Offloading With IFOM: The Uplink Case

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***Abstract*—Mobile data offloading has been proposed as a solution for network congestion. However, the majority of the state-of-the-art is focused on the downlink offloading, while the change of mobile user habits, like mobile content creation and uploading, makes uplink offloading a rising issue. In this work we focus on the uplink offloading using Ip Flow Mobility (IFOM). IFOM allows a LTE mobile User Equipment (UE) to maintain two concurrent data streams, one through LTE and the other through WiFi access technology, that presents uplink limitations due to the inherent fairness design of IEEE 802.11 DCF. In this paper, we propose two uplink offloading algorithms to improve the energy efficiency of the LTE mobile User Equipment (UE) and to increase the offloaded data volume under the concurrent use of access technologies that IFOM provides. In the first algorithm, UEs with heavy traffic are promoted and are given priority in accessing the WiFi Access Point (AP) to offload their data. In the second algorithm, we propose a proportionally fair bandwidth allocation over the data volume needs of the UEs. We theoretically analyse the proposed algorithms and evaluate their performance through simulations. We compare their performance with the 802.11 DCF access scheme and with a state of the art access algorithm under different number of offloading UEs. Through the provided evaluation we show that there is room for improvement in the uplink access scheme of the WiFi that affects the energy efficiency of a UE during IFOM uplink offloading.**

Keywords*—*Offloading, Uplink, IFOM, Energy Efficiency.

I. INTRODUCTION

The explosion of data demand that we are already witnessing is the main reason that drives cellular network operators into the upgrade of cellular access to 4G systems, as LTE, aiming to be able to serve the requested traffic by their customers. Nonetheless, despite the upgrade of the cellular infrastructure, the pace of the increase of data traffic [1] has led the research community to propose offloading techniques that will leverage the mitigation of the overload of the cellular network spectrum and the network's traffic congestion. According to the work of Paul *et al.* [2] on the dynamics of cellular data networks, downloads dominate uploads with more than 75% of the traffic coming from download traffic. On the other hand, smartphone applications slowly change the users attitude, transforming them into content creators. Facebook, Twitter, Youtube and Instagram are some of the main applications that let users upload their content (videos, photos, audio, text and combinations of them) at the time of creation. This change of use habits is highly demanding in terms of energy consumption as in LTE, uploading is nearly eight times more energy consuming compared to downloading [3]. Considering the solution of offloading the uplink traffic of users that are in the range of WiFi APs, the battery life of mobile users will be extended and at the same time the uplink load of an eNodeB will be mitigated.

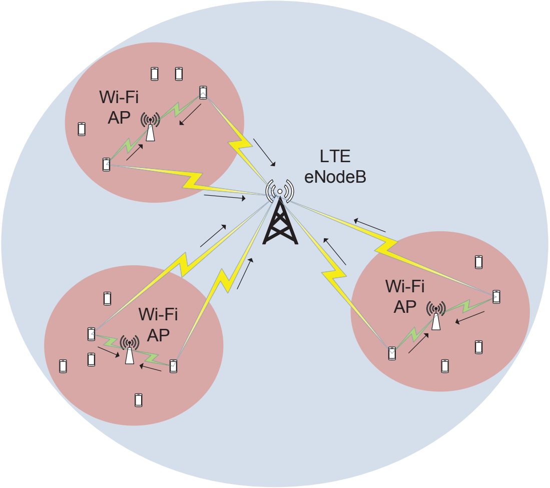

Fig. 1. Uplink offloading scenario with IP Flow Mobility (IFOM).

The attractive deployment costs of WiFi APs has led the providers and the research community to investigate offloading techniques for the cellular networks through WiFi. In [4], the authors investigate the offloading capabilities of WiFi under trace-driven simulations based on mobility habits of mobile users and they provide useful insights on temporal offloading. In [5], offloading through opportunistic communications is explored, where a user offloads to another peer user, which in its turn maintains a short range connection (e.g. WiFi or Bluetooth) or a cellular connection (e.g. EDGE or HSPA). In [6], the authors have proposed Wiffler, which is an application that is used to predict WiFi connectivity aiming to leverage the exploitation of offloading opportunities. Through the conducted measurements in city-wide testbeds they found that cellular and WiFi availability are negatively correlated, a fact that expands the benefit of offloading through WiFi in terms of network coverage. The authors in [7] study the economics of mobile data offloading through third-party WiFi or femtocell APs and they propose a market-based offloading scenario and study the market outcome with game theory. An optimal delayed WiFi offloading algorithm is proposed in [8]. The authors consider the case of file downloading by mobile users that move under the BreadCrumbs mobility model proposed in [9] and they provide an optimal algorithm that minimizes the mobile user's communication cost. In [10], methods for session continuity are proposed during non-seamless WiFi offloading in LTE networks. The performance of these methods is analysed in terms of throughput and energy consumption. The recent published works related to offloading are mainly focused on the downlink traffic offloading and do not consider the increasing tendency of uploading user created content. In our work we rise awareness of the uplink traffic offloading and its impact on the energy efficiency of the modern mobile communication devices.

With the release-10 of 3GPP, a User Equipment (UE) in LTE is able to concurrently maintain connections with the cellular network and a WiFi AP, in order to offload part of its traffic. The scheme that allows this connectivity is named IP Flow Mobility (IFOM) [11]. IP Flow Mobility is currently being standardized by 3GPP [12]. This technology allows an operator or a UE to shift an IP flow to a different radio access technology, without disrupting any ongoing communication. Consider a UE connected to a cellular base station having multiple simultaneous flows. For example, it maintains a voice call and a file upload, and it is moving into the range of a WiFi AP. The UE may shift the file upload on the WiFi network and when it moves out of the AP coverage it will make a seamless shift of the flow back to the cellular network. Another example could be the division of an application's data flow into two flows and the service of each flow by different radio access technologies.

In this paper we bring up the limitations of IEEE 802.11 DCF uplink access and we propose two uplink offloading algorithms for IFOM. The main contributions of this work are the following:

- To the best of our knowledge this is the first work that considers uplink offloading methods for WiFi and LTE networks that operate under the IFOM offloading technique.
- We propose two offloading algorithms to improve the uplink offloading. In the first algorithm, named Heavy Traffic Promotion (HTP) allocation, we give priority to UEs that present heavy upload data needs. In the second algorithm, named Proportionally Fair Bandwidth (PFB) allocation, we propose a proportionally fair bandwidth allocation over the data needs of the UEs.
- We compare the HTP and PFB algorithms with 802.11 DCF and with a state of the art uplink access scheme in terms of UEs' energy efficiency. In addition, we evaluate their offloading capabilities and show that a greater data volume is offloaded using our proposed algorithms.

The rest of the paper is organised as follows. In Section II we present the system model and we analyse the energy consumption of the LTE and WiFi network interface cards of UEs. In Section III and Section IV we analyse the HTP and PFB algorithms respectively. Section V contains the evaluation and simulation results and Section VI concludes our work.

II. System Model

We consider a macro-cell of a LTE network and we focus on its coverage area that is also covered by several WiFi APs that belong to the same LTE provider, as shown in Fig. 1. We assume that N LTE UEs are concurrently under the coverage of the macro-cell and one of the deployed APs. The UEs are equipped with a 802.11 network interface card in addition to their LTE connectivity. Each UE conforms to IFOM and needs to upload a file (e.g. a photo or a video) through a mobile application. We assume that the used applications are able to divide an IP flow into two flows and to define the size of each flow. The UEs are able to use concurrently the two access technologies with IFOM and direct one flow to LTE and the other to WiFi. Every UE$_i$ has a data volume need to upload equal to K_i bits, where $i = (1, ..., N)$ and these data needs are a priori known to the WiFi AP. The AP has a high bandwidth backbone (e.g. fiber connection). Thus, the bottleneck of this route lies in the wireless uplink access of the WiFi connection. The described scheme is applied to each one of the WiFi APs and we investigate the uplink data offloading for a time horizon equal to ΔT.

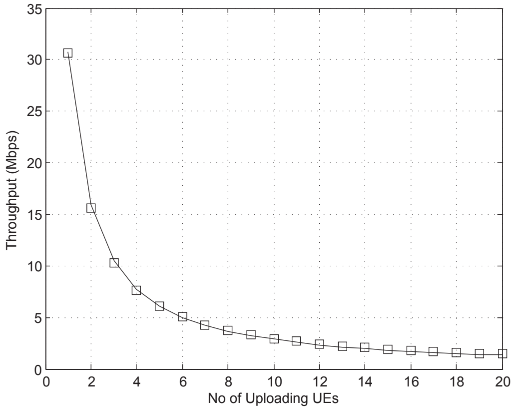

Fig. 2. Degradation of per user throughput in IEEE 802.11 DCF.

A. LTE Uplink Power Model

Regarding the LTE uplink power level of the UE we adopt the energy model proposed by Huang *et al.* in [3]. According to this model the power level of the UE's LTE interface during uplink transmission is expressed as

$$P_{LTE}^{ul} = \alpha_u R_{LTE}^{ul} + \beta \text{ [mW]} \tag{1}$$

where α_u is the uplink transmission power per Mbps, R_{LTE}^{ul} is the LTE uplink rate (in Mbps) and β is the base power of the LTE card for throughput equal to zero.

B. IEEE 802.11 DCF Energy Consumption in the Uplink

The uplink access mechanism of IEEE 802.11 DCF [13] is based on contention among users that are willing to transmit data to the AP and try to avoid collisions following the standard's binary exponential back-off algorithm. Following Bianchi's analysis [14] for saturated traffic conditions and validating with simulations we notice that the throughput of a user that tries to upload data through WiFi is significantly affected by the number of users that are under the coverage of the same AP. The per user throughput $S(N)$ (in Mbps), where N is the number of contending users, is expressed as

$$S(N) = \frac{P_s(N) P_{tr}(N) E[P]}{N \left[(1 - P_{tr}(N))\sigma + P_{tr}(N) P_s(N) T_s + P_{tr}(N)(1 - P_s(N) T_c)\right]} \tag{2}$$

$E[P]$, T_s, T_c and σ correspond to the average payload of a packet, the duration of a successful transmission, the duration of a collision and the time slot's duration respectively. $P_{tr}(N)$

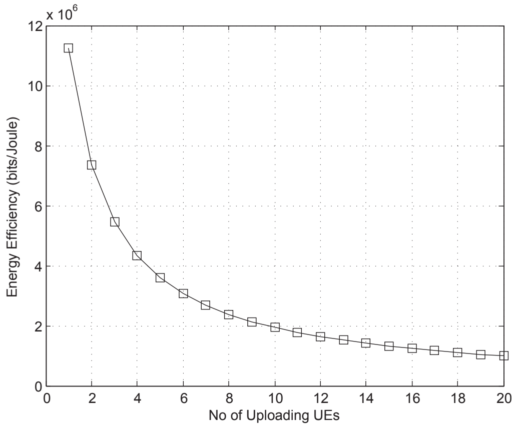

Fig. 3. Degradation of per user energy efficiency in IEEE 802.11 DCF.

is the probability that there is at least one transmission in a considered time slot and $P_s(N)$ is the probability that an occurring transmission is successful. In Fig. 2 the degradation of a user's throughput is presented for the cases of one to 20 users associated with the same AP under saturated traffic conditions and transmission rate equal to $R^{ul}_{WiFi} = 54$ Mbps. A user's energy efficiency $EE(N)$ (in bits/Joule), as a function of the number of contending users N is expressed as

$$EE(N) = \frac{P_s(N)P_{tr}(N)E[P]}{N\left[(1-P_{tr}(N))E_i + P_{tr}(N)P_s(N)E_s + P_{tr}(N)(1-P_s(N)E_c)\right]} \tag{3}$$

where E_i, E_s and E_c correspond to the energy consumption of a user during an idle, a successful transmission and a collision period. The duration of a successful transmission is equal to $T_s = T_H + T_{E[P]} + T_{SIFS} + T_{ACK} + T_{DIFS}$. The duration of a collision period is equal to $T_c = T_H + T_{E[P]} + T_{DIFS}$, and the duration of an idle period is equal to a time slot σ. Where T_H is the transmission duration of the PHY and MAC headers and $T_{E[P]}$ the average transmission duration of a packet's payload for transmission rate equal to $R^{ul}_{WiFi} = 54$ Mbps. Taking these duration expressions into consideration we analytically express the energy consumption values of (3) in (4).

$$\begin{aligned} E_s &= P_{Tx}(T_H + T_{E[P]}) + P_{idle}(T_{SIFS} + T_{DIFS}) + P_{Rx}T_{ACK} \\ E_c &= P_{Tx}(T_H + T_{E[P]}) + P_{idle}T_{DIFS} \\ E_i &= \sigma P_{idle} \end{aligned} \tag{4}$$

where P_{idle}, P_{Tx} and P_{Rx} are the power levels of the user's 802.11 network interface card. In Fig. 3 the degradation of a user's energy efficiency is presented for different number of uploading users.

C. Uplink Offloading Energy Consumption

Every UE under the concurrent coverage of the two access technologies will have the opportunity to offload w_iK_i bits through the WiFi AP, where $w_i \in [0,1]$ for $i = (1,...,N)$. The remainder data volume $(1-w_i)K_i$ is transmitted through the LTE connection of each UE. We assume that the UEs associated with the same WiFi AP present equal connection characteristics with the eNodeB. Every UE$_i$ with data needs equal to K_i that offloads its uplink according to w_i will present energy consumption $EC_i(N)$ as a function of the number of contending UEs N, which is expressed as

$$EC_i(N) = (1-w_i)K_i\frac{P^{ul}_{LTE}}{R^{ul}_{LTE}} + w_iK_i\frac{1}{EE(N)} \text{ [Joule]} \tag{5}$$

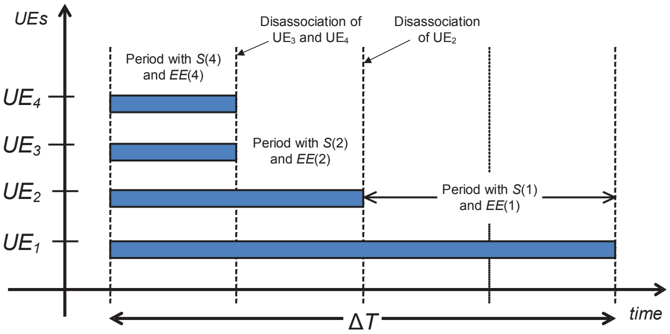

Fig. 4. An example of the HTP algorithm for four UEs.

III. HEAVY TRAFFIC PROMOTION ALLOCATION

In the Heavy Traffic Promotion (HTP) allocation algorithm, we propose a heuristic approach that lets the UE(s) with the maximum data volume needs K_{max} to access the WiFi during the whole time horizon ΔT. The rest of the UEs are allowed to upload to the AP for a period of airtime that is proportional to K_{max} and equal to $t^{WiFi}_i = (K_i/K_{max})\Delta T$. The N UEs start uploading through the WiFi at the start of ΔT and when their airtime ends they are disassociated of the AP. A timeline example of the HTP algorithm for four UEs is provided in Fig. 4.

From Fig. 4 we notice that with the HTP algorithm the period ΔT is divided into M time periods. In every time period m_j with $j = (1,...,M)$ different number of UEs is uploading through the WiFi AP following the 802.11 DCF. We denote as $c(m_j)$ the number of UEs associated with the AP during period m_j and as t_j the duration of period m_j. These periods present different per user throughput equal to $S(c(m_j))$ and different per user energy efficiency equal to $EE(c(m_j))$. We define the matrix B of binary elements and of dimensions $N \times M$ to express the presence of the N UEs during each time period. Thus, an element $b_{i,j} = 1$ if UE$_i$ is uploading through the WiFi AP during the period m_j and $b_{i,j} = 0$ if UE$_i$ is disassociated during period m_j.

The energy consumption of the WiFi network interface card of UE$_i$ can be expressed as

$$EC^{WiFi}_i = \sum_{j=1}^{M} \frac{b_{i,j}t_jS(c(m_j))}{EE(c(m_j))} \text{ [Joule]} \tag{6}$$

while the energy consumption of the LTE network interface card of UE$_i$ is equal to

$$EC^{LTE}_i = \left(K_i - \sum_{j=1}^{M} b_{i,j}t_jS(c(m_j))\right)\frac{P^{ul}_{LTE}}{R^{ul}_{LTE}} \text{ [Joule]} \tag{7}$$

The average per UE energy efficiency of IFOM offloading under the HTP algorithm is expressed in (8).

$$E_{eff}^{HTP} = \frac{\sum\limits_{i=1}^{N} K_i}{\sum\limits_{i=1}^{N} \left(EC_i^{WiFi} + EC_i^{LTE}\right)} \text{ [bits/Joule]} \tag{8}$$

Aiming to reveal the performance improvement of the HTP algorithm in terms of data volume offloading, we define the WiFi offloading index Off_{HTP}. The Off_{HTP} is expressed in (9) and is equal to the ratio of the total offloaded data volume through the WiFi following the HTP algorithm to the data volume that would be uploaded by the standard 802.11 DCF if only one user was accessing the AP to offload. The assessment of HTP's offloading capability according to the offloading index Off_{HTP} is presented in Section V.

$$Off_{HTP} = \frac{\sum\limits_{i=1}^{N} \sum\limits_{j=1}^{M} b_{i,j} t_j S(c(m_j))}{S(1)\Delta T} \tag{9}$$

IV. PROPORTIONALLY FAIR BANDWIDTH ALLOCATION

In the Proportionally Fair Bandwidth (PFB) allocation algorithm we aim to allocate exclusive access periods to each UE$_i$ equal to t_i, for $i = (1, ..., N)$. The exclusive access period for every UE$_i$ is proportionally fair over its data needs K_i. In these periods the UEs will be able to transmit through the WiFi AP with throughput $R_{WiFi}^{ul} = S(1)$. The proportionally fair airtime allocation over the UE$_i$'s data needs K_i is equal to

$$t_i = \frac{K_i}{\sum\limits_{i=1}^{N} K_i} \Delta T \tag{10}$$

Regarding the implementation of the PFB algorithm, in order to give to each UE$_i$ exclusive access to the WiFi AP for a period equal to t_i, we adopt the idea of unsolicited Clear To Send (CTS) frames initiated by the AP that was proposed in [15]. With a CTS frame the AP protects a specific UE to upload its data through WiFi, while all other UEs put their 802.11 network interface cards into sleep mode for a duration equal to the NAV information of the CTS. A timeline example for the WiFi access of the PFB algorithm for two UEs is presented in Fig. 5. We notice that due to non optimally scheduled user access, UE$_2$ is obliged to wait for a long period in comparison to its own access time. Even though during this waiting period UE$_2$'s WiFi card is in sleep mode, it consumes energy. We can further improve our algorithm by applying a shortest-job-first fashion approach scheduling that minimizes the average waiting time of the UEs. The average per UE energy consumption of the WiFi network interface card, during the uploading phase, is expressed as

$$EC_{Tx}^{WiFi} = \frac{1}{N} \left(\sum_{i=1}^{N} \frac{K_i}{\sum\limits_{i=1}^{N} K_i} \Delta T \frac{S(1)}{EE(1)} \right) \text{ [Joule]} \tag{11}$$

After scheduling the exclusive time periods t_i in augmenting order of duration, the average per UE energy consumption of the WiFi network interface card while in sleep mode with power level P_{WiFi}^{sleep} (in mW), is expressed as

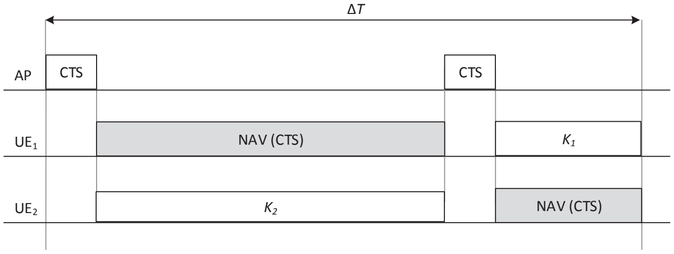

Fig. 5. An example of the PFB algorithm for two UEs.

$$EC_{sleep}^{WiFi} = \frac{1}{N} \sum_{i=1}^{N-1} (N-i) t_i P_{WiFi}^{sleep} \text{ [Joule]} \tag{12}$$

The average per UE energy consumption of the LTE network interface card is equal to

$$EC^{LTE} = \frac{1}{N} \sum_{i-1}^{N} \left((K_i - t_i S(1)) \frac{P_{LTE}^{ul}}{R_{LTE}^{ul}} \right) \text{ [Joule]} \tag{13}$$

Combining (11-13) the average per UE energy efficiency of IFOM offloading under the PFB algorithm is expressed in (14).

$$E_{eff}^{PFB} = \frac{\sum\limits_{i=1}^{N} K_i}{N(EC_{Tx}^{WiFi} + EC_{sleep}^{WiFi} + EC^{LTE})} \text{ [bits/Joule]} \tag{14}$$

The WiFi offloading index of the PFB algorithm, Off_{PFB} is equal to

$$Off_{PFB} = \frac{\sum\limits_{i=1}^{N} t_i S(1)}{S(1)\Delta T} \tag{15}$$

It follows from (15) that $Off_{PFB} = 1$, which means that the PFB algorithm fully exploits the offloading capabilities of the WiFi AP, as every UE is allocated exclusive offloading access to the AP.

V. EVALUATION AND SIMULATION RESULTS

We evaluate our proposed algorithms by running extensive simulations using MATLAB^{TM}. We compare HTP and PFB for a diverse number of UEs under the concurrent coverage of an eNodeB and a WiFi AP, namely for four to 20 UEs. We compare the performance of our algorithms in terms of energy efficiency and offloading capabilities with the standard 802.11 DCF and with an access mechanism titled Smart Exponential-Threshold-Linear (SETL) that was proposed in [16]. In the backoff algorithm proposed in SETL the Contention Window (CW) of a 802.11 user is increasing exponentially up to a threshold that is equal to $CW_{th} = (CW_{max}/2 + CW_{min})$. After this threshold, it is increasing linearly up to CW_{max} according to $CW_{th} + kCW_{min}$, where k is a positive integer. The simulations are repetitively conducted for an offloading time period $\Delta T = 5$ sec. The data volume needs of the UEs are assumed to follow a Zipfian distribution [17] of file sizes between $5-15$ MB. These data needs represent the volume of a photo to a small video, created by contemporary smartphones.

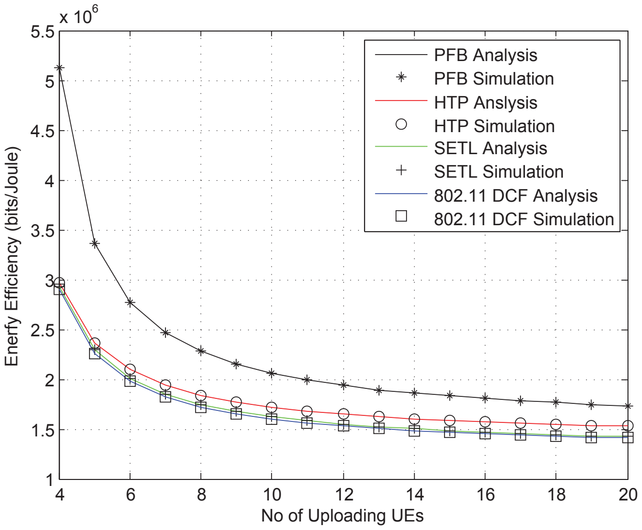

Fig. 6. Energy Efficiency Comparison.

TABLE I.
SIMULATION PARAMETERS

Parameter	Value
LTE uplink rate R_{LTE}^{ul}	5 Mbps
LTE uplink power per Mbps α_u	438.39 mW/Mbps
LTE base power β	1288.04 mW
LTE uplink power	$\alpha_u R_{LTE}^{ul} + \beta$ mW
WiFi packet payload	1500 bytes
WiFi Data/ Ctrl. transmission rate	54/ 6 Mbps
WiFi Tx/ Rx/ Idle/ Sleep Power	1900/ 1340/ 1340/ 75 mW
SIFS/ DIFS	10/ 50 μsec
Offloading period ΔT	5 sec
Number of UEs	4-20
Uplink data volume per UE (Zipfian distribution)	5-15 MB

The uplink power level of a UE's LTE interface card, P_{LTE}^{ul}, is assumed to follow (1). The 802.11 network interface card power levels P_{Tx}^{WiFi}, P_{Rx}^{WiFi}, P_{idle}^{WiFi} and P_{sleep}^{WiFi} are assumed to follow the measurements provided in [18]. The numerical values of the simulation parameters are presented in Table I.

In Fig. 6 we present the energy efficiency results under LTE uplink rate equal to 5 Mbps and we can see that analysis and simulations perfectly fit. It is notable that PFB performs better than 802.11 DCF, SETL and HTP in all range of different number of UEs under the concurrent coverage of LTE and WiFi. The energy efficiency gain of PFB is presented in Fig. 7. Especially for lower number of UEs, namely from four to ten, PFB presents substantial gains in terms of energy efficiency, ranging from 76% to 29% compared to 802.11 DCF and 74% to 27% gain compared to SETL. This happens because lower number of contending UEs leads to higher per user throughput in the WiFi uplink. Even for a large number of offloading UEs equal to twenty, PFB presents around 23% energy efficiency gain compared to 802.11 DCF and 22% gain compared to SETL. The proportionally fair access of PFB along with the exclusive access to the WiFi AP, are the main reasons this algorithm presents higher energy efficiency compared to 802.11 DCF and SETL. As shown in Fig. 8 HTP presents up to 8.6% energy efficiency gain compared to 802.11 DCF and up to 7.5% gain compared to SETL for large number of UEs. For low number of UEs HTP performs nearly the same as 802.11 DCF and SETL. Considering that the data volume needs follow a Zipfian distribution, for large number of UEs the HTP algorithm gives to UEs with heavy traffic the opportunity to offload under low contention conditions, while users with lower data needs upload through the AP at the start of ΔT for less time compared to heavy load UEs.

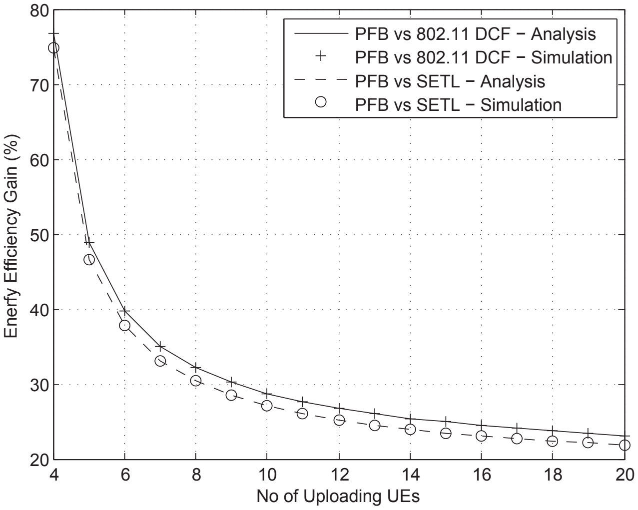

Fig. 7. Energy Efficiency Gain (%) of PFB.

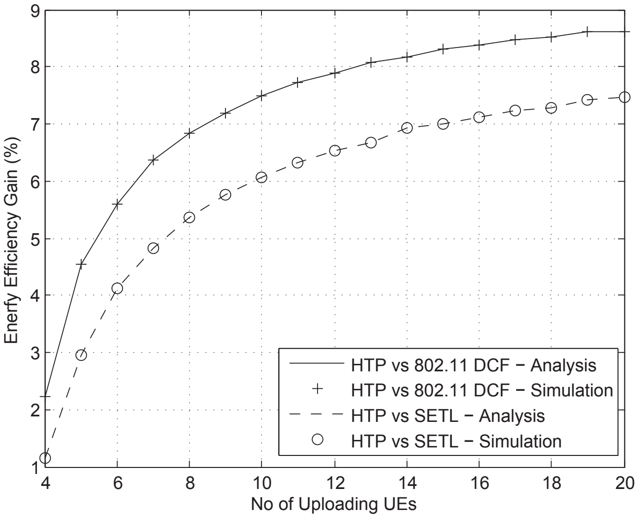

Fig. 8. Energy Efficiency Gain (%) of HTP.

A comparison of the offloading capability of each uplink approach is presented in Fig. 9. As expected from (15) PFB presents offloading index equal to one. This means that with PFB we achieve the maximum exploitation of the AP's capability to offload. HTP presents similar performance with SETL, achieving an offloading index near 0.93 for high contention conditions (20 offloading UEs) and 802.11 DCF presents an offloading index near 0.87 under the same high contention conditions. Regarding the implementation considerations of HTP and PFB it is notable to say that these algorithms can be easily deployed as they do not require any changes in the 802.11 network interface cards of the UEs. Only the APs need

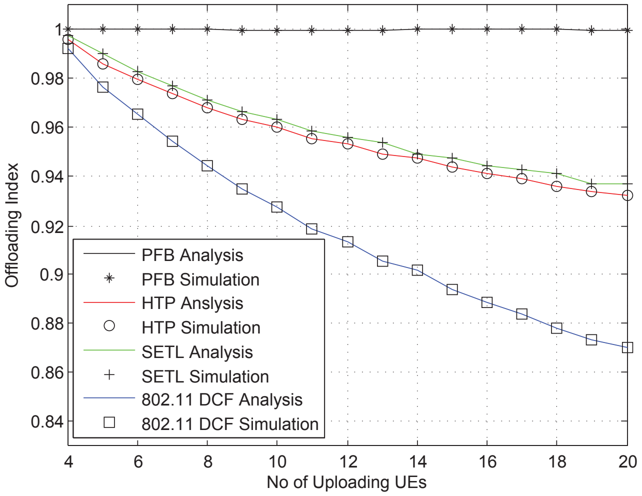

Fig. 9. Offloading Index for different number of UEs.

to be updated to apply these mechanisms. On the contrary, improved access schemes like SETL require changes to the 802.11 network interface cards of both the UEs and the APs.

VI. CONCLUSION

In this paper we propose two new uplink offloading algorithms under the IFOM technique. The first algorithm gives offloading priority to the UEs that present heavy data needs by assigning to them more airtime to transmit through the WiFi. The second algorithm provides a proportionally fair bandwidth allocation over the data needs of the UEs and gives to each UE exclusive access to offload through the AP. For each algorithm we proposed an implementation approach that does not demand any change to the already deployed UEs in the market. The proposed algorithms are evaluated in terms of energy efficiency and offloading capabilities. Through analysis and simulations we showed that our algorithms perform better compared to the SETL access algorithm and to the legacy IEEE 802.11 DCF.

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