2018 IEEE Symposium on Computers and Communications (ISCC)

Energy-Efficient Fragmentation-Avoidance Uplink Packet Scheduler for SC-FDMA-Based Systems

Fernando H. S. Pereira, Carlos A. Astudillo, and Nelson L. S. da Fonseca
fernandopereira@lrc.ic.unicamp.br, castudillo@lrc.ic.unicamp.br, nfonseca@ic.unicamp.br

***Abstract*—Energy Efficiency is one of the main concerns in the design of wireless communication protocols, especially for battery-enabled devices, such as smartphones, tablets and laptops. In this paper, we focus on the impact of *transmission fragmentation* and *resource fragmentation* on the energy efficiency of SC-FDMA systems. To deal with these two problems, we introduce the Best Edge Set (BESt) algorithm for adoption in packet schedulers for Single-Carrier Frequency Division Multiple Access (SC-FDMA) LTE/LTE-Advanced systems. The BESt algorithm employs a novel Physical Resource Block (PRB) allocation strategy to avoid *resource fragmentation* as well as a new way to prioritize User Equipment (UE) transmissions to reduce the *transmission fragmentation* and the energy consumed in transmissions. Simulation results show the advantages of using the BESt algorithm and the strong correlation between *transmission fragmentation* and energy efficiency.**

Keywords*—LTE-A networks, Uplink, scheduling algorithm, Energy Efficiency, Resource Fragmentation, Transmission Fragmentation.

I. INTRODUCTION

Given the energy limitation imposed by the batteries of mobile devices, Single-Carrier Frequency Division Multiple Access (SC-FDMA) was chosen by the Third Generation Partnership Project (3GPP) as the uplink multiple access technique for the 4G Long Term Evolution (LTE) networks [1]. Moreover, SC-FDMA has also been considered for 5G networks [2], [3], due to its low peak-to-average power ratio (PAPR) compared to other techniques, such as the Orthogonal Frequency Division Multiple Access (OFDMA), used in the downlink of 4G networks. Nonetheless, resources allocated to a User Equipment (UE) must be contiguous in the frequency domain, which makes resource allocation in SC-FDMA systems an *NP-Hard* problem [4].

For instance, in LTE systems the minimum schedulable resource unit is a Physical Resource Block (PRB), which is composed by a set of 12 contiguous subcarriers spaced by 15 kHz in frequency (180 kHz) and two 0.5 ms slots defining a 1 ms Transmission Time Interval (TTI) in time domain. The total amount of PRBs available for transmission in a system depends on the bandwidth allocated to a cell. Since the 3GPP does not specify how resources must be distributed, several sub-optimal scheduling approaches have been proposed, focusing on fulfilling different scheduling objectives. They can be classified into four main categories: *throughput maximization* [5], which performs channel-dependent scheduling; *fairness* [4],[6], which avoids resource starvation of users with poor channel quality; *Quality of Service (QoS) provisioning* [7] and *energy efficiency* [8], [9].

The *transmission fragmentation* and *resource fragmentation* are major problems which affect the energy consumption in end devices. The *transmission fragmentation* occurs when the buffers of a device does not become empty when using the received grant in a given TTI. Consequently, at least one more transmission must be performed to send the remaining data. Recent smartphone power consumption models [10] have established both a strong relationship between transmission power and end device consumption power as well as an energy consumption gap between the transmission (TX) state and other possible states (such as reception (RX) and active without RX/TX). As a consequence, the transmission fragmentation directly impacts the energy efficiency, since the higher the number of TX states triggered to send a given amount of data, the greater is the total energy consumption. In addition, contiguity of allocated resources affects the energy efficiency, which reduces the size of the schedulable resource chunks and leads to *transmission fragmentation*. In this paper, we show that such problems greatly affects the energy efficiency by increasing the number of grants for emptying the buffers at the end device.

In this paper, we propose the Best Edge Set (BESt) scheduler, an energy efficiency uplink packet scheduler for systems based on SC-FDMA. BESt aims at avoiding both resource fragmentation and transmission fragmentation by combining information about the amount of data to be transmitted and the availability of resources with a novel PRB allocation process which removes the fragmentation of the spectrum. The proposed algorithm is based on recent findings on end device power consumption [10] and achieves important improvements in energy efficiency without compromising the QoS support.

The rest of this paper is organized as follows. Section II discusses related work on energy consumption models and the scheduling algorithms for LTE/LTE-Advanced (LTE-A). Section III proposes the BESt algorithm. Section IV details the simulation model, the scenarios used as well as describes the obtained results. Finally, Section V concludes the paper.

II. RELATED WORK

The resource allocation and energy efficiency (EE) problems in LTE SC-FDMA uplink scheduling have been addressed in the literature using different approaches. In this section, we review the main approaches and highlight the differences between them and our proposal.

A. Non-energy efficiency oriented approaches

The First Maximum Expansion (FME) algorithm [6] employs a Proportional Fair (PF) utility function and explores

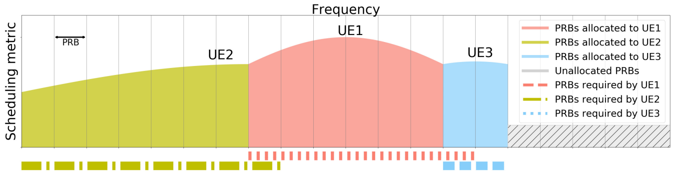


Figure 1: Example of problematic FME resource allocation scenario with not infinite-backlogged users.

the existing correlation of the UE channel quality in time and frequency. This algorithm explores the fact that, if a UE has a good channel quality for a given PRB, it is highly probable that the channel quality is also good for a neighbour PRB. The algorithm chooses the best UE-PRB pair based on PF and then expands the allocation to the immediate neighbour PRBs, as long as the selected UE is the best option for a specific PRB. When there is no more room for expansion, the UE is considered served and is removed from the queue. In this way, contiguity is achieved.

Originally, the FME assumes infinite backlogged UEs, meaning that every resource allocated will be effectively used for transmission. However, this assumption cannot be held in realistic scenarios, since some traffic types have small packets (such as VoIP) so extra resources allocated would be wasted. To overcome it, we used a straightforward adaptation of the FME algorithm for practical systems in which the PRB allocation for a UE stops when the allocated resources are sufficient to make empty the UE buffers. The schedules produced by FME often lead to transmissions in several TTIs. Although such *transmission fragmentation* does not affect much the resource distribution fairness, it negatively impacts the energy efficiency since the number of transmissions for the same amount of bytes increases.

Figure 1 illustrates a schedule which leads to both *transmission fragmentation* and *resource fragmentation* when using the FME algorithm. Moreover, these type of fragmentation occurs not only when the FME scheduler is employed but also when other SC-FDMA schedulers are used. In the example, there are three UEs to be scheduled in FME in a given TTI. UE_1 is scheduled first due to its high PF metric value, but the schedule does not cover the required amount of PRBs since UE_2 and UE_3 reach better PF scheduling metric. The FME chooses, then, the user with the highest value for the PF metric, which is the UE_3. Since UE_3 has a small demand, the allocation of PRBs stops before all resources are allocated. The remaining UE_2 is allocated after UE_3 but the FME scheduler cannot schedule the entire buffer, even though there are enough unallocated PRBs, since the resources are fragmented due to the previous allocation for UE_1 and UE_2. Thus, UE_1 and UE_3 will be forced to wait for a future scheduling opportunity to finish the transmission of the data in the buffer (*transmission fragmentation*), although there are PRBs available. Such type of scenario increases the energy consumption.

B. *Energy efficiency by employing error mitigation*

The work in [11] models the Uplink (UL) resource scheduling as a *Cake-Cutting problem*. It proposes a sub-optimal algorithm in which transmission power and the state of the buffer are captured in the definition of the utility function and the PRB allocation is similar to that adopted by the FME scheduler. UEs which requests are close to their deadlines or those requiring low transmission power are prioritized. Thus, there is a tendency to prioritize small requests since they will require less PRBs, implying in less transmission power. In this case, the energy efficiency comes indirectly from the QoS provisioning.

The work in [9] supports QoS requirements via a probabilistic model that express the number of allocated PRB as a function of the required data rate, Physical Resource Block Signal to Interference plus Noise Ratio (SINR) and the target Block Error Rate (BLER). The decision about which user is scheduled, however, is made offline by using a Markov chain, which is a limitation for practical adoption of this model.

C. *Energy efficiency by employing power allocation with QoS provisioning*

A widely explored framework for energy efficiency in the uplink channel is to minimize the UE transmission power under QoS constraints such as the Guarantee Bit Rate (GBR). The work in [8] proposes a scheduler based on the maximization of the bit-per-joule capacity, subject to QoS minimum data rate constraints. The optimization variables are inversely proportional to the total uplink transmission power. The PRB and power allocation are simultaneously considered by using an Invasive Weed Optimization (IWO) algorithm over the canonical dual formulation of the problem.

A two-phase disjoint PRB allocation and transmission power approach is presented in [12]. The PRB allocation is similar to the FME but limited to the cases in which the change in SINR neither reduces the throughput nor surpasses the number of PRBs required by the users. The transmission power is selected in a way that it is the minimum required value for the selected Modulation and Coding Scheme (MCS).

D. *Energy efficiency through UE buffer size awareness*

Chen *et al.* [13] proposes an algorithm for improving the energy efficiency of Machine-to-Machine (M2M) devices by active-time minimization by using a bi-dimensional (time and frequency) exhaustive search. A refinement of this approach is made by Shen *et al.* [14]. They provide two energy-efficient approaches for M2M devices: transmit power minimization and sleep-time maximization. The first approach considers M2M devices close to the eNodeB (eNB), since these devices usually have a high SINR, allowing the scheduling mechanism to concentrate on the PRB allocation. This algorithm does an exhaustive search similar to [13], with the difference that it searches the minimum total energy value for each M2M device in the queue. The MCS is assumed to be fix for all devices for all PRBs. Due to data criticality and lack of support for data reassembling, the algorithm schedules only complete packets. The second method focuses on devices at the border of the cell. These are devices for which the energy transmission costs cannot be mitigated. The scheduler aggregate packets from different data streams in a single node in the same TTI in order to reduce the total time in active state. However, the proposal does not take into consideration the UE maximum transmission power, usually lower for M2M devices than for Human-to-Human (H2H) devices. When multiple data streams accumulate over a single subframe, the transmission power grows, and it grows even more when the UE has low channel quality. In the two schedulers, the priority of devices are sorted by the Packet Delay Budget (PDB), similarly to [11], which makes them QoS-aware.

Differently from the previous QoS-aware schedulers, the work in [15] focuses on reducing the overall UE transmission power while meeting UE delay requirements. As indicated by the authors, the optimal solution would demand an offline scheduling to address the packet arrival randomness. Thus, they propose a heuristic algorithm which assigns priorities based on the UE request sizes.

E. Summary

Despite the existence of several proposals for energy efficiency of LTE uplink, the joint transmission and resource fragmentation problem have never been explored before. The power consumption models from [10] and [16] reinforce the rationality used in BESt and, at same time, contradicts the proportionality between power consumption and transmission power assumed in [8], [9], [11], [12], [14], [15]. Although previous studies introduced ideas somehow related to our proposal, none of them aimed at analyzing the fragmentation problem impact on the energy efficiency. For instance, in [14] and [13] the *transmission fragmentation* is not a critical issue for M2M communications due to the small packet size, typical of sensor nodes. Moreover, these solutions cannot be applied to H2H communications due to the lack of capacity to handle large packets, particularly when either the amount of date to be transmitted is larger than the total data transmission capacity in one TTI or the data can be fragmented. Furthermore, the mobility and the traffic irregularity aspects are intrinsic to H2H devices and do not fit well with the fixed MCS assumption and the transmission forecasting windows. Although the work in [11] has an implicit short-packet prioritization, it uses an FME-style PRB allocation that may lead to fragmentation even for small UE requests.

III. THE ENERGY-EFFICIENT RESOURCE ALLOCATION ALGORITHM FOR UPLINK SC-FDMA

This section introduces the best edge set allocation (BESt) algorithm, an SC-FDMA uplink packet scheduler designed to increase UE energy efficiency by exploring the UE energy consumption states and the request size. Modern UE power consumption models [10] show that transmission is one of the operations which most consumes energy in UEs. Based on this fact, the BESt algorithm addresses two important problems related to energy inefficiency in SC-FDMA systems: *resource fragmentation* and *transmission fragmentation*. The former is completely avoided by using the novel PRB allocation procedure, whereas the latter is significantly reduced by the analysis of the UE buffer request size. As a consequence the BESt algorithm reduces the total number of transmissions and the energy consumption while providing soft-QoS requirements.

Our proposal introduces the novel BESt PRB allocation strategy, which always allocates those PRBs at the extremes of the set of available resources (first or last set of available PRBs). Let Ch be the entire uplink channel and let $\mathcal{A}$ be the list of available PRBs ordered from the left to the right position in the spectrum. For instance, if $\mathcal{A} = \{PRB_1, PRB_2, \ldots, PRB_k\}$, a two-PRB allocation for a given UE can be either the set $\{PRB_1, PRB_2\}$ or $\{PRB_{k-1}, PRB_k\}$. As the MCS used in the transmission is the lowest supported MCS ($W_i^{S_i}$) among the set S_i of PRBs allocated to a given UE_i, the number of required PRBs to transmit a given amount of data may differ depending on the set of PRBs. The allocation strategy chooses the smaller set between the two candidate sets. This PRB allocation procedure ensures the absence of *spectrum fragmentation*.

Algorithm 1 BESt Scheduler

```
Input:
    $\mathcal{U} = \{UE_1, \ldots, UE_n\}$                ▷ List of schedulable UEs
    $Ch = \{PRB_1, \ldots, PRB_K\}$                 ▷ PRBs in the channel
Output:
    $S_1, \ldots, S_n$                            ▷ List of PRBs allocated to UE $i$

 1: $\mathcal{A} \leftarrow Ch$
 2: $\mathcal{L} \leftarrow \emptyset$
 3: $S_1, \ldots, S_n \leftarrow \emptyset$
 4: $\mathcal{Q} \leftarrow sort(\mathcal{U}, X)$
 5: for $UE_i \in \mathcal{Q}$ and $\mathcal{A} \neq \emptyset$ do
 6:     $W_i^{\mathcal{A}} \leftarrow$ worst MCS for $UE_i$ in $\mathcal{A}$
 7:     $W_i^{Ch} \leftarrow$ worst MCS for $UE_i$ in $Ch$
 8:     $B_i \leftarrow UE_i$ buffer size
 9:     $M_i \leftarrow min(|Ch|, maxPRB_i)$
10:     if $B_i > TBS(W_i^{Ch}, M_i)$ then
11:         $\mathcal{L} \leftarrow \mathcal{L} + UE_i$
12:     else if $B_i < TBS(W_i^{\mathcal{A}}, min(|\mathcal{A}|, M_i))$ then
13:         $S_i \leftarrow AllocatePRB(\mathcal{A}, UE_i)$
14:         $\mathcal{A} \leftarrow \mathcal{A} - S_i$
15: for $UE_i \in \mathcal{L}$ and $\mathcal{A} \neq \emptyset$ do
16:     $W_i^{\mathcal{A}} \leftarrow$ worst MCS for $UE_i$ in $\mathcal{A}$
17:     $W_i^{Ch} \leftarrow$ worst MCS for $UE_i$ in $Ch$
18:     $B_i \leftarrow UE_i$ buffer size
19:     $M_i \leftarrow min(|\mathcal{A}|, maxPRB_i)$
20:     $M_i^{+1} \leftarrow min(|Ch|, maxPRB_i)$
21:     $B_i^{+1} \leftarrow B_i - TBS(W_i^{\mathcal{A}}, M_i)$
22:     if $B_i^{+1} \leq TBS(W_i^{Ch}, M_i^{+1})$ then
23:         $S_i \leftarrow AllocatePRB(\mathcal{A}, UE_i)$
24:         $\mathcal{A} \leftarrow \emptyset$
25:         break
26: if $\mathcal{A} \neq \emptyset$ and $\mathcal{L} \neq \emptyset$ then
27:     $UE_i \leftarrow \mathcal{L}(1)$
28:     $M_i \leftarrow min(|\mathcal{A}|, maxPRB_i)$
29:     $S_i \leftarrow AllocatePRB(M_i, UE_i)$
30:     $\mathcal{A} \leftarrow \emptyset$
31: return $S_1, \ldots, S_n$
```

The proposed BESt approach is presented in Algorithm 1. First, the set of users ($\mathcal{U}$) with uplink data to transmit at TTI n is sorted by $X_i(n)$ scheduling metric value (Line 4), defined as

$$X_i(n) = \begin{cases} 1 + \dfrac{D_i(n)}{PDB^i}, & \text{for GBR bearers} \\ 1 - \dfrac{R_i(n)}{\max(\mathcal{R}(n))}, & \text{for non-GBR bearers} \end{cases}, \tag{1}$$

where $D_i(n)$ is the head of the line (HoL) packet delay of UE i at TTI n and PDB^i is the associated Packet Delay Budget (PDB) for GBR bearers. $R_i(n)$ is the average data rate of UE i and $\max(\mathcal{R}(n))$ is the maximum average data rate among all non-GBR UE requests at TTI n. If $\max(\mathcal{R}) = 0$, $X_i(n)$ is equal to 1. This metric aims at adding soft QoS-awareness to the scheduler while providing flexibility for improving the energy efficiency during the PRB allocation. This metric gives high priority to GBR bearers (those with strict QoS requirements) over non-GBR bearers (no QoS guarantees).

Then, the actual scheduling and resource allocations is divided into two phases: *complete allocation* and *partial allocation*. The former aims at scheduling those UEs which data request, B_i, can be completely served if they are scheduled in the current TTI, whereas the latter aims at allocating the remaining resources to a single UE that was not scheduled in the previous phase, provided that it can better explore these resources for reducing the energy consumption. Note that the eNB knows the UE buffer size through the standardized BSR messages sent by the UE.

To explain how the *complete allocation* phase works, let $\mathcal{Q}$ be the list of users sorted by its X_i value in decreasing order; and UE$_i$ be the first user in $\mathcal{Q}$ (the one with the highest X_i value). Let $TBS(\bullet)$ be the amount of data a certain number of PRBs can transport with a given MCS value and schedulable PRBs as the totality of PRBs in the channel, limited by the maximum number of PRBs a UE can transmit within its maximum transmission power ($maxPRB_i$). If the number of schedulable PRBs (M_i) using the worst MCS in the channel (W_i^{Ch}) is sufficient to empty the UE$_1$ buffers, the UE is defined *eligible* for complete allocation (Line 10). Users which are not eligible are added to the ordered set $\mathcal{L}$ to be considered later in the scheduling. If UE_i is eligible, then it is checked if the scheduling can be done with the available PRBs (Line 12). If it is possible, then the PRB allocation procedure is performed and the set of allocated resources removed from $\mathcal{A}$. Eligible users which cannot be completely served with the available resources are not scheduled and are left for the next TTI. This steps are repeated until all users in $\mathcal{Q}$ are checked or the number of available PRBs becomes 0.

If at the end of the previous phase, there are unallocated PRBs and $\mathcal{L}$ is not empty, the *partial allocation* phase (Lines 15 to 25) is started in order to select a user from $\mathcal{L}$ to assign the remaining PRBs. The highest priority is for the UE with the highest X_i metric value such that if $\mathcal{A}$ is entirely allocated to it, the UE will become eligible for the *whole allocation* phase in the next TTI (Lines 15 to 25). Although the channel quality varies over time, this assumption is a good prediction for UE channel quality in the next TTI. The calculation assumes that the maximum number of PRBs available for its cell bandwidth and the amount of data discounting the data that could be scheduled in the current TTI (note that $\mathcal{L}$ is already sorted due to the way which it was generated). If there is no UE fulfilling the above condition, all remaining PRB ($\mathcal{A}$) are allocated to the UE with the highest scheduling metric in $\mathcal{L}$ (the first UE), following the BESt PRB allocation strategy. This UE selection procedure reduces the *transmission fragmentation*.

Next, the BESt algorithm complexity is analyzed. The search for the worst case in the PRB allocation procedure and the search for the minimum MCS needs to verify the entire set of PRBs in the channel, so it is performed in $\mathcal{O}(|Ch|)$. The total amount of data a given set of PRB can transmit is computed in constant time. Therefore, both *complete* and *partial* allocation steps are $\mathcal{O}(|\mathcal{U}| \cdot |Ch|)$. Generating $\mathcal{Q}$ involves a sort of $\mathcal{U}$, which can be done in $\mathcal{O}(|\mathcal{U}| \cdot log(|\mathcal{U}|)$. Therefore, for a constant bandwidth, BESt is $\mathcal{O}(|\mathcal{U}| \cdot log(|\mathcal{U}|)$. Although BESt complexity is slightly higher than that of the FME algorithm ($\mathcal{O}(|\mathcal{U}|)$), the two perform quite similar for practical networks, since the range of expected number of users to be scheduled per TTI is small.

TABLE I: Simulation Parameters

Parameter	Value
System type	Single cell
System bandwidth	10 MHz
Cell radius	0.5 km
Environment Type	Urban
Duplexing mode	Frequency Division Duplexing (FDD)
Mobility model	Pedestrian A (3 km/h)

IV. PERFORMANCE EVALUATION

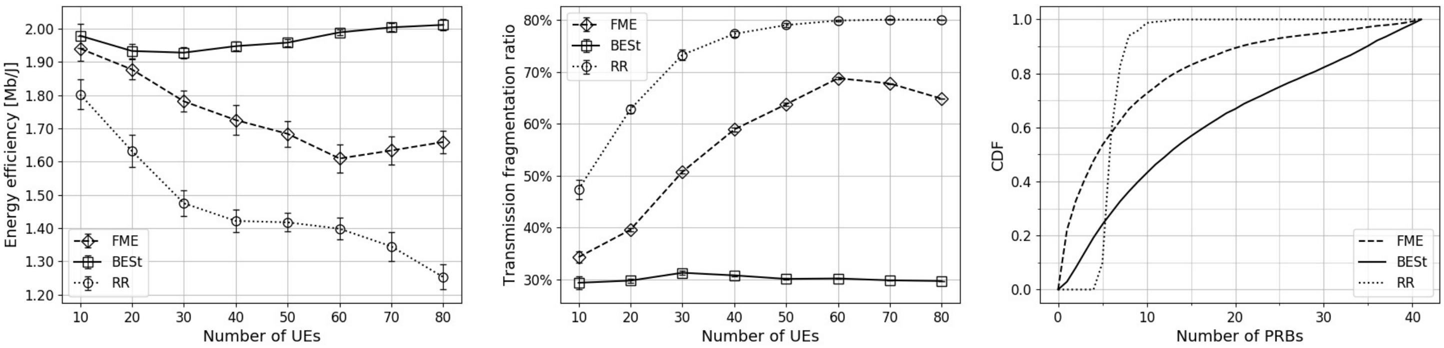
In this section, we evaluate the performance of the proposed BESt algorithm by using the LTE-Sim simulator [17]. LTE-Sim is a discrete-event packet-level simulator developed in C++, widely used for simulating Medium Access Control functions of LTE/LTE-A networks. We used a modified version of the LTE-SIM developed at LRC/UNICAMP, which introduces a model for the Random Access (RA) procedure [18], Packet Downlink Control Channel (PDCCH) management and scheduling [19], QoS support [19], and all types of Buffer Status Report (BSR) messages and Scheduling Request (SR) messages (on PUCCH), and energy consumption capabilities. We implemented the proposed BESt algorithm and the UE power consumption model proposed in [10]. We compare the performance of the BESt algorithm to that of the Round Robin (RR) algorithms and the modified version of the FME algorithm for realistic scenarios.

A. Simulation Model and Setup

This simulation model is composed by a single urban cell with a 500 m radius, an eNB and several UEs (varying from 10 to 80) uniformly distributed around it. The UEs are assumed to be in the RRC connected mode at the beginning of the simulations. The cell bandwidth is 10 MHz (*i.e.*, 50 available PRBs) in the frequency-division duplexing mode. All assumptions made in [19] about PDCCH, Physical Uplink Control Channel (PUCCH), UE distribution and traffic, and QoS bearer settings are also assumed here. The UE channel models is the

TABLE II: Traffic model and QoS requirements

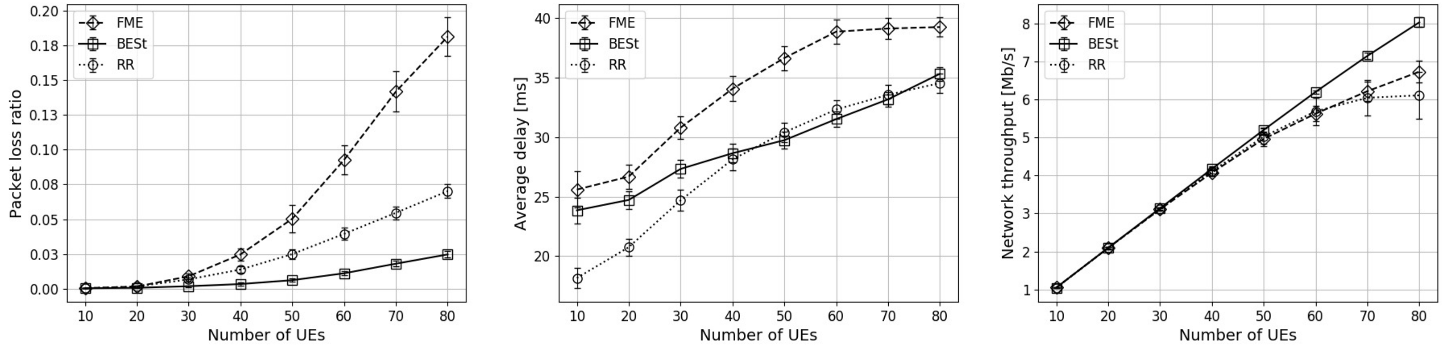
Traffic	**VoIP**	**Video**	**CBR**
Model	G.729 (ON/OFF)	H.264 Trace-based	250 Bytes every 8 ms
Bit Rate	12.2 kbps	128 kbps	250 kbps
QCI	1	2	8
PDB	100 ms	150 ms	300 ms
%	40%	40%	20%



(a) UE energy efficiency

(b) Transmission fragmentation ratio for video traffic

(c) CDF of the number of PRB allocated



(d) Packet Loss Ratio (PLR) of video users

(e) Average delay of video users

(f) Uplink network throughput

Figure 2: Network performance results

ITU Pedestrian-A at 3km/h and the mobility model is Random Walk. Even though the RA procedure is not performed by the UEs, the uplink resources reserved to it are reduced from the available PRB in the corresponding subframes (PRACH conf. index is 6). The Discontinued Reception (DRX) mechanism is not configured, since it does not affect the performance of the problem we are studying. Moreover, with active traffic, there is little chance of UEs to go to sleep with a typical long-DRX cycle of 320 ms and an inactivity timer of 100 ms [10]. Table I and Table II summarizes the traffic models and simulation parameters used in the simulations, respectively.

B. Simulation Results and Discussion

The figures presented in this section show mean values with 95% confidence interval derived from 50 independent replications. As our BESt algorithm aims at improving the energy efficiency while satisfying QoS requirements, the following metrics are analyzed: (i) *energy efficiency* for the transmission state (while transmitting), which is defined as the total amount of data transmitted divided by the the total amount of energy consumed to transmit that data; (ii) the *transmission fragmentation ratio*, which is the ratio between the number of times a UE receives a grant that does not serve its current request completely divided by the total number of transmissions; (iii) the *average package delay*, defined as the mean value for the difference between packet arrival time at the UE buffer and its delivery at the eNB; (iv) *PLR*, defined as the ratio between the number of packets lost and the total number of packets generated; and finally, (v) the *overall network throughput*, defined as the total amount of data transmitted by all UEs divided by the simulation period.

Figure 2(a) shows the energy efficiency for the three algorithms. The BESt algorithm performs with better energy efficiency than the FME and RR algorithms for all number of users considered in the simulation. While the energy efficiency of the BESt algorithm remains almost constant and even slightly improves with a high number of UEs in the cell, the energy efficiency of the FME and RR algorithms significantly decreases as the number of users in the cell increases. The high performance of our proposal is a result of both the approach which avoids *resource fragmentation* and the large reduction of the *transmission fragmentation* resulted from the employment of buffer-based UE prioritization (Fig. 2(b)). The BESt transmission fragmentation is up to 56 % and 62 % smaller than those given by FME and RR algorithms, respectively. Moreover, we found that the energy efficiency (Fig. 2(a)) and *transmission fragmentation* (Fig. 2(b)) present a strong negative correlation ($r = -0.95$ with $p < 0.01$).

Figure 2(c) shows the cumulative distribution function (CDF) of the number of PRB allocated per TTI for video traffic users with 80 UEs in the cell. In this highly loaded scenario, the FME algorithm yields more than half of schedules concentrated to small chunks (5 or less PRBs) and about 5%

of schedules concentrated in big chunks (30 or more PRBs). On the other hand, the RR algorithm leads to almost all chunks to be concentrated between 5 and 10 PRBs, due to RR performing blind resource allocation among a high number of simultaneous users. Conversely, the BESt algorithm is prone to allocate larger chunks (20% of the chunks have at least 30 PRBs) and less prone to allocate smaller chunks (30% have 5 PRBs or less). This tendency to allocate larger PRB chunks agrees with the transmission *fragmentation reduction* accordingly to the UE requests (Fig. 2(b)). The BESt algorithm maintains constant the transmission fragmentation ratio and the energy efficiency of the video traffic in the entire range of UEs. Unlike the BESt algorithm, the FME and RR algorithms sharply increase the transmission fragmentation as the number of UEs increases.

We focuses on the QoS analysis for video traffic since it is the application with the highest bandwidth demands and strict QoS requirements. The QoS scheduling metric and the fragmentation avoidance approach of the BESt algorithm produces lower PLR values than do the FME and RR algorithms (Fig. 2(d)). Note that the FME algorithm may suffer from predatory allocation of low channel quality UEs with Constant Bit Rate (CBR) traffic, which can potentially request a large amount of PRBs, impacting significantly the video PLR. This behaviours is always avoided by the BESt QoS scheduling metric and the way in which users are prioritized since UEs with high scheduling metric and small UE request have high priority over the ones with lower scheduling metric values and bigger UE requests (such as CBR traffic). Moreover, the delay of video traffic (Fig. 2(e)) increases as the number of users also increases. Given its QoS scheduling metric, the BESt algorithm achieves lower delays than do the FME algorithm. In fact, the BESt algorithm provides nearly zero PLR for VoIP traffic with all number of UEs. Finally, the uplink throughput is higher than those produced by the other two algorithms after 50 UEs (Fig. 2(f)). Even though the BESt approach tends to allocate lower MCS values than do the FME algorithm, the throughput is greatly compensated by its novel resource fragmentation avoidance approach.

V. CONCLUSION

In this paper, we have proposed BESt, a novel energy efficient packet scheduler for SC-FDMA uplink. The BESt algorithm avoids *resource fragmentation* induced by the contiguity constraint of SC-FDMA and reduces the *transmission fragmentation* which can highly affect the UE energy consumption. Results obtained via simulation under realistic traffic scenario used to assess typical packet schedulers in the literature show that the BESt algorithm can achieve energy efficiency gains up to 60 % when compared to the RR algorithm and 23 % when compared to the FME algorithm. Moreover, we show the strong correlation between *transmission fragmentation* and energy efficiency.

VI. ACKNOWLEDGEMENTS

The authors would like to thank grant #15/24494-8 from São Paulo Research Foundation (FAPESP), CNPq as well as the European Union's Horizon 2020 project under grant agreement no. 688941 (FUTEBOL) and the MCTI through RNP, for the financial support.

REFERENCES

[1] H. G. Myung, J. Lim, and D. J. Goodman, "Single carrier FDMA for uplink wireless transmission," *IEEE Vehicular Technology Magazine*, vol. 1, no. 3, pp. 30–38, Sept 2006.

[2] A. LI, A. BENJEBBOUR, X. CHEN, H. JIANG, and H. KAYAMA, "Uplink non-orthogonal multiple access (NOMA) with single-carrier frequency division multiple access (SC-FDMA) for 5G systems," *IEICE Transactions on Communications*, vol. E98.B, no. 8, pp. 1426–1435, 2015.

[3] U. Kumar, C. Ibars, A. Bhorkar, and H. Jung, "A waveform for 5g: Guard interval dft-s-ofdm," in *2015 IEEE Globecom Workshops (GC Wkshps)*, Dec 2015, pp. 1–6.

[4] S. B. Lee, I. Pefkianakis, A. Meyerson, S. Xu, and S. Lu, "Proportional fair frequency-domain packet scheduling for 3gpp lte uplink," in *IEEE INFOCOM 2009*, April 2009, pp. 2611–2615.

[5] J. Lim, H. G. Myung, K. Oh, and D. J. Goodman, "Channel-dependent scheduling of uplink single carrier fdma systems," in *IEEE Vehicular Technology Conference*, Sept 2006, pp. 1–5.

[6] L. A. M. R. de Temino, G. Berardinelli, S. Frattasi, and P. Mogensen, "Channel-aware scheduling algorithms for sc-fdma in lte uplink," in *2008 IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications*, Sept 2008, pp. 1–6.

[7] E. E. Tsiropoulou and S. Papavassiliou, "Utility-based uplink joint power and subcarrier allocation in sc-fdma wireless networks," *International Journal of Electronics*, vol. 98, no. 11, pp. 1581–1587, 2011.

[8] A. Aijaz, X. Chu, and A. H. Aghvami, "Energy efficient design of sc-fdma based uplink under qos constraints," *IEEE Wireless Communications Letters*, vol. 3, no. 2, pp. 149–152, April 2014.

[9] D. J. Dechene and A. Shami, "Energy efficient qos constrained scheduler for sc-fdma uplink," *Physical Communication*, vol. 8, pp. 81 – 90, 2013, broadband Single-Carrier Transmission Techniques.

[10] M. Lauridsen, L. Noël, T. B. Sørensen, and P. Mogensen, "An empirical lte smartphone power model with a view to energy efficiency evolution," *Intel Technology Journal*, vol. 18, no. 1, pp. 172–193, 2014.

[11] D. Triantafyllopoulou, K. Kollias, and K. Moessner, "Qos and energy efficient resource allocation in uplink sc-fdma systems," *IEEE Transactions on Wireless Communications*, vol. 14, no. 6, pp. 3033–3045, June 2015.

[12] F. Z. Kaddour, E. Vivier, L. Mroueh, M. Pischella, and P. Martins, "Green opportunistic and efficient resource block allocation algorithm for lte uplink networks," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 10, pp. 4537–4550, Oct 2015.

[13] Y. B. Chen, S. R. Yang, J. N. Hwang, and M. Z. Wu, "An energy-efficient scheduling algorithm for real-time machine-to-machine (M2M) data reporting," in *2014 IEEE Global Communications Conference*, Dec 2014, pp. 4442–4447.

[14] P. C. Shen, S. R. Yang, and P. Lin, "Energy-efficient scheduling algorithms for real-time data reporting in 4g lte machine-to-machine communication networks," in *2016 International Wireless Communications and Mobile Computing Conference (IWCMC)*, Sept 2016, pp. 1057–1062.

[15] M. Kalil, A. Shami, A. Al-Dweik, and S. Muhaidat, "Low-complexity power-efficient schedulers for lte uplink with delay-sensitive traffic," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 10, pp. 4551–4564, Oct 2015.

[16] B. Dusza, C. Ide, L. Cheng, and C. Wietfeld, "An accurate measurement-based power consumption model for lte uplink transmissions," in *2013 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, April 2013, pp. 49–50.

[17] G. Piro, L. A. Grieco, G. Boggia, F. Capozzi, and P. Camarda, "Simulating LTE cellular systems: An open-source framework," *IEEE Trans. Veh. Technol.*, vol. 60, no. 2, pp. 498–513, Feb. 2011.

[18] T. P. C. d. Andrade, C. A. Astudillo, L. R. Sekijima, and N. L. S. d. Fonseca, "The random access procedure in long term evolution networks for the internet of things," *IEEE Communications Magazine*, vol. 55, no. 3, pp. 124–131, March 2017.

[19] T. P. C. de Andrade, C. A. Astudillo, and N. L. S. da Fonseca, "Allocation of control resources for machine-to-machine and human-to-human communications over LTE/LTE-A networks," *IEEE Internet of Things J.*, vol. 3, no. 3, pp. 366–377, June 2016.