Transmission and Reception Alignment for User Equipment Energy Efficiency in LTE Networks

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***Abstract*—Energy efficiency has become an essential component in the design of communication protocols, especially for battery-enabled user equipment (UE) devices such as smartphones. In this letter, an energy-efficient UE packet scheduling scheme for LTE/LTE-Advanced cellular networks is proposed. It achieves energy savings by promoting the simultaneous occurrence of transmissions and receptions. Simulation results show that this approach improves the energy efficiency of the device by increasing the number of simultaneous transmissions and receptions; the network performance, however, suffers little impact.**

***Index Terms*—Downlink scheduling algorithm, energy efficiency, frequency division duplexing, long term evolution.**

I. Introduction

ENERGY efficiency is a key design criterion for communications protocols for battery-enabled devices such as smartphones, since the operation of such devices is susceptible to a rapid battery drain caused by the load on the communication interfaces. Mechanisms to improve energy efficiency are especially relevant since user traffic demand surpasses the increase in battery capacity [1], [2].

A significant portion of the mobile network traffic is generated by bidirectional applications (*i.e.*, Uplink (UL)/Downlink (DL) traffic), such as real-time applications, as well as P2P file sharing, and social networking [3]. In those applications, the UL portion of the total amount of traffic (UL+DL) varies from 15% to 50% [3], and this may even increase with the rise of cloudification of mobile applications and mobile tethering.

Moreover, UL transmissions consume more radio and energy resources than do DL transmissions. This is mainly due to (*i*) the use of Single-Carrier Frequency Division Multiple Access (SC-FDMA) technique in UL data transmissions and the resultant resource allocation contiguity constraints (which may generate less efficient use of resources due to uplink resource fragmentation [4]); and (*ii*) the higher spectral efficiency by using the DL because the maximum modulation format in the UL is 64QAM, whereas that in the DL is 256QAM.

The 3GPP introduced a simple power consumption model for Long Term Evolution (LTE) User Equipment (UE) [5] which classifies activity level state of smartphone modems: deep sleep, light sleep, active with data reception, and active without data reception. More recently, Lauridsen *et al.* [6] developed a more accurate empirical model which expresses the power consumption as a function of the transmission power level. The energy efficiency of the bidirectional state (active with data transmission and reception) is an important aspect of this model as well as of an early 3GPP extended model [5], [6]. These models show that the amount of energy consumed by simultaneous data transmission and reception in a Frequency Division Duplexing (FDD) system is similar to that by transmission alone.

Most of the existing proposals for reducing the energy consumption of smartphones during packet scheduling address a single direction either uplink or downlink direction, although some exceptions do consider them jointly including the energy efficiency in Time Division Duplexing (TDD) systems for LTE [7] and Worldwide Interoperability for Microwave Access (WiMAX) [8]. Several energy-efficient packet schedulers produce energy gain by optimizing user transmission power allocation [9], or the modulation and coding schemes of data transmission requirements [10]. These proposals, however, do not take advantage of the possibility of energy saving from the exploitation of bidirectional smartphone traffic pattern in the more frequent triggering of the bidirectional state.

In this letter, we propose the Green Alignment Packet Scheduler (GAPS), which is a UE energy-efficient scheduling mechanism for FDD-based LTE/LTE-A networks based on the energy consumption in the bidirectional state [6]. The proposed scheme pre-processes the downlink scheduling requests and selects some of them to forward to an existing scheduler which will then perform the final resource allocation. The GAPS scheme monitors the UL scheduling outputs to facilitate selection of simultaneous DL and UL transmissions. By doing this, the number of transmission/reception alignments increases, thus capitalizing on the energy efficiency of the bidirectional state.

The rest of this letter is organized as follows. Section II introduces the proposed UE energy-efficient scheduler for LTE networks. Section III details the simulation model and the scenario used, and discusses the results obtained. Finally, Section IV concludes this letter.

II. Green Alignment Packet Scheduling

This section introduces the GAPS scheme designed to trigger the bidirectional state. To perform downlink scheduling, the GAPS scheme employs information not only from the downlink bearers (packet flows in LTE) to be scheduled but also from the uplink schedules. The proposed scheme splits downlink packet scheduling into two steps: *pre-processing* and *resource allocation*. In the first step, the GAPS scheme pre-processes the downlink bearers in order to form subsets of schedulable requests. In the second step, the resulting subsets

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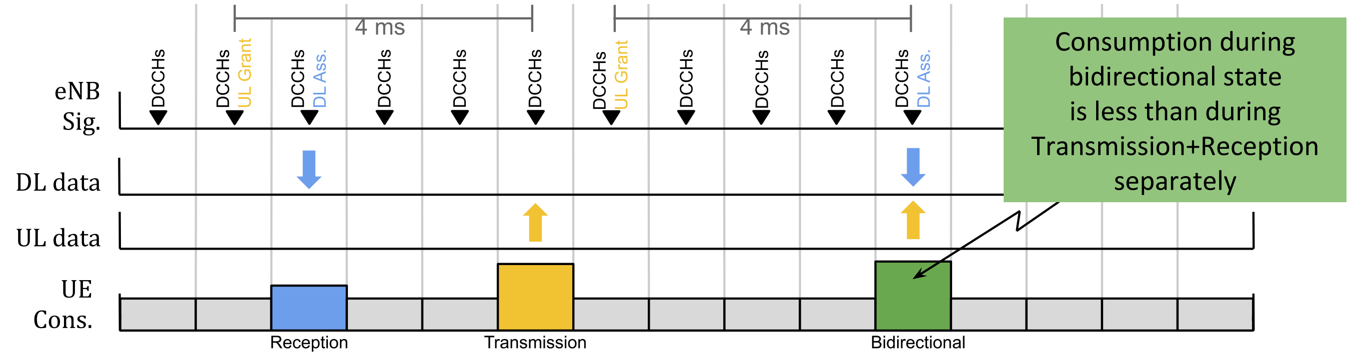


Fig. 1. Energy consumption impact of transmission and reception alignment.

TABLE I
NOTATION

db_i, du_i, dx_i	bearer, user and factor of i-th triple in $\mathcal{D}$
hu_i, ht_i	user and scheduling instant of i-th pair in $\mathcal{H}$
$\mathcal{M}, \mathcal{B}$	*machable* and *blockable* user sets
$\mathcal{A}, \mathcal{P}, \mathcal{R}$	*advantageous*, *postponable* and *regular* bearer sets

are then passed on to an existing downlink scheduler. The GAPS scheme can operate jointly with any existing scheduler, thus allowing the achievement of other performance goals.

Figure 1 illustrates the eNodeB (eNB) signalling for UE activity and the UE energy consumption for transmission, reception and simultaneous transmission and reception based on the Lauridsen *et al.*'s empirical model [6]. This figure shows that the bidirectional state consumes much less energy than the sum of the consumption in the transmission and reception states separately. This bidirectional state is triggered when both the downlink and uplink data streams are *aligned*, *i.e.*, when both occur during the same Transmission Time Interval (TTI). Such an alignment occurs when the downlink bearers are scheduled at the instant of effective uplink transmission, rather than at the instant when uplink packet scheduling is performed. The LTE specification defines that the uplink scheduling grant be released by the eNB at Δt TTIs before the TTI of an uplink transmission. This interval is fixed and dependent on the specific eNB implementation, with a minimum Δt value of 4 TTIs. Conversely, the downlink scheduling assignment and downlink transmission are performed in that same TTI.

The *pre-processing* step of the proposed scheduling approach is presented in Pseudocode 1. Notation is shown in Table I. Let $\mathcal{D}$ be a set of triples (db_i, du_i, dx_i) containing the information of the bearers to be scheduled; db_i identifies the bearer, du_i the UE to be scheduled and the factor $dx_i = \frac{HoL_i}{PDB_i}$ gives the proximity of the Head of the Line (HoL) packet delay of the UE bearer i (HoL_i) to its Packet Delay Budget (PDB) [11]. Let $\mathcal{H}$ be a set of historical data, composed of ordered pairs (hu_i, ht_i), the elements of which identify the UE and the instant at which an uplink scheduling grant was issued, respectively. The number of elements in $\mathcal{H}$ is limited by the number of grants that have been assigned in an interval of a duration equal to a sliding window size (SW) in milliseconds, where SW $\in \mathbb{N}$.

Pseudocode 1 Pre-Processing Step of the GAPS Scheme

Input:
$\mathcal{D} = \{(db_1, du_1, dx_1), \ldots, (db_m, du_m, dx_m)\}$
$\mathcal{H} = \{(hu_1, ht_1), \ldots, (hu_n, ht_n)\}$

1: $\mathcal{M}, \mathcal{B} \leftarrow \emptyset$
2: **for** $(hu_i, ht_i) \in \mathcal{H}$ **do**
3:   **if** $ht_i + \Delta t = TTI_0$ **then**
4:     $\mathcal{M} = \mathcal{M} \cup \{hu_i\}$
5: $\mathcal{B} = \{hu_i | (hu_i, ht_i) \in \mathcal{H}\} - \mathcal{M}$
6: $\mathcal{A}, \mathcal{P}, \mathcal{R} \leftarrow \emptyset$
7: **for** $(db_i, du_i, dx_i) \in \mathcal{D}$ **do**
8:   **if** $du_i \in \mathcal{M}$ **then**
9:     $\mathcal{A} = \mathcal{A} \cup \{db_i\}$
10:   **else if** $du_i \in \mathcal{B}$ and $dx_i < X_{th}$ **then**
11:     $\mathcal{P} = \mathcal{P} \cup \{db_i\}$
12:   **else**
13:     $\mathcal{R} = \mathcal{R} \cup \{db_i\}$
14: **return** $\mathcal{A}$, $\mathcal{R}$

The set $\mathcal{H}$ is processed to identify the sets of *matchable* ($\mathcal{M}$) and *blockable* ($\mathcal{B}$) UEs, which are, respectively, the UEs for which an uplink transmission is going to occur in the next TTI (TTI_0) and the non matchable ones which have received an uplink grant within the Sliding Window (SW) (Lines 1 to 5). After this identification, bearers in D are classified as *advantageous* ($\mathcal{A}$), *postponable* ($\mathcal{P}$) and *regular* ($\mathcal{R}$) sets (Lines 7 to 13). The set $\mathcal{A}$ contains all bearers for which the associated UE is *matchable* and $\mathcal{P}$ contains all bearers which associated UE is *blockable* and the dx values are smaller than a given threshold X_{th}. This threshold is used to avoid bearer starvation and delay violation based on the bearer delay requirement. The remaining bearers are added to the set $\mathcal{R}$.

After $\mathcal{A}$ and $\mathcal{R}$ are identified, they are submitted to the *resource allocation* step for the actual mapping of resources and bearers. A first instance of the downlink scheduler employed in this step allocates resources to $\mathcal{A}$ so that UL and DL alignments will be favored. If $\mathcal{A}$ is completely scheduled and further resources are still available, a second instance of the downlink scheduler allocates any additional resources to $\mathcal{R}$, that contains bearers for which their HoL packet delay value is close to the PDB, or those with no possibilities of generating alignments (no recent uplink activity). The processing of $\mathcal{P}$ is postponed for possible alignment in subsequent TTIs.

The GAPS algorithm is executed every TTI, and the additional time to execute the GAPS algorithm is not significant, since the computational complexity of the *pre-processing* step is less than that of the classical scheduling algorithms used in the *resource allocation* step, as shown below.

The computational complexity of the *pre-processing* step involves three main factors: (*i*) the construction of the *matchable* ($\mathcal{M}$) user set (Lines 2 to 4); (*ii*) the construction of the *blockable* ($\mathcal{B}$) user set (Line 5); and (*iii*) the construction of the *advantageous* ($\mathcal{A}$), *postponable* ($\mathcal{P}$) and *regular* ($\mathcal{R}$) bearer sets (Lines 7 to 13). For the construction of ($\mathcal{M}$), all the pairs in $\mathcal{H}$ must be processed. Each pair indicates the existence of an uplink grant within the sliding window period. In the worst case, each UE may have only a single register per TTI. Thus, the number of registers is limited to the maximum size of $\mathcal{H}$, which is equal to SW, since only one grant can be assigned per TTI. Therefore, this process requires $SW \cdot n$ steps, where n is the number of UEs to be scheduled. Since SW is a constant, the complexity is $O(n)$. The processing of $\mathcal{H}$ is also required for the construction of $\mathcal{B}$, which takes $O(n)$ steps as well. The computation for the construction of the sets $\mathcal{A}$, $\mathcal{P}$, and $\mathcal{R}$ is a function of the total number of bearers to be scheduled $b_{total} = |\mathcal{D}| = b{\cdot}n$, where b is the average number of bearers per user. The maximum value of b is a small constant value. Consequently, the complexity of this process is also $O(n)$. Therefore, the computational complexity of the GAPS*pre-processing* step is $O(3n) = O(n)$, which is lower than that of classical time-domain scheduling algorithms such as Maximum Throughput (MT) and Proportional Fair (PF). These algorithms have a computational complexity of $O(n \log n)$. Therefore, the contribution of GAPS to the computational complexity of the overall scheduling process is not dominant.

Even though our proposal is presented for the LTE-FDD technology, the scheme can be easily extended and applied to other technologies such as 5G new radio (5G-NR) operating in sub 6 GHz FDD frequency bands, since it focuses on request pre-processing, classification and scheduling, which require only high level information about the bearers. Moreover, our proposal can be jointly used with any packet scheduler to perform the actual resource-to-user allocation.

III. Performance Evaluation

In this section, we evaluate the performance of the proposed GAPS scheme via simulation by using an extended version of the LTE-SIM [12], which implements the Lauridsen *et al.*'s UE energy consumption model [6] and the two-stage scheduling proposal (time and frequency domain) [11].

The following metrics are considered in the evaluation: (*i*) *device energy efficiency*, defined as the ratio between total amount of data transmitted and received by all UEs in the network and their total energy consumption in sending/receiving this data; (*ii*) *average downlink packet delay*, defined as the mean time between the generation of a packet and its delivery on DL; (*iii*) *total time* (in TTIs or, equivalently, in ms) spent in each active state (*i.e.*, transmission, reception and the bidirectional state); and finally, (*iv*) *aggregated network throughput*, defined as the total amount of data transmitted by all UEs in the network in a specific direction (downlink or uplink) divided by the duration of the simulation (100 s). The figures presented in this section show mean values with confidence intervals of 95% confidence interval derived from 30 independent replications.

TABLE II
Traffic Model and Bearer QoS Requirements

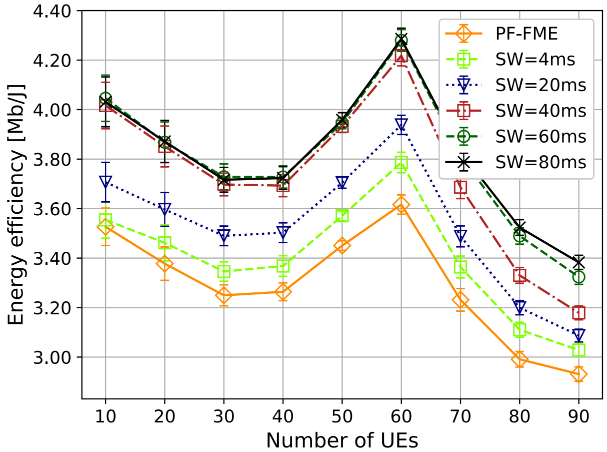
Traffic	Model	Bit Rate	QCI	PDB	%Bi UEs	%DL UEs
VoIP	G.729 (ON/OFF)	12.2 kbps	1	100 ms	40%	0%
Bi-Video	H.264 (trace-based)	242 kbps	2	150 ms	40%	0%
CBR	1000 bytes/8 ms	1 Mbps	8	300 ms	0%	20%

A. Simulation Model and Setup

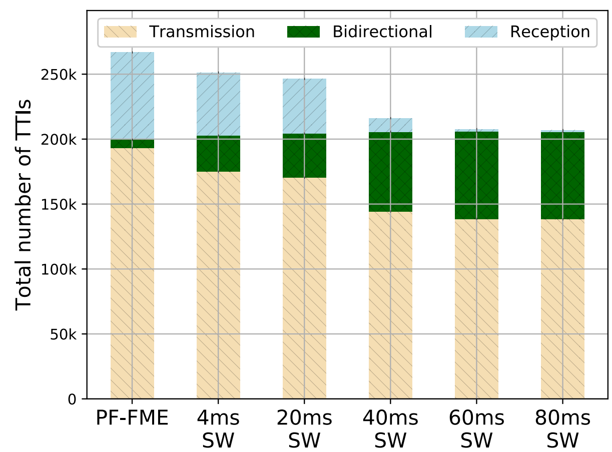
The simulation scenarios include an eNB serving a single cell of 500 m radius with 5 MHz bandwidth in the FDD mode. The UEs were uniformly distributed within that cell, varying from 10 UEs to 90 UEs. The ITU Pedestrian-A channel model [12] was used, and the UEs followed the random walk mobility model moving at a speed of 3 km/h. Regular, padding and periodic (40 ms) Buffer Status Reports (BSRs) were configured. Physical Uplink Control Channel (PUCCH) resource were also configured every 10 ms for sending Scheduling Request (SR) messages. Thus, the Random Access (RA) procedure is not used. However, the Physical Random Access Channel (PRACH) resources are removed from the available Packet Uplink Shared Channel (PUSCH) resources following a typical 6 PRACH configuration index pattern. Four Physical Resource Blocks (PRBs) were reserved exclusively for the PUCCH, leaving the remaining PRBs for the PUSCH. Discontinued Reception (DRX) was not configured because the UE does not go into the deep sleep mode for a DRX cycle period shorter than 64 ms [6].

UEs were assigned with either a single bidirectional application (bidirectional video or voice over IP, VoIP), or a downlink-only application (Constant Bit Rate (CBR)). For bidirectional UEs, two bearers were created, one for uplink traffic and the other for downlink traffic. Bidirectional video UEs transmit and receive a video sequence in the Foreman trace [12], which is a head-and-shoulders type of sequence captured by a hand-held device. Such a sequence has low video activity, similar to that of videoconferencing/videocalling traffic [13]. The sequence was encoded at 242 kbps by using the H.264 standard, typically used in real-time video applications such as Skype and WebEx. This sequence has a temporal resolution of 30 fps and a spatial resolution of 352x288 (CIF size). The starting time difference between the UL and DL video sequences of the same UE was uniformly distributed between 0 ms and 20 ms, and the starting time difference between two different users was uniformly distributed between 0 ms and 40 ms. VoIP traffic was modelled as an ON/OFF Markov model [12], with the ON state corresponding to packet generation on the uplink bearer and the OFF periods corresponding to packet generation on the downlink bearer. Traffic with downlink predominance is represented in our simulation by an aggregation of CBR sources, which can include, for example, file downloads or offline video streaming. Each bearer and traffic type was configured as shown in Table II. Note that the proportion of offered DL/UL traffic in the simulations was about 3 : 1, which is in accordance with recent mobile data usage reports from operating cellular networks [14].

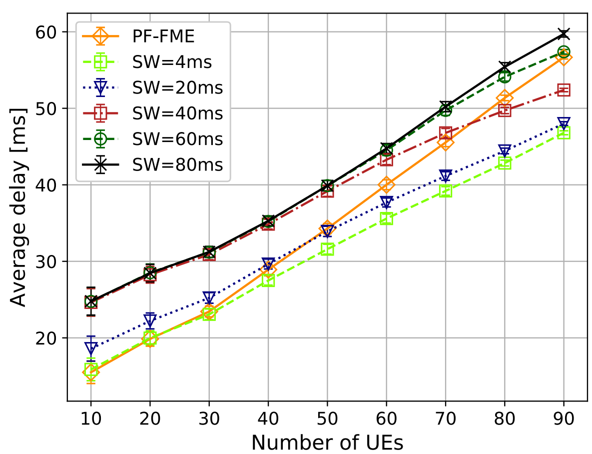
Since GAPS can be used jointly with any downlink scheduling algorithm, the widely-used time-domain and frequency-domain PF was selected for use in the GAPS *resource*



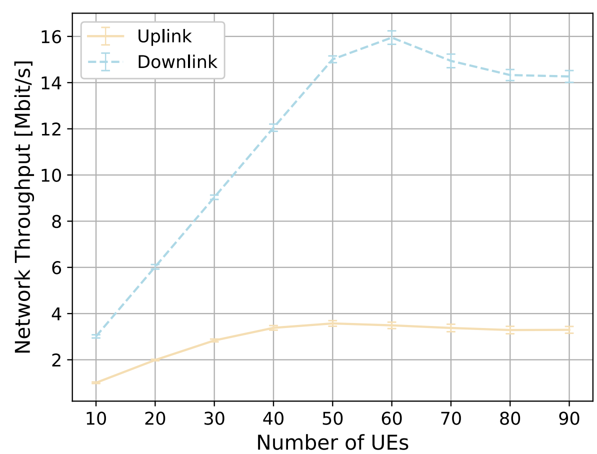
(a) Device energy efficiency



(b) State distribution for bidirectional video users with 60 UEs



(c) Average downlink packet delay of bidirectional video users



(d) Aggregated network throughput

Fig. 2. Network performance results.

allocation step. The scheduling produced by these schedulers with the use of GAPS is compared to that generated without its use. The SW value was varied from 4 ms to 80 ms in order to analyze its impact on network performance and the X_{th} value was fixed to 0.9. In the uplink, the First Maximum Expansion with PF metric (PF-FME) algorithm was used.

B. Simulation Results and Discussion

The energy efficiency results shown in Fig. 2a can be analyzed in three distinct regions, depending on the channel loads. In Region A (from 10 UEs to 40 UEs), the UL and DL channels are underloaded; in Region B (from 40 UEs to 60 UEs), the DL channel is underloaded while the UL channel is saturated; in Region C (from 60 UEs to 90 UEs) both channels are saturated. The channel load results can be seen in Fig. 2d. The GAPSscheme yields a greater energy efficiency (up to 18% more) than does the PF algorithm for all SW values in all regions. This improvement is obtained by increasing the proportion of time spent by the UEs in the bidirectional energy consumption state (Fig. 2b). The simulation setup includes three types of traffic: CBR, VoIP and video. The CBR traffic is limited to downlink and, consequently, cannot be aligned. Moreover, even though VoIP traffic is bidirectional, it has reduced chances of alignment due to its ON-OFF pattern. VoIP users rarely receive and transmit at the same time. Therefore, bidirectional video traffic is the most likely to be aligned, *i.e.*, the one which leads to a higher overall gain in energy efficiency (Fig. 2a).

The energy efficiency increases as the SW value increases up to the video inter-arrival packet interval (40 ms). The SW value influences how long a data transmission can be delayed to promote possible alignment for triggering the more energy efficient bidirectional energy consumption state in the UE. This implies one additional TTI in the idle state. In Regions A and B, the energy efficiency impact is not statistically significant for an SW value greater than 40 ms, although in region C, there was a slight decrease in energy efficiency as the SW decreased. This is an effect of missed alignment opportunities brought about by the approaching of the downlink scheduling delay of video users to the sliding window duration. Thus, the SW value plays an important role in the energy efficiency gain.

In the region A, the energy efficiency decreases as the number of UEs increases because of the underloading of UL and DL and the employment of SC-FDMA in the UL. In this region, both UL and DL throughput increase with the number of UEs (Fig. 2d). Moreover, the contiguity restriction imposed by SC-FDMA increases the resource fragmentation as the number of UEs grows, leading to a larger number of smaller transmissions [4]. Thus, the influence of the transmission state on the energy consumption increases, reducing the overall energy efficiency as the number of UEs increases.

Conversely, in region B, the energy efficiency increases with the number of UEs because only the UL channel is saturated. Despite the overloading condition of the UL, the network throughput continues to increase dominated by the DL-oriented traffic, which leads the overall energy consumption towards the reception state side, which is significantly more efficient. In Region C, with both channels saturated, the network throughput stabilizes and packet losses increase, thus decreasing the energy efficiency.

Figure 2b shows the energy consumption state distribution of video users for 60 UEs, which is the scenario with the largest number of alignments. The proportion of the bidirectional state increases consistently with the SW value up to 40 ms. State distributions are similar for SW values longer than 40 ms. The GAPS scheme increases the number of bidirectional states up to one order of magnitude in comparison with the result of the use of PF algorithm. Moreover, the reception state is reduced to less than 1% for SW values greater than 40 ms (the video inter-arrival packet interval).

Even though the GAPS scheme slightly increases the average downlink delay for video traffic (Fig. 2c), the delay increase induced by the GAPS pre-processing step (of less than 15 ms) is limited by the value of SW and is significantly smaller than the PDB for this type of traffic leading to no increase in Packet Loss Ratio (PLR). As expected, when the SW value is large (60 and 80 ms) video packets are more likely to be postponed, which makes the increase in their delay slightly more accentuated than that in shorter SW values (4 and 20 ms). The behaviour of SW equals 40 ms is similar to that of larger SW values until reaching scheduling delay of 40 ms, where some video alignment opportunities fall off the sliding window. Furthermore, since the PF algorithm does not take the PDB into account, its delay increases more rapidly than does the delay produced by the GAPS scheme.

Figure 2d shows the aggregated network throughput for the UL and DL channels. As the throughput produced no statistically significant difference for the algorithms and setups evaluated, a single curve per channel is plotted. The UL channel becomes saturated before the DL channel because the former supports a lower modulation order than does the latter as well as sharing resources with the PUCCH and PRACH, thus decreasing the number of PRBs available for uplink data transmission. Therefore, the gain in energy efficiency obtained by using the GAPS has no impact on the system capacity.

IV. Conclusion

In this letter, we have proposed the GAPS scheme, a novel downlink packet scheduling for improving UE energy efficiency in LTE/LTE-A cellular networks. Unlike existing schedulers, GAPS explores the high energy efficiency of the bidirectional state by promoting transmission and reception alignment based on uplink scheduling information. Moreover, the GAPS scheme can be used in combination with existing packet schedulers. It leads to an increase in the proportion of bidirectional states (up to one order of magnitude for bidirectional video traffic). Future work should consider the dynamic adjustment of the SW value based on the traffic pattern. Additional assessment of the efficiency of the GAPS algorithm for bidirectional applications such as file sharing, cloud synchronization, and the inclusion of offline video streaming in downlink bandwidth sharing should be also undertaken.

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