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Energy-conservation in 802.11 WLANs via transmission-strategy-aware airtime allocation

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ABSTRACT

In a typical 802.11 wireless local area network (WLAN), different wireless stations may communicate with the access point (AP) with different transmission rates, transmit-power levels, and data payload sizes. Such phenomenon is often referred to as transmission-strategy diversity. In this paper, we study the energy-conservation problem in 802.11 WLANs in the presence of transmission-strategy diversity. This problem is addressed from a unique angle – the system-level fairness which is quite different from most of current research that focuses on improving the performance of each individual wireless station. To emphasize fair energy consumption among contending stations, we introduce a new fairness notion, called *energy-conservation fairness*, which is in sharp contrast to the conventional throughput fairness and airtime fairness. Another contribution of this paper is an energy-efficient scheme that allocates airtime shares to contending stations so as to achieve combined airtime and energy-conservation fairness. Our simulation results show that, when the energy-conservation fairness is considered, both aggregate system throughput and overall system energy-efficiency can be improved significantly with all contending stations consuming a similar amount of energy.

1. Introduction

Since most wireless stations are battery-powered and have a limited amount of energy, energy-conservation has always been one of the most important issues in IEEE 802.11 WLANs (Wireless Local Area Networks) [1] and has continuously been drawing considerable attention. Despite the need for a holistic, system approach to this issue, most of current research has been focusing on each individual station's energy consumption. To remedy this deficiency, we will in this paper consider the energy-conservation problem from the perspective of *system-level* fairness in 802.11 WLANs and offer some interesting observations and insights.

1.1. Transmission-strategy diversity in 802.11 WLANs

The 802.11 PHYs (physical layers) provide multiple transmission rates by employing different modulation and channel coding schemes. For example, the 802.11b PHY [2] provides 4 rates up to 11 Mbps at the 2.4 GHz band, the 802.11a PHY [3] provides 8 rates up to 54 Mbps at the 5 GHz band, and the 802.11 g PHY [4] supports 12 rates up to 54 Mbps at the 2.4 GHz band. Furthermore, an increasing number of commercial 802.11 products support multiple transmit-power levels. For example, the Cisco Aironet 350 Series Client Adaptor [5] is an 802.11b-based WLAN device and supports 6 transmit-power levels from 0 dBm to 20 dBm.

Various energy-conservation mechanisms have been proposed by exploiting the above-mentioned multiple transmission rates and multiple transmit-power levels provided by 802.11 devices. The key idea is to allow a wireless station to, based on the link quality between itself and the receiver, select the most energy-efficient transmission

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strategy, which consists of transmission rate, transmit power, and/or data payload length. In a typical 802.11 WLAN, some stations may be far away from their AP (Access Point) and the quality of their radio transmissions is low, and some stations may be near their AP and experience better wireless channel condition. As a result, different wireless stations may choose different transmission strategies to communicate with the AP. We call such phenomenon *transmission-strategy diversity* in 802.11 WLANs.

1.2. Motivation and contributions

Throughput fairness is one of the well-studied fairness notions in 802.11 WLANs. Its goal is to fairly allocate contending stations bandwidths in proportion to their associated weights. Recently, with throughput fairness as the design goal, a serious system performance degradation is found to be inevitable in the presence of the transmission-strategy diversity. In particular, a performance anomaly caused by the transmission-rate diversity (a special form of the transmission-strategy diversity) was first discovered experimentally in [6] and later studied in-depth via modeling and analysis in [7]. Since then, the concept of *airtime fairness* has been introduced and recognized as a more reasonable design goal than throughput fairness for multi-rate 802.11 WLANs [8]. Unfortunately, the transmit-power diversity – another form of the transmission-strategy diversity – was not considered in the airtime fairness notion. Therefore, even when the perfect airtime fairness is achieved, high-power stations consume much more energy than low-power stations.

In this paper, we first introduce a new fairness notion, called *energy-conservation fairness*, to emphasize fair energy consumption by all contending stations in an 802.11 WLAN. Note that different fairness notions yield different airtime allocations. In practice, instead of requesting for airtime fairness or energy-conservation fairness alone, a typical fairness request from a wireless station should be in a hybrid form so as to achieve energy-conservation fairness subject to a minimum airtime share requirement. Determining the airtime allocation for such a hybrid scenario is not as straightforward as that for airtime or energy-conservation fairness alone. We then present a three-step scheduling algorithm to solve this constrained optimization problem.

Note that it is difficult to control the airtime allocation in an 802.11 WLAN. Many researchers have proposed various ways to achieve this goal by adjusting the channel access parameters of contending stations, which involves complicated computation and is difficult, if not impossible, to realize since the MAC layer is typically hard-coded in the device firmware. The 802.11e standard [9] is an extension to the current 802.11 MAC for QoS (Quality-of-Service) provisioning. One of the key improvements in 802.11e is to introduce a new concept called TXOP (Transmission Opportunity). A TXOP is a time interval during which a wireless station is allowed to transmit for each medium access. So, we propose to control the airtime allocation in an 802.11e EDCA (Enhanced Distributed Channel Access) [9] system by adjusting the TXOP limits for different contending stations.

1.3. Organization

The rest of the paper is organized as follows. We discuss the related work in Section 2. Section 3 presents three fairness notions for 802.11 WLANs. The proposed energy-efficient airtime-allocation scheme is described in Section 4 and the related implementation issues are discussed in Section 5. Section 6 presents and evaluates the simulation results, and the paper concludes in Section 7.

2. Related work

How to determine the energy-efficient transmission-strategy for an individual wireless station has been studied extensively by many researchers and is not the focus of this paper. In [10], the authors presented a scheme in which the most battery energy-efficient combination of FEC (Forward Error Correction) code and ARQ (Automatic Re-transmission reQuest) protocol is chosen and adapted over time for data transmissions. In [11], the authors proposed a power-control scheme to save energy by choosing the optimal transmit-power levels for different packet sizes. Several intelligent TPC (Transmit Power Control) schemes were proposed in [12–14], which share the similar idea of exchanging RTS/CTS frames to reserve the wireless channel before each data transmission attempt that may then be conducted at a lower power level to save energy. The authors of [15,16] proposed an adaptive transmission protocol for spread-spectrum networks, which adjusts the power in a transmitted data frame and the rate of the RS (Reed-Solomon) code to respond to variations in the propagation loss and partial-band interference. In [17], we proposed *MiSer* for 802.11 DCF systems, which selects the most energy-efficient rate-power combination for each data transmission attempt, and uses an enhanced RTS/CTS mechanism to deal with "hidden nodes" as well as the unique TPC-caused interference in 802.11 DCF systems.

Numerous scheduling algorithms have been proposed to achieve the weighted throughput fairness among contending stations in a wireless network. To mention a few, the algorithms described in [18–21] are centralized by design, while those in [22–27] are distributed and may be embedded into contention-based 802.11 DCF systems. In particular, those in [25–27] were specifically designed for 802.11 DCF systems. It has also been shown in [28–32,8] that the desired airtime fairness in 802.11 DCF systems may be achieved by manipulating the channel access parameters of contending stations. In [33], an OAR (Opportunistic Auto Rate) protocol was proposed to maintain the fair airtime usage in a multi-rate wireless network. Instead of controlling the channel access parameters, OAR controls the *More Fragment* bit in the 802.11 MAC header such that a particular station may be allowed to transmit multiple data frames back-to-back in a burst. The authors of [34] implemented a TBR (Time-Based Regulator) algorithm running on the AP, which provides time-based fairness by regulating packets. Some weighted temporal fairness schemes were also proposed for cellular networks [35].

By contrast, our airtime-allocation scheme is designed to deal with generic fairness requests (airtime fairness or energy-conservation fairness or a combination thereof), which has not been addressed elsewhere.

3. Three fairness notions for multi-rate multi-power-level 802.11 WLANs

In this section, we first review two popular fairness notions in 802.11 WLANs, namely, *throughput fairness* and *airtime fairness*,[1] and then introduce a new fairness notion called *energy-conservation fairness*. Moreover, we discuss how the transmission-strategy diversity may affect the system performance under each of the three fairness notions.

Table 1 lists the notations to be used throughout this paper, where station *i*'s transmission strategy consists of data payload length (L_i), transmission rate (R_i), and transmit-power consumption (P_i). When station *i* is in the idle mode, its power consumption is denoted by O_i. The power factor (ω_i) will be discussed in the next section.

Table 1
List of notations to be used throughout this paper

Notations	Comments
i	station ID
ϕ_i	associated weight
ω_i	power factor
L_i (octets)	data payload length
R_i (Mbps)	data transmission rate
P_i (mW)	transmit-power consumption
O_i (mW)	idle power consumption
K_i	average # of medium accesses per unit time
N_i	# of data frame transmissions per medium access

3.1. Throughput ($\mathscr{B}$) fairness

Throughput fairness is an extensively-studied fairness notion in 802.11 WLANs. Its goal is to allocate contending stations bandwidths in proportion to their associated weights:

$$\forall i, \quad \mathscr{B}_i = L_i N_i K_i \propto \phi_i. \tag{1}$$

The 802.11 DCF [1] is designed to offer equal transmission opportunities (or long-term equal medium access probabilities) to all contending stations, and each station is only allowed to attempt a single frame transmission for each medium access. In other words, with the DCF, we have

$$\forall i,\ j, \quad K_i = K_j, \quad N_i = N_j = 1. \tag{2}$$

Therefore, when the stations transmit data frames with the payload size in proportion to their associated weights, i.e., $\forall i, L_i \propto \phi_i$, the DCF yields the desired throughput fairness.

1. *Impact of data-payload-size diversity:* From the above analysis, one can see that throughput fairness under the DCF is achieved only when the data payload sizes of contending stations are proportional to their associated weights.
2. *Impact of transmission-rate diversity:* From Eq. (1), we can see that transmission-rate diversity has no impact on throughput fairness. This is surprising at the first sight but rather logical because, as long as a wireless station wins the contention to access the wireless medium, it is allowed to transmit its data frame regardless of the selected transmission rate. On the other hand, under certain circumstances, the transmission-rate diversity may degrade significantly the aggregate system throughput. As pointed out in [6], in a multi-rate 802.11 WLAN where different stations may transmit data at different rates, the DCF results in the following performance anomaly: *the throughput of stations transmitting at higher rates may be affected greatly by stations transmitting at lower rates, and hence, those high-rate stations may suffer an unexpected throughput degradation under the notion of throughput fairness.* This is because, according to the definition of throughput fairness, we have
$$\mathscr{B}_{\text{high\_rate}} = \mathscr{B}_{\text{low\_rate}} \cdot \frac{\phi_{\text{high\_rate}}}{\phi_{\text{low\_rate}}} < R_{\text{low\_rate}} \cdot \frac{\phi_{\text{high\_rate}}}{\phi_{\text{low\_rate}}}, \tag{3}$$
meaning that the throughput of a high-rate station is bounded below a certain level determined by other low-rate contending stations, regardless of its own transmission rate. For example, under the uniform throughput fairness ($\phi_{\text{high\_rate}} = \phi_{\text{low\_rate}}$), the throughput of any contending station in the network is always bounded below the lowest transmission rate among all contending stations and, consequently, so is the aggregate system throughput.
3. *Impact of transmit-power diversity:* It is clear from Eq. (1) that transmit-power diversity has no impact on throughput fairness.

3.2. Airtime ($\mathscr{A}$) fairness

Recently, airtime fairness has been introduced to deal with the above-described performance anomaly, and is considered a more reasonable and intuitive fairness notion than throughput fairness for multi-rate 802.11 WLANs. Its goal is to allocate contending stations fair amounts of airtime (rather than bandwidths) in proportion to their associated weights:

$$\left.\begin{aligned} &\forall i, \quad \mathscr{A}_i = \tfrac{L_i N_i K_i}{R_i} = \tfrac{\mathscr{B}_i}{R_i} \propto \phi_i \\ &\sum_{i=1}^{n} \mathscr{A}_i = 1 \end{aligned}\right\} \Rightarrow \forall i, \quad \mathscr{A}_i = \frac{\phi_i}{\sum_{i=1}^{n} \phi_i}. \tag{4}$$

Under the notion of airtime fairness, each contending station is guaranteed to receive a certain percentage of the total airtime. This way, the throughput performance of an individual station is isolated from, and unaffected by, those of other stations. The authors of [34] showed that airtime fairness can make significant improvements in the aggregate system throughput in multi-rate 802.11 WLANs.

1. *Impacts of data-payload-size and transmission-rate diversities:* Unlike throughput fairness, both data-payload-size and transmission-rate diversities affect airtime fairness. Airtime fairness may be achieved when certain

[1] *Throughput fairness* and *airtime fairness* are also often referred to as *bandwidth fairness* and *time-based fairness*, respectively.

requirements of data payload sizes and transmission rates of contending stations are satisfied. For example, combining Eq. (4) with Eq. (2), we can see that airtime fairness under the DCF is achieved only when the stations' frame transmission durations are proportional to their associated weights, i.e., $\forall i,\ \frac{L_i}{R_i} \propto \phi_i$.
2. *Impact of transmit-power diversity:* It is clear from Eq. (4) that transmit-power diversity has no impact on airtime fairness.
3. *Throughput fairness revisited:* Throughput fairness defined by Eq. (1) is indeed equivalent to

$$\forall i, \quad \mathscr{A}_i \propto \frac{\phi_i}{R_i}. \tag{5}$$

Hence, we have

$$\left.\begin{array}{l} \forall i, \quad \mathscr{A}_i \propto \frac{\phi_i}{R_i} \\ \sum_{i=1}^{n} \mathscr{A}_i = 1 \end{array}\right\} \Rightarrow \forall i, \quad \mathscr{A}_i = \frac{\frac{\phi_i}{R_i}}{\sum_{i=1}^{n} \frac{\phi_i}{R_i}}. \tag{6}$$

This says that throughput fairness (i) requires each contending station to receive an airtime share proportional to the ratio of its associated weight to its transmission rate, and (ii) is equivalent to airtime fairness in single-rate 802.11 WLANs.

Remark. Some researchers [25–32,8] proposed to achieve throughput or airtime fairness by selecting different channel access parameters (and hence, K_i values) for different contending stations.

3.3. Energy-conservation ($\mathscr{E}$) fairness

Transmit-power diversity is a unique phenomenon in the emerging multi-rate multi-power-level 802.11 WLANs, which is not considered in airtime fairness. To understand the impact of transmit-power diversity, let us consider the following scenario. In a typical 802.11 WLAN, some wireless stations may be far away from the AP and hence transmit at high power levels to overcome the low quality of their radio transmissions, while some stations may be near the AP and can communicate with AP at low transmit-power levels. In this scenario, even when the perfect airtime fairness is achieved and all the contending stations have an equal share of the total airtime usage, high-power stations consume much more energy than low-power stations. Based on the above observations, we introduce a new fairness notion, called *energy-conservation fairness*, to emphasize fair energy consumption by all contending stations in proportion to their associated weights:[2]

$$\forall i, \quad \mathscr{E}_i = \frac{L_i N_i K_i (P_i - O_i)}{R_i} = \frac{\mathscr{B}_i (P_i - O_i)}{R_i} = \mathscr{A}_i (P_i - O_i) \propto \phi_i$$
$$\Rightarrow \forall i, \quad \mathscr{A}_i \propto \frac{\phi_i}{P_i - O_i}. \tag{7}$$

As a result, we have

$$\left.\begin{array}{l} \forall i, \quad \mathscr{A}_i \propto \frac{\phi_i}{P_i - O_i} \\ \sum_{i=1}^{n} \mathscr{A}_i = 1 \end{array}\right\} \Rightarrow \forall i, \quad \mathscr{A}_i = \frac{\frac{\phi_i}{P_i - O_i}}{\sum_{i=1}^{n} \frac{\phi_i}{P_i - O_i}}. \tag{8}$$

Thus, energy-conservation fairness (i) requires each contending station to receive an airtime share proportional to the ratio of its associated weight to the difference between its transmit-power consumption and its idle power consumption, (ii) is equivalent to airtime fairness in single-power-level 802.11 WLANs, and (iii) is equivalent to both airtime and throughput fairness in single-rate single-power-level 802.11 WLANs.

1. *Impacts of data-payload-size, transmission-rate, and transmit-power diversities:* From Eq. (7), we can see that energy-conservation fairness is affected by all three types of diversity. It may be achieved only when certain requirements about data payload sizes, transmission rates, and transmit-power consumptions of contending stations are satisfied.

3.4. Fairness measures

We use three fairness measures, $\mathscr{I}_{\mathscr{B}}, \mathscr{I}_{\mathscr{A}}$, and $\mathscr{I}_{\mathscr{E}}$, to quantitatively evaluate throughput, airtime, and energy-conservation fairness, respectively, of an airtime-allocation scheme. For example, the energy-conservation fairness measure may be calculated as:

$$\mathscr{I}_{\mathscr{E}} = \frac{\left(\sum_{i=1}^{n} \frac{\mathscr{A}_i (P_i - O_i)}{\phi_i}\right)^2}{n \cdot \sum_{i=1}^{n} \left(\frac{\mathscr{A}_i (P_i - O_i)}{\phi_i}\right)^2}. \tag{9}$$

When all contending stations have the same energy consumption performance, the perfect energy-conservation fairness is achieved and $\mathscr{I}_{\mathscr{E}}$ is 1. In general, $\mathscr{I}_{\mathscr{E}}$ is between 0 and 1, and the closer to 1 the $\mathscr{I}_{\mathscr{E}}$ value, the fairer an airtime-allocation scheme gets in terms of energy conservation. Similarly, we can calculate $\mathscr{I}_{\mathscr{B}}$ and $\mathscr{I}_{\mathscr{A}}$.

4. Energy-efficient airtime allocation

Instead of requesting for airtime fairness or energy-conservation fairness alone, a typical fairness request from a wireless station may be in a hybrid form. Here we focus on *minimum-airtime-share constrained energy-conservation fairness*, which combines airtime fairness with energy-conservation fairness. In order to characterize a wireless station's desired minimum airtime share, we introduce the following notation. As shown in Table 1, each station is associated with a *power factor*, denoted by ω, in addition to its associated weight ϕ. The minimum airtime share of station i in this hybrid scenario is then $\omega_i \mathscr{A}_i$ where $\mathscr{A}_i$ is calculated according to Eq. (4) – definition of airtime fairness.

Determining the airtime allocation for this hybrid problem is not as straightforward as that for airtime fairness or energy-conservation fairness alone. In this section, we

[2] In this paper, we assume no power-saving mode, meaning that, when an 802.11 device is not actively transmitting or receiving, it remains in the idle mode and keeps sensing the channel. Furthermore, we assume that, when an 802.11 device is in the idle mode, it consumes the same amount of power as when it is receiving data.

Table 2
Example scenario: information of four contending stations

i (station ID)	1	2	3	4
ϕ_i	1	1	1	1
ω_i	1	1	$\frac{1}{4}$	$\frac{1}{2}$
$(P_i - O_i)$	$P_{\min}$	$3P_{\min}$	$4P_{\min}$	$4P_{\min}$

describe a three-step energy-efficient airtime-allocation scheme as a possible solution. Moreover, to help better understand how our scheme works, we will show how each step of our scheme is applied to the following simple example scenario:

Example scenario. Four stations are contending for the shared wireless medium, and their associated weights, power factors, and transmit-power information are listed in Table 2. The objective is to find the airtime allocation that yields the best energy-conservation fairness while meeting the minimum-airtime-share constraint for each station.

4.1. Step I: calculate original airtime shares

The first step of our scheme is to find the original values ($\mathscr{A}^{\text{or}}$) of the airtime shares, which are obtained by considering airtime fairness only. Hence, according to Eq. (4), we have

$$\forall i, \quad \mathscr{A}_i^{\text{or}} = \frac{\phi_i}{\sum_{i=1}^n \phi_i}. \tag{10}$$

Now, we apply *Step I* to our example scenario. Consider station 3, for instance. Then, we have $\mathscr{A}_3^{\text{or}} = \frac{1}{1+1+1+1} = \frac{1}{4}$. Similarly, we can calculate the original airtime shares for other contending stations, and the results are listed in Table 3.

4.2. Step II: determine lower bounds of final airtime shares

The second step is to determine the lower bounds ($\mathscr{A}^{\text{bd}}$) of final airtime shares based on the power-factor information as well as the energy-conservation fairness requirement.

Theorem. *Let $P_{\min}$ denote the difference between the minimum possible transmit-power consumption and the idle power consumption, then $\mathscr{A}_i^{\text{bd}} \equiv \mathscr{A}_i^{\text{or}} \cdot \max\left\{\omega_i, \frac{P_{\min}}{P_i - O_i}\right\}$ is the lower bound of station i's final airtime share $\mathscr{A}_i$.*

Proof. First, according to the definition of the power factor, we have

$$\forall i, \quad \mathscr{A}_i \geqslant \mathscr{A}_i^{\text{or}} \cdot \omega_i. \tag{11}$$

Table 3
Example scenario: original airtime shares

i (Station ID)	1	2	3	4
ϕ_i	1	1	1	1
ω_i	1	1	$\frac{1}{4}$	$\frac{1}{2}$
$(P_i - O_i)$	$P_{\min}$	$3P_{\min}$	$4P_{\min}$	$4P_{\min}$
$\mathscr{A}_i^{\text{or}}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$

Next, assume that station i has a final airtime share $\mathscr{A}_i$ that is less than $\mathscr{A}_i^{\text{or}} \cdot \frac{P_{\min}}{P_i - O_i}$. Then, there must exist at least one other station, say, station j, such that $\mathscr{A}_j > \mathscr{A}_j^{\text{or}} \cdot \frac{P_{\min}}{P_j - O_j}$. Otherwise, we have the following contradiction:

$$1 = \sum_{i=1}^n \mathscr{A}_i < \sum_{i=1}^n \left(\mathscr{A}_i^{\text{or}} \cdot \frac{P_{\min}}{P_i - O_i}\right) \leqslant \sum_{i=1}^n \mathscr{A}_i^{\text{or}} = 1. \tag{12}$$

With stations i and j, we have

$$\begin{aligned}
\frac{\mathscr{A}_i(P_i - O_i)}{\phi_i} &< \mathscr{A}_i^{\text{or}} \cdot \frac{P_{\min}}{P_i - O_i} \cdot \frac{P_i - O_i}{\phi_i} \\
&= \frac{\phi_i}{\sum_{i=1}^n \phi_i} \cdot \frac{P_{\min}}{P_i - O_i} \cdot \frac{P_i - O_i}{\phi_i} = \frac{P_{\min}}{\sum_{i=1}^n \phi_i} \\
&= \frac{\phi_j}{\sum_{i=1}^n \phi_i} \cdot \frac{P_{\min}}{P_j - O_j} \cdot \frac{P_j - O_j}{\phi_j} \\
&= \mathscr{A}_j^{\text{or}} \cdot \frac{P_{\min}}{P_j - O_j} \cdot \frac{P_j - O_j}{\phi_j} < \frac{\mathscr{A}_j(P_j - O_j)}{\phi_j}.
\end{aligned} \tag{13}$$

According to the definition of energy-conservation fairness measure, it is clear that increasing $\mathscr{A}_i$ and decreasing $\mathscr{A}_j$ will yield a larger $\mathscr{I}_{\mathscr{E}}$, meaning that better energy-conservation fairness will be achieved. This result has been proved in [36]. We repeat the above process until the airtime share for each wireless station is at least $\mathscr{A}^{\text{or}} \cdot \frac{P_{\min}}{P - O}$, i.e.

$$\forall i, \quad \mathscr{A}_i \geqslant \mathscr{A}_i^{\text{or}} \cdot \frac{P_{\min}}{P_i - O_i}. \tag{14}$$

Finally, combining Eqs. (11) and (14) together, we have a lower bound for station i's final airtime share:

$$\mathscr{A}_i \geqslant \mathscr{A}_i^{\text{or}} \cdot \max\left\{\omega_i, \frac{P_{\min}}{P_i - O_i}\right\} \equiv \mathscr{A}_i^{\text{bd}}. \qquad \square \tag{15}$$

It is interesting to observe that, when all the wireless stations specify their power factors to be 1, we have

$$\begin{cases} \forall i, \quad \mathscr{A}_i \geqslant \mathscr{A}_i^{\text{bd}} = \mathscr{A}_i^{\text{or}} \cdot \max\left\{1, \frac{P_{\min}}{P_i - O_i}\right\} = \mathscr{A}_i^{\text{or}} \\ \sum_{i=1}^n \mathscr{A}_i = 1 \end{cases}$$
$$\Rightarrow \forall i, \quad \mathscr{A}_i = \mathscr{A}_i^{\text{bd}} = \mathscr{A}_i^{\text{or}}. \tag{16}$$

In this case, airtime fairness is achieved. On the other hand, choosing power factors to be 0 means that energy-conservation fairness is the only concern. Any value between 0 and 1 for the power factor represents a compromise between airtime fairness and energy-conservation fairness.

Now, we apply *Step II* to our example scenario. Consider station 3, for instance. We have $\mathscr{A}_3^{\text{bd}} \equiv \mathscr{A}_3^{\text{or}} \cdot \max\left\{\omega_3, \frac{P_{\min}}{P_3 - O_3}\right\} = \frac{1}{16}$. Similarly, we can calculate lower bounds of airtime shares for other contending stations, and the results are listed in Table 4.

4.3. Step III: generate the final airtime allocation

The third step is to generate the final airtime allocation based on the lower bound information and, again, the energy-conservation fairness requirement. Fig. 1 shows

Table 4
Example scenario: lower bounds of final airtime shares

i (Station ID)	1	2	3	4
ϕ_i	1	1	1	1
ω_i	1	1	$\frac{1}{4}$	$\frac{1}{2}$
$(P_i - O_i)$	$P_{\min}$	$3P_{\min}$	$4P_{\min}$	$4P_{\min}$
$\mathscr{A}_i^{\text{or}}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$
$\mathscr{A}_i^{\text{bd}}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{16}$	$\frac{1}{8}$

```
Initialization: ∀ i,  𝒜_i = 𝒜_i^bd;
while (∑_{i=1}^n 𝒜_i < 1) {
    for (i = 1 : n)  Ē_i = 𝒜_i · (P_i − O_i)/φ_i ;
    Sort Ē_i's in ascending order;
    Ē_min = min(Ē_i);
    Ē_next_min = the second-smallest Ē_i value;
    if (Ē_next_min == Ē_min) Ē_next_min = ∞;
    ϒ = {i, where Ē_i = Ē_min};
    for (each i ∈ ϒ) {
        δ_𝒜i = min{ (1−∑_{i=1}^n 𝒜_i)·(φ_i/(P_i−O_i)) / ∑_{i∈ϒ} (φ_i/(P_i−O_i)),  (Ē_next_min − Ē_min) / ((P_i−O_i)/φ_i) };
        𝒜_i = 𝒜_i + δ_𝒜i;
    }
}
```

Fig. 1. Pseudo-code of *Step III* to generate the final airtime allocation.

the pseudo-coded algorithm for *Step III*. The algorithm starts by using the lower bounds ($\mathscr{A}_i^{\text{bd}}$) as the initial values of final airtime shares, and stops when all $\left(1 - \sum_{i=1}^{n} \mathscr{A}_i^{\text{bd}}\right)$ shares of the total airtime usage have been allocated to contending stations to yield the best energy-conservation fairness. As shown in the pseudo code, the values of $\mathscr{A}_i$'s are increased by rounds. At each round, the normalized energy consumptions ($\overline{\mathscr{E}}$) of all contending stations are first sorted in ascending order. Then, the stations with minimum $\overline{\mathscr{E}}$ values are allocated extra shares of airtime ($\delta_{\mathscr{A}}$) in proportion to $\frac{P-O}{\phi}$, until either their normalized energy consumptions are raised to the second smallest amount or all the available airtime shares have been allocated, whichever occurs first.

Now, we apply *Step III* to our example scenario, and the results are listed in Table 5. One can see that, in this example, final airtime shares are obtained after one round of increments. We only recap the computation details for $\mathscr{A}_3$ as follows:

Table 5
Example scenario: generate final airtime allocation

i (Station ID)		1	2	3	4
ϕ_i		1	1	1	1
ω_i		1	1	$\frac{1}{4}$	$\frac{1}{2}$
$(P_i - O_i)$		$P_{\min}$	$3P_{\min}$	$4P_{\min}$	$4P_{\min}$
$\mathscr{A}_i^{\text{or}}$		$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$
$\mathscr{A}_i^{\text{bd}}$		$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{16}$	$\frac{1}{8}$
Round 1	$\delta_{\mathscr{A}_i}$	$\frac{1}{4}$	–	$\frac{1}{16}$	–
	$\mathscr{A}_i$	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{8}$	$\frac{1}{8}$

[Round 1]

$$\sum_{i=1}^{4} \mathscr{A}_i = \frac{11}{16} < 1, \quad \Upsilon = \{1,3\}$$

$$\Rightarrow \delta_{\mathscr{A}_3} = \min\left\{\frac{\left(1 - \frac{11}{16}\right)\cdot\frac{1}{4}}{1 + \frac{1}{4}}, \frac{\frac{1}{2} - \frac{1}{4}}{4}\right\} = \frac{1}{16}.$$

The final airtime shares of other contending stations can be obtained by performing similar computations. Energy-conservation fairness measure of our airtime allocation is

$$\mathscr{I}'_{\mathscr{E}} = \frac{\left(\frac{1}{2} + \frac{1}{4}\cdot 3 + \frac{1}{8}\cdot 4 + \frac{1}{8}\cdot 4\right)^2}{4\left[\left(\frac{1}{2}\right)^2 + \left(\frac{1}{4}\cdot 3\right)^2 + \left(\frac{1}{8}\cdot 4\right)^2 + \left(\frac{1}{8}\cdot 4\right)^2\right]} = 0.9643,$$

while $\mathscr{I}_{\mathscr{E}}$ of the airtime-allocation scheme based on airtime fairness alone is

$$\mathscr{I}''_{\mathscr{E}} = \frac{\left(\frac{1}{4} + \frac{1}{4}\cdot 3 + \frac{1}{4}\cdot 4 + \frac{1}{4}\cdot 4\right)^2}{4\left[\left(\frac{1}{4}\right)^2 + \left(\frac{1}{4}\cdot 3\right)^2 + \left(\frac{1}{4}\cdot 4\right)^2 + \left(\frac{1}{4}\cdot 4\right)^2\right]} = 0.8571.$$

Clearly, our scheme performs better in terms of energy-conservation fairness. Notice, however, that our scheme does not achieve the perfect energy-conservation fairness. This is due to the minimum airtime shares required by the contending stations. It is easy to calculate that the following airtime allocation $\left\{\frac{6}{11}, \frac{2}{11}, \frac{3}{22}, \frac{3}{22}\right\}$ achieves the perfect energy-conservation fairness, where station 2's airtime share $\left(\frac{2}{11}\right)$ is lower than its desired minimum level $\left(\frac{1}{4}\right)$.

5. Implementation issues

Various schemes have been proposed to achieve the desired airtime allocation in 802.11 WLANs by controlling the channel access parameters of contending stations, which involves complicated computation and is infeasible since the MAC layer is typically hard-coded in the device firmware. The 802.11e [9] standard is an extension to the current 802.11 MAC for QoS (Quality-of-Service) provisioning, and it introduces a new concept called TXOP (Transmission Opportunity) that makes it possible to have a simple way of achieving the desired airtime allocation.

5.1. IEEE 802.11e, EDCA, and TXOP

The 802.11e defines a single coordination function, called the HCF (Hybrid Coordination Function), which is composed of two channel access mechanisms: EDCA (Enhanced Distributed Channel Access) and HCCA (HCF-Controlled Channel Access). This paper focuses on the contention-based 802.11e EDCA, which is designed to provide distributed and differentiated accesses to the shared wireless medium among contending stations. It provides four ACs (Access Categories) and each frame arriving at the EDCA MAC is mapped into an AC based on its user priority. Each AC uses a different set of channel access parameters, including AIFS (Arbitration Inter-Frame Space) and $CW_{\min}/CW_{\max}$ (minimum/maximum contention window sizes), to achieve prioritized medium access.

An EDCA TXOP is an interval of time during which a particular station is allowed to occupy the wireless medium and transmit after it wins the medium contention according to the EDCA access rules. During an EDCA TXOP, there can be one or more consecutive frame exchanges between the station and the AP, separated by the minimum SIFS (Short Inter-Frame Space) interval. The maximum duration of an EDCA TXOP is called the TXOP limit.

In an 802.11e EDCA network, there are two ways of allocating airtime shares to contending stations: (i) via controlling the channel access parameters of each wireless station, or (ii) via controlling the TXOP limit of each wireless station. With the first method, each station occupies the medium for the same amount of time during each access but has a different medium access frequency. With the second method, all contending stations will use the same channel access parameters, but each station will occupy the shared wireless medium for a different amount of time during its access.

5.2. Controlling channel access parameters: not a good idea

As one can see from the above, the idea of controlling channel access parameters has been used by the EDCA to provide service differentiation among ACs. Thus, if we reuse the same idea for the purpose of providing the desired fairness among contending stations belonging to the same AC, it will inevitably introduce ambiguities between coarse (among ACs) and fine (among contending stations belonging to the same AC) levels of service differentiations in an 802.11e EDCA network. To avoid unnecessary confusions, we choose to provide the user-desired fairness by controlling the TXOP limits.

5.3. Controlling the TXOP limits: our choice

1. *Calculation of TXOP limits:* As listed in Table 1, L_i and R_i represent the data payload size and the transmission rate of station i, respectively. Hence, the transmission duration of a single data frame (excluding the physical and MAC layer overheads) by station i is $D_i = \frac{L_i}{R_i}$. Let m denote the station index such that $D_m = \max_{1 \leqslant i \leqslant n} D_i$. Then, in order to achieve the desired airtime allocation among contending stations, the number of frame transmissions per medium access by station i is $N_i = \frac{D_m}{D_i} \cdot \frac{A_i}{A_m}$. Subsequently, the TXOP limit for station i can be calculated as

$$\begin{aligned} \text{TXOP}_i = N_i \cdot \left(\text{tPLCPoverhead} + \frac{L_i + \text{aMACheader}}{R_i}\right) \\ + (2 \cdot N_i - 1) \cdot \text{tSIFStime} \\ + N_i \cdot \left(\text{tPLCPoverhead} + \frac{L_{\text{ack}}}{R_{\text{ack}}}\right), \end{aligned} \quad (17)$$

where L_{ack} is the Ack frame size, and R_{ack} is the Ack transmission rate. Apparently, this scheme works perfectly when N_i is an integer. If N_i is not an integer, a frame must be fragmented to achieve precise airtime control.

We use the same example scenario as that in Section 4 to illustrate how to compute the TXOP limits. Assume that all four stations are equipped with 802.11b devices, and the transmission rates and the data payload sizes of the four contending stations are 11, 5.5, 5.5, 5.5 Mbps and 1024, 1024, 512, 256 octets, respectively. Then, we have:

$$\left.\begin{aligned} D_1 = \tfrac{L_1}{R_1} = \tfrac{1024}{11} \\ D_2 = \tfrac{L_2}{R_2} = \tfrac{1024}{5.5} \\ D_3 = \tfrac{L_3}{R_3} = \tfrac{512}{5.5} \\ D_4 = \tfrac{L_4}{R_4} = \tfrac{256}{5.5} \end{aligned}\right\} \Rightarrow \begin{cases} D_m = \tfrac{1024}{5.5} \\ m = 2. \end{cases} \quad (18)$$

Hence

$$\begin{cases} N_1 = \frac{D_m}{D_1} \cdot \frac{A_1}{A_m} = 2 \cdot \frac{1/2}{1/4} = 4 \\ N_2 = \frac{D_m}{D_2} \cdot \frac{A_2}{A_m} = 1 \cdot \frac{1/4}{1/4} = 1 \\ N_3 = \frac{D_m}{D_3} \cdot \frac{A_3}{A_m} = 2 \cdot \frac{1/8}{1/4} = 1 \\ N_4 = \frac{D_m}{D_4} \cdot \frac{A_4}{A_m} = 4 \cdot \frac{1/8}{1/4} = 2 \end{cases} \quad (19)$$

and the TXOP limits are

$$\begin{cases} \text{TXOP}_1 = 5.1064 \text{ ms} \\ \text{TXOP}_2 = 2.0342 \text{ ms} \\ \text{TXOP}_3 = 1.2895 \text{ ms} \\ \text{TXOP}_4 = 1.2411 \text{ ms.} \end{cases} \quad (20)$$

2. *Implementation issues:* In order to achieve the desired fairness, the AP needs to (i) collect the associated weights and power factors as well as the transmission-strategy information from all contending stations; (ii) determine the airtime allocation and calculate the corresponding TXOP limits; and (iii) convey the TXOP limits to each station. The wireless stations and the AP may exchange these information with the help of two newly-defined 802.11e elements: the *TSPEC (Traffic Specification)* element and the *EDCA Parameter Set Information* element.

6. Performance evaluation

In this section, we evaluate the effectiveness of our proposed energy-efficient airtime-allocation scheme via simulation.

6.1. Simulation setup

We assume that each 802.11e wireless station is equipped with an 802.11b wireless network interface. Based on the power characteristics of the Cisco Aironet 350 Series Client Adaptor [5], we list the available options for the transmission strategy of the simulated wireless network interface in Table 6. The idle power consumption is 1.35 W and the frame size is 1024 octets unless specified otherwise. In fact, [5] only specifies the total power consumption of the adaptor (2.25 W) at the 20 dBm transmit-power level. We set the total power consumption values at other transmit-power levels by assuming an exponential relation [37–39] between the efficiency of the power amplifier and the transmit-power level of the wireless network interface. Since we are only interested in how the proposed scheme deals with the transmis-

Table 6
Available transmission-strategy options

Option	Transmission Rate (Mbps)	Transmit-power Level (dBm)	Transmit-power Consumption (W)
1	1	20	2.25
2	2	20	2.25
3	5.5	20	2.25
4	11	20	2.25
5	11	17	1.95
6	11	15	1.85
7	11	13	1.75
8	11	7	1.50
9	11	0	1.40

sion-strategy diversity and improves the aggregate throughput and the overall system energy-efficiency, not the exact amount of improvements, those power consumption values have little impact on the conclusions to be drawn in this section. Moreover, we assume that the RTS, CTS, and Ack frames are always transmitted at 1 Mbps with 20 dBm power.

Note that the combinations of low transmission rates (1, 2, or 5.5 Mbps) and low transmit-power levels (17, 15, 13, 7, or 0 dBm) are not listed in Table 6, meaning that they are not viable options for the transmission strategy. This is because, according to our analysis in [17], when a wireless station is moving away from the AP or, in general, when the link condition between a wireless station and the AP gets worse, the station always tries to first increase the transmit power and then, as the transmit power reaches the maximum, switch to lower but more robust transmission rates. Fig. 2 illustrates the relation [7] between a wireless station's transmission strategy and the station-to-AP distance, which we will use in the simulation. For example, this figure reads that, when the station is 40–50 m away from the AP, it transmits at 11 Mbps with 20 dBm power.

We evaluate the following two schemes: (i) 802.11 DCF with which each station contends with the same channel access parameters and is only allowed to transmit one data frame per channel access; and (ii) the proposed energy-efficient airtime-allocation scheme with varying power factor ω from 1.0 to 0.0. They are compared with each other in terms of aggregate system throughput (in Mbps), overall system energy-efficiency (in Mbits/Joule), and fairness. We conduct simulation with different numbers of contending stations and various network topologies. Each simulation run lasts 15 min. Each station transmits in a greedy mode, i.e., its data queue never gets empty.

6.2. Simulation results with two contending stations

In the first part of the simulation, we consider a simple network configuration in which only two stations (STA1 and STA2) contend for the shared wireless medium and communicate with the AP. The associated weights for both stations are $\phi_1 = \phi_2 = 1$. As shown in Fig. 3, STA1 is static and 45 m away from the AP. Hence, according to Fig. 2, STA1 always transmits at 11 Mbps with 20 dBm transmit power. In contrast, STA2 is mobile and moves towards the AP. The starting and ending points are 115 m and 5 m from the AP, respectively. Correspondingly, STA2 adapts its transmission strategy along with its movement, from 1 Mbps rate and 20 dBm power at the starting point, to 20 Mbps rate and 0 dBm power at the ending point.

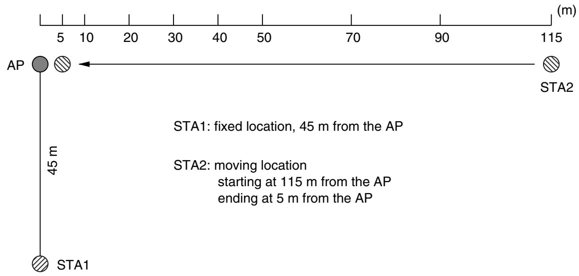

Fig. 3. Two-station network configuration.

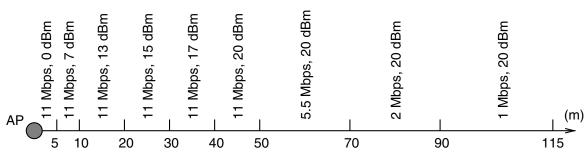

Fig. 2. Relation between a station's transmission strategy and the station-to-AP distance.

We first compare the testing schemes when STA2 is at different distances from the AP. The ratio of two stations' throughput and the aggregate system throughput are plotted in Fig. 4a and b, respectively. The ratio of two stations' energy consumption and the system energy-efficiency are shown in Fig. 4d and e, respectively. Fig. 4c plots the ratio of two stations' airtime shares. In general, as shown in (b) and (e),[3] when STA2 gets closer to the AP, both the aggregate system throughput and the system energy-efficiency improve for all schemes. This is because STA2 can transmit at a higher rate or with a lower power level as it moves closer to the AP. However, different schemes show different increasing patterns determined by their respective design philosophies, which are discussed next.

We make the following four observations. First, the 802.11 DCF (cross points in the figure) achieves the perfect throughput fairness (evidenced by DCF's unity throughput ratio shown in (a)) regardless of the distance between STA2 and the AP. However, since DCF is not designed to handle the transmission-strategy diversity, it yields poor aggregate throughput when STA2 is far away from the AP and transmits at a lower rate than STA1. The resultant airtime-share discrepancy is shown in (c), and we can see that a larger rate difference results in a larger airtime-share discrepancy and hence a lower aggregate throughput.

Second, when $\omega = 1.0$ (plus points in the figure), our scheme allocates airtime shares to STA1 and STA2 in proportion to their associated weights. Since we use $\phi_1 = \phi_2 = 1$ in the simulation, both stations are assigned an equal airtime share (shown in (c)). Airtime fairness guarantees that the throughput of the high-rate STA1 is not affected by the low transmission rate of STA2. As a result, the aggregate system throughput is improved signifi-

[3] In the rest of Section 6, we use (a)–(e) instead of Fig. 4a–e for simplicity and clarity.

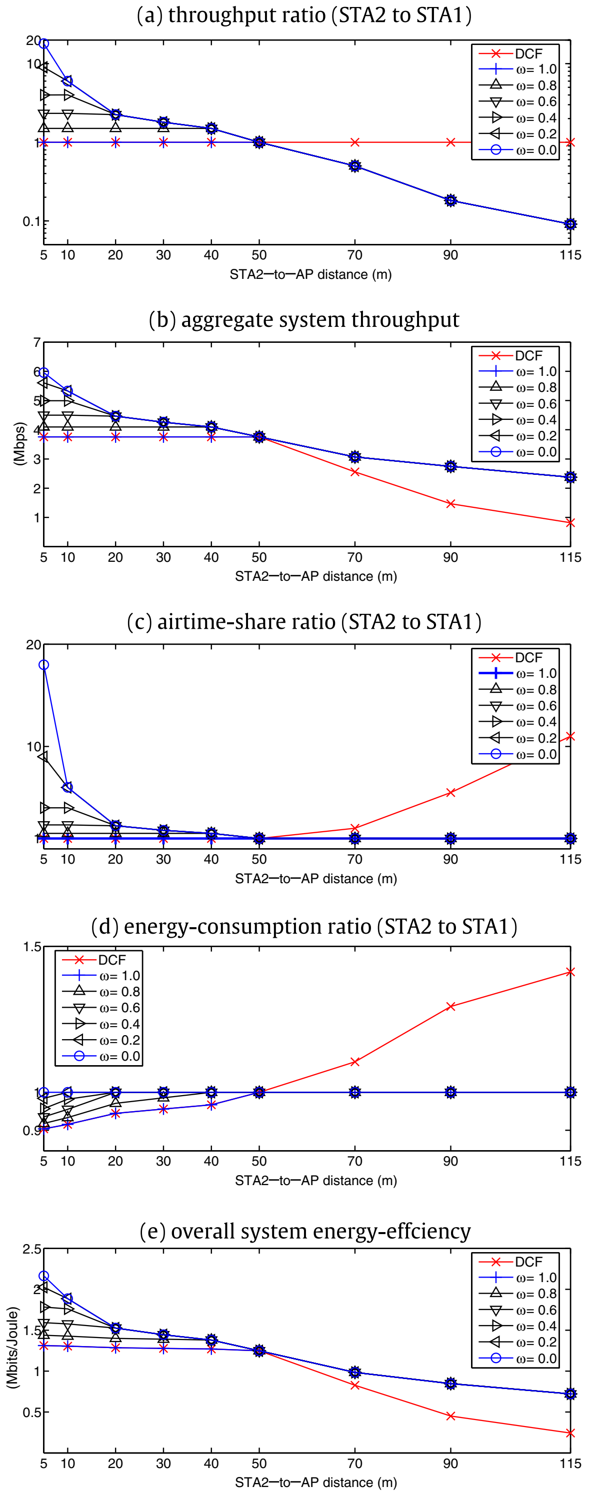

Fig. 4. Comparison for two-station network configuration.

cantly (shown in (b)). In the cases when STA2 moves within 50 m to the AP and transmits at the same 11 Mbps as STA1, airtime fairness is, in fact, equivalent to throughput fairness, which can be clearly seen from the partial overlapping in all performance curves for "$\omega = 1.0$" and "DCF."

Third, when $\omega = 0.0$ (circle points in the figure), our scheme allocates airtime shares to STA1 and STA2 in such a way that the perfect energy-conservation fairness is achieved (refer to its unity energy consumption ratio in (d)). In contrast, since transmit-power information is not considered in either throughput or airtime fairness, unbalanced power consumptions can be observed in (d) for both schemes as STA2 moves close to the AP and starts transmitting at lower power levels than STA1. One key advantage of introducing the energy-conservation fairness is that the system energy-efficiency may be improved significantly. As one can see from (e), the system may deliver about 70% more data per unit of energy consumption than when throughput or airtime fairness is used. This is because, with energy-conservation fairness, more airtime shares are allocated to lower-power stations that typically transmit at higher rates, as explained in Section 6.1 and shown in Fig. 2.

When STA2 is more than 50 m away from the AP, energy-conservation fairness is equivalent to airtime fairness as both stations transmit at the same maximum 20 dBm power level. When STA2 moves within 50 m to the AP and raises its transmission rate to the maximum 11 Mbps, it starts decreasing its transmit power. As a result, STA2 is allocated more airtime share, which results in a larger-than-one airtime-share ratio, and consequently, a larger-than-one throughput ratio.

It is interesting to see that, as STA2 gets closer and closer to the AP from the 50-m radius, the aggregate throughput increases despite the fact that both stations already reach the maximum transmission rate of 11 Mbps. This is surprising at the first sight, but reasonable for the following reason. In our scheme, the desired airtime allocation is achieved by choosing different TXOP limits for different contending stations. So, when STA2 transmits at the same rate but a lower power than STA1, it is assigned a larger TXOP limit that allows transmission of more data frames per medium access, while STA1's TXOP limit only allows transmission of one single data frame per medium access. When both stations transmit at the same rate and the same power level, they will be assigned the same small TXOP limit that only accommodates one data frame transmission. Therefore, there are less and less medium contentions and collisions per unit of time when STA2 moves closer to the AP from the 50-m boundary, which improves the channel utilization and hence the aggregate throughput.

Finally, any ω value between 1.0 and 0.0 represents a compromise between airtime fairness and energy-conservation fairness. In general, their performance curves are between those of "$\omega = 1.0$" and those of "$\omega = 0.0$". Moreover, as we have discussed earlier, all three fairness notions and combinations thereof are equivalent to one another when there is no transmission-strategy diversity in the network. This can be seen from the figure that all the performance curves intersect at the point when STA2 moves to the 50-m boundary and operates with the same transmission strategy as STA1.

Next, we compare the testing schemes over the entire STA2 movement duration and results are plotted in Fig. 5. Clearly, by considering transmission-strategy diversity in fairness, the aggregate system throughput

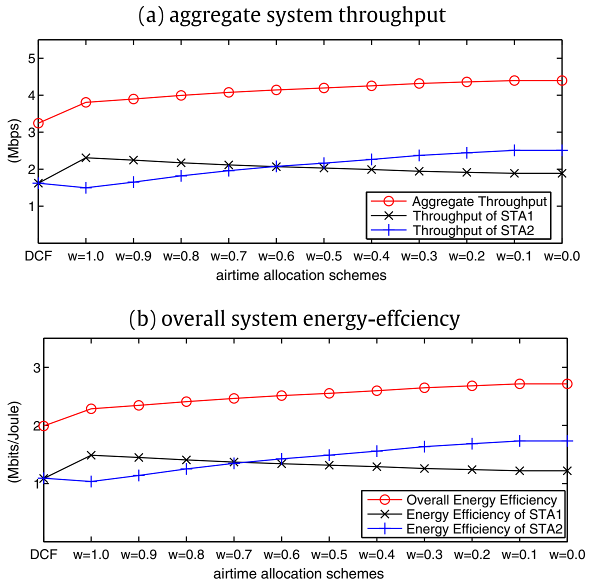

Fig. 5. Comparison for two-station network configuration measured over the entire STA2 movement duration.

and the overall system energy-efficiency are improved significantly.

Let's look at STA2's throughput and energy-efficiency performance, shown as plus points in the figure. One can see that, when energy-conservation fairness is the only concern ($\omega = 1.0$), STA2 performs the best. It is allowed to transmit less and "bank" its energy when it is far away from the AP. Later on, as it moves closer to the AP and the link quality improves, it may use the banked energy more efficiently by transmitting at higher rates and lower power levels. The amount of improvement varies with the network configuration, such as STA2's speed and trajectory, as well as STA1's location. STA1 performs the best in terms of both throughput and energy-efficiency when the airtime fairness is considered. In this case, STA1 is guaranteed its airtime share. With all the other schemes, STA1's airtime share is reduced due to either the low transmission rate of STA2 (with DCF) or the low transmission power level of STA2 (with schemes when $\omega < 1.0$).

6.3. Simulation results with 50 contending stations

In the second part of the simulation, we consider a more realistic scenario where 50 stations are randomly placed within a circle around the AP with a 115-m radius. All stations are static with an equal weight. Results are plotted in Fig. 6 in which each point represents an average over 100 simulation runs.

In Fig. 6a, we compare the three fairness measures of the testing schemes. Obviously, DCF achieves the perfect throughput fairness but performs poorly in terms of airtime and energy-conservation fairness. The perfect airtime fairness is achieved when $\omega = 1.0$, and the power factor of $\omega = 0.0$ yields the best energy-conservation fairness, which all conform to their respective design goals.

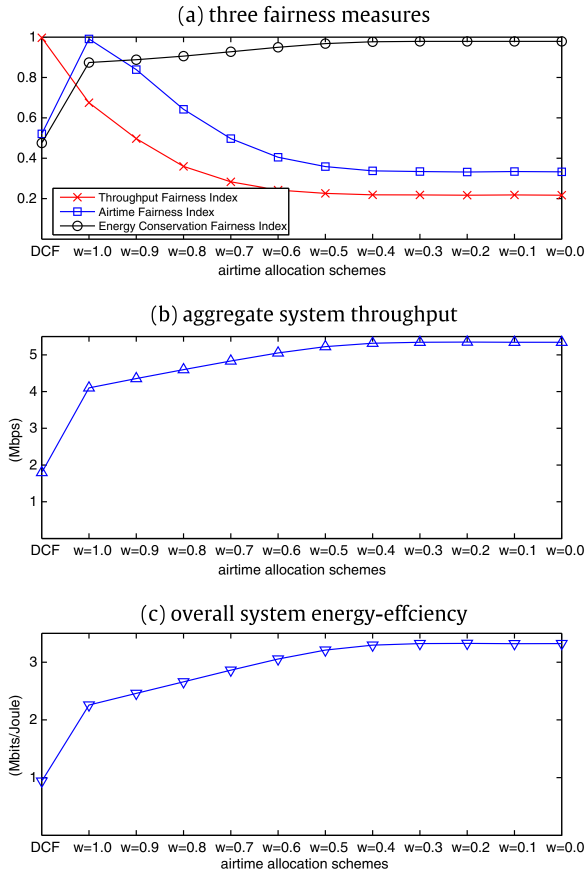

Fig. 6. Comparison for random-topology network configuration.

Energy-conservation fairness improves both the aggregate system throughput and the overall system energy-efficiency significantly, because its airtime allocation is determined by considering both aspects of the transmission-strategy diversity: transmission-rate diversity and transmit-power diversity. In particular, it improves the aggregate system throughput by more than 25% over airtime fairness and more than 2.5 times over the DCF; it improves the energy-efficiency by about 40% over airtime fairness and more than three times over the DCF.

7. Conclusion

In a multi-rate multi-power-level 802.11 WLAN, different wireless stations may communicate with the AP using different transmission rates, different transmit-power levels, and/or with different data payload sizes. This phenomenon is often referred to as *transmission-strategy diversity*. In this paper, we introduce a new fairness notion, called *energy-conservation fairness*, to deal with transmission-strategy diversity, and particularly, transmit-power diversity, in multi-rate multi-power-level 802.11 WLANs. It stresses fair energy consumption by all contending stations in the same network. We also present an energy-efficient airtime-allocation scheme to meet generic fairness requirements that combine airtime fairness with energy-conservation fairness. Our simulation results show that, when the energy-conservation fairness is considered, both aggregate system throughput and overall system energy-efficiency can be improved significantly while all contending stations consume a similar amount of energy.

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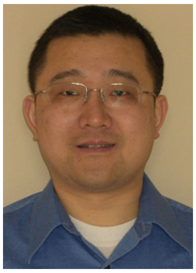

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