Performance Evaluation of an Adaptive Semi-Persistent LTE Packet Scheduler for M2M Communications

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Abstract— **Large number of M2M devices are anticipated to be operating in future LTE networks which impose several system design challenges and wide range of service requirements. The LTE standard suffers from excess control channel overhead associated with radio resource allocation method for small, sporadic traffic per terminal which is often the nature of M2M communications. The rigid QoS support framework of LTE for limited number of voice and data services also fails to address the specific QoS requirements of M2M traffic classes. In this paper, we propose an adaptive LTE uplink scheduler which allocates radio resources to M2M traffic classes in either dynamic or adaptive semi-persistent manner based upon their traffic patterns and delay requirements. We also transform the concept of semi-persistent scheduling (SPS) implemented for VoIP scheduling in LTE to an adaptive SPS scheme which provides flexibility in allocated resource volume to accommodate changes in traffic dynamics. This new adaptation of SPS is particularly suitable for supporting random bursts of event-based M2M traffic yet has less control channel overhead than the dynamic scheduler. We demonstrate from simulation results that the proposed adaptive scheduler can maximize uplink data capacity by reducing dependency on downlink control channel as well as satisfy the QoS requirements of different M2M traffic classes compared to full dynamic and rigid SPS approaches.**

***Index Terms*—LTE, M2M, packet delay budget, semi-persistent, dynamic, packet scheduling**

I. INTRODUCTION

The future of telecommunication networks is envisioned to be largely influenced by Machine-to-Machine (M2M) communications. The major challenges to enable a truly networked society involve a massive growth in the number of connected devices and an increasingly wide range of applications with varying requirements and characteristics. The number of human-centric communication devices is predicted to be exceeded tenfold by “communicating machines” in the future [1]. Consequently, one of the key drivers for further evolution of Long Term Evolution (LTE) radio access technology is the support of massive machine type communications [2].

Machine-to-Machine (M2M) communications enable various network-accessible devices (referred to as an "Internet of Things") to communicate with remote application infrastructures (database/servers) for monitoring and control purposes. M2M applications encompass a wide range of use cases such as smart grids, smart cities, surveillance systems, asset tracking, eHealth, connected consumers, Intelligent Transportation Systems (ITS), industrial automation and so on. Besides, the increased usage of smart devices in day-to-day life also involves automatic background data exchanges by large number of devices, which amounts to additional load on networks. Considering the vastness of M2M applications and their varying traffic intensity/urgency it is crucial yet challenging to develop an appropriate packet scheduling strategy for M2M traffic.

Although the data capacity and wide coverage of LTE systems offer to cater for M2M traffic as well as conventional voice/data traffic, the resource scheduling strategies and channel structures of LTE were designed for Human-to-Human (H2H) and Human-to-Machine (H2M) traffic in the first place. This design perspective is reflected in the Quality of Service (QoS) classes supported by LTE [3], which includes guaranteed bit rate (GBR) and non-GBR (best effort) voice, video and web-based traffic. Moreover, any downlink/uplink scheduled data transmission for a connected user has to be signaled by the eNodeB in downlink control channel beforehand, dictating which shared channel resources should be used for the data transmission. This approach is suitable for human end-users because the data channel resources consumed by each user are sufficiently large and some of the users require a certain bit rate continuously. On the contrary, M2M payload size is small and data resource consumption per M2M device is typically small and infrequent. As a result, despite the data channel providing enough available resources to accommodate M2M traffic, the LTE system is likely to be limited by control channel capacity when it comes to supporting large number of M2M devices.

Unlike traditional traffic, M2M traffic is more uplink-biased than downlink [4]. Therefore, the successful deployment of M2M communications in LTE environment requires an optimum scheduling policy to maximize the uplink data channel capacity for massive number of M2M devices and also to satisfy the M2M traffic specific requirements in terms of packet delay tolerance, jitter, loss etc. with minimum control signalling exchange.

Several literatures have focused on simultaneously reducing delay and signalling for M2M communications over LTE. In [5], a dynamic resource allocation method for contention based access (CBA) has been proposed where the amount of CBA resources is increased until the estimated latency satisfies the QoS requirement. In [6], a class-dependent back-off scheme was introduced for radio network overload control which uses system load and classification information of machine-type devices to generate MTC specific back-off interval. In [7], the authors proposed a cluster-based massive access management scheme by dividing the M2M devices in a number of clusters where the clusters are allocated periodic grants in a fixed or opportunistic manner depending on their QoS requirements. But they only considered static allocations for purely deterministic traffic patterns. In [8], the authors developed an analytical Effective Bandwidth (EB) model to determine grant period required by a stochastic service flow to meet statistical delay requirements. Although they proposed a mechanism of tuning the grant period to meet QoS but no mechanism of modifying the allocated resources was suggested. Their proposed improvement by adding intra-cluster queue-length awareness also suffered from extra signalling requirement.

In this paper, we address the issues of control channel overhead and delay requirements together and propose an adaptive packet scheduling scheme for LTE uplink which combines the semi-persistent scheduling (SPS) policy with the default dynamic scheduling scheme. The concept of SPS in the LTE standard itself is not new, being deployed for Voice over IP (VoIP) service which also suffers from control channel bottleneck for scheduling large number of VoIP users. However, the implementation of SPS in case of M2M traffic is not as straight-forward and needs to be modified to adapt to M2M traffic characteristics and satisfy their different QoS requirements as well. To this aim, we propose a novel version of SPS i.e. adaptive SPS scheme to adjust to the bursty nature of M2M traffic and randomness in their traffic arrival patterns. We also form a class-based adaptive scheduling policy where radio resources to different M2M traffic classes are allocated in either dynamic or adaptive SPS fashion based upon their traffic characteristics and corresponding delay tolerance. We explain the rationale behind this new scheduling approach for M2M traffic and demonstrate with simulation results how this approach can maximize achievable uplink capacity at the same time meet satisfactory QoS level.

The rest of the paper is organized as follows: Section II discusses the limitations and required optimization of the LTE dynamic scheduler for M2M communications and the relevance of this work. In Section III, the proposed adaptive SPS algorithm is explained. In Section IV, the simulation environment and traffic models are described and Section V provides the simulation results and following analysis. Section VI concludes the paper and outlines possible future extension.

II. BACKGROUND

A. The Scope of LTE in M2M Communications

Different standard bodies have proposed M2M system architecture and/or service requirements from different perspectives. The European Telecommunication Standards Institute (ETSI) has proposed a service-oriented M2M functional architecture [9] which is divided into two domains i.e. i) device and gateway domain and ii) network domain. The M2M devices can connect to the LTE radio access network either directly or via an M2M gateway.

A pattern based approach can be very effective for scheduling M2M traffic with less signalling overhead. To identify the patterns and customize the resource allocation strategies for them is quite complicated on a per device basis due to their vast number and wide varieties. However, the role of M2M gateway as data aggregator can facilitate pattern based scheduling for potentially huge number of devices. In [10], the concept of M2M relay nodes is introduced which can be used as another form of data concentrator. The eNodeB can allocate resources to the M2M gateways/ relay nodes based on their traffic patterns and QoS requirements. There might be multiple service classes subscribed by the gateway/relay nodes (similar to a general subscriber) and the intended class can be indicated in the bearer establishment request. Nevertheless, communication via the M2M gateway/relay nodes increase the air interface delay to some extent by adding an extra hop, but it is acceptable as long as the M2M applications meet their specific delay constraints. Besides, the provision of individual M2M device access to the eNodeB should also be open for event-based requests which require very low latency data transfer.

B. LTE Dynamic Scheduling

The evolved base station or eNodeB is the sole controller of the LTE radio access network which acts as a bridge between the User Equipment (UE) and the Evolved Packet Core (EPC), relaying data between the radio connection and the corresponding IP based connectivity towards the EPC.

The eNodeB packet scheduler performs scheduling decisions for both downlink and uplink by allocating certain time-frequency resources in terms of Physical Resource Block (PRB) [11] chunks to the devices, along with link adaptation parameters. As the scheduling decisions are made for downlink and upcoming uplink subframes in every Transmission Time Interval (TTI), the new allocations are indicated to the LTE devices via the Physical Downlink Control Channel (PDCCH) [11] dictating when and using which resources they are allowed to transmit/receive data. This mechanism of the dynamic scheduler is efficient for scheduling high data-rate services enabling resource adaptation flexibility and utilizing time-frequency diversity for better QoS. But the limitation of this policy lies in the large control signalling requirement for every possible transmission. The number of control channel resources in the PDCCH actually limits the number of users that can be scheduled every TTI if every user needs only a small allocation (e.g. a single/two PRBs) in the data channel.

C. Semi-Persistent Scheduling (SPS)

The aforementioned problem of control channel saturation was noticed in the case of LTE dynamic scheduling for VoIP service. VoIP is mainly characterized by small packets arriving at regular intervals with tight delay constraints. To handle the situation, semi-persistent scheduling (SPS) was developed where the eNodeB scheduler allocates a sequence of TTI-PRB resource chunks located in every 20ms where the user device can send all its initial transmissions using a pre-assigned (indicated in the initial control channel grant) transport format [12]. If necessary, the scheduler may reallocate different resources or reassign different transport format to enable link adaptation. All the retransmissions are scheduled dynamically using the control channel.

SPS has proven to support higher system capacity in LTE uplink due to having significantly less control overhead than dynamic scheduling and SPS can guarantee VoIP QoS as well [13]. But SPS lacks the diversity gains of dynamic scheduling and is proven to work only for strictly periodic fixed size packet flow. The small payload size and large number of M2M devices also mandate for a control-less scheduling hence the potential of SPS for M2M communications deserves inspection.

D. Rationale for Combination of Dynamic and SPS Approach for M2M Communications

Both dynamic and SPS approaches have their respective advantages and disadvantages. Moreover, the M2M application paradigm is vast and diverse and cannot be modelled into a single scheduling service-class. According to the M2M features and delay constraints/tolerance different M2M devices might call for a mix of scheduling mechanisms.

Dynamic scheduling is very useful for ensuring low latency data transfer for emergency M2M device-triggered traffic such as priority alarm, fault reporting and theft/vandalism reporting etc. Sometimes the M2M application server also requires urgent measurement reports from M2M devices (e.g. metering for high pressure pipelines, device tracking) and the eNodeB can dynamically allocate a resource to the corresponding device so that it can send a fast response.

Nevertheless, many of the M2M devices might also follow a stochastic traffic pattern where the mean arrival rate is known but the actual arrival instances and/or burst sizes are unpredictable and random. Such traffic can be modelled by a Poisson process and the optimum scheduling policy is a critical issue. Although SPS is a better choice from control signalling perspective and can provide more uplink capacity for large number of devices, the burstiness and randomness in the traffic pattern cannot be served efficiently with fixed size periodic grants. The optimum solution would be a combination of dynamic and SPS where the flexible resource allocations come with a lower control overhead. Therefore, an adaptive SPS which combines the benefits of both approaches is desired for quality M2M communications.

III. PROPOSED ADAPTIVE SCHEDULING ALGORITHM

A. Formulation of Adaptive SPS Algorithm

The basis of our proposed adaptive SPS algorithm is utilizing the buffer information reported by the device within its transmitted uplink MAC protocol data unit (MPDU) to adjust the number of PRBs allocated for the next SPS transmission. This allows the SPS scheme to achieve better resource efficiency and QoS with still less control overhead than the dynamic one. The Buffer Status Report (BSR) [14] is piggybacked with the uplink data itself, hence does not require any physical control channel resources. The eNodeB considers this BSR index while forming the next uplink grant and the device can also store this information for future use. In the dynamic scheduling scheme, for each new allocation decision downlink control signalling is required to send the new grant to the device.

However, in the proposed adaptive scheme, with the initial adaptive SPS grant the following parameters are informed to the device:

SPS period, T_{SPS};
uplink subframe number, i;
initial frame offset, j;
Modulation and Coding Scheme (MCS) index, I_{MCS};
PRB starting index, k and
Maximum number of PRBs for allocation, $N_{PRB(max)}$

T_{SPS} is the applicable period of adaptive semi-persistent allocation and is equal to an integer number of LTE frames. The LTE frame duration being 10 ms, the supported SPS periods are hence integer multiples of 10 ms. This restriction is required to avoid changes in the allocated uplink subframe number. Frame offset is the number of frames the device has to wait until it can start its adaptive SPS transmission. More than one device can use the same uplink resources for adaptive SPS transmission if they have the same SPS period but different initial frame offsets assigned to them which means they are multiplexed in time.

The allocated number of PRBs for each adaptive SPS allocation is calculated as follows:

$$N_{PRB} = \begin{cases} min\{N_{PRB(BSR)}, N_{PRB(max)}\}, if\ N_{PRB(BSR)} > 0 \\ 1, otherwise \end{cases} \quad (1)$$

$N_{PRB(BSR)}$ is the required number of PRBs to accommodate the data volume reported in the latest BSR that was received from the device. The value of $N_{PRB(max)}$ is set with the initial grant depending on the availability of contiguous uplink PRBs at the scheduling moment which may depend on the instantaneous traffic load. The applicable MCS value I_{MCS} is the same as the initial transmission since we are assuming M2M devices/gateways with low mobility and good channel conditions here. The adaptive SPS scheme can be seen as a form of dynamic scheduling without requiring control signalling unless there is either a change of required MCS (for link adaptation) or the adaptive SPS allocation needs to be cancelled/period modified due to uplink resource constraints. The eNodeB scheduler reserves the variable number of PRBs (as calculated from (1)) every SPS period in the designated uplink subframe and the corresponding device sends the data in exactly those PRBs since it knows the PRB starting index *k* and can determine the value of N_{PRB} from its last sent buffer status. Nevertheless, the retransmissions are scheduled dynamically.

B. Selection of SPS Period for Delay Sensitive M2M Traffic

For delay sensitive M2M traffic with a strict packet delay budget denoted by T_{PDB}, the selection of SPS period T_{SPS} should be made considering the associated T_{PDB} for satisfying their delay constraints. Fig. 1 demonstrates the hypothetical worst case delay experienced by a packet for the adaptive SPS scheme, assuming the system has enough capacity to accommodate the data reported by the latest BSR i.e. $N_{PRB(max)}$ is sufficiently large.

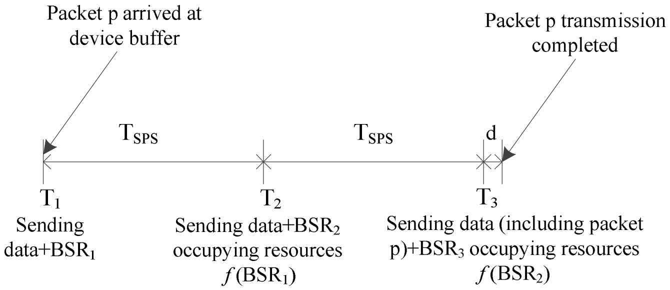

Fig. 1: Worst Case Packet Delay for Adaptive SPS

In Fig. 1, the device sends uplink data along with BSR_1 to the eNodeB at time T_1. The packet *p* arrives at the device buffer immediately at T_1, so its volume was not indicated in BSR_1. Accordingly, the device and eNodeB both calculates the allocated PRB numbers for next adaptive SPS transmission at time T_2 as function of BSR_1. Therefore, packet *p* cannot be accommodated in the allocated resources at T_2 rather its volume is indicated in BSR_2 sent at T_2. The resource size at T_3 is determined from BSR_2 and has enough room for packet *p*. Since the LTE TTI or subframe duration is equal to 1 ms which we denote here by *d*, the transmission of packet *p* is completed at time $(T_3 + d)$.

If all values are expressed in milliseconds (ms), the worst case hypothetical delay of a packet T_{max} for the adaptive SPS algorithm can be expressed by Eq. (2).

$$T_{max} = 2T_{SPS} + d \qquad (2)$$

Setting the value of T_{max} as T_{PDB} (ms) and substituting *d* by its value we obtain the condition for T_{SPS} to ensure all the packets meet their delay budget (if allowed by the system capacity) as shown in (3).

$$T_{SPS} \leq \frac{T_{PDB}-1}{2} \qquad (3)$$

C. Class-based Selection of Scheduling

In a realistic M2M environment the traffic arrival rate may be arbitrary and the selection of scheduling scheme (dynamic/adaptive SPS) would depend on the traffic parameters and also the feasibility of adaptive SPS to support the required QoS. Fig.2 shows the functionality of the class-based adaptive scheduler upon receiving a grant request from a specific traffic class.

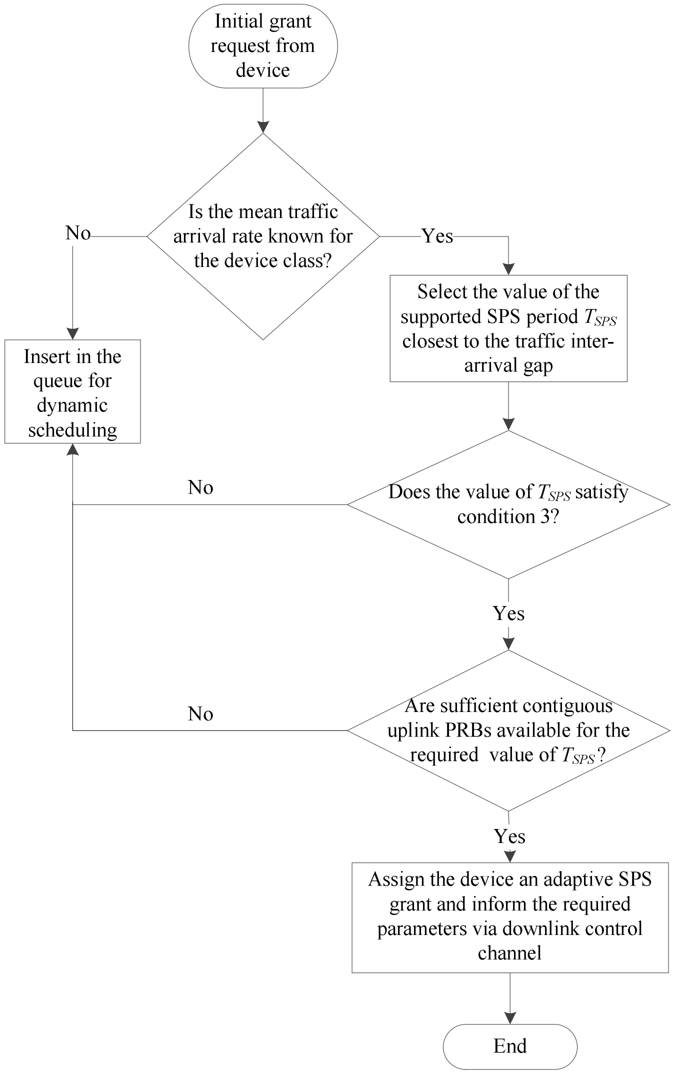

Fig. 2: Functionality of Class-based Scheduling

The scheduling algorithm chooses between the dynamic or adaptive SPS scheduling scheme based upon the knowledge about the device traffic class. If the mean traffic arrival rate λ_{MEAN} is known, the required value of T_{SPS} is determined to be the closest SPS period to the traffic inter-arrival gap ($1/\lambda_{MEAN}$) and also an integer multiple of LTE frame duration. If the corresponding value of T_{SPS} satisfies the delay budget requirement as set by Eq. (3) and sufficient uplink resources are available to be allocated periodically, the device is allocated an adaptive SPS grant, subject to related parameters. The initial adaptive SPS grant is conveyed via the control channel and the subsequent allocations follow without requiring any additional signalling. If any of the necessary checks for the adaptive SPS are not met the default scheduling scheme is dynamic.

IV. SIMULATION ENVIRONMENT

The performance of the proposed adaptive scheduler has been assessed using an OPNET simulation model, the parameters for which are specified in Table I.

Table I: Simulation Parameters

Parameter	Value
Frequency Band	3GPP Band 37 [15] (1910-1930 MHz uplink / downlink)
Mode	TDD Configuration 6
Channel bandwidth	3MHz
Cyclic prefix type	Normal
Max. device Tx power	200 mW
Max. eNodeB Tx power	5W
Device Rx sensitivity	-95dBm
eNodeB Rx sensitivity	-123dBm
Device antenna gain	-1dBi
eNodeB antenna gain	15dBi
Device height	1.5m
eNodeB height	40m
SR periodicity	10ms
PUCCH channels	2
HARQ re-transmissions	Supported
Channel model	Suburban fixed Erceg model with Terrain Type C [16]
Radio network model	Single cell, 2km radius (12.57 km2)

The simulations employ two different classes of M2M traffic i.e. class A and B. The traffic generated by the M2M devices is assumed to be aggregated by an M2M gateway serving the corresponding area network. The LTE eNodeB serves the M2M gateways as the wide area network. The scope of the delay budget is therefore from the gateway to the eNodeB at the MAC layer.

Table II illustrates the traffic model employed in the simulations for 100 M2M gateways. The ratio of class A gateways and class B gateways is 50:50 for all simulation scenarios.

Table II: Traffic Model

Traffic Class	Number of M2M Gateways	Number of M2M Devices/ Gateway	Number of Served M2M Devices	Packet Delay Budget (ms)	Request Arrival Rate (Requests/Second) (Poisson process)	Number of Packets/Request
A	50	50	2500	20	1	Uniform (1,3)
B	50	30	1500	50	1	Uniform (1,2)

Mean packet size is 30 bytes in the application layer; the IP/UDP header adds 28 bytes.

The proposed adaptive scheduler serves the gateways based on their traffic patterns and delay budget values in either dynamic or adaptive SPS mode. The performance of the proposed scheduler is compared with a fully dynamic scheduler and also with another scheduler that can schedule in either dynamic or a non-adaptive (fixed) SPS mode.

V. RESULTS

Fig. 3 shows the difference between the adaptive SPS and the fixed SPS scheme in their PRB allocation strategies. The adaptive SPS grant size is adapted to the buffer status reported by the M2M gateways whereas, the fixed SPS can only allocate a periodic fixed size grant for each SPS allocation that is non-adaptive to the actual traffic dynamics.

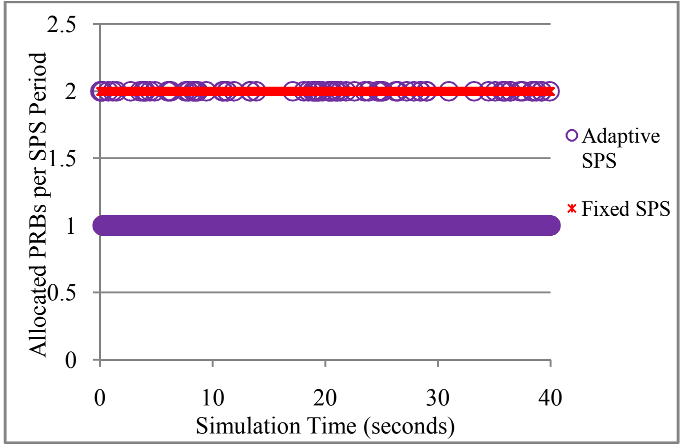

Fig. 3: Allocated PRBs per SPS Period for Adaptive and Fixed SPS

For comparison purpose, the grant size for the fixed SPS is chosen as 2 PRBs per SPS period, which is equal to the ceiling of allocated PRBs $\left(N_{PRB(max)}\right)$ for the adaptive SPS scheme. The grant size of 2 PRBs is a reasonable assumption for accommodating M2M data chunk. As shown in Fig. 3, the adaptive SPS allocates variable number of PRBs up to the ceiling, so that the allocated resources match with the instantaneous requirements.

Fig. 4 shows the percentage of uplink packets served within their respective delay budgets for the three schedulers. The adaptive scheduler adopts dynamic scheduling for traffic class A (since class A packets having a delay budget of 20 ms require an SPS period less than 10 ms (condition 3) which is not supported) and adaptive SPS for traffic class B which meets the necessary conditions (SPS period of 20 ms and ceiling of 2 PRBs). Full dynamic scheduler serves both traffic classes in dynamic manner. The “dynamic + fixed SPS” scheme adopts dynamic for class A and allocates traffic class B in fixed SPS manner.

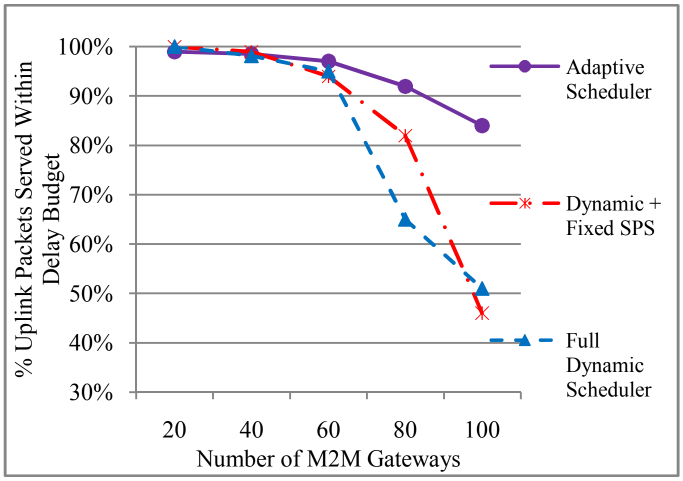

Fig. 4: Percentage of Uplink Packets Served Within Delay Budget Values

As demonstrated in Fig. 4, the adaptive scheduler performs the best in terms of meeting packet delay requirements as number of M2M gateways are increased from 20 to 100, satisfying 84% for 100 gateways. However, the performances of the full dynamic and "dynamic + fixed SPS" rapidly degrade when gateway number increased beyond 60.

The reason behind the performance degradation of the full dynamic scheduler is the excess amount of control overhead associated with each dynamic allocation. This conclusion can be drawn from Fig. 5 where the mean downlink control channel utilization values are compared for the three schedulers.

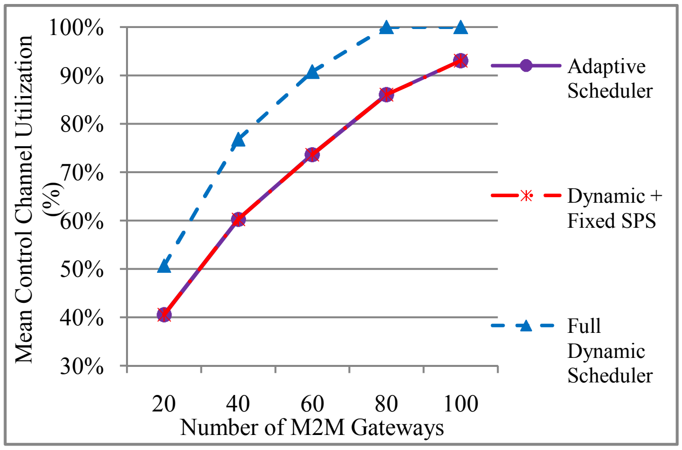

Fig. 5: Mean Downlink Control Channel Utilization Comparison

The adaptive scheduler and the and "dynamic + fixed SPS" have similar downlink control channel utilizations because both of them implement dynamic scheduling for class A traffic (which consumed most of the control channel resources) and for traffic class B both schedulers allocate in semi-persistent manner which does not require control signalling for subsequent allocations. For the full dynamic scheduler, the control channel capacity being saturated for 80 M2M gateways, severely impacts the packet delay performance.

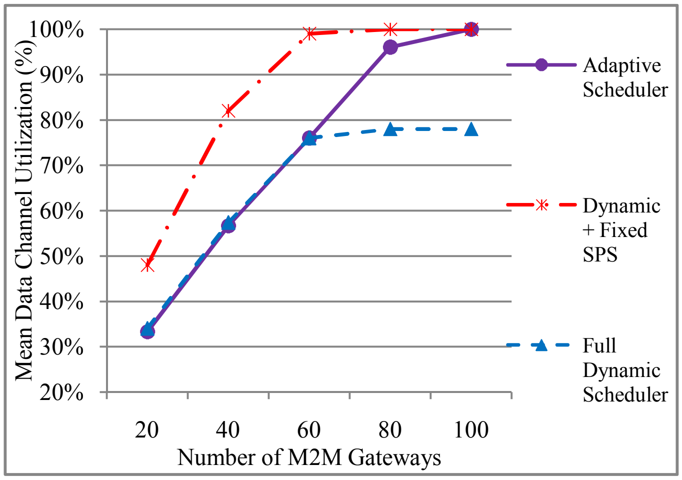

Fig. 6: Mean Uplink Data Channel Utilization Comparison

Although the "dynamic + fixed SPS" scheme is as good as the adaptive scheme is terms of control channel efficiency, it is outperformed by the adaptive scheduler in terms of data channel efficiency. As shown in Fig. 6, the "dynamic + fixed SPS" scheme exhibits higher data channel utilization than the other two schedulers for the same amount of traffic served. So the data channel capacity is saturated for the "dynamic + fixed SPS" scheme earlier than the others. This is due to its rigid SPS allocation structure which cannot adapt to traffic changes. The fixed SPS grants a constant number of PRBs regardless the actual amount of traffic in the device buffer whereas the adaptive SPS has the flexible buffer based allocation strategy. Thus the adaptive scheduler can save uplink resources like the dynamic scheduler and can actually offer more capacity in the uplink to cater for other traffic. The fixed SPS scheme could be modified to constantly allocate smaller resources to the gateways (fixed grant size of 1 PRB) to have lower data channel utilization but that would definitely be inadequate for serving the stochastic bursty traffic as Fig.3 shows the gateway buffer status frequently demanding 2 PRBs allocation size as allocated by the adaptive SPS scheme.

Fig. 6 also shows an important observation for the full dynamic scheduler. The mean data channel utilization for the full dynamic scheduler reaches a plateau at 78% for 80 M2M gateways. This is due to the saturation of downlink control channel (as seen in Fig. 5) which impedes the further uplink allocations. So the system bottleneck for dynamic scheduler comes from the control channel and reduces available uplink capacity. The proposed adaptive scheduler avoids this limitation by scheduling traffic class B in adaptive SPS manner and can exploit the full capacity in uplink for 100 gateways.

VI. CONCLUSIONS

The issue of excessive control overhead associated with LTE dynamic scheduler has been widely discussed as a roadblock for M2M communications over LTE. The semi-persistent allocation policy which is currently in practice for VoIP, although offering a solution with less control signalling, does not allow for the flexibility/modification in allocated radio resources. In this paper, we have proposed an adaptive SPS algorithm which draws on the opportunities of both dynamic and semi-persistent approaches and can allocate periodic yet flexible radio resources to stochastic M2M traffic sources to serve them within their delay budgets.

We also consider the necessity of dynamic scheduling for certain emergency M2M traffic which require low latency data transfer and proposed a class-based adaptive scheduler which selects the appropriate scheduling scheme between dynamic and adaptive SPS for different M2M traffic classes. The adaptive SPS is enabled for M2M traffic classes if they meet certain criteria and allowed by the system capacity. The adaptive SPS scheme allows the periodic allocations to vary in number of PRBs within a certain range and the number of PRBs for a particular allocation is determined based on the mutual knowledge of the eNodeB and the device (the latest reported BSR). This approach is resource efficient from both data and control channel perspective as seen from simulation results. The proposed adaptive scheme also performs better than the full dynamic and "dynamic + fixed SPS" schedulers in meeting delay budget of uplink packets. The adaptive scheme can also utilize the most of the uplink capacity among the three schedulers.

Our future work will focus on advancement of the adaptive scheduler to adapt to varying channel conditions with low control signalling.

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