference present in a dense network with high frequency reuse, we propose a three phase approach:

- *ICI phase*: first, based on measurements carried out by the same SC and on those of the users, the SC evaluates the blocks of contiguous available RBs, according to the measured interference. Other information exchanged over the X2 interface, such as the High Interference Indicator

(HII) or the Overload Indicator (OI) [8][9], can also be used to extract this information.

- *Resource mapping*: based on the availability of contiguous RBs, on the quality of the channel and on the QoS requirements of the traffic to be scheduled, the users' demand is mapped to the available resource. We create then a matrix with information about all the possible RBs-UE matchings. This matrix is denoted by F, which is a $n \times m$ matrix where n is the total number of RBs and m is the number of UEs in the system. Knowing the channel quality per RB, it is possible to define how many RBs are needed to satisfy the demand of UE j, if it starts transmitting in RB i. For instance, $f_{3,22} = 4$ means that UE 3 needs 4 contiguous RBs, if it starts transmitting in RB 22. In case an assignment is not feasible, i.e. the channel quality is too poor to satisfy the user demand, the correspond $f_{i,j}$ element is set to -1.
- *Scheduling phase*: based on the *Resource mapping* phase, RBs are properly allocated to the users according to the selected optimization criteria.

We design a MILP model that performs the scheduling phase having as input the resource mapping matrix F. Our model performs a three-step optimization process, driven by multiple objectives: i) the maximization of the overall throughput, ii) the minimization of the radio resource usage, and iii) the minimization of the ICI.

The optimization is carried out through a single hierarchical objective function. This is described by Eq. 1, where: α, β and γ are coefficients used to give different priority to each optimization variable; $x_{i,j}$ is the problem decision variable, d_j is the user demand, while $f_{i,j}$ are the elements of F, and $r_{i,j}$ is the utilization factor, i.e. the ratio between the user demand d_j and the corresponding Transport Block (TB) size.

$$max \sum_{j=1}^{n} \sum_{i=1}^{m} (\alpha d_j - \beta f_{i,j} - \gamma r_{i,j}) x_{i,j} \qquad (1)$$

subject to the following constraints: (1) *exclusivity*: each RB can be assigned to only one UE; (2) *interference avoidance*: UEs should not be scheduled on highly interfered RBs; (3) *adjacency*: RBs assigned to a given UE have to be contiguous.

Due to space constraints, the solution of the MILP model, and its evaluation are discussed in a separate contribution, while here we focus on the practical evaluation in the NS3 LTE module of the heuristic scheduling algorithm that solves the optimization model.

B. Proposed Algorithm

The SC-FDMA UL scheduling problem is already demonstrated in literature to be NP-hard [10], consequently, we propose in this section a greedy algorithm, which solves the MILP problem in a feasible time, compatible with the LTE scheduling application. In particular, the algorithm has been designed paying special attention to the feasibility of implementation in standards and considering that it has to be executed every TTI. In addition, the computational cost is low, which assures that it can be implemented also in devices with reduced computational capability, as it may be the case for BSs in future dense 5G deployments [11].

The pseudo-code is described in Algorithm 1. The algorithm's inputs are :

- d_j is the demand vector containing the traffic demand for each UE. This vector is updated on a TTI basis, since it changes as a function of: i) the demand served in previous TTIs, and ii) the traffic produced by each UE.
- $f_{i,j}$ is the resource mapping matrix.

The function *sort()* takes care of sorting the elements of a queue. The function *pop()* extracts the first element of the queue. Finally, the function *isFeasible()* verifies the SC-FDMA adjacency constraint, i.e. whether a set of contiguous RBs can be assigned to a user. All the users are sorted in a queue (DS), based on the demand (d_j); then the first element, i.e. the user with largest demand, is removed from queue (CU). The vector represented by the column $f_{i,j} = f_{i,CU}$ is selected and sorted (FS), then the first element (CC) is removed from the FS queue and the feasibility of the assignment is tested. Both the outer loop (related to the assignment of all RBs) and the inner loop (related to the feasibility of the assignment) continue till the queues are empty or all the RBs are assigned. In the algorithm, two reducing phases are performed, one before starting the main loop and the second at each iteration of the main loop. Those phases have as their main objective the reduction of the search space, and of the time to find the solution. Every time the reductions are performed, the algorithm searches for the infeasible sets, i.e. it eliminates from $f_{i,j}$ the entries $f_{i,j} = -1$.

Algorithm 1 Greedy algorithm

{Initialization}
Define $d_j \leftarrow$ array of the demand
Define $f_{i,j} \leftarrow$ RBs, Users Matrix
Reducing the problem dimension
Define $RB_{available} \leftarrow$ total available RBs
Define $RB_{used} = 0 \leftarrow$ assigned RBs
$DS \leftarrow$ Sorted Queue of d_j in descendent order
while $DS \neq$ empty **or** $RB_{used} \neq RB_{available}$ **do**
    Reducing the problem dimension
    $CU = peak(DS)$
    $FS \leftarrow$ Sorted Queue of $f_{i,CU}$ in ascendent order
    while $FS \neq$ empty **do**
        $CC = peak(DS)$
        if $isFeasible(CU, CC)$ **then**
            $RB_{used} += CC$
            Schedule user CU onto the set of RBs identified by $f_{CU,CC}$ and CC
            BREAK
        end if
    end while
end while

IV. Results

In this section we first describe the scenario set up. Then we introduce two meaningful M2M applications and their simulation model. Finally, we discuss the results obtained applying the proposed scheduler to the two selected M2M traffic classes, in comparison to the state of the art Round Robin (RR) scheme.

A. Scenario Setup

We implement our algorithm in LENA, the NS3 LTE module. The simulation details are shown in Table I. As already mentioned in section II, we propose a near future smart city scenario, characterized by a densely deployed small cell network, as it is shown in Figure 2. The SCs are located in correspondence of lamp posts or similar street furnitures. The lamp posts are located every 25 m and a small cell is located every 3 lamp posts, i.e. every 75 m, as represented in Figure 2. The yellow and red circles represent the lamp posts without and with installed small cell, respectively. Each SC has to provide traffic and schedule 60 UEs over an access segment based on 50 RBs, which corresponds to a 10 MHz LTE UL implementation. Without loss of generality, we considered a 10 MHz LTE implementation, which ensures 25 Mbps of theoretical maximum throughput to a single UE at the physical layer, so, enough for the kind of traffic that we are focusing on, and which allows multi-user scheduling per TTI.

Parameter	Value
Cellular layout	Circular Cell
Inter SC distance	75m
SC radius	75m
SC height	8m
SC Ptx	10 dBm
Frequency	2.5 GHz
UL Bandwidth	10 MHz
Simulation Time	5 sec
RBs assigned per SC	50
Users distribution	Uniform in SC radius
No. of Users	60
Max Tx power of users	10 dBm
User Antenna Gain	0 dBi
Channel Model	Friss Channel Model
Control Plane	Ideal Channel

TABLE I
SIMULATION SYSTEM PARAMETERS

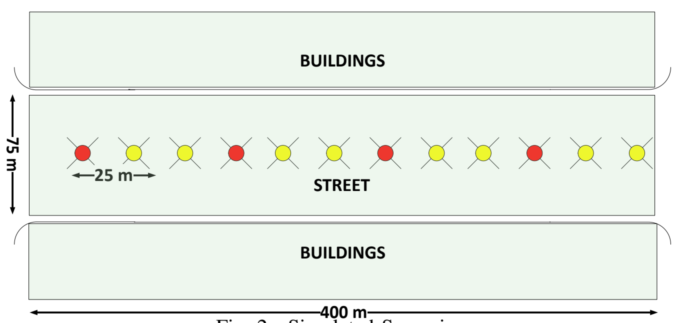

Fig. 2. Simulated Scenario

B. Simulated Traffic

Figure 3 shows the state diagram of the traffic model of a M2M device, which is based on three states:

- OFF State: In this state the devices are in a deep sleep mode and only a very low power clock is running. The devices move to the ON state when a timer expires.
- ON/Monitoring Mode: the devices in this state generate information on a time-driven fashion. In practice, the device monitors some physical variable and sends periodical information.
- ON/Alarm Mode: this model depends on the application and type of sensor the device is equipped with. In general, the device is triggered by a particular event, when there is the need to send more frequent information than in the monitoring mode. For instance, a temperature sensor in a building provides regular information, e.g., every 5-10 minutes, on the temperature in the building. However, if the temperature exceeds a certain threshold, this may be associated to a fire alarm, so that the device enters the alarm mode and sends information every 1-5 seconds.

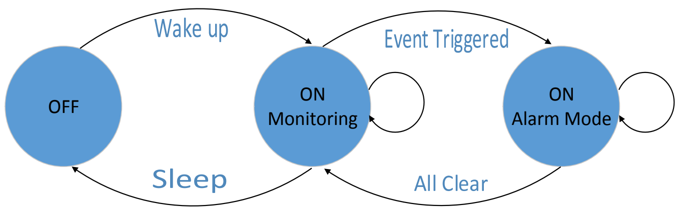

Fig. 3. M2M state diagram

Devices in ON state, are supposed to be connected and synchronized with the LTE network. As for the simulation results, we will focus on devices in alarm mode, in order to consider the most demanding conditions to evaluate the scheduler.

For the purpose of the evaluation of the proposed algorithm, we consider a traffic based on the mix of two M2M applications:

1) *Traffic monitoring*: we consider a traffic monitoring application, in alarm mode, where there may be the need for exchange of several information to re-route human/vehicular traffic. The application is modeled by User Datagram Protocol (UDP) packets with periodicity of 10 msec.
2) *Video surveillance*: we consider in this case a continuous traffic, generated for example by a HQ streaming application, or by devices that act as collectors of information from different sensors. In both cases, there is the need to send a high amount of data. This could be modeled by a full buffered traffic generator.

The traffic demand is uniformly distributed between the two M2M applications.

C. Algorithm Results

We consider 60 UEs uniformly distributed in each small cell coverage area. In this contribution, we show results over

15 different realizations of our scenario, i.e. simulation round in the figures. We take as a benchmark to our proposed scheduling algorithm the RR scheduling scheme. The details on the RR implementation can be found in the LENA open documentation [7]. RR assigns resources equally to all users without taking into account neither the channel-quality nor the demand. On the other hand, our approach (CA in the figures) is a channel-aware and demand-aware algorithm.

We present results in terms of fairness, throughput and delay. Figure 4 shows that our proposed approach offers 30% increase in throughput with respect to RR. Figure 5 shows the statistics of the delay computed at the PDCP layer. This delay included the component related to the RLC layer that has to wait for different transmissions in order to aggregate a packet before sending it to the PDCP layer. Results highlight that our algorithm maintains a lower average delay, for the different simulations. In fact, we have an average delay in the order of 0.17 s while the RR achieves an average delay of approx. 0.33 s. Finally, to evaluate the throughput versus fairness tradeoff, Figure 6 represents the fairness in terms of J-index. Our algorithm results in a lower fairness with respect to RR, approximately 10% less, which is the price to pay for increasing other Key Performance Indicators (KPIs).

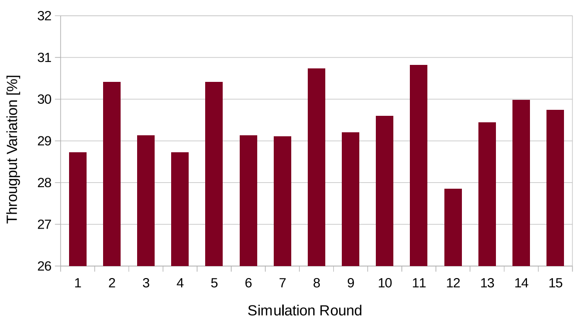

Fig. 4. Throughput improvement of the proposed algorithm with respect to RR

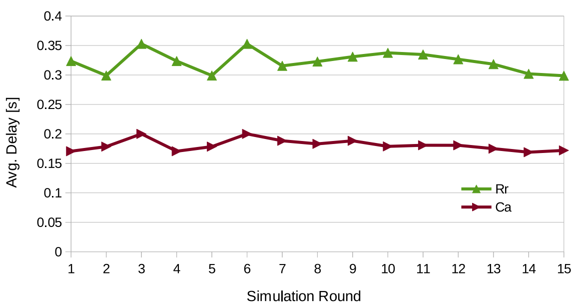

Fig. 5. Delay at the PDCP layer

V. Conclusion

In this paper, we have presented a feasible and fast heuristic algorithm that solves the NP-hard problem of scheduling M2M traffic in the UL of a LTE system. We have shown simulation results obtained on the standard compliant NS3 module for LTE.

We have demonstrated the superiority of our approach, in terms of delay and throughput, with respect to the state of the art Round Robin approach. In particular, our approach

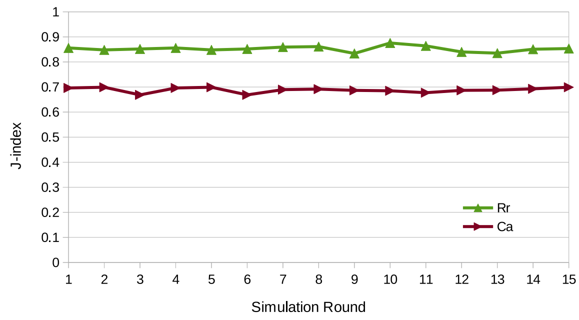

Fig. 6. Fairness in terms of J-index

achieved approximately 30% increase in throughput and approx. 50% decrease in term of delay with respect to RR, this comes at the price of 10% reduction in fairness.

As for the future works, we are currently working on extensions including Carrier Aggregation functionalities.

VI. Acknowledgment

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