Energy Efficiency in Mixed Access Networks*

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ABSTRACT

This paper tackles the multifaceted challenges of controlling *mixed access networks* with base stations, access points and D2D relay stations. Mixed access networks are of uncompelling importance since the next generation cellular access networks are envisioned to use different access technologies at once. We propose a unified framework to model throughput, airtime and power consumption of mobile terminals under any workload conditions in SDN-controlled mixed access networks. With our analysis, we formulate an access selection problem to optimize energy efficiency at the terminal side, while providing fair throughput guarantees. We show that the problem is NP-hard and propose an online low-complexity heuristic that largely outperforms legacy access selection policies. Our results indicate that energy efficiency can be traded off for fairness and that D2D relay is key to increase *both* energy efficiency and fairness.

Keywords

Access Selection; Device-to-Device Communications; 5G; SDN

1. INTRODUCTION

Mixed-technology access networks with heterogeneous protocols and resource allocation schemes are sprouting. On the one hand, telco operators already implement WiFi hotspots alongside the traditional cellular infrastructure [16]. On the other hand, the standardization of Device-to-Device (D2D)-assisted cellular networks is now becoming reality [2] and future cellular networks (e.g., 5G) are envisioned to support D2D communications. Currently available multi-homed mobile devices are already supporting D2D communications in addition to cellular and WiFi connectivity. In addition, many other short-range communication technologies, such as millimeter-Wave and Visible-Light Communications (VLC), are drawing the attention of industries and the research community [15, 17]. In this context, D2D-assisted cellular access networks might allow bundling user traffic in groups and implement dynamic relay, without requiring additional infrastructure deployments. So they allow improving the service towards destinations experiencing poor channel quality. Therefore *D2D can be seen as an alternative network access technology*. In the following, we focus on access networks in which D2D connectivity complements the presence of standard access points (APs) and base stations (eNBs). We refer to such networks as *mixed access networks* with heterogeneous devices acting as Points of Access (PoAs).

Energy efficiency becomes of paramount importance in mixed access networks. Indeed, mobile terminals, which may occasionally act as D2D PoAs, want to seamlessly experience broadband connectivity while preserving their battery lifetime [12]. D2D-assisted cellular access networks have been proven to substantially improve throughput and fairness compared to standard cellular access networks, although they often increase power consumption [3, 4]. Unfortunately, existing network access techniques rarely account for energy efficiency and throughput at the same time. They mostly aim to either improve battery lifetime of devices [14] or seek for throughput [18]. Moreover, energy efficient-aware approaches like [11] neglect the coupling between uplink and downlink resource allocation, or between cellular and 802.11 utilization due to the operation of D2D relays. As of today there is no model or technique available to make informed access selection decisions based on analytical estimate of throughput and power consumption, and hence energy efficiency, in a mixed access network.

We start our work by deriving a *novel comprehensive model which accounts for the intertwined nature of cellular and* 802.11 *resource allocation when D2D comes into play*. In fact, while the bandwidth available at the cellular access affects the load of D2D over 802.11 channels, it is also true that the performance of 802.11 mobile terminals connected to APs and D2D transmissions are entangled and affect the quantity of traffic that can be offloaded, and therefore cellular users. Our model includes an innovative approach to the characterization of 802.11 cliques under any traffic load condition, using a simple yet effective description of 802.11 as a system with a variable number of fully backlogged terminals. With our approach, standard tools like Bianchi's analysis [5] can be reinterpreted and applied. With our model, we compute the *airtime* used by terminals for communicating to any kind of PoAs, even when experiencing heterogeneous channel qualities and under variable load conditions. The airtime characterization is novel and key in our proposal, since it is needed to compute throughput and power consumption of the terminals. Building on our model, we *formulate a new network-controlled access selection problem* that aims to maximize the energy efficiency achieved at terminal side

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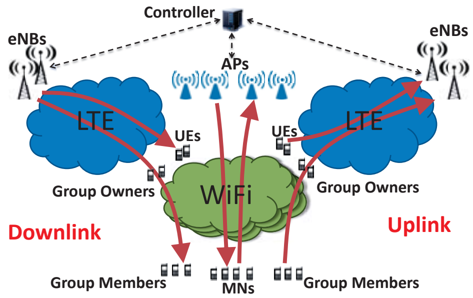


Figure 1: SDN-controlled mixed access network.

when the SDN control paradigm is enforced. As a major point, in the proposed formulation, not only uplink and downlink are simultaneously considered, but also they are jointly optimized in terms of cellular and 802.11 resource allocation. Since the resulting problem is NP-Hard, we design a *novel and efficient heuristic for access selection in SDN-controlled mixed access networks*. We validate our model and the heuristic via packet-level simulations and show that, thanks to D2D-enabled relay, the access selection mechanism we propose achieves up to 75% higher efficiency and much fairer throughput distributions than standard access selection procedures. Notably, our results scale well with the density of terminals.

2. MIXED ACCESS NETWORKS

In a mixed access network, users can attach to a single PoA, i.e., an AP, an eNB or a D2D relay. Users directly connected to an eNB can act as relay for uplink and downlink transmissions of other users, using D2D. We denote by MNs the users attached to an AP, and by UEs the ones attached to an eNB, whereas for relays and users attached to relays we use WiFi-Direct terminology, i.e., Group Owners (GOs) and Group Members (GMs), respectively. Each UE can become GO and form and manage a single WiFi-Direct group to handle the traffic of all the users (GMs) accessing the network through that GO. D2D transmissions use 802.11 frequencies and therefore do not interfere with cellular communications. Resource allocation relies on SDN, with a controller collecting info from PoAs to enforce policies dynamically.

Figure 1 illustrates the above-mentioned network elements. To avoid wasting valuable resources, the SDN controller collects info on channel qualities and traffic demands of mobile terminals, and estimates the throughput each user can achieve under the current PoA association by means of the analytical scheme we present in Section 3. Then the controller enforces rate limiting, to ensure that no resource is misused. The controller also manages access selection decisions, to optimize the energy efficiency at the terminal side, following the scheme we present in Section 4.

3. SYSTEM MODEL

To evaluate access selection policies, we start by proposing a novel model for the estimation of throughput and power consumption at terminal side. We first model cellular and 802.11 throughput and power consumption under given loads. Then we model the impact of the coupling between cellular and 802.11 due to D2D relay.

3.1 Analytical framework

Network. We denote by B the number of eNBs in the access network, whereas $\mathcal{B}$ represents the set of eNBs. The set $K_J = \{k_{1J}, ..., k_{iJ}, ..., k_{n_J J}\}$ is the set of users attached to eNB J. The number of GMs attached to the WiFi-Direct group managed by k_{iJ} is denoted by g_{iJ}. If k_{iJ} is not a GO, $g_{iJ} = 0$. The uplink demand of k_{iJ} is d^u_{iJ}. Such demand includes the uplink traffic of k_{iJ} plus the uplink traffic of the g_{iJ} GMs attached to it. The downlink demand is instead indicated as d^d_{iJ}, which includes the demand of k_{iJ} and of all its GMs. We define a set $\mathcal{A}_q$ composed by A_q APs/GOs using the same channel and in radio range with each other (i.e., in the same clique q). However, we omit the index q when analyzing a given clique. Accordingly, we denote the set of users attached to a particular AP/GO $W \in \mathcal{A}$ by $K_W = \{k_{1W}, ..., k_{iW}, ..., k_{n_W W}\}$. The 802.11 traffic demands of k_{iW} are indicated as d^u_{iW} and d^d_{iW} in uplink and downlink, respectively. Therefore, the notation used for 802.11 users is similar to the one used for cellular users, although the exact meaning will be clear from the context.

Uplink and downlink coupling. We analyze the uplink and downlink jointly, accounting for the fact that they are coupled. For example, if the downlink throughput achieved by a GO over the cellular link changes, we consider the change in the downlink relay, which will affect the uplink traffic from GMs, and, consequently, the uplink load over the cellular link of the GO.

Cellular transmissions. We assume that power control is operated only in the uplink channel, and that uplink and downlink occur on different frequencies. Furthermore, we assume that all the eNBs use the same cellular bandwidth, i.e., frequency reuse 1 is used. We assume that the cellular transmissions adopt OFDMA to allocate resources to the users. We also assume that eNBs are always active in downlink (e.g., due to intense download activity), whereas the uplink might be not saturated (e.g., due to bottlenecks at GOs).

Cellular scheduling. We assume that eNBs operate independently from each other and that use a Vertical First Scheduling (VFS) [10], i.e., users are scheduled over consecutive subframes with a Weighted Round Robin (WRR) policy and subframes are filled avoiding empty spaces. VFS reduces the airtime by design and achieves high energy saving.

Scheduling of GOs. Since GOs haul the traffic of other users, we assume that their weight in WRR is proportional to the number of GMs connected plus one (the GO itself).

D2D and 802.11 operation. The model follows 802.11 a/b/g specifications with no power control. Furthermore, we assume that APs or GOs serve their users in Round Robin (RR) order.

802.11 cliques. We assume that, due to the use of different channels or due to distance, we have N_W independent (non-interfering) 802.11 sets. Since many orthogonal channels are available, and since GO and GMs have to be in proximity, we further assume that all users and APs in a set form a clique.

Demands and arrival processes. We assume demands and arrival processes are stationary and independent, but not identically distributed for each user and for uplink and downlink. Arrivals are packets with the same average size for all cases.

It is worth noticing that different assumptions on the scheduling, resource allocation, packet size or on the network control operation can be easily accommodated in our model.

3.2 Analysis of cellular operation

The throughput in the cellular network is strictly related to the bit efficiency achieved and the airtime used, i.e., the portion of time during which transmissions are active. Similarly, the power consumption under VFS scheduling is proportional to the airtime of the terminals [10]. Therefore, we develop an analytical method to compute bit efficiency and airtime.

3.2.1 Uplink

Let us first consider uplink transmissions to the eNB. Let π_{iJ} be the transmission power used by UE k_{iJ}, which is the result of the uplink power control mechanism in place and it is set to $\pi_{iJ} = \min\left(\frac{SNR_T \cdot \mathcal{N}}{L(k_{iJ}, J)}, \pi^{\max}\right)$, where SNR_T is the target SNR that each user tries to achieve in uplink transmissions [1], $\mathcal{N}$ is the noise power, $L(k_{iJ}, J)$ is the path loss in the transmissions from k_{iJ} to eNB J, while $\pi^{\max}$ is the maximum power transmission allowed.

We now show how to calculate the average uplink bit efficiency b^u_{iJ} achieved by each uplink transmitter, that is, the average number of bits that each UE can transmit per Hertz and per second. The average level of interference sensed by each eNB is the power received from users attached to other eNBs. Thus, using the Shannon formula (normalized to the bandwidth used) and considering that distinct eNBs operate independently, the bit efficiency is:

$$b^u_{iJ} = \log_2\left(1 + \frac{\pi_{iJ} L(k_{iJ}, J)}{\mathcal{N} + \sum\limits_{M \in \mathcal{B}\setminus\{J\}} \sum\limits_{x=1}^{n_M} a^u_{xM} \pi_{xM} L(k_{xM}, J)}\right), \quad (1)$$

where a^u_{xM} is the uplink airtime of an interfering user in a different cell, and the second term in the argument of the log function is the signal-to-noise-plus-interference ratio (SINR).

With VFS, the airtime used in uplink is the portion of symbols needed to serve the throughput T^u_{iJ}, out of a total of N_S symbols transmitted per second over the entire uplink bandwidth. Since the number of symbols per second required is $T^u_{iJ}/(T_S B_S b^u_{iJ})$, where T_S and B_S are time and bandwidth used to transmit an OFDM symbol, the airtime is:

$$a^u_{iJ} = \frac{T^u_{iJ}}{T_S B_S b^u_{iJ} N_S}. \quad (2)$$

The above formulas show that there is a complex relation between airtime, bit efficiency and throughput. Indeed, bit efficiency and airtime achieved by a particular user depend on bit efficiency and airtime of interfering users, which in turn depend on bit efficiency and airtime of the user under analysis.

Denoting by r^u_{iJ} the unsatisfied demand (in terms of symbols/s), the airtime is also expressed as:

$$a^u_{iJ} = \frac{1}{N_S}\left(\frac{d^u_{iJ}}{T_S B_S b^u_{iJ}} - r^u_{iJ}\right), \quad (3)$$

in which r^u_{iJ} can be computed iteratively.

We propose Algorithm 1 to solve the problem without approximations, for a given set of users, demands, and channel qualities. The algorithm, which is a recursive fixed point algorithm, estimates iteratively the uplink airtime of each user in the scenario and its achieved average bit efficiency. The algorithm starts by assigning users airtime proportionally to the relay group size $g_{iJ} + 1$. Then, Algorithm 1 estimates the bit efficiency, fixing the resource allocation, and the new resulting resource allocation, given the bit efficiency just computed. In the algorithm, the available N_S symbols/s are distributed to users according to the weights of the WRR scheduler. Unused resources are then assigned to the users whose demands are higher than their fair share.

Upon convergence, or after a maximum number of iterations, Algorithm 1 returns the airtime allocation that corresponds to the served demand (computed as in line 20 of the algorithm's pseudocode). The throughput can be then computed by inverting (2), and the uplink power consumption P^u_{iJ} is computed based on uplink airtime and transmission power [10]:

$$P^u_{iJ} = a^u_{iJ}\left(P_0 + \alpha\, \pi^{(dBm)}_{iJ}\right) + (1 - a^u_{iJ})\, P_{idle}, \quad (4)$$

where P_0 is the power consumed by the terminals when the transmission power is $1\, mW$, α is a proportionality factor (in W/dBm), $\pi^{(dBm)}_{iJ} = 10 \log_{10} \frac{\pi_{iJ}}{1mW}$, and P_{idle} is the power consumption of the terminals when no transmission is in place.

Algorithm 1 **Uplink cellular bit efficiency and airtime computation**

Input: $g_{iJ}, \pi_{iJ}, d^u_{iJ} \forall\, k_{iJ} \in K_J, \forall J \in \mathcal{B}$,
$L(k_{iJ}, J)\ \forall\, k_{iJ} \in K_J, \forall J \in \mathcal{B}$,
$L(k_{iM}, J)\ \forall\, k_{iM} \in K_M, \forall M \neq J \in \mathcal{B}, \forall J \in \mathcal{B}$,
$cnt^{\max}, N_S, b^{\max}, T_S, B_S, \mathcal{N}$

Initialization:
Compute WRR weights w_{iJ}, initialize airtimes a^u_{iJ}, a^o_{iJ} and counter cnt:

$w_{iJ} = \frac{g_{iJ}+1}{\sum_{x=1}^{n_J}(g_{xJ}+1)}, \forall\, k_{iJ} \in K_J, \forall J \in \mathcal{B}$

$a^u_{iJ} = w_{iJ},\ \forall k_{iJ} \in K_J, \forall J \in \mathcal{B}$
$a^o_{iJ} = 0,\ \forall k_{iJ} \in K_J, \forall J \in \mathcal{B}$ [for previous round's values]
$cnt = 1$

Procedure
Iterative procedure (at most $cnt^{\max}$ loops).
1: **while** $cnt \le cnt^{\max}$ && $(\exists J \in \mathcal{B}$ and $k_{iJ} \in K_J : a^u_{iJ} \neq a^o_{iJ})$ **do**
First, update bit efficiency:
2: **for** $\forall\, k_{iJ} \in K_J, \forall J \in \mathcal{B}$ **do**
3: Compute $b^u_{i,J}$ using (1)
4: $b^u_{iJ} = \min(b^u_{iJ}, b^{\max})$; [bit efficiency has an upper limit]
5: **end for**
Second, update resource allocation (symbols assigned proportionally to w_{iJ}; unused resources redistributed iteratively):
6: **for** $J \in \mathcal{B}$ **do**
7: $N_R = N_S$; [available uplink symbols/s]
8: $r^u_{iJ} = \frac{d^u_{iJ}}{T_S B_S b^u_{iJ}}, \forall\, k_{iJ} \in K_J$; [unsatisfied demand of k_{iJ}]
Iterative resource allocation:
9: **while** $N_R > 0$ && $\exists\, i : r^u_{iJ} > 0$ **do**
10: $N_a = 0$; [symbols/s allocated by eNB J]
11: **for** $i : r^u_{iJ} > 0$ **do**
12: $r_a = \min\left(r^u_{iJ}, \frac{w_{iJ} N_R}{\sum_{x: r^u_{xJ} > 0} w_{xJ}}\right)$; [symbols/s for k_{iJ}]
13: $N_a = N_a + r_a$
14: $r^u_{iJ} = r^u_{iJ} - r_a$
15: **end for**
16: $N_R = N_R - N_a$
17: **end while**
Update airtime values:
18: **for** $k_{iJ} \in K_J$ **do**
19: $a^o_{iJ} = a^u_{iJ}$
20: Compute a^u_{iJ} with (3)
21: **end for**
22: **end for**
23: $cnt = cnt + 1$
24: **end while**

Output: $b^u_{iJ}, a^u_{iJ}, \forall\, k_{iJ} \in K_J, \forall J \in \mathcal{B}$

3.2.2 Downlink

The downlink transmission power of an eNB is constant over time and equal to π_J. The bit efficiency depends on inter-cell interference generated by the transmissions of other eNBs, which are always active. As a result, the average bit efficiency achieved b^d_{iJ} by eNB J in the transmissions to user k_{iJ}, can be computed as:

$$b^d_{iJ} = \log_2\left(1 + \frac{\pi_J L(J, k_{iJ})}{\mathcal{N} + \sum\limits_{M \in \mathcal{B}\setminus\{J\}} \pi_M L(M, k_{iJ})}\right), \quad (5)$$

where $L(M, k_{iJ})$ represents the path loss among eNB M and user k_{iJ}. Note that, differently from the uplink case, the bit efficiency in downlink is not affected by the user airtime, and so it can be computed without iterations.

Downlink resource allocation follows the same VFS scheduling policy used in uplink, so that an expression equivalent to (2) holds by replacing the superscript u with d. So, to compute the downlink user airtime and throughput, we only need to compute the amount of unsatisfied demand r_{iJ}^d, using the WRR policy for resource allocation. For such computation we use an algorithm similar to Algorithm 1, and omitted for sake of brevity, in which the "while-do" statement is not necessary. In fact, a single iteration (equivalent to lines 6-22 of Algorithm 1) suffices to return the downlink airtime of each user, from which we compute the downlink throughput:

$$T_{iJ}^d = T_S B_S b_{iJ}^d a_{iJ}^d N_S. \tag{6}$$

Finally, the power consumption due to downlink activity is:

$$P_{iJ}^d = a_{iJ}^d P_R + (1 - a_{iJ}^d) P_I, \tag{7}$$

where P_R is the power consumed by the terminal while receiving and P_I is consumed when the terminal is idle.

3.3 Analysis of 802.11 operation

In order to compute the throughput and the power consumption achieved in 802.11, we analyze a generic clique. We first show how to compute the bit efficiency of 802.11 transmitters. Second, with the bit efficiencies we propose a new model to compute the throughput based on system *states*. We then compute the duration of the states, which is key to estimate the power consumption.

Bit efficiency. The bit efficiency b_{iW}^d achieved by each PoA W is univocally determined by the particular destination k_{iW}:

$$b_{iW}^d = \log_2 \left(1 + \frac{\pi_W L(W, k_{iW})}{\mathcal{N}} \right), \tag{8}$$

where π_W is the fixed transmission power of W and $L(W, k_{iW})$ is the path loss from W to k_{iW}. Eq. (8) does not include interference because successful 802.11 transmissions in a clique occur when only one device transmits.

However, the average bit efficiency of W depends on the distribution of transmissions from W to the terminals attached to W. Indeed, differently from what assumed in state-of-the-art proposals, the average bit efficiency is neither an input of the problem nor a constant, since it changes with the traffic distribution across terminals served by W, and the traffic distribution changes with the number of devices in the clique and with their demand. For this reason we present here a novel approximation method to compute throughput and power consumption.

The basic idea behind our model is that, in each 802.11 channel, operations can be split in intervals of time during which the set of active (backlogged) devices remains unchanged. In each of such intervals, active APs, GOs, MNs and GMs can be regarded as a saturated system for which the analysis of Bianchi for a clique [5] can be used. Thereby, each interval corresponds to a *system state* for which we can compute bit efficiencies, throughputs and airtimes.

Let us consider the PoAs $W \in \mathcal{A}$. In a generic state s, terminals with packets to transmit to W are denoted as set $Q_W^u(s)$, whereas $Q_W^d(s)$ is the set of terminals with packets to receive from W. Now, while the average bit efficiency b_{iW}^d of terminal $k_{iW} \in Q_W^u(s)$ is computed with an expression similar to (8), the bit efficiency of PoA W is the average of its bit efficiencies experienced when transmitting to its attached terminals in round robin in state s (packets have the same average length, otherwise per-user average packet sizes shall be used as weights in the following expression):

$$b_W(s) = \left| Q_W^d(s) \right| \Bigg/ \sum_{i:k_{iW} \in Q_W^d(s)} \frac{1}{b_{iW}^d} \ . \tag{9}$$

Throughput and state duration. Due to the packet-fairness of the 802.11 MAC protocol, all transmitters achieve the same throughput (in packets per second). Having assumed a common average packet lengths for all transmitters, all throughputs in a clique are statistically identical. Such common value is the throughput $R(s)$ computed in state s with Bianchi's formula [5], in which the average transmission time is computed with the bit efficiencies derived as described above. Note that $R(s)$ accounts for the presence of *all* active PoAs and for their attached terminals active in state s, so it expresses the coupling between different PoAs using the same channel in the same area. Moreover, the throughput of a PoA is fairly shared between its MNs or GMs. Therefore uplink throughputs $T_{iW}^u(s)$ and downlink throughputs $T_{iW}^d(s)$ of the MNs (or GMs) of W, in state s, are as follows:

$$T_{iW}^u(s) = R(s); \qquad T_{iW}^d(s) = \frac{R(s)}{|Q_W^d(s)|}. \tag{10}$$

We now need to compute the time spent in each state. To this aim, we note that the order in which states are visited is not important, because the arrival processes are independent. So we consider a unit interval and the demand corresponding to that interval, and reorder the states occurring in such interval. We start with the state with more active devices, namely s_1: the system remains in such state until the uplink or downlink demand of one device is completely served. This is simply given by:

$$t_1 = \min_{i:k_{iJ} \in \bigcup\limits_{W \in \mathcal{A}} \left(Q_W^u(s_1) \cup Q_W^d(s_1) \right),\ x \in \{d,u\}} \left(\frac{d_{iW}^x}{T_{iW}^x(s_1)} \right). \tag{11}$$

After t_1, the system switches to state s_2 in which one less 802.11 downlink/uplink flow is active, which changes the average system throughput. Thus, the computation of t_2 and of the durations of the successive states can be done sequentially, until all demands are served or $\sum_i t_i = 1$.

Having used a unit interval in the computation, the values t_i represent the fractions of time spent in each state. The resulting average throughputs on 802.11 are therefore as follows:

$$T_{iW}^u = \sum_i t_i R(s_i); \qquad T_{iW}^d = \sum_i \frac{t_i R(s_i)}{|Q_W^d(s_i)|}. \tag{12}$$

Note that the approach proposed is an approximation, since it assumes that after a flow activates or deactivates, the system reaches instantaneously its steady state, in which Bianchi's formula holds. However, we will show via simulation that this approximation introduces negligible error.

Airtime and power consumption. In order to compute the power consumption of APs and MNs (or GOs and GMs in 802.11), we exploit the results of [9]. Throughput and airtime determine the power consumption of PoAs (P_W) and terminals (P_{iW}):

$$P_W = P_{idle} + \gamma_{tx} a_W^{tx} + \gamma_{rx} a_W^{rx} + \sum_{k_{iW} \in K_W} \left(\beta_{tx} \frac{T_{iW}^d}{E[S_p]} + \beta_{rx} \frac{T_{iW}^u}{E[S_p]} \right); \tag{13}$$

$$P_{iW} = P_{idle} + \gamma_{tx} a_{iW}^{tx} + \gamma_{rx} a_{iW}^{rx} + \beta_{tx} \frac{T_{iW}^u}{E[S_p]} + \beta_{rx} \frac{T_{iW}^d}{E[S_p]}; \tag{14}$$

where P_{idle} is power consumed by an 802.11 device when idle, γ_{tx} and γ_{rx} are the powers consumed by a device per airtime unit in transmission/reception, β_{tx} and β_{rx} are the powers consumed per packet transmitted/received per second, and $E[S_p]$ is the average packet length. In the formulas, we have denoted by a_{iW}^{tx} and a_{iW}^{rx} the transmission/reception airtime of k_{iW}, whereas a_W^{tx} and a_W^{rx} denote airtimes at PoA W.

We now show how to compute the airtime as an average over states s. We denote by τ_s and p_s respectively the probability that a system slot (which has variable length, as defined in [5]) contains a transmission and the conditional probability that a transmission is successful in state s, given that the transmission occurs. Using the same approach of [5], we can compute τ_s and p_s from the number $D(s)$ of transmitting devices (PoAs and terminals) in state s:

$$D(s)=\left|\bigcup_{W\in\mathcal{A}} Q^u_W(s)\right|+\left|\left\{W\in\mathcal{A}:\exists k_{iW}\in Q^d_W(s)\right\}\right|; \quad (15)$$

$$p_s=1-(1-\tau_s)^{D(s)-1}; \quad (16)$$

$$\tau_s=\frac{2(1-2p_s)}{(1-2p_s)(C+1)+p_sC[1-(2p_s)^m]}; \quad (17)$$

where C is the the minimum congestion window size of 802.11 and m is the maximum number of transmission attempts for a packet. The absolute probability to have a success for any of the transmitters is then $P_s=\tau_s(1-\tau_s)^{D(s)-1}$, so that the probability of collision in a slot for a given transmitter is τ_s-P_s. Thus, solving (16) and (17) for τ_s, leads to the airtime computation for state s:

$$a^{tx}_W(s)=\frac{\left(P_s/\left|Q^d_W\right|\right)\sum_{k_{iW}\in Q^d_W}\delta^d_{iW}+(\tau_s-P_s)\delta_c}{\bar{\delta_s}}; \quad (18)$$

$$a^{rx}_W(s)=P_s\frac{\sum_{k_{iW}\in Q^u_W}\delta^u_{iW}}{\bar{\delta_s}}; \quad (19)$$

$$a^{tx}_{iW}(s)=\frac{P_s\delta^u_{iW}+(\tau_s-P_s)\delta_c}{\bar{\delta_s}}; \quad (20)$$

$$a^{rx}_{iW}(s)=\frac{P_s}{\left|Q^d_W\right|}\frac{\delta^d_{iW}}{\bar{\delta_s}}; \quad (21)$$

where δ_c is the duration of a slot containing a collision (either an RTS frame or a packet), whereas δ^u_{iW} and δ^d_{iW} are successful transmission durations (including 802.11 overheads) from k_{iW} to PoA W and vice versa, respectively. Considering that unused slots have fixed duration δ_e, the average slot duration $\bar{\delta_s}$ in state s is:

$$\bar{\delta_s}=P_s\sum_{W\in\mathcal{A}}\left(\sum_{k_{iW}\in Q^u_W}\delta^u_{iW}+\frac{1}{\left|Q^d_W\right|}\sum_{k_{iW}\in Q^d_W}\delta^d_{iW}\right)$$
$$+(1-\tau_s)^{D(s)}\delta_e+\left(1-D(s)P_s-(1-\tau_s)^{D(s)}\right)\delta_c. \quad (22)$$

Finally, the average airtime values are computed by averaging each of (18)–(21) according to the state durations t_i. Note that, differently from existing studies, the above equations take into consideration the presence of several PoAs in a clique, and the fact that PoAs serve terminals with different channel qualities.

3.4 Network-controlled coupling

So far we have considered traffic demands of GOs as an input of the model. However the real demand of GOs depends on what they receive to relay. Moreover, it is possible that the traffic to relay cannot be handled in full. It is therefore possible that cellular resources are wasted for traffic that can not be relayed by the GOs.

However, an SDN network controller may avoid such problem by acting as coordinator among the cellular network and the 802.11 groups. The controller needs to estimate the quantity of traffic that GOs can actually relay given the limitation of cellular and 802.11 resources and enforce a rate limiting on the activity of GOs and GMs. Such control beneficially impacts the resource allocation of UEs that do not act as relays, since more resources are freed for UEs. In addition, since GOs' activity on the 802.11 channels is reduced with respect to the uncontrolled case, also APs and their MNs indirectly benefit from the presence of a controller. The controller operates iteratively, as described in what follows.

Step 0: Cellular downlink resources are allocated with the procedure presented in Section 3.2.2, the demand of GOs being computed as the local GO traffic plus the demands of GMs:

$$d^d_{iJ}=d^d_W+\sum_{k_{iW}}d^d_{iW},\quad \forall\text{UE } k_{iJ} \text{ acting as PoA } W. \quad (23)$$

In the notation adopted in the above expression, we have used the fact that a GO acts as UE for the eNB and as AP for GMs. The controller computes the cellular downlink throughput T^d_{iJ} of any GO k_{iJ} (alias PoA W). Only part of such throughput belongs to k_{iJ}, namely $T^d_W\le T^d_{iJ}$, while the rest is for relay.

Step 1: Using RR and T^d_{iJ}, compute downlink throughputs of GO k_{iJ} and its GMs, for all GOs.

Step 2: Compute uplink 802.11 throughput T^u_{iW} of all GMs using the procedure described in Section 3.3, but replacing d^d_{iW} with the GM downlink throughputs found in **Step 1**.

Step 3: Use the procedure of Section 3.2.1 to compute cellular uplink, using GMs' 802.11 throughputs computed in **Step 2** as GO relay uplink demands.

Step 4: The resulting cellular uplink throughput of each GO is split across its GMs as in downlink (with RR). Such throughput values are set by the controller as rate limits of the GMs.

Step 5: Recompute the operational point of 802.11 with the limits fixed for relay traffic in **Step 1** and **Step 4**. Any GM obtains exactly the rate fixed with rate limiting, while a GO can receive no more than what imposed in **Step 1**.

Step 6: Recompute cellular downlink allocation with the procedure of Section 3.2.2, using as GO downlink relay demands the relay throughputs (in 802.11) computed in **Step 5**.

Step 7: If any of the downlink GO throughputs computed at **Step 6** differ from what used in **Step 1** of this iteration, unused resources are redistributed to UEs and GOs for which the allocation did not change from **Step 1** to **Step 6**, and whose demand is not satisfied. The redistribution uses WRR with weights $g_{iJ}+1$. Then a new iteration starts from **Step 1**.

Uplink cellular resources and 802.11 resources are univocally determined for each downlink cellular allocation, so the algorithm converges as soon as downlink cellular resource allocation converges. The convergence of iterations is guaranteed because downlink resources are limited and, at each iteration, the amount of downlink cellular resources assigned to UEs increases.

With the above, we have computed not only throughputs, but also the rate limits to impose. So we can also compute airtimes and power consumptions as described in Sections 3.2 and 3.3.

4. ACCESS SELECTION

In this section we present a new access selection mechanism that improves the energy efficiency of wireless terminals in mixed access networks. Exploiting the fact that carefully selecting the attachment of the terminals to proper PoAs leads to different throughputs and power consumptions, our access selection mechanism aims to maximize the total terminal energy efficiency figure:

$$E=\sum_{y\in\mathcal{M}}(T^u_y+T^d_y)/P_y, \quad (24)$$

where $\mathcal{M}$ is the set of UEs (some of which acting as GOs), MNs, and GMs present in the system, T^u_y and T^d_y are the throughputs achieved by terminal y in uplink and downlink, respectively, whereas P_y is the power consumed by y.

In our access selection mechanism, UEs become GOs *if needed*, i.e., if there is a benefit in terms of total energy efficiency (24). However, purely pursuing the total energy efficiency might lead to low and unfairly distributed throughputs. For instance, an AP might be more energy efficient than an eNB but guarantee less throughput when the number of MNs becomes large and collisions drastically degrade the throughput in 802.11. Furthermore, when acting as a GO, a UE may use a non-negligible part of its energy to relay the traffic of the attached GMs. This *cannot be more energy efficient* for the GO, i.e., the individual energy efficiency of a GO is negatively impaired by the relay traffic, and being a GO is not beneficial for the UE acting as GO. However, the presence of GOs improves connectivity, and a GO might turn to be a GM at some point in time, so there is a clear incentive for keeping GOs in the loop.

To account for the above considerations, in the following, we formulate an access selection problem that aims to maximize the total energy efficiency under throughput and energy constraints defined on a per-terminal basis.

4.1 Problem Formulation

We use the total energy efficiency as utility function, and we add per-terminal constraints to guarantee that (i) the achieved terminal throughput is at least α_T times the highest throughput potentially achieved under any other access choice, $\alpha_T \in (0,1]$, and (ii) the energy efficiency achieved by a GO is at least the α_E times the energy efficiency achieved by acting as a simple UE, $\alpha_E \in (0,1]$. Denoting by E_y the energy efficiency of terminal y, and by $\mathcal{V}$ the set of feasible terminal access combinations, the resulting formulation of our optimization problem is as follows:

$$\max_{\substack{\underline{V}=\{K_J:J\in\mathcal{B},\forall J;\\ K_W:W\in\bigcup_q \mathcal{A}_q,\forall W\}\in\mathcal{V}}} \sum_{k_{iW}:W\in\bigcup_q \mathcal{A}_q} \frac{T^u_{iW}+T^d_{iW}}{P_{iW}} + \sum_{J\in\mathcal{B}} \left(\sum_{k_{iJ}\notin\bigcup_q \mathcal{A}_q} \frac{T^u_{iJ}+T^d_{iJ}}{P^u_{iJ}+P^d_{iJ}} + \sum_{k_{iJ}\in\bigcup_q \mathcal{A}_q} \frac{T^u_{k_{iJ}}+T^d_{k_{iJ}}}{P^u_{iJ}+P^d_{iJ}+P_{k_{iJ}}} \right);$$

s.t.:

$$\begin{aligned}
&\forall y: y=k_{iW} && T^u_{iW}+T^u_{iW} \geq \alpha_T \max_{\mathcal{V}} \left(T^u_y+T^d_y\right);\\
&\forall y: y=k_{iJ}\notin\bigcup_q \mathcal{A}_q && T^u_{iJ}+T^d_{iJ} \geq \alpha_T \max_{\mathcal{V}} \left(T^u_y+T^d_y\right);\\
&\forall y: y=k_{iJ}\in\bigcup_q \mathcal{A}_q && T^u_{k_{iJ}}+T^d_{k_{iJ}} \geq \alpha_T \max_{\mathcal{V}} \left(T^u_y+T^d_y\right);\\
&\forall y: y=k_{iJ}\in\bigcup_q \mathcal{A}_q && E_{k_{iJ}} \geq \alpha_E \max_{\mathcal{V}} E_y.
\end{aligned} \tag{25}$$

Above we have split the contribution to the total energy efficiency in terms of MNs (the first summation) and UEs (second summation). The contribution of UEs is further split between non-GOs (UEs $k_{iJ}\notin\bigcup_q \mathcal{A}_q$) and GOs (UEs $k_{iJ}\in\bigcup_q \mathcal{A}_q$).

Due to the fact that, in a real mixed access network, the access selection mechanism has to take separate decisions every time a new terminal enters the network, we actually tackle the above optimization problem in on-line fashion. The resulting on-line problem can be reduced to an on-line Generalized Assignment Problem (GAP) [6], in which items arrive one after the other and they have to be assigned to bins of fixed capacity. In GAP a decision has to be made at the arrival of each item and cannot be changed later. When assigned to a bin, the item requires a given capacity and provides a given benefit. Depending on the bin, capacity and benefit may change. In our on-line problem each terminal can be seen as an item in GAP, while each of the PoAs is a bin. Depending on the PoA, the capacity required and the energy efficiency (the benefit) achieved by a terminal changes. However, our problem is more constrained than GAP. First, assigning a terminal to a given PoA also changes the capacity required and the energy efficiency (the benefit) achieved by other terminals. Second, we need to assign a PoA to each terminal. Therefore, if the capacity requested by a subset of terminals to a PoA is higher than the actual capacity of the PoA, each terminal has to shrink its capacity request so to fit into the PoA, at the expenses of reduced efficiency. So, our problem is a GAP with extra constraints and with bin-occupancy-dependent benefits. Since GAP is NP-Hard, so is our on-line problem.

4.2 On-line Energy Efficient Access Selection

In order to find a solution to our optimization problem, we propose the *Marginal Benefit Heuristic* (MBH), inspired by the well known heuristic that has been proposed for solving a GAP [6]. Upon the arrival of a terminal, MBH works as follows:

1. MBH computes the energy efficiency of each terminal before the attachment of the new terminal.

2. MBH evaluates the attachment of the new terminal to any feasible PoA. For each possibility, MBH computes the energy efficiency of affected terminals.

3. At this point, all the PoAs not ensuring at least α_T of the maximum throughput that could be received by the new terminal are discarded. Likewise, when the PoA is a GO, the MBH algorithm evaluates the energy efficiency degradation experienced by the GO. To have a reference point, all the GMs attached to the GO under analysis are considered as attached directly to their closer eNBs and the GO energy efficiency is computed. If by serving all its GMs and the new terminal the energy efficiency of the GO drops below α_E times the energy efficiency it would achieve while acting as a simple UE, then this GO is no further considered.

4. The MBH choses a PoA which guarantees the highest marginal benefit w.r.t. the same PoA without the new terminal attached.

MBH differs from the classic heuristic used for GAP mainly because it does not require to evaluate the allocation of a new incoming terminal to each and every possible PoA. In fact, the additional constraints we introduced, i.e., on throughput and energy guarantees for the incoming terminal, identify a subset of possible target PoAs. Another difference is the fact that MBH, differently from GAP heuristics, accepts negative marginal benefits, since MBH needs to allocate the new terminal to one PoA in any case. Moreover, and most importantly, our heuristic has to recompute the resource allocation for each possible assignment.

5. NUMERICAL EVALUATION

In this section we first validate our method to analyze 802.11 performance. The cellular part of the model is quite straightforward so we skip validation results here. Afterwards, we show how our MBH scheme outperforms state of the art approaches and we shed light on the trade-off between maximizing system energy efficiency and achieving fair throughputs.

5.1 802.11 model validation

To validate the throughput and power consumption model we presented in Section 3.3, we used a packet-level simulator written in MatLab. In our simulations, a GO and a number of GMs randomly picked among 2 and 10 were positioned in a squared area of size $50m \times 50m$, following a uniform distribution. The channel quality among the GO and the different GMs (and vice versa) was computed as in (8). The simulator considers that all the GMs and the GO can listen to the transmission of all the others. Transmissions were therefore regulated by the 802.11 MAC protocol, whose main parameters are show in Table 1. Packet arrivals followed Pois-

Table 1: 802.11 parameters

Carrier	2.5 GHz
C (Min congestion window)	16
m Max retry	5
Other MAC param. (SIFS, DIFS,...)	802.11n
Max Transmission rate	144 $Mbps$
$\mathcal{N}$ Noise Level	$3.98 \times 10^{-18} W/Hz$
Bandwidth	20 MHz
Path Loss	Log-Distance, Exponent 3
Transmission Power	100mW

Table 2: Cellular transmission and power parameters

Carrier	2.45 GHz
Bandwidth	20 MHz
Subframe Duration	1 ms
Symbols per RB	84
Max Power Uplink	200 mW
Power Downlink	1 W
SNR target Power Control	20dB
Max Symbol Efficiency	5.55 b/sym
Noise Level	3.98×10^{-18} W/Hz
Path Loss Model	Log-Distance, Exponent 3
P_{idle}	0 W
P_0	2.3815 W
α	0.0649 W/dbm
P_R	0.225 W
γ_{tx}	0.11 mW
γ_{rx}	0.09 mW
β_{tx}	0.55 W
β_{rx}	0.4 W

son processes with intensity fixed during the simulation and picked uniformly at random in the set $\{0.25, 0.5, 1, 2, 3, 5, 7.5, 10\}Mbps$.

In Figure 2 we compare simulated and analytically computed throughput and airtime of terminals. Each point corresponds to a simulated throughput (airtime), whereas the red line indicates where the point should be if the model was error-free. As it is easy to see, the approximation introduced with our state-based analysis is practically negligible, and the largest relative error is 7.43% for throughput and 9.31% for airtime. Although not explicitly shown in the figure, the 95% percentiles of the error on throughput and airtime are as low as the 3.04% and 3.17%, respectively.

5.2 Access Selection Performance

In this section we evaluate the performance of our access selection mechanism MBH. In particular, we quantify the gain in terms of energy efficiency achieved by MBH against state of the art solutions when the values of α_T and α_E change. We also consider the effects of access selection decisions on aggregate throughput and its fair distribution among terminals.

In an area of $400m \times 400m$, we first fixed the position of 7 eNBs so to have an inter-site distance equal to 100m. Furthermore, in each experiment, we positioned randomly 10 APs with uniform distribution. The APs select the particular channel they use depending on their location (the same holds for UEs acting as GOs). In this way, terminals scheduled on the same channel are co-located and form a clique. We further introduce 500 users, one after the other, at random positions. At their arrival, we apply MBH under different configurations for α_T and α_E. User demands are like described in Section 5.1, and downlink and uplink demands of a terminal are picked independently. Note that we evaluate the performance of MBH under increasing density of terminals.

802.11 and cellular parameters are set up as shown in Table 1 and Table 2, respectively. The latter also shows the particular power consumption parameters used, extracted from [10], [9], and [8]. Furthermore, we set P_{idle} to zero. In this way we effectively evaluate only the power consumption due to active transceivers.

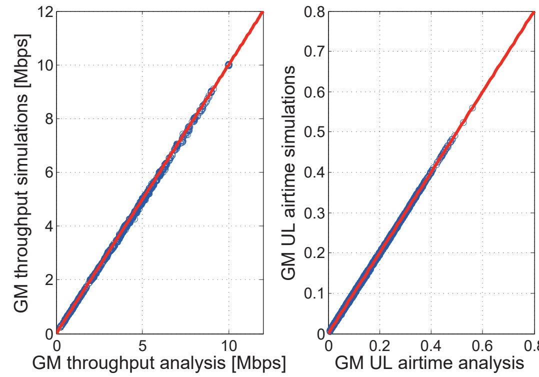


Figure 2: 802.11 model validation.

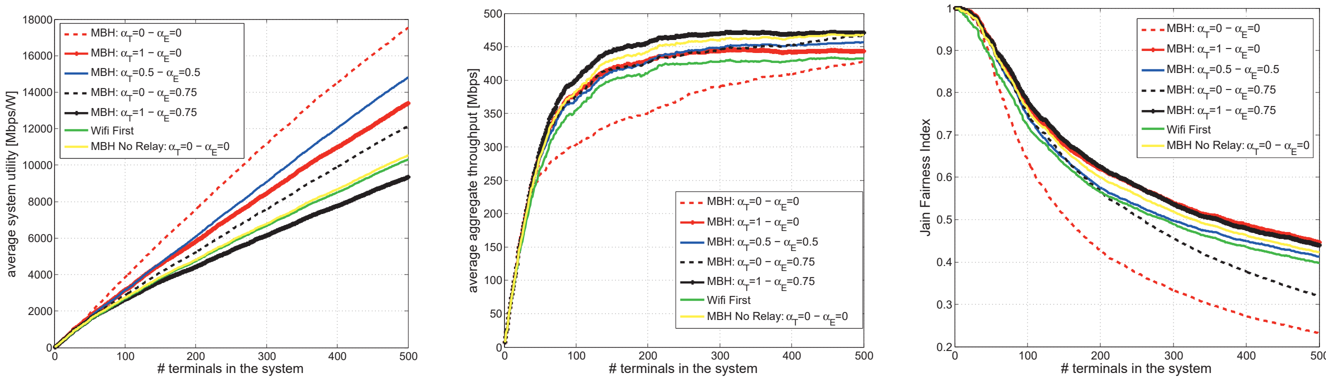
Figure 3 presents the results achieved in terms of utility (i.e., energy efficiency), aggregate throughput and fairness varying the values assumed by α_T and α_E. Results are compared with a standard *WiFi First policy* [18], in which a new user is attached to the strongest AP, if available, or to the strongest eNB if no AP is available. Results are also compared with a version of MBH which ignores D2D relay opportunities. The number of independent 802.11 channels considered in Figure 3 is 3, but similar results have been achieved with more channels.

The main tendency shown by Figure 3 is that MBH is able to achieve huge energy efficiency gains when compared to WiFi First policy if there is no guarantee on per-user throughput and GO power efficiency. When α_T and α_E are set to zero, indeed, MBH improves energy efficiency at terminal side by about the 75% if compared to the WiFi First policy. However, a careful inspection of the results shows that MBH with α_T and α_E set to zero aggregates the traffic and the energy efficiency to a small number of users present in the scenario. As a result, both the aggregate traffic and the per-user fairness decrease w.r.t. the WiFi First policy. Increasing the value of α_T allows coping with this problem. Indeed, restricting the access selection of the new users to the subset of PoAs ensuring at least α_T times the maximum achievable throughput improves drastically the aggregate throughput and fairness. However, such result is achieved at the expense of GO energy efficiency, and the figure shows that utility drops when throughput grows. For instance, when α_T is 1 (and $\alpha_E = 0$), a new user always attaches to the PoA ensuring the larger achievable throughput, and MBH energy efficiency gain drops to 35%—which is still remarkable—with 15% higher fairness w.r.t. WiFi First.

By increasing α_E, we can ensure that GOs limit their D2D relay activity, i.e., we reduce the average number of GOs in the system. In turn, this reduces the achievable energy efficiency gain. Nevertheless, Figure 3 shows that a trade-off between system energy efficiency, fairness and power consumption wasted due to relay is possible. For instance, when we select $\alpha_T = 0.5$ and $\alpha_E = 0.5$, we achieve gain in energy efficiency close to 50%, while achieving competitive aggregate throughput and fairness w.r.t. WiFi First. We also ensure that at most half of the power consumed by a GO is reserved for relay. We also note that D2D is key to enable energy efficient access networks. In fact, when MBH is not allowed to create relay links, performance figures drop and become very close to (though better than) what achievable with WiFi First. Note also that, interestingly, the utility gain is barely affected by the population density, which tells that MBH scales well.

6. RELATED WORK

Several techniques exists that deal with access selection and energy efficiency. Nguyen-Vuong *et al.* [14] propose to increase the



(a) Utility (energy efficiency). (b) Aggregate throughput. (c) Jain fairness index.

Figure 3: Performance of MBH considering different values of α_T and α_E (with 3 channels for 802.11).

battery lifetime of terminals by connecting them to the least power expensive technology among the ones available. No guarantees on the throughput achieved and no consideration on the different loads of the PoAs is taken into account. Desset *et al.* [7] assume uplink and downlink demands are known at the terminal. The user then chooses the access technology that is able to serve its traffic with the lowest cost. However, in their scheme, access selection effects on neighboring terminals are not considered and terminals are not allowed to access the network if there is no PoA that can satisfy their demand. Lee *et al.* [11] account for D2D relay in downlink, though the energy efficiency of each terminal is considered as independent, and resource allocation as PoA-independent. Access selection is then solved as a knapsack problem. Malandrino *et al.* [13]—even if their work does not explicitly address an access selection mechanism—show how, in an access network with underlay D2D support, scheduling the least interfering users at once may reduce terminals power consumption, which is in line with our findings. However, we provide analytical reasons behind this phenomenon, which goes well beyond what hinted in [13].

We remark that, differently from previous proposals, our approach dynamically adapts to load distributions, works at any system load with both uplink and downlink traffic, accounts for the fact that throughput and power consumption of users connected to the same PoA are tightly coupled, and that resource allocation for distinct PoAs using distinct access technologies can be coupled.

7. CONCLUSIONS

We have proposed a framework to compute throughput, airtime and power consumption in SDN-controlled mixed access networks. A controller is envisioned to avoid waste of cellular and 802.11 resources by enforcing rate limiting on the generation of traffic handled by means of D2D communications. Our model is unique and accurate, and its novelty consists not only in accounting for the coupling between cellular and 802.11 resource allocation/utilization in uplink and downlink with D2D relay, but also in the method used to analyze the 802.11 operation by identifying network states. With the analysis, we have formulated an on-line access selection problem for energy efficiency. Given the NP-hardness of the problem, we have proposed MBH, an on-line heuristic that largely outperforms existing association policies and provides enhanced levels of fairness by means of D2D-based relay.

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