Energy-efficient fair channel access for IEEE 802.11 WLANs

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***Abstract*—*Greening* the communication protocols is nowadays recognized as a primary design goal of future global network infrastructures. The objective function for optimization is the amount of information transmitted per unit of energy, replacing the amount of information transmitted per unit of time (i.e., throughput). In this paper we investigate the case of IEEE 802.11-based WLANs and first show that, given the existing diversity of power consumption figures among mobile devices, performing a fair allocation of resources among devices is challenging. We then propose a criterion to objectively balance between the most energy-efficient configuration (where all resources are given to the single most energy efficient device) and the throughput-optimal allocation (where all devices evenly share the resources regardless of their power consumption). By means of analytical modeling, we derive a closed-form expression for the optimal configuration of the WLANs with respect to the energy-efficiency criterion. We validate our analysis through simulations, and show that our approach betters the prevalent allocation schemes discussed in literature in terms of energy efficiency, while maintaining the notion of fairness among competing devices.**

I. Introduction

Mobile devices are increasingly equipped with multiple radios to wirelessly access communication networks such as the Internet. The IEEE 802.11 wireless local area network (WLAN) technology[1] is dominating and deployed at large, e.g., in public hotspots, campus, or home networks. Until recently, stations operated within these networks mostly belonged to the class of notebook computers; the stations of this class shared quite similar feature specifications with respect to energy supply. As one result, modeling and optimization for within these WiFi networks has mainly been focusing on bandwidth efficiency and throughput-fair bandwidth allocation (see, e.g., [1], [2]), but has not looked into energy trade-offs.

However, we currently witness an increasing diversity in mobile computing devices that operate on battery power to allow for untethered operation populating 802.11 networks. This includes powerful notebook computers (which might be operated on AC power), slate or tablet computers such as the iPad, netbooks, smartphones and ebook readers, personal digital assistants such as Blackberries, or embedded systems and MP3 players. For this novel set of computers, wireless and battery powered operation is the norm rather than the exception. Compared with traditional notebooks, these new devices have a substantially different energy profile. Hence, energy efficiency as an optimization goal is of paramount importance, and we argue that a fresh approach is needed to due to today's heterogeneous set of nodes, each of which differs substantially with respect to energy consumption.

We next introduce a simple numerical example[2] to illustrate that the two performance parameters that we consider, throughput and energy efficiency, constitute different objectives. Let us consider a toy WLAN scenario consisting on one Access Point (AP) and two associated stations (STA_1 and STA_2, respectively), which operate using the IEEE 802.11b physical layer. The maximal fair throughput allocation is tied to the minimum Contention Window (CW_{min}) and can be obtained using, e.g., a numerical search, giving the value of $CW_{min} = 17$. However, using this configuration, substantial amounts of energy might be consumed by collisions of frames from both stations. Indeed, when optimizing the network configuration with respect to energy efficiency, we obtain significantly different values for CW_{min} that depend on the energy parameters of the interface: for the case of, e.g., the energy parameters of a SocketCom CF interface [3], the most energy efficient configuration is approximately three times larger, i.e., $CW_{min} = 56$.

This relation between throughput optimization and energy efficiency optimization has received only little attention so far. To the best of our knowledge, there have been two main contributions: on one hand, Bruno et al. [4] considered p-persistent CSMA-based WLANs and proved that, based on a naïve energy consumption model, throughput and energy efficiency can be jointly optimized; on the other hand, our previous work of [5], based on a more sophisticated energy consumption model, showed that throughput and energy efficiency constitute different optimization objectives.

The key limitation of previous works is that they only consider *homogeneous* scenarios, where all devices share the same power consumption characteristics. However, current

[1]We will use the terms WiFi or WLAN interchangeably.

[2]Our energy consumption model used to derive these figures is described with detail in Section III.

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wireless chipsets show very different power consumption figures, as we illustrate in Table I for three interfaces reported in [3]. These three interfaces represent the case of: A) a non-energy optimized interface, where the power consumed is very similar in all the states; B) an interface with moderate energy consumption, where the idling state is more optimized (about one tenth of the power consumed when receiving); and C) an interface with roughly similar power ratios that those of B, but with larger energy consumption figures.

We argue that any configuration that aims at optimizing the energy efficiency of a wireless network needs to take into account this interface diversity. Our contribution is to analyze the case of *heterogeneous* scenarios, where WLAN stations differ with respect to their power consumption figures. In particular, we propose a criterion to objectively balance between the most energy-efficient configuration (where all resources are given to a single device) and the traditional throughput-optimal allocation (where the configuration is oblivious to the energy consumption parameters of the interfaces). By means of analytical modeling, we derive a closed-form expression for the optimal configuration of IEEE 802.11-based WLANs with respect to our energy-efficiency criterion.

The rest of the paper is organized as follows. In Section II we motivate the need for energy efficient yet fair channel access and propose a new optimization criterion to address the case of heterogeneous receiver sets. In Section III we present the energy consumption model that allows for prediction of the WLAN energy consumption. In Section IV we take advantage of this model to derive a closed-form expression to achieve the optimal configuration of the network. We validate this configuration in Section V through extensive simulations and numerical searches. Section VI concludes the paper.

II. Optimization Criterion for Energy Efficiency

In previous work [5] we addressed the optimization of the energy efficiency in WLANs in homogeneous scenarios, i.e., WLAN deployments where all stations are identical with respect to power consumption. Given this assumption, it is straightforward to define a criterion to optimize the network parameters for energy efficiency: the objective is to find the common CW_{min} that all nodes have to use in order to maximize the energy efficiency η, defined as the information transmitted over the energy consumed,

$$\eta = \frac{throughput}{power}$$

In [5] we derived the closed-form expression for the optimal CW_{min} to use, which depends on the power consumption figures of the WLAN interface. We further showed that different WLAN interfaces (in particular, those of Table I) require significantly different configurations of this parameter.

For the case of heterogeneous scenarios, where different stations have different power consumption figures, it is not trivial to define the performance figure to optimize, as utilizing a naïve approach towards optimization of the network-wide energy consumption might result in the starvation of devices. In the following we illustrate why these heterogeneous scenarios constitute a different and more challenging case to tackle.

TABLE I
POWER CONSUMPTION (IN WATTS) FOR DIFFERENT WIRELESS INTERFACES WHEN THEY OPERATE IN THREE DIFFERENT STATES: TRANSMISSION (ρ^{tx}), RECEPTION (ρ^{rx}) AND IDLE (ρ^{id}), AS REPORTED IN [3]

#	Card	ρ^{tx}	ρ^{rx}	ρ^{id}
A	Lucent WaveLan	1.650	1.400	1.150
B	SoketCom CF	0.924	0.594	0.066
C	Intel PRO 2200	1.450	0.850	0.080

TABLE II
THROUGHPUT AND ENERGY-EFFICIENCY PERFORMANCE OF A WLAN WITH TWO STATIONS MODELED AFTER INTERFACES A AND B FROM TABLE I, USING TWO DIFFERENT STRATEGIES

	Strategy I	Strategy II
Throughput	7.50 Mbps	7.98 Mbps
STA_1	3.75 Mbps	7.91 Mbps
STA_2	3.75 Mbps	0.07 Mbps
Efficiency	3.48 bpJ	3.83 bpJ

A. Motivation for a criterion for energy efficient yet fair channel access

Let us consider the same WLAN scenario as in the previous section with one AP and two stations. However, in this case STA_1 and STA_2 are modeled after the interface parameters A and B from Table I, respectively. We denote with CW_1 (CW_2) the CW_{min} configuration used by STA_1 (STA_2), and use two different strategies to configure these parameters:

- Strategy I: We set $CW_1 = CW_2$, in order to have a fair share of the wireless resources, and perform a sweep on the $CW = \{8, 1024\}$ parameter space to choose the value that maximizes throughput.
- Strategy II: We let CW_1 and CW_2 diverge, and perform a sweep on the $CW = \{8, 1024\}$ parameter space to find the configuration that maximizes the energy efficiency η of the WLAN.

For the first strategy the resulting optimal CW value, as we said in the previous section, is $CW = 17$. For the second strategy, the resulting configuration is $CW = \{CW_1, CW_2\} = \{8, 1024\}$. We report the obtained values of throughput and energy efficiency (in bits per Joule, bpJ) in Table II, with the following main results:

- The first strategy, as expected, provides a bandwidth-fair allocation where both stations receive the same throughput, while the overall energy efficiency is 3.48 bpJ.
- The second strategy, on the other hand, results in an energy-efficiency improvement of approximately 10%. However, the resulting throughput allocation is extremely unfair, as STA_2 is practically starved.

The fact that the most energy-efficient allocation (Strategy II) is obtained using an extremely unfair allocation is caused by the CSMA-based channel access scheme, as choking one interface will prevent the energy wastage caused by collisions. The price to pay for increasing the efficiency is then to introduce unfairness. However, it is interesting to observe that to achieve the η-maximal configuration, the starved station is the one with the *most efficient* interface. We found this rather striking, although it can be explained as follows. Given that the AP cannot deactivate an interface, and therefore there is a minimum power consumed as given by the ρ^{id} parameter, there are two extremely unfair but efficient allocations with the same throughput performance, i.e.:

1) To choke STA_1, with the limiting power consumption: $\rho^{tx}_B + \rho^{id}_A \approx 2.1\ W$.
2) To choke STA_2, with the limiting power consumption: $\rho^{tx}_A + \rho^{id}_B \approx 1.7\ W$.

The resulting configuration, then, penalizes the more efficient station in order to provide the largest energy savings. Note that for the case of interface A the difference between the power consumed when transmitting and idling is $0.5\ W$, while for the case of interface B this difference is $0.86\ W$. This way, given the unavoidable "base" power consumption of the idling state, it is more efficient to give all the bandwidth to the station with the smallest (absolute) difference between ρ^{id} and ρ^{tx} parameters.

This simple scenario serves to illustrate the risks of using a naïve strategy to optimize the overall energy efficiency: not only it could result in extremely unfair throughput allocations, but also it could penalize the most energy-efficient interfaces. On the other hand, it is clear that the use of throughput-only allocation criteria, while resulting in throughput-fair allocations, do not consider energy efficiency at all as they do not take into account the set of $\{\rho\}$ parameters.

Based on the above, we claim that a trade-off between energy efficiency maximization and throughput fairness is needed. In the following we discuss our proposed criterion to define this trade-off[3].

B. A criterion for energy efficient and fair channel access

The use of overall energy efficiency figures, as we have seen in the previous section, is not well suited to properly address general (i.e., heterogeneous) scenarios. The use of throughput-based approaches, on the other hand, does not consider the impact of the different power consumption parameters and therefore may result in energy wastage. We argue that a trade-off between these two approaches is needed.

In order to define a trade-off between these two different optimization objectives, we first define the *per-station* energy efficiency η_i as the ratio between the throughput obtained and the power consumed by a given station i:

$$\eta_i = \frac{throughput_i}{power_i}$$

[3]Note that, throughout this discussion, we have only considered power consumption figures, and not parameters such as, e.g., the remaining battery capacity. Although such battery parameters have been considered before in energy-related scenarios (e.g., in [6]), we argue that they are not well suited for the scenarios that we envision. Indeed, the approach that we propose provides an incentive to energy-efficient devices by favoring them over inefficient ones. In contrast, a solution that favored battery constrained devices would incentivize battery limited devices which would harm the overall performance. Following this reasoning, in this paper we only focus on the energy efficiency of the different wireless interfaces implementing the MAC protocol.

Note that η_i provides the throughput the station i is successfully transmitting weighted by the energy the station has to spend and, therefore, it partially takes into account if a station is being choked. This way, for our toy example, the resulting values for the first configuration strategy are $\eta = \{5.54, 2.54\}$ bpJ, while for the case of the second strategy the values are $\eta = \{5.02, 0.11\}$ bpJ.

Based on these η_i variables, our challenge is to define an appropriate criterion for their configuration. To this aim, note that we have a two-fold objective: on one hand, we want to maximize the overall efficiency η in the WLAN; on the other hand, we want to preserve some degree of fairness between the η_i's, thus avoiding that any station is starved. In order to solve this tradeoff, Kelly's *proportional fairness* criterion [7] is well accepted in the literature. This criterion was originally proposed in the context of wired networks, and has been widely used to address a variety of throughput fairness issues [8] including other fairness problems of wireless packet networks [9], [10]. This criterion is defined as follows. A throughput allocation $\{r_1, \ldots, r_n\}$ is proportionally fair if it is feasible, and for any other feasible allocation $\{r^*_1, \ldots, r^*_n\}$ the aggregate of proportional changes is not positive, i.e.,

$$\sum_i \frac{r^*_i - r_i}{r_i} \leq 0 \qquad (1)$$

Note that, with the above definition, in a two station scenario the throughput of one station would be decreased by say 10% only as long as this allowed an increase in the throughput of the other station of more than 10%, which represents a balance between two extreme allocations (i.e., throughput is equally shared, or throughput is given to the most efficient station). To investigate the proportional fair allocation further, we consider a small feasible perturbation around the proportional fair allocation $r_i \rightarrow r_i + dr_i$. From (1),

$$\sum_i \frac{dr_i}{r_i} \leq 0$$

which can be rewritten as

$$\sum_i (\log(r_i))' dr_i \leq 0$$

It follows from the above that the proportional fair allocation represents a local maximum of the function $\sum \log(r_i)$. Since this is a concave function, it has only one maximum, and therefore the local maximum is also the global maximum. This way, we can identify the proportional fair (PF) allocation with the one that maximizes the sum of the logarithms:

$$PF \Longleftrightarrow \max \sum \log(r_i)$$

In this paper, following the previous works of [8]–[10] we advocate for the use of the PF criterion to solve the fairness issue that arises in a WLAN with heterogeneous stations. This way, we propose to use the energy-efficiency proportional fairness (EF) criterion, based on the maximization of the sum of the per-station energy efficiency, i.e.,

$$EF \Longleftrightarrow \max \sum \log(\eta_i) \qquad (2)$$

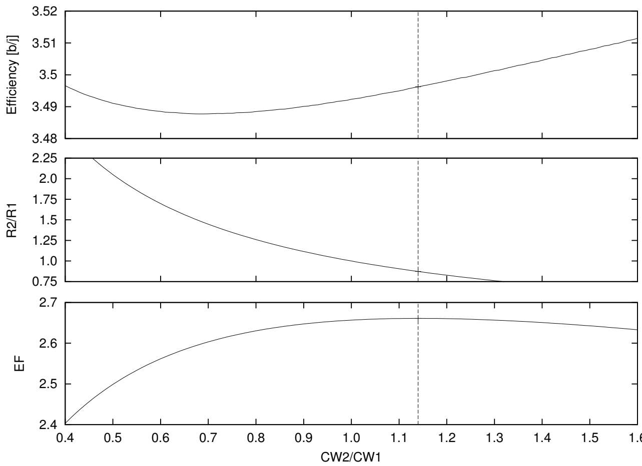

Fig. 1. Total efficiency, throughput ratio and EF performance of a WLAN with two stations for different CW configurations.

To illustrate why the use of the EF criterion prevents extremely unfair allocations while supporting energy-efficient configurations, we consider the same heterogeneous scenario with one AP and two different stations modeled after the power consumption figures of Interfaces A and B from Table I. In order to analyze different configurations of the CW, we set $CW_2 = kCW_1$ with k ranging from 0.4 to 1.6, and for each k value we perform a sweep on the $CW_1 = \{1, 4096\}$ to obtain the configuration that maximizes the overall efficiency. For each resulting configuration we compute the throughput of each station and the EF value given by (2)[4]. Results are shown in Fig. 1, and can be summarized as follows:

- Large CW_2/CW_1 ratios increase the overall efficiency η, but lead to the starvation of STA_2, as can be seen from the R_2/R_1 ratio. This is the result that we have seen in the previous section, namely, that the most energy-efficient configuration is the one that chokes the most efficient interface.
- However, the value of EF is not maximized for such extremely unfair allocations, but instead the maximum is reached when $k \approx 1.15$. From this point on, the relative increase in η_1 (η_2) is not compensated by the relative decrease of η_2 (η_1) and, therefore, the allocation is not EF-optimal.

In our toy example, the η-optimal allocation is given by the configuration $CW = \{3, 384\}$, which provides an overall efficiency $\eta = 3.82$ bpJ and a throughput allocation $R_i = \{8.23, 0.06\}$ Mbps. On the other hand, the EF-optimal configuration $CW = \{26, 30\}$ results in the following performance figures: $\eta = 3.49$ bpJ and $R_i = \{3.97, 3.47\}$ Mbps. For this case, then, the EF-optimal configuration exchanges an 8.6% reduction in the overall efficiency in order to improve throughput fairness[5] from 0.51 to 0.995. Furthermore, the EF-optimal configuration of the CW is not only different from the maximum throughput allocation ($CW = 17$), but also from the the case of maximum energy efficiency for homogeneous scenarios ($CW = 56$ for the case of interface B, $CW = 19$ for the case of interface A).

The EF-criterion, therefore, can be used to define trade-off between a fair throughput allocation and an energy-efficiency configuration. Note that, although the rest of the paper is devoted to the case of 802.11 WLANs, the criterion could be applied to any scenario with heterogeneous interfaces.

III. Energy consumption analysis

In the previous section we have illustrated why heterogeneous WLANs constitute a challenging scenario, and we have proposed a criterion to achieve a trade-off between throughput fairness and energy efficiency. In order to derive the EF-optimal configuration for heterogeneous WLANs, in this section we present an analytical model used to characterize the energy consumption in a WLAN. First we introduce an accurate yet complex model. We subsequently present a simpler model that sacrifices accuracy for analytical tractability. The accuracy of both models is validated in Section V-A.

The model assumes an IEEE 802.11b WLAN with N stations sharing the wireless channel. We assume saturation conditions [12] (i.e., stations always have a frame ready for transmission transmit) in order to analyze the most stringent scenario in terms of fairness. We also assume that the only reason for frame loss is a collision (i.e., ideal channel conditions with no capture effect), and that upon accessing the channel stations transmit a frame of fixed size L at the maximum modulation rate[6].

We denote with CW^i_{min} the CW_{min} used by station i. We first obtain the probability that a station i with minimum contention window CW^i_{min} transmits upon a backoff counter decrement τ_i by means of the following equation given by [12]

$$\tau_i = \frac{2}{1 + CW^i_{min} + p_i CW^i_{min} \sum_{j=0}^{m-1} (2p_i)^j},$$

where m is a parameter that specifies the maximum size of the CW ($CW_{max} = 2^m CW_{min}$) and p_i is the probability that a transmission attempt of station i collides. This probability can be computed as

$$p_i = 1 - \prod_{j \neq i} (1 - \tau_j).$$

The above constitutes a system of non-linear equations that can be solved numerically (see [14] for a more detailed discussion), giving the values of the τ_i's. Note that for the case of $CW^i_{min} = CW^i_{max} = CW^i$ the computation of the transmission probability is simplified as

$$\tau_i = \frac{2}{CW^i + 1}$$

Under these conditions, to model the energy consumption of the WLAN we follow a similar approach to the one of

[4]Note that, for the sake of readability, throughout the paper we use EF to refer *both* to the quantity $\sum \log(\eta_i)$ resulting from a particular configuration, and to the criterion that maximizes this value. The distinction will be clear based on the context.

[5]According to Jain's fairness index [11].

[6]Note that the model could be extended to relax these assumptions [13].

[15], extending our previous model of [5] to account for the heterogeneity of the scenario, with station i having the set of power consumption figures $\{\rho_i^{tx}, \rho_i^{rx}, \rho_i^{id}\}$. Based on the transmission probabilities τ_i's, we compute the energy consumed per slot by station i, denoted by e_i, by applying the total probability theorem as follows:

$$e_i = \sum_{j \in \Theta} E_i(j) p(j) \tag{3}$$

where Θ is the set of events that can take place in a single timeslot[7], while $E_i(j)$ and $p(j)$ are the energy consumed in case of event j and its probability, respectively. The set Θ of events, as well as their probabilities, is listed as follows:

- The slot is empty, $p(e)$
- There is a success from the considered station, $p(s,i)$
- There is a success from another station, $p(s,\neg i)$
- There is a collision and the considered station is involved, $p(c,i)$
- There is a collision but the considered station is not involved, $p(c,\neg i)$

The probability of each event can be computed based on τ_i's as follows

$$p(e) = \prod (1-\tau_j)$$

$$p(s,i) = \tau_i \prod_{j \neq i} (1-\tau_j)$$

$$p(s,\neg i) = \sum_{j \neq i} \tau_j \prod_{k \neq j} (1-\tau_k)$$

$$p(c,i) = \tau_i (1 - \prod_{j \neq i} (1-\tau_j))$$

$$p(c,\neg i) = 1 - \tau_i - p_e - p_{s,\neg i}$$

While the energy consumed by station i for each of the previous events can be computed as

$$E_i(e) = \rho_i^{id} T_e$$

$$E_i(s,i) = \rho_i^{tx} T_s + \rho_i^{rx} T_{ack} + \rho_i^{id} (SIFS + DIFS)$$

$$E_i(s,\neg i) = \rho_i^{rx} (T_s + T_{ack}) + \rho_i^{id} (SIFS + DIFS)$$

$$E_i(c,i) = \rho_i^{tx} T_s + \rho_i^{id} EIFS$$

$$E_i(c,\neg i) = \rho_i^{rx} T_s + \rho_i^{id} EIFS$$

where T_e is the duration of an empty slot time, $SIFS$, $DIFS$ and $EIFS$ are constants defined by the 802.11 standard, and T_s and T_{ack} are the transmission durations of a frame of size L and the acknowledgement frame, respectively, which can be computed as

$$T_s = T_{PLCP} + \frac{H+L}{C}$$

$$T_{ack} = T_{PLCP} + \frac{ACK}{C}$$

[7] A timeslot is defined as the amount of time between two backoff counter decrements of a station, see [12].

TABLE III
POWER CONSUMED (IN MJ) PER EVENT FOR THE INTERFACES OF TABLE I AND 802.11B

#	$E(e)$	$E(s,i)$	$E(s,\neg i)$	$E(c,i)$	$E(c,\neg i)$
A	0.0230	2.2834	1.9801	2.2454	1.9421
B	0.0013	1.2151	0.8148	1.1349	0.7346
C	0.0016	1.8930	1.1651	1.7759	1.0481

where T_{PLCP} is the length of the frame preamble, H is the frame header, C the modulation rate being used, and ACK represents the length of an acknowledgement frame.

Given the above expression for the energy consumption of station i in a timeslot, we can express the energy efficiency of station i as the ratio between the bits successfully transmitted over the energy consumed in a slot time:

$$\eta_i = \frac{p(s,i)L}{e_i} \tag{4}$$

It can be seen that the full expression for η_i consists of the sum of several terms that non-linearly depend on the τ_i's. In order to improve the analytical tractability, we quantify the energy consumed per timeslot for the three interfaces we consider in Table III. Based on the observed results, we make the following approximations:

$$E(s,i) \approx E(c,i)$$

$$E(s,\neg i) \approx E(c,\neg i)$$

Based on the above two approximations, we have the following approximate expression for (3)

$$\hat{e_i} = p_e E_i(e) + \tau_i E_i(s,i) + (1 - p_e - \tau_i) E_i(s,\neg i) \tag{5}$$

Note that the use of (5) results in an overestimation of the power consumed, as for the terms being approximated we take the largest of them. We further rearrange (5) as

$$\hat{e_i} = E_i(s,\neg i)(1 - \alpha_i p(e) + \beta_i \tau_i)$$

where we introduce the (non-negative) parameters α_i and β_i, used to quantify the relative energy consumed when idling or transmitting over the case when there is a transmission from a station different from i, i.e.,

$$\alpha_i = 1 - \frac{E_i(e)}{E_i(s,\neg i)}$$

$$\beta_i = \frac{E_i(s,i)}{E_i(s,\neg i)} - 1$$

Note that we denote with η the energy efficiency as computed with the use of (3) and with $\hat{\eta}$ the efficiency computed using (5). In Section V-A we assess the accuracy of both expressions to model the energy consumption and efficiency in a heterogeneous WLAN.

IV. EF CONFIGURATION FOR 802.11 WLANS

Based on the energy consumption model presented in the previous section, in this section we derive the configuration that optimizes WLAN performance according to our EF criterion. We start with the following expression for the energy efficiency $\hat{\eta_i}$ as derived in the previous section:

$$\hat{\eta_i} = \frac{L}{E_i(s, \neg i)} \frac{p(s,i)}{1 - \alpha_i p(e) + \beta_i \tau_i}$$

Computing the EF-optimal configuration requires to find the τ_i's maximizing the efficiency fairness, i.e.,

$$\max \sum_i \log \hat{\eta_i}$$

To find this configuration, we first perform the following partial derivatives and set them to zero

$$\frac{\partial}{\partial \tau_k} \sum_i \log \hat{\eta_i} = 0 \quad , \quad \forall k,$$

that results in the following expression

$$\frac{1}{\tau_k} - \frac{N-1}{1-\tau_k} - \frac{\alpha_k \prod_{j \neq k}(1-\tau_j) + \beta_k}{1 - \alpha_k p(e) + \beta_k \tau_k} - \sum_{i \neq k} \frac{\alpha_i \prod_{j \neq k}(1-\tau_j)}{1 - \alpha_i p(e) + \beta_i \tau_i} = 0$$

Multiplying both sides by $(1 - \tau_k)$ and re-arranging results in the following

$$\frac{1}{\tau_k} = \frac{\beta_k(1-\tau_k)}{1 - \alpha_k p(e) + \beta_k \tau_k} + \sum_{\forall i} \frac{1 + \beta_i \tau_i}{1 - \alpha_i p(e) + \beta_i \tau_i}$$

that can be approximated as

$$\frac{1}{\tau_k} \approx \sum_{\forall i} \frac{1 + \beta_i \tau_i}{1 - \alpha_i p(e) + \beta_i \tau_i}$$

Therefore, the τ_k that provides the EF-optimal configuration does not depend on the k, but it is the same for all stations. We have therefore one first result stating that, in order to achieve an EF-optimal configuration in 802.11 WLANs, stations have to fairly share the channel[8], i.e.,

$$\tau_i \approx \tau_k \quad \forall i, k \tag{6}$$

The remaining challenge is therefore to compute the optimal transmission probability (from now on we will write $\tau_i = \tau \; \forall i$). Because of the logarithm's properties, the maximization problem can reformulated with the product of each station's efficiency, i.e.,

$$\max \sum_i \log \eta_i \Longleftrightarrow \max \prod_i \eta_i$$

Under the assumptions *i)* $\tau \ll 1$, which is reasonable in optimal operation as large τ values would lead to a high collision probability, and *ii)* $\beta_i < 1$, which is also reasonable given the values from Table III, we can approximate $\hat{\eta_i}$ as

$$\hat{\eta_i} = \frac{L}{E_i(s, \neg i)} \frac{\tau(1-\tau)^{N-1}}{1 - \alpha_i p(e) + \beta_i \tau} \approx \frac{L}{E_i(s, \neg i)} \frac{\tau(1-\tau)^{N-1}}{1 - \alpha_i p(e)}$$

By making the approximation

$$\prod_i (1 - \alpha_i p(e)) \approx \left(1 - \frac{\sum \alpha_i}{N} p(e)\right)^N$$

the EF-optimal configuration can be computed by maximizing

$$\max \prod_i \eta_i \Longleftrightarrow \max \frac{\left(\tau(1-\tau)^{N-1}\right)^N L^N}{\left(\prod_i E_i(s, \neg i)\right)(1 - p_e \frac{\sum_i \alpha_i}{N})^N}$$

Therefore, the optimal configuration for the τ's can be obtained by maximizing the following expression

$$\max \frac{\tau(1-\tau)^{N-1}}{1 - p_e \frac{\sum_i \alpha_i}{N}}$$

Performing the derivative and making it equal to zero yields

$$((1-\tau)^{N-1} - (N-1)\tau(1-\tau)^{N-2})(1 - (1-\tau)^N \frac{\sum_i \alpha_i}{N}) = N(1-\tau)^{N-1} \frac{\sum_i \alpha_i}{N} \tau (1-\tau)^N$$

The above can be solved used a second-order Taylor expansion of $(1-\tau)^N$, that results in the following approximate solution for τ^*

$$\tau^* \approx \frac{1}{N} \sqrt{2\left(\frac{N}{\sum \alpha_i} - 1\right)} \approx \frac{1}{N} \sqrt{2 \frac{T_e}{T_s} \left(\frac{1}{N} \sum \frac{\rho_i^{id}}{\rho_i^{rx}}\right)} \tag{7}$$

Therefore, an AP that gathers the ρ parameters of all N stations in the WLAN could compute the CW that provides the optimal energy-fair configuration as follows:

$$CW^* = \frac{2}{\tau^*} - 1$$

Remark: For the case of *homogeneous* WLANs, where all stations have the same set of ρ parameters, it results in the expression that we already derived in [5]:

$$\tau^* \approx \frac{1}{N} \sqrt{\frac{2\rho^{id} T_e}{\rho^{rx} T_s}}$$

Note that one of the major disadvantages of the use of (7) is that it requires fetching the $\{\rho^{id}, \rho^{rx}\}$ parameters of all WLAN stations. Indeed, this would require not only a communication protocol to convey this information, but also that all stations are aware of their power consumption values, two non-trivial requirements. In order to tackle this inconvenience, we can make the following *coarse* approximation (see Table I)[9]

$$\sqrt{\frac{\rho^{id}}{\rho^{rx}}} \approx 1$$

[8]Note that we already saw for the case of two stations that the optimal ratio between CW was $k \approx 1.15$.

[9]Note that, indeed, this is a coarse approximation that is reasonably accurate for the case of Interface A, but it is not very accurate for the cases of interfaces B and C. However, given the heterogeneity of WLAN interfaces the approximation cannot aspire to be numerically accurate for all devices, and therefore our approximation is only accurate in terms of the order of magnitude.

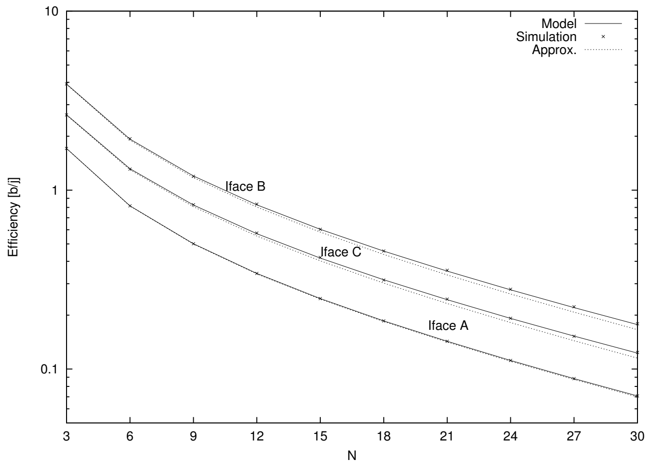

Fig. 2. Overall energy efficiency η of a heterogeneous WLAN with N stations.

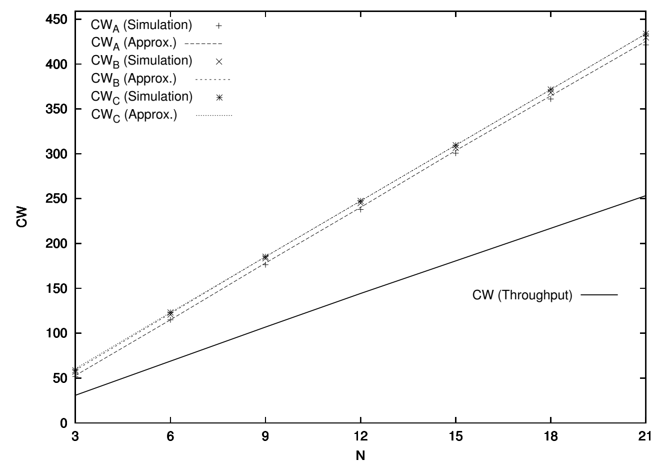

Fig. 3. Optimal CW configuration according to the accurate and approximate energy consumption models for a heterogeneous WLAN with interfaces A, B and C.

which results in the following approximate expression for the optimal τ

$$\hat{\tau^*} \approx \frac{1}{N}\sqrt{\frac{2T_e}{T_s}} \tag{8}$$

In the next section, after the performance validation of the energy consumption model, we will assess the EF performance of a WLAN configured using (7) and (8), and compare it against exhaustive searches in the CW space as well as the default standard configuration.

V. Performance evaluation

In this section we will assess the accuracy of the energy consumption model, as well as the performance obtained using the configuration strategies derived in the previous section. For this purpose we have extended the simulator used in [13], which is an event-driven simulator that models the MAC protocol of 802.11 EDCA with high accuracy.

A. Validation of the energy consumption analysis

To validate the accuracy of the analytical models we first consider a WLAN using the standard DCF configuration with N stations, where one third of the stations is modeled after interface A, B and C of Table I, respectively. We compute the total energy efficiency as given by simulations ("Simulation"), the analytical model of (4) ("Model") and the use of the approximate expression $\hat{e_i}$ (5) ("Approx."), with the results represented in Fig. 2.

The figure shows that both models are able to predict WLAN energy behavior, as analytical results closely follow those from simulations. It can be seen as well that the energy efficiency η rapidly decreases with N (note that the y-axis is in log scale), a result caused by the increase in the number of collisions for the static DCF configuration, and that the approximate model slightly underestimates the overall efficiency, because it overestimates the energy consumed in a timeslot.

Despite the accuracy of both models, it should be noted that our aim is not to predict the WLAN behavior in terms of energy consumption, but to derive the configuration that maximizes the EF performance. To validate if the models are well suited to this aim, we perform the following experiment: for a varying number N of stations, we set $CW_{min} = CW_{max}$ and perform a search on the CW of stations A, B and C (denoted with CW_A, CW_B and CW_C, respectively) to find the configuration that maximizes EF performance. This search is done i) using simulations and ii) by means of the approximate energy consumption model given by (5). The results are depicted in Fig. 3, where we also plot for comparison purposes the CW that optimizes throughput performance.

These results further confirm that the throughput-optimal and the EF-optimal configuration are obtained with significantly different values of the CW. Furthermore, we confirm that the approximate model for the energy consumption can be used to derive the configuration that maximizes the EF performance, as simulations and numerical searches provides very similar CW values. Note that the results from Fig. 3 also validate the relation obtained in (6), as the resulting CW's values for the three different interfaces are very similar.

B. Validation of the proposed EF configuration

We next validate the performance of the two proposed configuration rules, namely (7) and (8), for a heterogeneous WLAN scenario[10] with different mixtures of the interfaces listed in Table I. We perform the comparison in terms of the EF value as given by (2), although note that the maximum achievable EF values depend on the considered scenario. For each scenario we will compute using simulations the EF performance of four different configuration approaches:

- The default standard configuration, denoted as "DCF".
- The configuration given by (7), denoted as "EF-config.".
- The configuration given by (8), denoted as "Approx.".
- The maximum achievable EF performance resulting from an exhaustive search on the CW parameter space, denoted as "Exhaustive". (Note that this value is used only

[10]Note that we already addressed in detail homogeneous scenarios in [5].

TABLE IV
EF PERFORMANCE OF THE FOUR CONSIDERED CONFIGURATION APPROACHES FOR A HETEROGENEOUS WLAN SCENARIO.

Scenario			EF Performance			
N_A	N_B	N_C	DCF	Approx.	EF-Config	Exhaustive
5	5	5	-5.99	-0.57	-0.29	-0.27
	5	10	-5.27	5.04	5.46	5.55
	10	5	-17.33	-6.31	-5.85	-5.82
	10	10	-19.62	-1.67	-1.05	-0.96
10	5	5	-22.14	-11.47	-11.23	-11.20
	5	10	-24.48	-6.90	-6.53	-6.45
	10	5	-36.86	-18.61	-18.20	-18.18
	10	10	-42.13	-14.82	-14.26	-14.19

as reference, given its practical unfeasibility due to the required computational time.)

We denote with N_A, N_B and N_C the number of WLAN stations with the power characteristics of interfaces A, B and C from Table I, respectively. In order to generate different mixtures of interfaces, we first consider scenarios where only two types of interfaces are present, and then we consider scenarios where the three interfaces are present.

1) Two different interfaces: In a first series of experiments we consider the combinations of two out of the three interfaces from Table I. We study the following configurations: *i)* $N_A + N_B > 0, N_C = 0$ which we denote as “A+B”, *ii)* $N_A + N_C > 0, N_B = 0$, denoted as “A+C”, and *iii)* $N_B + N_C > 0, N_A = 0$, denoted as “B+C”. For each configuration we set the total number of stations to $N = 20$ and perform a sweep on the number of stations corresponding to one of the interfaces, namely N_A, N_A and N_B, respectively. The resulting EF values for the four considered configurations are given in Fig. 4, and can be summarized as follows:

- The performance of the default standard configuration rapidly decreases with the number of stations, as most of the resources are wasted in energy-consumed collisions.
- Our configuration provides EF values very close to the ones achievable by means of the exhaustive search. Indeed, as results from Fig. 4 show, the differences between the “EF-config.” and the “Exhaustive” lines are almost negligible, this way proving the ability of (7) to drive the WLAN to the EF-optimal point of operation.
- When the energy consumption information is not available, a WLAN configured according to the “Approx.” approach of (8) provides performance values that, although smaller than the maximum achievable ones, significantly outperforms the ones derived from the use of the standard configuration. The larger N_A the better this approximation results, given that ρ^{rx} and ρ^{id} are very similar for this interface.

2) Three different interfaces: We next address a configuration involving the three interfaces from Table I. In this case, we vary the number of stations equipped with a specific interface between two values, i.e., $\{5, 10\}$, which results in 8 different scenarios. The resulting performance results of the four considered configurations are given in Table IV.

Results show, like in the previous case, that the DCF performance is very poor for all scenarios, worsening (compared against the other configuration approaches) as the total number of stations increases. On the other hand, the proposed configuration is always very close to the maximum achievable value, while the use of the approximate expression of (8) results in a small performance decrease, that worsens when N_A is relatively small. This way, these results further confirm the validity of (7) to provide the EF-optimal configuration in a heterogeneous WLAN.

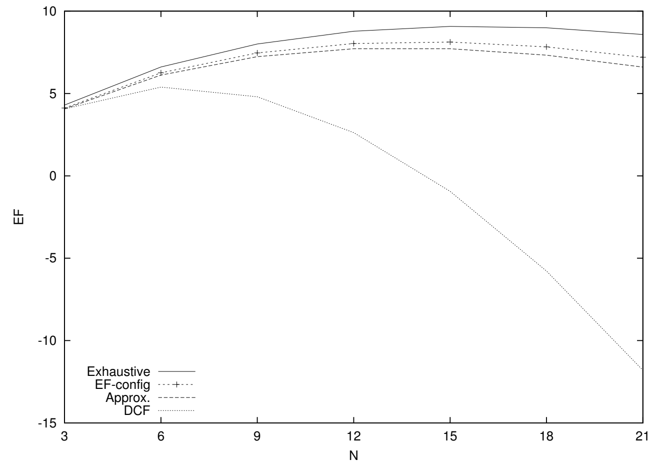

Fig. 5. EF performance for a heterogeneous WLAN with non-overhearing stations.

C. Non-overhearing stations

One of the assumptions of the energy consumption analysis of Section III is that all stations always *overhear* the transmission of a frame, regardless of its destination. This may become less accurate with modern interfaces, as these do not necessarily overhear all the transmission, but instead they listen to the frame preamble T_{PLCP} and header H in order to determine whether they should receive the whole frame (this way consuming ρ^{rx}) or instead they should switch to a less power consuming state (ρ^{id}) until the end of the transmission.

In order to analyze if the derived configuration rules of (7) and (8) are still valid when relaxing this assumption, in this section we consider a heterogeneous scenario with the three interfaces from Table I, we set $N_A = N_B = N_C$ and perform a sweep on the total number of stations N. The resulting EF performance of the four different configuration approaches is represented in Fig 5.

The results show that the proposed configuration approaches provide EF values close to the maximum achievable ones, with the approximate expression providing smaller values. However, it can be seen that for the case of these non-overhearing interfaces the performance is not as close to the exhaustive searches as in the previous cases –the configuration of these scenarios constitutes part of our future work.

VI. CONCLUSIONS

Energy-efficient operation of mobile devices is a key challenge for the design of future communication systems, which

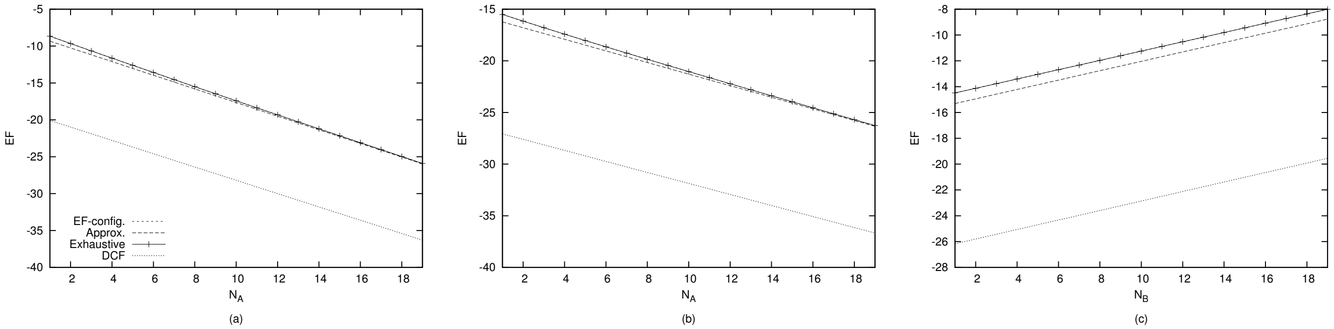

Fig. 4. EF performance for a heterogeneous WLAN with two types of interfaces: a) A+B, b) A+C, c) B+C.

comprises the optimization of the energy consumption of wireless communications. Yet, contemporary work in the area of WLANs mainly focuses on the optimization of throughput. In this paper we have argued that, in contrast to traditional throughput oriented metrics, the objective function for performance optimization should rather be the amount of information transmitted per unit of energy consumed.

Following the above objective, we have presented an analytical model of the power consumption of an IEEE 802.11 WLAN with heterogeneous (w.r.t. energy consumption) devices, which models the existing diversity of WLAN stations more precisely than prior models. By means of the proposed model, we have shown that such scenarios with heterogeneous devices constitute a new research challenge, as compared against previous homogeneous problems. In particular, we have identified the risk of extreme throughput unfairness, if the optimization aims at maximizing overall efficiency only.

The above shows a tradeoff between energy efficiency and throughput fairness which, to the knowledge of the authors, has not been studied before. In order to address this tradeoff, we have proposed a novel criterion, named EF, which is based on the well accepted notion of Proportional Fairness. We have then derived the closed-form expression of the configuration to use in a WLAN to achieve our EF criterion. It is worth noting that the criterion is not limited to WLAN but could be applied to any scenario and wireless technology with heterogeneous interfaces.

We have addressed the problem from a formal viewpoint with a well defined performance criterion. In fact, it is interesting to observe that the use of the EF-optimal configuration, for the case of 802.11WLANs, results in relatively fair throughput allocations, although we have also seen that this configuration is significantly different from the standard or the throughput optimal ones. The proposed configuration have been validated through extensive simulations, and has been shown to perform very similarly to the maximum achievable values derived from exhaustive searches on the configuration space.

ACKNOWLEDGMENTS

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