Cooperative Relay Service in a Wireless LAN

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***Abstract*— As a family of wireless local area network (WLAN) protocols between physical layer and higher layer protocols, IEEE 802.11 has to accommodate the features and requirements of both ends. However, current practice has addressed the problems of these two layers separately and is far from satisfactory. On one end, due to varying channel conditions, WLANs have to provide multiple physical channel rates to support various signal qualities. A low channel rate station not only suffers low throughput, but also significantly degrades the throughput of other stations. On the other end, the power saving mechanism of 802.11 is ineffective in TCP-based communications, in which the wireless network interface (WNI) has to stay awake to quickly acknowledge senders, and hence, the energy is wasted on channel listening during idle awake time.**

In this paper, considering the needs of both ends, we utilize the idle communication power of the WNI to provide a Cooperative Relay Service (CRS) for WLANs with multiple channel rates. We characterize energy efficiency as energy per bit, instead of energy per second. In CRS, a high channel rate station relays data frames as a proxy between its neighboring stations with low channel rates and the Access Point, improving their throughput and energy efficiency. Different from traditional relaying approaches, CRS compensates a proxy for the energy consumed in data forwarding. The proxy obtains additional channel access time from its clients, leading to the increase of its own throughput without compromising its energy efficiency. Extensive experiments are conducted through a prototype implementation and ns-2 simulations to evaluate our proposed CRS. The experimental results show that CRS achieves significant performance improvements for both low and high channel rate stations.

***Index Terms*— Wireless LAN, Cooperation, Idle Communication Power, Energy Efficiency**

I. INTRODUCTION

MOBILE devices are usually driven by battery power. Due to limited battery capacity, it is essential to reduce power consumption of mobile devices without degrading their performance. In mobile communications, wireless network interfaces (WNIs) consume a significant portion of energy. For instance, the energy consumed by WNIs can account for more than 50% of the energy consumption in handheld computers and up to 10% in laptop computers [8], [16]. As shown in [20], the energy consumption of a WNI is dominated by its idle time, instead of the amount of transferred data. To save energy in wireless devices, the basic principle is to put the WNI into sleep mode when it is idle, e.g., IEEE 802.11 power saving mechanism [6]. Nonetheless, due to the overhead of mode switch and lagged data reception, frequent waking up and sleeping of a WNI may result in serious performance degradation and may even increase the overall energy consumption in a mobile device. Furthermore, to improve throughput and reduce response time of a wireless client, its WNI should always stay awake in a TCP session to quickly acknowledge the sender. The reason is that the switch to sleep mode, which induces delayed ACK sending on the client side and exaggerated estimation of round-trip-time (RTT) on the server side, will adversely affect TCP throughput [15]. Similarly, for UDP-based applications, a WNI has to be always active during iterative or recursive RPC calls, such as directory listing in NFS [8]. As a result, a significant portion of power is wasted on channel listening, which we call the *idle communication power* of a station.

In addition to battery power, mobile devices are very susceptible to physical signal quality degradation caused by noise, fading, attenuation, and interference. Due to varying channel conditions, wireless local area networks (WLANs) have to provide multiple data channel rates to support various signal qualities, such as IEEE 802.11a/g (6-54 Mbps, 8 levels) and IEEE 802.11b (1-11 Mbps, 4 levels). The basic IEEE 802.11 channel access method, Distributed Coordination Function (DCF), provides an equal opportunity for channel contention among all stations. Since a low channel rate station takes a much longer time to receive or transmit a data frame, it occupies a longer channel access time and penalizes stations with high channel rates. Therefore, low channel rate stations not only suffer low throughput themselves, but also significantly degrade throughput of other stations, and thus that of the entire WLAN [11]. To address this performance anomaly in multi-rate WLANs, a time-based fairness channel access method has been proposed, in which each station is allotted an equal fraction of channel occupation time, regardless of its channel rate [21]. However, while the time-based scheme protects high channel rate stations from unfair performance degradation, it aggravates the throughput of stations with low channel rates.

In this paper, we utilize the idle communication power of the WNI to provide a *Cooperative Relay Service* (CRS) for multi-rate WLANs, where mobile stations in a WLAN cooperatively form a local relay network to avoid possible low channel rate transmissions. This cooperation improves the per-node and aggregate performance in a WLAN, in terms of both throughput and energy utilization. The rationale behind this cooperation is based on the understanding of *energy efficiency*

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in wireless communications. Instead of simply measuring the energy consumed on a WNI per second (i.e., power consumption), we characterize the energy efficiency during a communication session as *energy per bit*. This metric reflects the actual performance demands that users care about, because the WNI of a station can be put into sleep mode when it has no network workload. In CRS, a high channel rate station relays data frames as a proxy between its neighboring stations with low channel rates and the Access Point, when it is idle for listening to new data arrivals. Thus, the throughput and energy efficiency of its clients can be significantly improved. Meanwhile, since the proxy's WNI still consumes energy when it is idle, the extra energy consumed on data forwarding is moderate and can be compensated by its clients. Under the condition of time-based fairness, the proxy obtains additional channel occupancy time from its clients, resulting in an increase of its own throughput without degrading its energy efficiency. With such an incentive mechanism, the forwarding service is *profitable* and thus becomes a resource that stations want to *compete* for, which is different from previous multi-hop routing algorithms in ad hoc networks. Through the trade between channel access time and channel transmission rate of mobile stations, this cooperation yields mutual performance gains for both the proxy and its clients.

We analyze the performance gains of proxies and clients in CRS through a mathematical model. The analytical results give theoretical bounds of performance gains under different circumstances. Guided by the theoretical results, we elaborate our system design, which consists of three components working in the data link layer: (1) an auction-based proxy selection algorithm to choose relay stations for low channel rate clients; (2) a multi-hop forwarding algorithm to coordinate intermediate stations along a forwarding path; (3) a token-based, energy-aware channel allocation algorithm to provide channel occupancy time compensation to proxy stations under time-based fairness and max-min fairness. This cooperation layer, albeit thin, is powerful in accommodating the diverse channel rate distribution incurred by the spatial location and other physical configurations.

To evaluate our proposed Cooperative Relay Service, we implement a prototype of CRS and conduct extensive experiments on our testbed composed of a desktop and six laptops. We also perform simulations using ns-2 with both real and synthetic Web workloads, in order to investigate how CRS works in a more generic environment and with a larger number of mobile stations. Our results show that by integrating the proxy forwarding and channel time compensation mechanisms, high channel rate stations (proxies) not only significantly improve the network performance and energy efficiency of low channel rate stations (clients), but also remarkably increase their own throughput and the aggregate throughput of the entire WLAN, without compromising their energy efficiency. Compared with the time-based fairness scheme, the client and proxy throughput can be improved by 138% and by 23%, respectively, and the aggregate throughput of the entire WLAN can be improved by 79%.

The remainder of this paper is organized as follows. Section II surveys related work. Section III describes our system model and performance metrics. Section IV analyzes the channel time allocation and compensation mechanisms of CRS with a mathematical model. Section VI details our system design. We evaluate the performance of CRS in Section VI and make concluding remarks in Section VII.

II. RELATED WORK

Most current WLANs support multiple channel rates for mobile stations with different signal qualities. In outdoor WLANs, radio signal strength attenuates rapidly with the increase of propagation distance. For indoor environments, studies [14], [21] have shown that rate diversity is prevalent in many WLANs and exists even in a small room, because of the diversity of signal quality caused by noise, interference, multi-path, and user mobility. Even the signal quality of two stations that are equidistant from the access point may be significantly different. In [21], the authors also showed that wireless channels are often saturated due to channel contention among different users. Furthermore, in measurement study [13], Jardosh et al. found that in a congested 802.11b WLAN, the number of frame transmissions at 1 Mbps and 11 Mbps are high for all congestion levels, because current rate adaptation mechanisms of 802.11b wireless devices seldom use the 2 Mbps and 5.5 Mbps data rates, which makes the channel utilization even worse.

In study [11], Heusse et al. identified a performance anomaly in 802.11b that supports four different channel rates. A mobile station transmitting at 1 Mbps degrades the throughput of stations with high channel rates (e.g., 11 Mbps) down below 1 Mbps. The main reason is that a mobile station with lower channel rate takes much longer time to transmit or receive a data frame, and hence, it occupies much more channel time than higher channel rate stations.

To address this anomaly, Tan and Guttag proposed a time-based fairness scheduling algorithm in multi-rate WLANs [21]. In their algorithm, channel access time is equally allocated among all stations with different channel rates. Thus, high channel rate stations are shielded from throughput degradation, but the performance of low channel rate stations is decreased.

IEEE 802.11 supports a power saving mechanism [6]. When a mobile station has no communication workload, it may switch to power saving mode and notify the Access Point to buffer incoming data for it during its sleeping time. In 802.11 WLANs, the Access Point periodically broadcasts beacon frames so that mobile stations can synchronize their clocks. In each beacon frame, the Access Point also transmits a *traffic indication map*, which contains a list of sleeping stations that have data frames buffered at the Access Point. A station in power saving mode periodically wakes up and listens to the beacon frame. If there are data frames buffered at the Access Point for it, the station polls the Access Point, and then the Access Point transmits the data frames to this station. Afterwards the station returns to sleep mode again.

IEEE 802.11 power saving mode may significantly degrade the performance of network communications. For TCP-based communications, the round-trip-time (RTT) of a TCP connection in 802.11 power saving mode is increased by up to a beacon interval (about 100 ms), which is much greater than a typical end-to-end RTT over the Internet. As a result, the throughput of TCP is significantly decreased. In [15], the authors demonstrated the performance degradation of Web accesses caused by power saving mode, and proposed a bounded slowdown protocol to resolve the problem by adapting the sleep and awake durations based on the prediction of network activities. For UDP-based communications, Anand et al. [8] have shown the performance degradation of RPC calls caused by power saving mode, and presented a self-tuning power management approach to adapting the behavior of a station's WNI to the access pattern and intent of its applications. These solutions are orthogonal to our scheme, and can be integrated with CRS for better network performance and power savings.

Exploiting spatial reuse in cellular networks, Hsieh and Sivakumar [12] have studied multi-hop ad hoc models to improve network throughput and reduce energy consumption for stations with poor signal qualities. However, spatial reuse is infeasible in WLANs due to the channel overlapping problem. In [18], Luo et al. proposed a unified cellular and ad-hoc network architecture, using both a 3G cellular network interface and an 802.11 network interface. In [22], a relay-enabled MAC protocol is proposed for ad hoc networks. In [17], the authors proposed a multi-hop WLAN architecture and demonstrated its benefits to wireless clients. However, none of these solutions can provide effective incentive mechanisms to encourage stations to relay data for other stations. In contrast, our CRS approach quantitatively compensates proxy stations by rewarding them with additional channel occupancy time, and thus improves their throughput without compromising their energy efficiency.

III. SYSTEM MODEL AND PERFORMANCE METRICS

The system model and related notations are described as follows. The WLAN in consideration is composed of an *Access Point* (*AP*), S_0, and n ($n \geq 2$) *mobile stations*, $S_1, S_2, ..., S_n$. The radio channel is shared by all stations and the Access Point. Two stations S_i and S_j can communicate with each other at a channel rate $R_{i,j}$ ($i \neq j$ and $0 \leq i, j \leq n$). Specifically, each station S_i ($1 \leq i \leq n$) can communicate with the AP with channel rate $R_{0,i}$, and we denote $R_{0,i}$ as R_i for simplicity. Assume the fraction of channel occupancy time allocated to station S_i is t_i, in which the fraction for data transmission is f_i ($0 \leq f_i \leq 1$). In time-based fairness scheduling [21], each station is assigned the same fraction of channel time. Thus, $t_i = \Delta t = \frac{1}{n}$ ($1 \leq i \leq n$), and we also have the bound $0 < t_i \leq \frac{1}{2}$.

Let P_t be the power consumption (energy per second) of a station's WPI in the transmission mode, and P_r be the power consumption of a station's WPI in the listening or data receiving mode. Assume $P_t = \alpha P_r$ ($\alpha > 1$) [1]. Although the working power of a WNI reflects the energy consumption over time, it is inadequate to characterize the efficiency of a station's energy utilization for data delivery. A continuous data transmission of a station gives us an illusion that users care about the energy consumption per unit time. However, in reality the WNI can be put into sleep mode or turned off when there is no communication workload, and hence, users essentially care more about the energy consumption per unit data. Here, we define two performance metrics for a mobile station as follows:

- *Throughput*, $T(S_i)$, the total number of effective bits a station transmits and receives per unit time [2];
- *Energy utility*, $E(S_i)$, the average number of effective bits per unit energy. That is, $E(S_i) = \frac{T(S_i)}{P(S_i)}$.

According to the assumptions of our model, we have

$$\begin{cases} P(S_i) &= P_t t_i f_i + P_r(1 - t_i f_i) \\ &= P_r(1 + (\alpha - 1)t_i f_i), \\ T(S_i) &= R_i t_i, \\ E(S_i) &= \frac{1}{(\alpha-1)f_i + \frac{1}{t_i}} \frac{R_i}{P_r}, \end{cases} \tag{1}$$

where $1 \leq i \leq n$.

A mobile station can improve its throughput either by obtaining more time slots for its own communication or by increasing the channel rate at which its data are transmitted. To save energy, the station should reduce the energy cost of every effective bit or increase the energy utility, and turn off or sleep the WNI when a communication session terminates. In CRS, the allotted time of a station with low channel rate can be traded for a higher throughput and a higher energy utility. The solution is to recruit mobile stations with high channel rates as proxies to harvest their idle time and forward data frames for the stations with low channel rates. If a high channel rate station obtains extra time slots from low channel rate stations, and a low channel rate station increases its data transmission rate through a high channel-rate path relayed by high channel rate stations; then it will be a *win-win* scenario.

To encourage a high channel rate station to relay data for a low channel rate station, its energy utility should not be reduced. In CRS, a proxy station uses the bonus time slots contributed by its clients for its own communication, leading to the increase of its throughput and the decrease of its WNI working time. As a result, although the proxy station spends extra energy for the data forwarding, its energy utility can remain intact or even increase. We define the performance gains of this cooperative relay scheme for a station S_i relative to the basic time-based fairness scheme, in terms of throughput and energy utility as follows:

$$\begin{cases} g_T(S_i) &= \frac{T'(S_i)}{T(S_i)}, \\ g_E(S_i) &= \frac{E'(S_i)}{E(S_i)}, \end{cases} \tag{2}$$

where $T(S_i)$, $E(S_i)$ and $T'(S_i)$, $E'(S_i)$ are the throughput and energy utility of a station S_i before and after the relay service it provides/receives, respectively. Table I lists the notations used in this paper.

IV. CHANNEL TIME ALLOCATION AND COMPENSATION

In this section, we analyze the allocation of channel time in CRS and the compensation mechanism for supporting data

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[1] A WNI can work in three modes with different power consumption levels: transmission, receiving/listening, and sleep modes. The power consumption of transmission mode is usually much higher than that of receiving/listening mode. For example, the typical current intensity of Cisco Aironet 350 series WNIs is 450 mA at transmission mode, 270 mA at receiving/listening mode, and 15 mA at sleep mode (all under 5V DC), respectively [1].

[2] The bits for MAC level retransmission and the forwarding data for other stations are not counted as effective bits.

TABLE I
SYMBOLS AND NOTATIONS

Symbol	Meaning and Unit
P_t	power consumption of WNI in transmission mode (Joule/sec)
P_r	power consumption of WNI in listening/receiving mode (Joule/sec)
α	P_t/P_r, $\alpha > 1$
$P(S_i)$	power consumption of station S_i (Joule/sec)
$T(S_i)$	throughput of station S_i (bit/sec)
$E(S_i)$	energy utility of station S_i (bit/Joule)
$R_{i,j}$	the channel rate between station S_i and S_j (bit/sec)
t_i	the fraction of channel time allocated to S_i
f_i	the fraction of outgoing traffic in S_i's workload
$x^i_{j,k}$	the fraction of channel time during which the traffic of S_i is forwarded between S_j and S_k
y^i_j	the fraction of channel time that S_i rewards S_j
$U(S_i)$	utilization of allocated time of station S_i
$g^0_T(S_i)$	the throughput gain when S_i has no clients
$g^0_E(S_i)$	the energy utility gain when S_i has no clients
$g_T(S_i)$	the throughput gain of S_i
$g_E(S_i)$	the energy utility gain of S_i

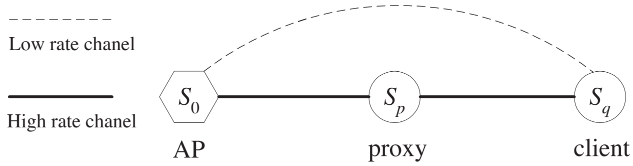

Fig. 1. S_p forwards data for S_q

forwarding. More specifically, how much time a low rate station has to offer the high rate station for the forwarding service so that the latter will not be penalized. We analyze a simple one-hop case first, and then extend the one-hop relay to the general case of multi-hop relay.

A. Channel Occupancy Time Allocation

Assuming that the time-based fairness scheduling is enabled, each station is assigned an equal fraction of channel time in units of time slot. In such a WLAN, a station S_p that can communicate with AP at a high channel rate can work as the *proxy station* for a station S_q that can only communicate with AP at a low channel rate, as long as S_p and S_q can communicate at a high channel rate with each other, as shown in Figure 1. To enable such a service, the time slots used for data forwarding should come from the time slots of the *client stations*. Meanwhile, since transmitting data for clients consumes its energy, the proxy station should be rewarded additional time slots from its client stations for compensation. We define the fraction of channel time that a client S_q rewards its proxy S_p to keep the energy utility of S_p unchanged as the *cost price* (or valuation) of the forwarding service, denoted as $cost(p,q)$.

We define the fraction of channel time that a station is assigned under time-based fairness as the *assigned time* of the station, and the fraction of channel time that a station can use for its own communication as the *effective time* of the station. We also define the fraction of channel time that a client rewards each of its proxies as its *rewarding time* to the proxy or the *rewarded time* of that proxy. The effective time of a proxy is its assigned time plus all rewarded time from its clients. The effective time of a client is its assigned time subtracting the fraction of channel time it rewards its proxies and the fraction of channel time for its data relaying (transmitting or receiving) along the path from the AP and its immediate proxy (*relaying time*).

We further define the sum of a station's assigned time under time-based fairness and its rewarded time from its clients as the *allocated time* of the station, which can be used for its own communication or to reward its proxies. Therefore, we define the *utilization of the allocated time* of a station S_i, $U(S_i)$, as the ratio of its effective time to its allocated time.

B. Performance Gain Analysis for One-hop Relay

First, we consider one client and one proxy for simplicity. Assume client station S_q is relayed by proxy station S_p. The assigned time of S_q should be divided into three pieces:

$$t_q = \Delta t = x_{0,p} + x_{p,q} + y^q_p, \tag{3}$$

where $x_{0,p}$ is the fraction of channel time used for data relaying between AP (S_0) and proxy station S_p (relaying time), $x_{p,q}$ is the fraction of channel time that client station S_q is transmitting/receiving data to the proxy station (effective time), and y^q_p is the fraction of channel time that the client station compensates S_p (rewarding time). The utilization of S_q's allocated time is $U(S_q) = \frac{x_{p,q}}{\Delta t}$.

The effective time of S_p is

$$t'_p = t_p + y^q_p = \Delta t + y^q_p, \tag{4}$$

where t_p is its assigned time and y^q_p is its rewarded time from client S_q. The utilization of S_p's allocated time is 1 since it can use all its assigned time and rewarded time for its own communication. Figure 2 shows the channel time allocation in one-hop proxy forwarding.

Lemma 1: In one-hop forwarding, the allocated time utilization, rewarding time, throughput gain and energy utility gain of a client S_q when it pays the cost price to its proxy S_p

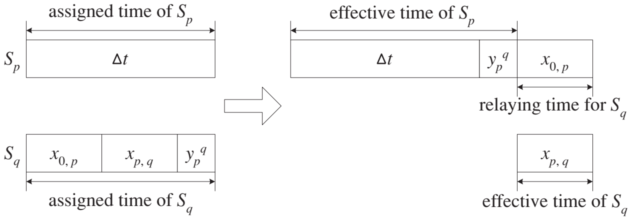

Fig. 2. Channel time allocation

for the forwarding service are

$$\begin{cases} U(S_q) & = & \frac{R_{0,p}}{R_{0,p}+R_{p,q}+(\alpha-1)\Delta t[f_q R_{p,q}+(1-f_q)R_{0,p}]}, \\ y_p^q & = & (\Delta t)^2 U(S_q) R_{p,q}(\alpha-1)(\frac{f_q}{R_{0,p}}+\frac{1-f_q}{R_{p,q}}), \\ g_T(S_q) & = & \frac{R_{p,q}}{R_{0,q}} U(S_q), \\ g_E(S_q) & = & \frac{R_{p,q}}{R_{0,q}} U(S_q) \frac{(\alpha-1)\Delta t f_q+1}{U(S_q)(\alpha-1)\Delta t f_q+1}. \end{cases}$$

Proof: Two constraints dictate how much time a low rate station has to offer to a high rate station: (1) every client station allocates sufficient time for the transmission and forwarding of its data; (2) the energy utility of the high rate station remains the same.

First, we have

$$T'(S_q) = x_{0,p} R_{0,p} = x_{p,q} R_{p,q}, \tag{5}$$

which implies that the flow rate in each hop along the forwarding path of client S_q are equal.

Second, the energy utility of the proxy is unchanged, that is, the cost price of S_p serving S_q is the rewarding time of S_q to keep the energy utility of S_p unchanged

$$E(S_p) = E'(S_p). \tag{6}$$

Equation 1 gives the power consumption, throughput and energy utility of S_p when it has no clients. Denote the power consumption, throughput and energy utility of S_p when S_p serves client S_q as $P'(S_p)$, $T'(S_p)$, and $E'(S_p)$, respectively, we have

$$\begin{cases} P'(S_p) & = & P_r(1+(\alpha-1)t_p^f), \\ T'(S_p) & = & R(S_p)(\Delta t + y_p^q), \\ E'(S_p) & = & \frac{P'(S_p)}{T'(S_p)}, \end{cases} \tag{7}$$

where $t_p^f = f_p(\Delta t + y_p^q) + f_q x_{0,p} + (1-f_q)x_{p,q}$ is the total time of proxy S_p used for data transmission. In t_p^f, $f_p(\Delta t + y_p^q)$ is the time that S_p transmits its own upstream workload to AP, $f_q x_{0,p}$ is the time that S_p forwards the upstream workload of S_q to AP, and $x_{p,q}$ is the time that S_p forwards the downstream workload of S_q to S_q.

Resolving Equations 3, 5, and 6, we have

$$\begin{cases} T'(S_q) & = & \frac{\Delta t}{\frac{1}{R_{0,p}}+\frac{1}{R_{p,q}}+(\alpha-1)\Delta t(\frac{f_q}{R_{0,p}}+\frac{1-f_q}{R_{p,q}})}, \\ U(S_q) & = & \frac{x_{p,q}}{\Delta t} = \frac{T'(S_q)}{R_{p,q}\Delta t} \\ & = & \frac{R_{0,p}}{R_{0,p}+R_{p,q}+(\alpha-1)\Delta t[f_q R_{p,q}+(1-f_q)R_{0,p}]}, \\ y_p^q & = & t_p(\alpha-1)(f_q x_{0,p}+(1-f_q)x_{p,q}) \\ & = & \Delta t(\alpha-1)T'(S_q)(\frac{f_q}{R_{0,p}}+\frac{1-f_q}{R_{p,q}}), \end{cases} \tag{8}$$

where $y_p^q = cost(p,q)$. According to Equation 2, for client station S_q, we have

$$\begin{cases} g_T(S_q) & = & \frac{R_{p,q}}{R_{0,q}} U(S_q), \\ g_E(S_q) & = & \frac{R_{p,q}}{R_{0,q}} U(S_q) \frac{(\alpha-1)\Delta t f_q+1}{U(S_q)(\alpha-1)\Delta t f_q+1}. \end{cases} \tag{9}$$

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$U(S_q)$ and $g_T(S_q)$ increase with the increase in the number of stations (the decrease of Δt) in the WLAN. We have $U(S_q) < \frac{R_{p,q}}{R_{0,p}+R_{p,q}}$ and $g_T(S_q) < \frac{R_{p,q}}{R_{0,q}} \frac{R_{p,q}}{R_{0,p}+R_{p,q}}$. Relaying is only useful when the throughput gain $g_T(S_q) > 1$. Since $U(S_q) < 1$, $f_q \geq 0$, by examining Equation 9, we have $g_E(S_q) \geq g_T(S_q)$. That is, relaying can always increase the energy utility of a client station as long as its throughput can be improved.

For a special case when $R_{0,p} = R_{p,q}$, we have

$$\begin{cases} y_p^q & = & \frac{(\alpha-1)\Delta t^2}{2+(\alpha-1)\Delta t}, \quad 0 < y_p^q \leq \frac{1}{2(\alpha+3)}, \\ T'(S_q) & = & \frac{\Delta t R_{0,p}}{2+(\alpha-1)\Delta t}, \quad 0 < T'(S_q) \leq \frac{R_{0,p}}{\alpha+3}, \\ U(S_q) & = & \frac{1}{2+(\alpha-1)\Delta t}, \quad \frac{2}{\alpha+3} \leq U(S_q) < \frac{1}{2}, \\ g_T(S_q) & = & \frac{1}{2+(\alpha-1)\Delta t} \frac{R_{0,p}}{R_{0,q}}, \\ & & \frac{2}{\alpha+3} \frac{R_{0,p}}{R_{0,q}} \leq g_T(S_q) < \frac{1}{2} \frac{R_{0,p}}{R_{0,q}}, \\ g_E(S_q) & = & \frac{1+(\alpha-1)\Delta t f_q}{2+(\alpha-1)\Delta t(1+f_q)} \frac{R_{0,p}}{R_{0,q}}. \end{cases} \tag{10}$$

A proxy station can serve multiple clients at the same time, and these client stations may have different channel rates and different data transmitting/receiving ratios. We have the following lemma.

Lemma 2: Assume station S_p provides forwarding services to k client stations, $S_{q_1}, S_{q_2}, ..., S_{q_k}$ $(k > 1)$, and these client stations independently contribute their rewarding time to S_p to keep the energy utility of S_p unchanged, we have

$$\begin{cases} U(S_p) & = & 1, \\ g_T(S_p) & = & 1+(\alpha-1)\sum_{i=1}^{k} T'(S_{q_i})(\frac{f_{q_i}}{R_{0,p}}+\frac{1-f_{q_i}}{R_{p,q_i}}), \\ g_E(S_p) & = & 1, \end{cases}$$

where $T'(S_{q_i})$ is the throughput of client $S_{q_i}(1 \leq i \leq k)$ when the forwarding service is on.

Proof: It is easy to see that $U(S_p) = 1$ and $g_E(S_p) = 1$. Since each client rewards S_p independently, similar to the last formula in Equation 8, we have

$$\begin{aligned} \frac{1}{t_p} & = \frac{(\alpha-1)(f_{q_1}x_{0,p}+(1-f_{q_1})x_{p,q_1})}{y_p^{q_1}} \\ & = ... \\ & = \frac{(\alpha-1)(f_{q_k}x_{0,p}+(1-f_{q_k})x_{p,q_k})}{y_p^{q_k}}, \\ \frac{1}{t_p} & = \frac{1+(\alpha-1)\sum_{i=1}^{k}(f_{q_i}x_{0,p}+(1-f_{q_i})x_{p,q_i})}{t_p+\sum_{i=1}^{k} y_p^{q_i}}. \end{aligned}$$

The effective time of S_p is $t'_p = t_p + \sum_{i=1}^{k} y_p^{q_i}$. Thus, we have

$$\begin{aligned} g_T(S_p) & = \frac{T'(S_p)}{T(S_p)} = \frac{t'_p}{t_p} = 1 + \frac{\sum_{i=1}^{k} y_p^{q_i}}{t_p} \\ & = 1+(\alpha-1)\sum_{i=1}^{k} T'(S_{q_i})(\frac{f_{q_i}}{R_{0,p}}+\frac{1-f_{q_i}}{R_{p,q_i}}). \end{aligned}$$

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In case $R_{0,p} = R_{p,q_i}$ $(1 \leq i \leq k)$, we have

$$g_T(S_p) = 1+(\alpha-1)\frac{k\Delta t}{2+(\alpha-1)\Delta t}. \tag{11}$$

Since $k\Delta t = \frac{k}{n} < 1$, $g_T(S_p)$ is bounded by

$$1 < g_T(S_p) < \frac{\alpha+1}{2}. \tag{12}$$

C. A Generic Analysis for Channel Allocation in Multi-hop Forwarding

A station S_i that is relayed by other stations can still work as the proxy for stations with even lower channel rates, and gets rewarded time from its clients. However, only a fraction of its rewarded time can be used for its own communication, since S_i also needs to reward its relaying stations. We consider the relay chain $S_0 \rightarrow S_1 \rightarrow \cdots \rightarrow S_{i-1} \rightarrow S_i$ starting from the AP (S_0). In order for S_1 to relay data for S_2, S_1 has to keep its energy utility unchanged. After S_1 decides to relay data for S_2, S_2 will have a higher energy utility than before. S_2 would like to keep this new energy utility unchanged when it decides to relay for S_3, and so on. The following Lemma describes the performance gain of a station in such scenarios. The proof basically formalizes the above process.

Denote the throughput gain and energy utility gain when S_i has no clients as $g_T^0(S_i)$ and $g_E^0(S_i)$, respectively. We have the following lemma.

Lemma 3: Assume each station has at most one immediate relaying station in a WLAN, and each station rewards its relaying stations independently to keep their energy utilities unchanged. For station S_i that is relayed by $i-1$ ($i \geq 1$) stations along the path $S_0 \rightarrow S_1 \rightarrow ... \rightarrow S_{i-1} \rightarrow S_i$, and S_i has m_i indirect or direct clients ($S_{q_1}, S_{q_2}, ..., S_{q_{m_i}}$), we have

$$\begin{cases} g_T^0(S_i) &= \frac{R_{i-1,i}}{R_{0,i}} U(S_i), \\ g_E^0(S_i) &= \frac{R_{i-1,i}}{R_{0,i}} U(S_i) \frac{(\alpha-1)\Delta t f_i + 1}{U(S_i)(\alpha-1)\Delta t f_i + 1}, \end{cases}$$

where $U(S_i) = \frac{1}{1+R_{i-1,i}\sum_{j=1}^{i-1}[\frac{1}{R_{j-1,j}} + (\alpha-1)\Delta t(\frac{f_i}{R_{j-1,j}} + \frac{1-f_i}{R_{j,j+1}})]}$, and

$$\begin{cases} g_T(S_i) &= g_T^0(S_i)(1 + \frac{\sum_{j=1}^{m_i} y_i^{q_j}}{\Delta t}) & i \geq 1, \\ g_E(S_i) &= g_E^0(S_i) & i \geq 1, \end{cases}$$

where $y_i^{q_j} = \Delta t(\alpha-1)T'(S_{q_j})(\frac{f_{q_j}}{R_{i-1,i}} + \frac{1-f_{q_j}}{R_{i,i_j}})$, $T'(S_{q_j})$ is the throughput of S_{q_j} when it is forwarded by S_i, and S_{i_j} is the next hop station of S_i to reach S_{q_j}.

Proof: For station S_i ($i > 1$) that is relayed by stations $S_1, ..., S_{i-1}$, we have

$$t_i = (x_{0,1}^i + ... + x_{i-2,i-1}^i) + x_{i-1,i}^i + (y_1^i + ... + y_{i-1}^i). \tag{13}$$

The flow rate of S_i's own traffic in each hop along the forwarding path is equal, so we have

$$T'(S_i) = x_{0,1}^i R_{0,1} = ... = x_{i-2,i-1}^i R_{i-2,i-1} = x_{i-1,i}^i R_{i-1,i}. \tag{14}$$

For a relaying station of S_i, S_j ($0 < j < i$), when S_j has no clients, we have

$$\begin{cases} P(S_j) &= P_t \Delta t f_j U(S_j) + P_r(1-\Delta t f_j) \\ &= P_r[1 + (\alpha-1)\Delta t f_j U(S_j)], \\ T(S_j) &= R(S_j)\Delta t U(S_j), \end{cases} \tag{15}$$

where $U(S_j) = 1$ when S_j has no proxy ($j = 1$), and $U(S_j) < 1$ when S_j is relayed by other stations ($1 < j < i$). When S_j serves station $S_{j+1}, ..., S_i$, we have

$$\begin{cases} P'(S_j) &= P_r[1 + (\alpha-1)t_j^f], \\ T'(S_j) &= R(S_j)(\Delta t + \sum_{l=j+1}^{i} y_l^j)U(S_j), \end{cases} \tag{16}$$

where $t_j^f = f_j(\Delta t + \sum_{l=j+1}^{i} y_l^j)U(S_j) + \sum_{l=j+1}^{i} f_l x_{j-1,j}^l + \sum_{l=j+1}^{i}(1-f_l)x_{j,j+1}^l$. In t_j^f, $f_j(\Delta t + \sum_{l=j+1}^{i} y_l^j)U(S_j)$ is the time used by S_j to transmit its own workload to S_{j-1}, $f_l x_{j-1,j}^l$ is the time used by S_j to transmit the upstream workload of S_l to S_{j-1}, and $(1-f_l)x_{j,j+1}^l$ is the time used by S_j to transmit the downstream workload of S_l to S_{j+1}.

Considering the energy utility of S_j, we have

$$\begin{cases} E(S_j) &= \frac{R(S_j)}{P_r} \frac{\Delta t U(S_j)}{1+(\alpha-1)\Delta t f_j U(S_j)}, \\ E'(S_j) &= \frac{R(S_j)}{P_r} \frac{(\Delta t + \sum_{l=j+1}^{i} y_l^j)U(S_j)}{1+(\alpha-1)t_j^f}. \end{cases}$$

The energy utility of S_j should be unchanged, that is, $E(S_j) = E'(S_j)$. By substituting $E(S_j)$ and $E'(S_j)$, we have

$$(\alpha-1)f_j + \frac{1}{\Delta t U(S_j)} = (\alpha-1)f_j + \frac{1 + (\alpha-1)\sum_{l=j+1}^{i}(f_l x_{j-1,j}^l + (1-f_l)x_{j,j+1}^l)}{(\Delta t + \sum_{l=j+1}^{i} y_l^j)U(S_j)}.$$

Simplifying the above equation, we have

$$\frac{1}{\Delta t} = \frac{(\alpha-1)\sum_{l=j+1}^{i}(f_l x_{j-1,j}^l + (1-f_l)x_{j,j+1}^l)}{\sum_{l=j+1}^{i} y_l^j}.$$

Since each station S_l ($j+1 \leq l \leq i$) rewards time slots to S_j independently, we get

$$\frac{1}{\Delta t} = \frac{(\alpha-1)(f_l x_{j-1,j}^l + (1-f_l)x_{j,j+1}^l)}{y_l^j}.$$

Thus, we have

$$\begin{aligned} y_l^j &= \Delta t(\alpha-1)(f_l x_{j-1,j}^l + (1-f_l)x_{j,j+1}^l) \\ &= \Delta t(\alpha-1)T'(S_l)(\frac{f_l}{R_{j-1,j}} + \frac{1-f_l}{R_{j,j+1}}), \end{aligned} \tag{17}$$

where $T'(S_l)$ is the throughput of S_l when it is served by S_j and $T'(S_l) = R_{l-1,l} \times t_l U(S_l)$, where $U(S_l)$ is the allocated time utilization of S_l.

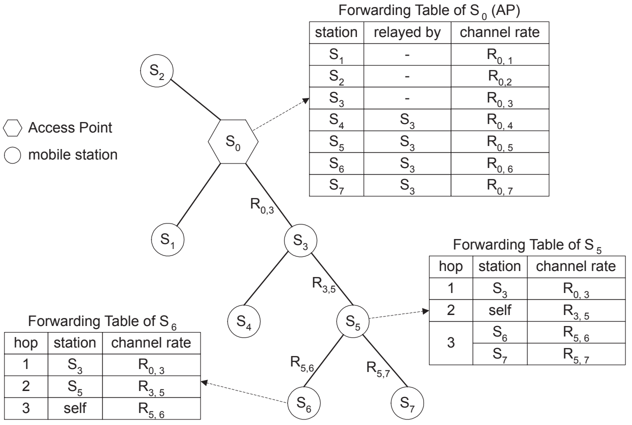
When S_i has no clients, we have $t_i = \Delta t$. Considering Equation 13, 14, and 17, for station S_i, we have

$$U(S_i) = \frac{T'(S_i)}{R_{i-1,i}t_i} = \frac{1}{1+R_{i-1,i}\sum_{j=1}^{i-1}[\frac{1}{R_{j-1,j}} + (\alpha-1)\Delta t(\frac{f_i}{R_{j-1,j}} + \frac{1-f_i}{R_{j,j+1}})]}. \tag{18}$$

Accordingly, we get

$$\begin{cases} g_T^0(S_i) &= \frac{T'(S_i)}{T(S_i)} = \frac{R_{i-1,i}t_i U(S_i)}{R_{0,i}\Delta t} = \frac{R_{i-1,i}}{R_{0,i}}U(S_i), \\ g_E^0(S_i) &= \frac{E'(S_i)}{E(S_i)} = \frac{R_{i-1,i}}{R_{0,i}}U(S_i)\frac{P(S_i)}{P'(S_i)} \\ &= \frac{R_{i-1,i}}{R_{0,i}}U(S_i)\frac{(\alpha-1)\Delta t f_i + 1}{U(S_i)(\alpha-1)\Delta t f_i + 1}. \end{cases} \tag{19}$$

When S_i has m_i clients $S_{q_1}, ..., S_{q_{m_i}}$, since each client rewards S_i time slots independently, the throughput becomes



Forwarding Table of S_0 (AP)

station	relayed by	channel rate
S_1	-	$R_{0,1}$
S_2	-	$R_{0,2}$
S_3	-	$R_{0,3}$
S_4	S_3	$R_{0,4}$
S_5	S_3	$R_{0,5}$
S_6	S_3	$R_{0,6}$
S_7	S_3	$R_{0,7}$

Forwarding Table of S_5

hop	station	channel rate
1	S_3	$R_{0,3}$
2	self	$R_{3,5}$
3	S_6	$R_{5,6}$
	S_7	$R_{5,7}$

Forwarding Table of S_6

hop	station	channel rate
1	S_3	$R_{0,3}$
2	S_5	$R_{3,5}$
3	self	$R_{5,6}$

Fig. 3. Multi-hop forwarding structure

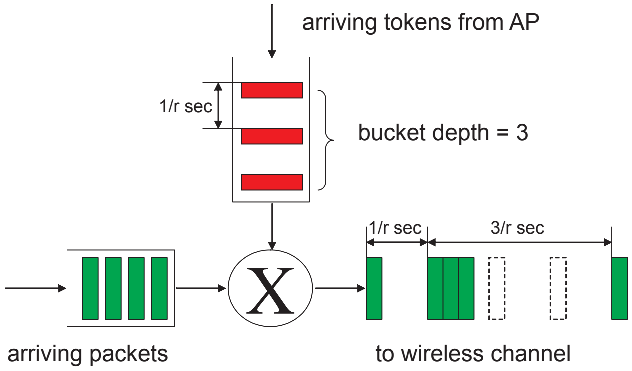


Fig. 4. Token bucket: the AP distributes tokens in a rate r (one round per $1/r$ seconds)

$T''(S_i) = U(S_i)R_{i-1,i}(\Delta t + \sum_{j=1}^{m_i} y_i^{q_j})$. Thus the performance gain is

$$\begin{cases} g_T(S_i) = \frac{T''(S_i)}{T(S_i)} = g_T^0(S_i)(1 + \frac{\sum_{j=1}^{m_i} y_i^{q_j}}{\Delta t}) & i \geq 1, \\ g_E(S_i) = g_E^0(S_i) & i \geq 1, \end{cases}$$

where $y_i^{q_j}$ follows Equation 17.

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V. SYSTEM DESIGN

CRS consists of three components: (1) The *proxy selection algorithm* runs on AP, choosing relay proxies for stations with low channel rates. (2) The *energy-aware channel scheduling algorithm* also runs on AP, arbitrating channel time allocation and ensuring time-based and max-min fairness among stations. (3) The *multi-hop forwarding algorithm* is a distributed algorithm running on both AP and mobile stations, in order to coordinate intermediate stations along the forwarding path. The three algorithms work together to enable the cooperative relay among stations in a WLAN.

As shown in Figure 3, stations in the WLAN are organized into a tree rooted at the AP for the cooperative relay service. Each non-root node of the tree represents a station, and the weight of each edge represents the channel rate between its two end nodes. In CRS, each station maintains a forwarding table. The forwarding table of the AP (root) holds the topology and edge weights of the entire relay tree. The forwarding table of a station holds the weight of each edge along the path from the AP to itself, and the topology and edge weights of the subtree rooted at itself. In CRS, the height of the relay tree should be small, typically two or three in 802.11b. Since spatial reuse is infeasible in a WLAN, both the receiving and forwarding of a data frame occupy the same radio channel. With the increase in the number of forwarding hops, the improvement of a client's throughput decreases rapidly. Furthermore, due to possible mobility of the station, it is much easier to maintain a short tree than a tall tree.

A. Proxy Selection and Association

With the time slot rewarding mechanism in CRS, the forwarding service is *profitable* and thus becomes a resource that stations want to *compete* for. To ensure a fair competition, we propose an auction-based mechanism for proxy selection.

Our proxy selection algorithm runs on the AP, which works as the auctioneer. When a station S_q needs the forwarding service, it broadcasts a sequence of *SFP* (search for proxy) messages with different channel rates, which also work as a measurement of maximal channel rates between S_q and other stations. Upon receiving the SFP, each high channel rate station computes the expected throughput gain it can provide for S_q and the cost price based on Lemma 3, then bids for the forwarding service with the cost price. After a short bidding time, the AP collects the bids from all bidders, and then selects the station that can provide the largest throughput gain for S_q as the proxy (see Appendix A for details of this auction). Other factors, such as the history of activity and the mobility of proxy candidates, may also be taken into consideration for proxy selection.

When a proxy is selected, the AP sends (or piggybacks) the MAC address of the proxy and the corresponding price to S_q. Then S_q sends a *RFR* (request for relay) message to the proxy, and the proxy acknowledges the request and reports to the AP to commit the proxy association. When the client does not need data forwarding any longer, it sends a notification to the AP directly with low channel rate to cancel the forwarding service.

B. Channel Allocation and Scheduling

The allocation of channel time and channel scheduling can be easily implemented in 802.11 WLANs under PCF (point coordination function) with polling MAC control. However, most commercial 802.11 products only support the basic DCF (distributed coordination function) MAC control. In the following, we describe the channel scheduling of CRS for 802.11 WLANs under DCF.

In CRS, the channel is allocated in units of time slot, same as the unit of station's back-off time for PHY medium access (50 μs for FHSS and 20 μs for DSSS). As shown in Figure 4, the time slot allocation is performed by the AP based on the *token bucket model*. Each station is assigned a certain number of *tokens* for channel contention. A station competes for channel only when it has available tokens. At regular intervals, the AP evenly distributes tokens among stations, ensuring time-based fairness. When the bucket of a station is full, the overflowing tokens are returned to AP, and are re-distributed equally to other stations for max-min fairness. The token bucket shapes the frame transmission of a station at a constant rate in the long run, while allowing bursty frame transmission of a station in the short term. The tokens can be distributed individually or be piggybacked within the data/control frames to stations.

A station can transmit data frames only when it has enough tokens, which will be deducted based on the time it occupies channel. Similarly, the AP buffers data frames for stations without tokens, and postpones their data transmission to the next round of time-slot allocation. Since channel contention is fair for all stations with tokens, the channel occupancy time of each station is dependent on the token allocation scheme in the long term, although it is non-deterministic in the short term.

We use a similar method to that in [21] to measure the channel occupancy time of a station. For each station, there are two token counters, one maintained at the station itself and the other at the AP. Upon receiving/sending a data frame from/to the AP, the station deducts the corresponding tokens from its token counter. At the same time, the AP deducts the same number of tokens of that station as well.

To simplify token management, a proxy station does not maintain token counters for its clients. Once a client associates with its proxy, the tokens, including those that the client should reward its proxy and those that are used by its proxy to receive/forward data frames for the client, are delivered to the proxy directly by the AP during token distribution. Correspondingly, the same number of rewarding tokens is deducted from the token counter of the client by the AP. Once a client cancels the forwarding service, its proxy automatically stops data forwarding at the next round of token distribution, because the AP will no longer convey the client's rewarding tokens.

C. Multi-Hop Forwarding

1) Basic Mechanism: To support multi-hop forwarding, each data frame is appended with two fields indicating the original source and final destination MAC addresses of the frame, respectively. Each station maintains a forwarding table as shown in Figure 3. Upon receiving a data frame, the station compares the final destination MAC address with its own MAC address. If they are different, the station looks up the MAC address for the next-hop station in its forwarding table. Then it modifies the destination address of the frame header (not the appended final destination address) and forwards it to the next-hop station.

2) Forwarding Path Maintenance: The channel rates along the forwarding path of a client and the channel rate between the client and the AP may change with the mobility of stations or signal fading. Furthermore, the forwarding path may even be broken. To adapt to possible channel rate changes, each client periodically re-evaluates the forwarding service it receives. If the service quality is significantly degraded, it re-broadcasts SFPs to look for a new proxy.

3) Power Management in Multi-hop Forwarding: Most power saving solutions such as those in [8], [15] utilize heuristic algorithms to adapt the sleeping of a WNI with its network activities. When a station has no network traffic, it will still be up for a while before it goes to sleep, based on the prediction of its network activity. The station may also change its waking up period adaptively to save the energy consumed on beacon listening.

In CRS, a station has the flexibility to set its own power saving policy. In 802.11, any station that wants to sleep needs to send a request to the AP, so that the AP can buffer the incoming data frames for it. When a proxy decides to switch to power saving mode, it notifies all its clients (direct or indirect). After receiving ACKs from these clients, the proxy sends a request to the AP, and shifts to power saving mode. Then the clients search for new proxies.

D. Discussion

Our system design is applicable to IEEE 802.11a/b/g protocols. Recently, IEEE 802.11e [7] has been approved as a standard to provide a set of Quality of Service enhancements for WLAN applications. In a WLAN with 802.11e MAC QoS enhancements, each station is assigned a transmission opportunity (TXOP) in terms of time slot by the AP, during which the station can transmit a burst of data frames continuously, in contrast to sending a single frame in 802.11a/b/g. Since the algorithm for TXOP assignment is open to the hardware manufacturer, it is easy to achieve time-based fairness in an 802.11e WLAN. Furthermore, 802.11e supports Direct Link Protocol (DLP), which enables two stations to communicate with each other directly, without traversing the AP. In contrast, all traffic must be relayed by the AP in the infrastructure mode of 802.11 a/b/g WLANs. Thus, it is straightforward to implement multi-hop forwarding in 802.11e WLANs. With the QoS support for traffic of different access categories, including voice, video, best effort, and background communications, we may need to re-define the fairness and performance metrics in 802.11e WLANs. However, the principle of CRS still holds.

VI. PERFORMANCE EVALUATION

In this section, we first present a prototype implementation of CRS and its experimental evaluation on FTP-like workloads, and then evaluate CRS with trace-driven simulation on Web-like workloads. Our purpose is twofold: (1) to demonstrate that the cooperative relay in CRS is feasible under the framework of the current IEEE 802.11 protocol; and (2) to validate its efficacy in significantly improving the throughput and energy utility for stations in a WLAN.

A. Prototype Implementation

We have implemented a prototype of CRS and built a small scale testbed, which includes an Access Point and six mobile stations. The AP is a desktop PC running Linux kernel 2.4.20, equipped with a NetGear MA311 802.11b PCI wireless adaptor. The mobile stations are six HP laptop computers running Linux kernel 2.4.20, each equipped with a NetGear MA401 802.11b PCMCIA wireless adaptor. One of the laptops

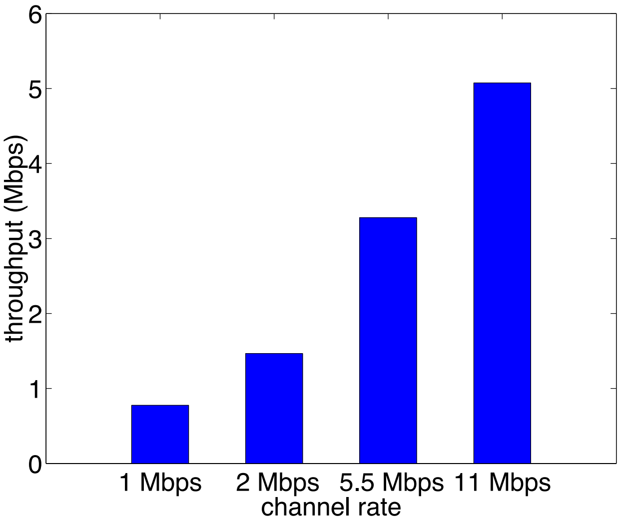


Fig. 5. The effective throughput of 802.11b WLAN under different channel rates

works as the proxy, the others work as the clients. All wireless adaptors in the AP and mobile stations use the Intersil Prism2 chipset.

We have modified the HostAP Linux driver for Prism2/2.5/3 [3] as the driver of our Access Point. The AP maintains the forwarding structure for each station associated with it, as described in Section V. The bidding time for proxy selection is set to 50 ms and the token distribution interval is set to 100 ms. Each token denotes 20 μs channel occupancy time. To implement token distribution, the HostAP driver maintains the number of available tokens owned by each station associated with the AP. In each round of token distribution, the HostAP driver first evenly allocates tokens based on the number of stations, then transfers the rewarding tokens from each client to its proxy based on their service agreement.

We have also modified the ORiNOCO Linux driver 0.15rc2 for wireless cards [4] as the driver of our proxy and client stations. Inside the driver, we have implemented a simple multi-hop forwarding protocol. In order to support this forwarding, all stations, including the AP, must work in the ad-hoc mode instead of the infrastructure mode.

B. Experimental Evaluation and Simulation

1) Performance Baseline Measurement: For user level communications, the ideal channel rate of IEEE 802.11 WLAN cannot be achieved in practice, due to the overhead of control frames, inter-frame spaces, physical and MAC layer headers, channel contention back-off time, and possible data losses. Therefore, we set up a small 802.11b WLAN with only an AP and a mobile station, and use the effective throughput of the station under this environment as the baseline for performance comparison. We transferred a large file from the AP to the station, and measured the user level throughput under different channel rates. Figure 5 shows the effective bandwidth of the 802.11b WLAN under channel rates of 1 Mbps, 2 Mbps, 5.5 Mbps, and 11 Mbps, respectively. The higher the channel rate, the less efficient the channel utilization. The reason is that all physical layer headers are transmitted at the lowest channel rate according to 802.11b, in order to ensure that all stations can listen to the channel for collision avoidance. However, the diversity of user level throughput under different channel rates is still large enough to benefit stations in an 802.11b WLAN through the cooperative relay service. In WLANs with more levels of channel rates such as 802.11a/g, CRS would have greater potential to improve the system performance.

TABLE II
CHANNEL ALLOCATION SCHEME

Scheme	Scheme Description
DCF	802.11 DCF MAC (without data forwarding)
TBF	time-based fairness scheduling (without data forwarding)
CRS	cooperative relay service
TBF-FW	time-based fairness scheduling with data forwarding

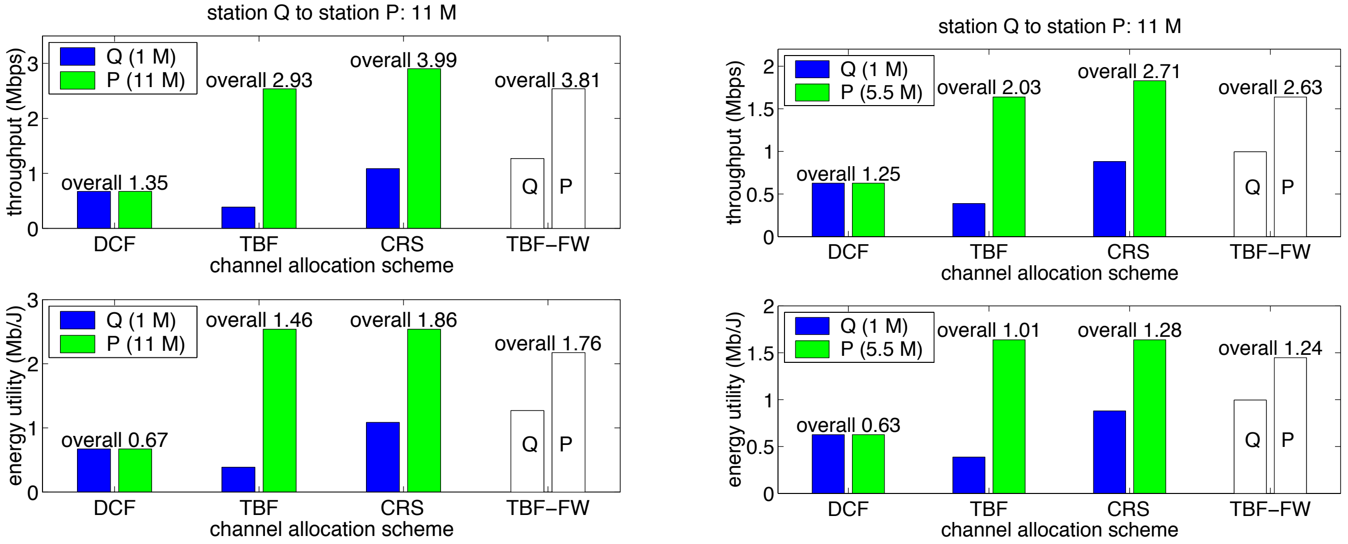
2) Evaluation on FTP-like Workload: We have implemented four channel allocation schemes as listed in Table II and compared their throughput and energy utility with FTP-like workload. In these schemes, DCF denotes the normal DCF MAC in an 802.11 WLAN, TBF denotes the time-based fairness channel contention mechanism proposed in [21], and CRS denotes our proposed cooperative relay service. In our CRS testbed, the client pays the cost price for the forwarding service because there is only one proxy in the WLAN (see Appendix A). In order to show the advantage of rewarding mechanism in CRS, we have also implemented data forwarding under time-based fairness for comparison, called TBF-FW. In this scheme, each station is assigned equal channel time to ensure time-based fairness, and the proxy voluntarily forwards data for its clients using the channel time of its clients, without any time slot rewarded. Note that this is a *phantom* scheme just used for comparison, neither proposed nor implemented before.

In the experiments, the proxy and each client station simultaneously downloaded a large file from the HostAP machine. The throughput is computed based on the data volume transferred between each client and its proxy (or between the proxy and the AP) and the corresponding transmission time under different channel allocation schemes. The energy consumed on data transmission is computed as the product of the transmission time of physical frames and the power consumption of the wireless card in the transmitting mode (provided by its manufacturer). The energy consumed on receiving/listening is computed in a similar way.

We have conducted experiments for the one-hop forwarding case, where the WLAN consists of one AP, one proxy (denoted by P), and multiple clients (denoted by Q) varying from one to five. Assuming all clients have the same channel rate, there are eight possible combinations for the cooperative relay service:

- the channel rate is 1 M or 2 M between Q-AP, 11 M between P-AP, and 11 M between Q-P;
- the channel rate is 1 M or 2 M between Q-AP, 5.5 M between P-AP, and 11 M between Q-P;
- the channel rate is 1 M or 2 M between Q-AP, 11 M between P-AP, and 5.5 M between Q-P;
- the channel rate is 1 M or 2 M between Q-AP, 5.5 M between P-AP, and 5.5 M between Q-P.

Each experiment has been repeated three times. Figures 6, 7, and 8 show the performance of different channel allocation



(a) Channel rates between stations: Q-AP, 1 M; P-AP, 11 M; Q-P, 11 M

(b) Channel rates between stations: Q-AP, 1 M; P-AP, 5.5 M; Q-P, 11 M

Fig. 6. The throughput and energy utility of stations under different channel allocation schemes (1 proxy and 1 client)

schemes in a WLAN with one AP, one proxy, and one, three, and five clients, respectively. In the figures, the number on the top of each bar group denotes the overall throughput (in Mbps) or the overall energy utility (in Mb per Joule) of all stations (the proxy and clients) in the WLAN. The performance of phantom TBF-FW is presented with white bars.

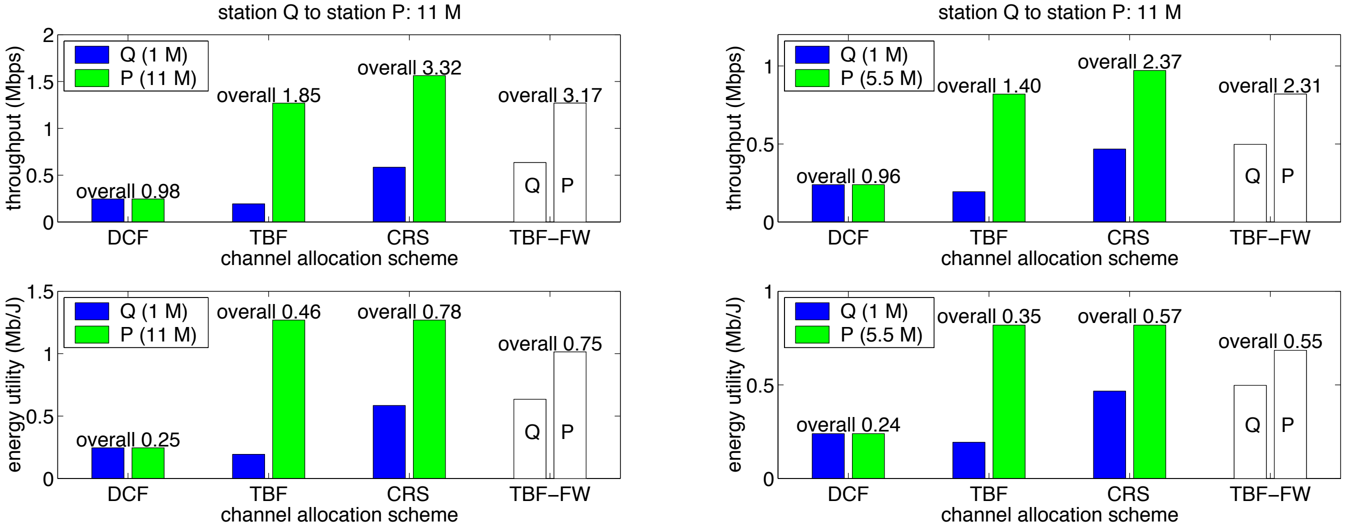
The results are summarized as follows. CRS has the highest overall performance with respect to both throughput and energy utility, while DCF has the worst overall performance. By enforcing time-based fairness, TBF improves the performance of high channel rate stations but decreases the performance of low channel rate stations. TBF-FW improves the throughput of low channel rate stations (clients) by data forwarding, but significantly decreases the energy utility of the forwarding station (proxy), which the proxy is unwilling to do. Thus this phantom scheme is not likely to be feasible in practice. In contrast, in CRS, the proxy is rewarded with time slots by its clients, resulting in an improvement of its own throughput without decreasing its energy utility. A client station sacrifices a small portion of its time slots for the forwarding service, but the overhead is minor. For example, as shown in Figure 7(a), the client throughput of CRS is 138% higher than that of DCF, more than two times over that of TBF, and about 93% of that of TBF-FW, while the proxy throughput of CRS is more than five times over that of DCF, and 23% higher than those of TBF and TBF-FW. Meanwhile, the proxy energy utility of CRS is more than four times over that of DCF, and is same as that of TBF. In contrast, the proxy energy utility of TBF-FW is 20% lower than that of TBF without any throughput improvement for the forwarding service. Furthermore, with CRS, the overall performance in the WLAN is also better than that of TBF-FW. These results indicate that CRS not only provides a strong incentive for data forwarding, but also balances the tradeoff between the performance of individual stations and the entire WLAN.

Figure 9(a) shows the growth of the proxy throughput gain of CRS (the proxy throughput of CRS over that of TBF) with the increase in the number of clients in a WLAN where the proxy (working at 11 Mbps channel rate with the AP) serves all other stations (working at 1 Mbps with the AP and 11 Mbps with the proxy). With time slot rewarding, the throughput of the proxy can be improved by 14% over TBF, even when it has only one client. Figure 9(b) shows the proxy energy utility gain of TBF-FW (the proxy energy utility of TBF-FW over that of TBF) in the same circumstances as above. The gain value is always less than 1, meaning that the proxy energy utility of TBF-FW is worse than that of TBF. In TBF-FW, the proxy may have to consume more than 22% energy on serving its clients, which could prevent the proxy from providing such service.

3) Evaluation on Web-like Workload: In order to evaluate the performance of CRS under Web-like workload in WLANs, we have conducted trace-driven simulation on real and synthetic workloads with ns-2 version 2.28 [5].

We have modified the ns-2 Mac/802.11 module to support multiple channel rates and data forwarding. We have also implemented a simple power saving module in the simulator, based on the mechanisms adopted by commercial wireless cards such as the PSPCAP mode in Cisco Aironet 350 series [1]. When a proxy has no network activities for its own communication for more than two seconds (the typical sleep threshold for most wireless products), it notifies its clients and the AP to go to sleep. Upon receiving the notification, the AP marks its state as sleep, and uses the low channel rate for transmitting data to clients. Then the proxy switches to the sleep mode, and the clients search for new proxies. The unused rewarding tokens maintained by AP will be returned to clients in the next round of token distribution. The power saving module of clients works in a similar way to that of the proxy.

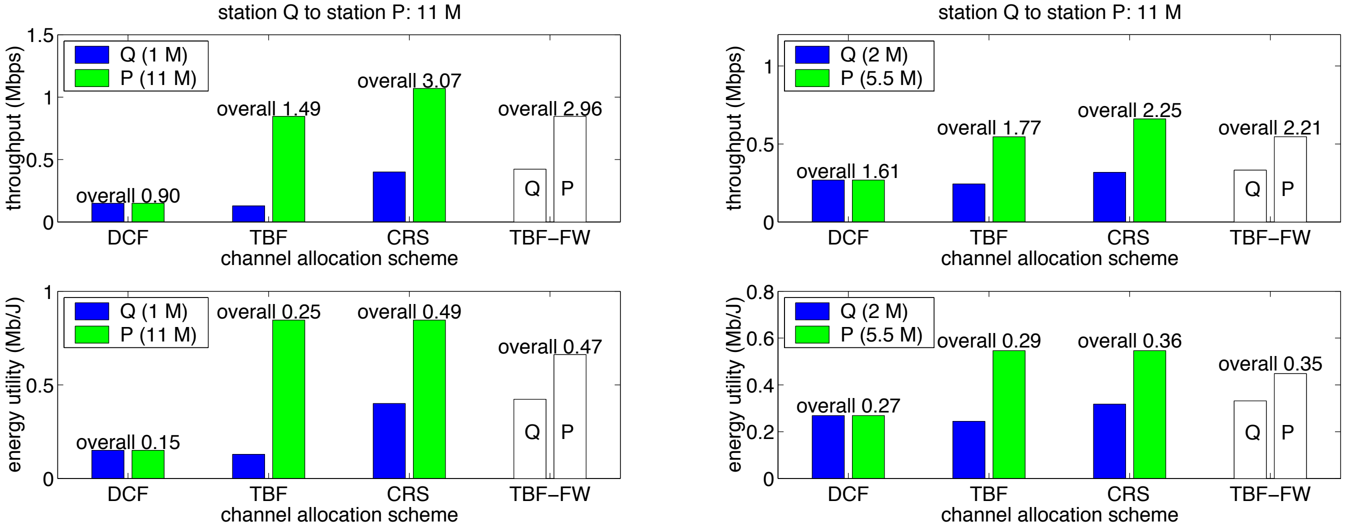
In the simulation on real workloads, we selected two representative segments from the BU Web client traces [2]: one represents Web workload at peak time, in which eleven users accessed 760 objects in 2,158 seconds; the other represents



(a) Channel rates between stations: Q-AP, 1 M; P-AP, 11 M; Q-P, 11 M

(b) Channel rates between stations: Q-AP, 1 M; P-AP, 5.5 M; Q-P, 11 M

Fig. 7. The throughput and energy utility of stations under different channel allocation schemes (1 proxy and 3 clients)



(a) Channel rates between stations: Q-AP, 1 M; P-AP, 5.5 M; Q-P, 11 M

(b) Channel rates between stations: Q-AP, 2 M; P-AP, 5.5 M; Q-P, 11 M

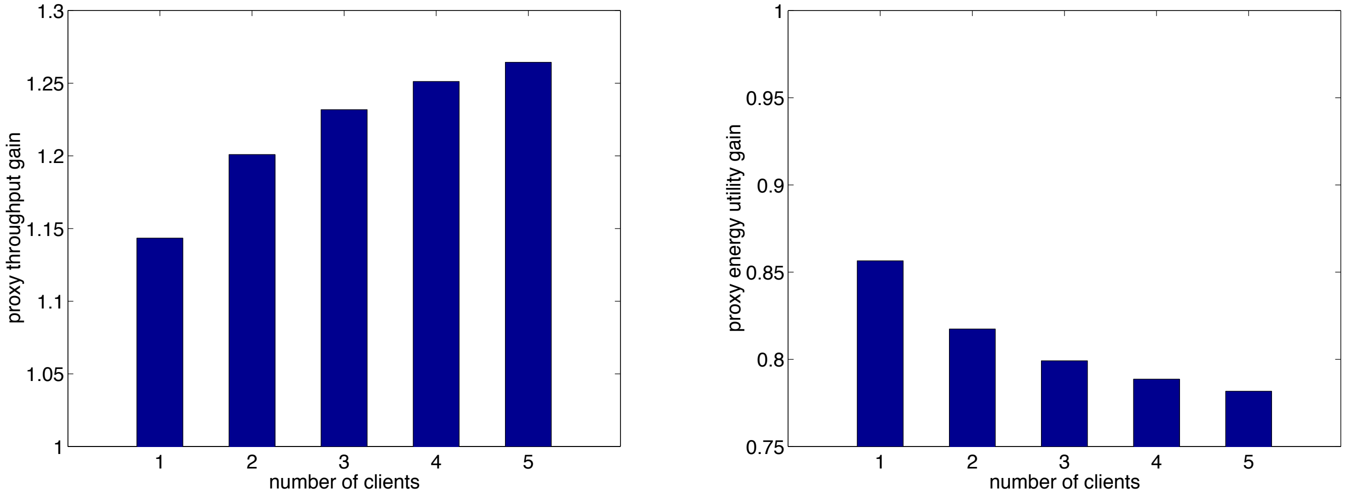
Fig. 8. The throughput and energy utility of stations under different channel allocation schemes (1 proxy and 5 clients)

Web workload at non-peak time, in which five users requested 523 objects in 4,623 seconds. We randomly selected six stations in the peak time workload and three stations in the non-peak time workload as high channel rate stations, which communicate with the AP at 11 Mbps. The channel rates between other stations and the AP are set to 1 Mbps.

Figures 10(a) and 10(b) show the average response time of each Web request (the duration from the time an object is requested to the time it is delivered) and the average energy utility for proxies and clients in the peak time and non-peak time workloads, respectively. In the peak time workload, the response time of low channel rate clients under CRS is reduced by up to 35% compared with that under TBF, and the response time of proxies under CRS is reduced by 12% compared with that under TBF. On the other hand, energy utility does not increase noticeably, because both workloads are not traffic intensive: each user only requests about 39 KB to 630 KB data from the Web. With such low traffic, the energy saved on a client is minor compared with the energy wasted during its idle time before it can go to sleep.

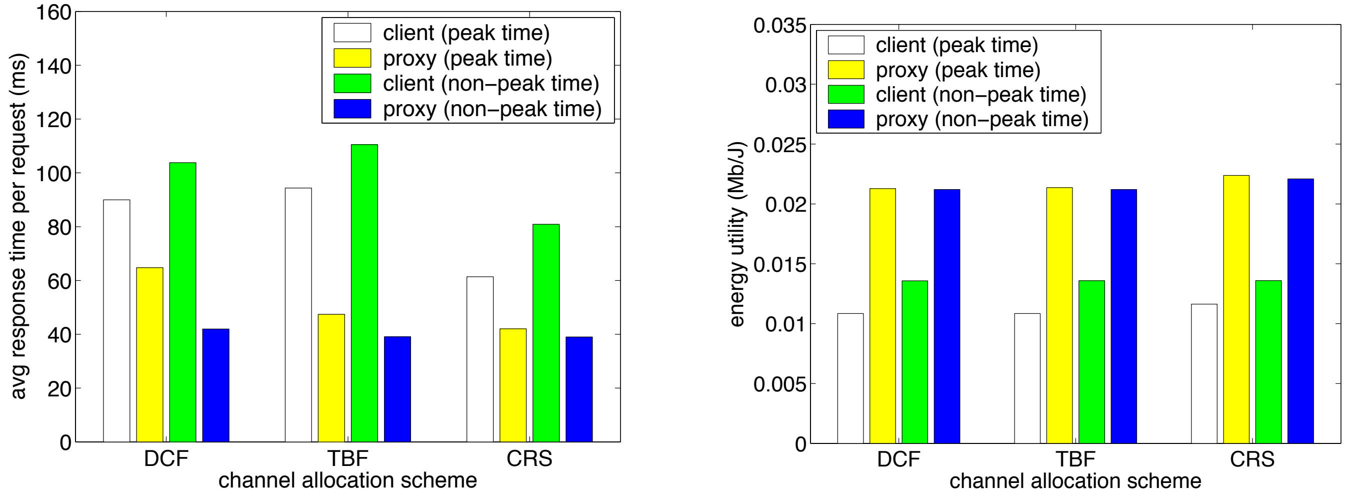
In the simulation on synthetic workloads, we used the Surge Web workload generator [9] to generate 10 Web workloads with different numbers of users ranging from 2 to 20. With the default parameter settings, in each workload, a user requests about 4.8 MB to 15.3 MB data from the Web in 30 minutes. The size of each file ranges from 77 bytes to 3.1 MB. In our simulation, we randomly set half of stations working at 11 Mbps mode and the rest half of stations working at 1 Mbps mode.

Figures 11(a) and 12(a) show the average response time of clients and proxies in these synthetic workloads, respectively, which are normalized against the performance under DCF (i.e., the performance ratio between TBF/CRS and DCF). Figures 11(b) and 12(b) show the energy utility of clients



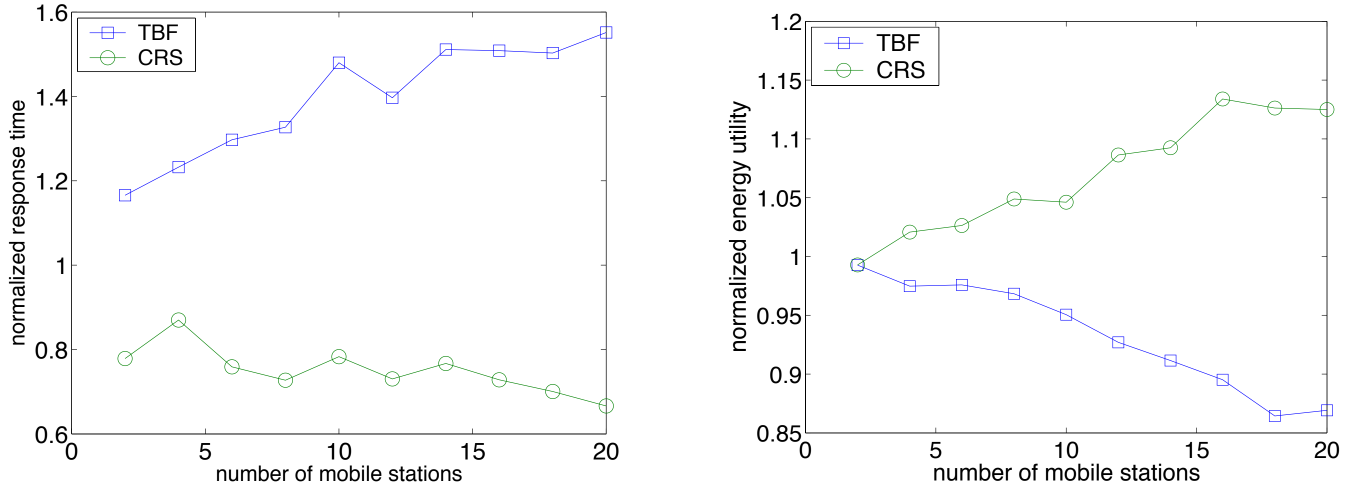
(a) Improvement of proxy throughput gain in CRS (b) Reduction of proxy energy utility gain in TBF-FW

Fig. 9. Performance gain of proxy with different number of clients



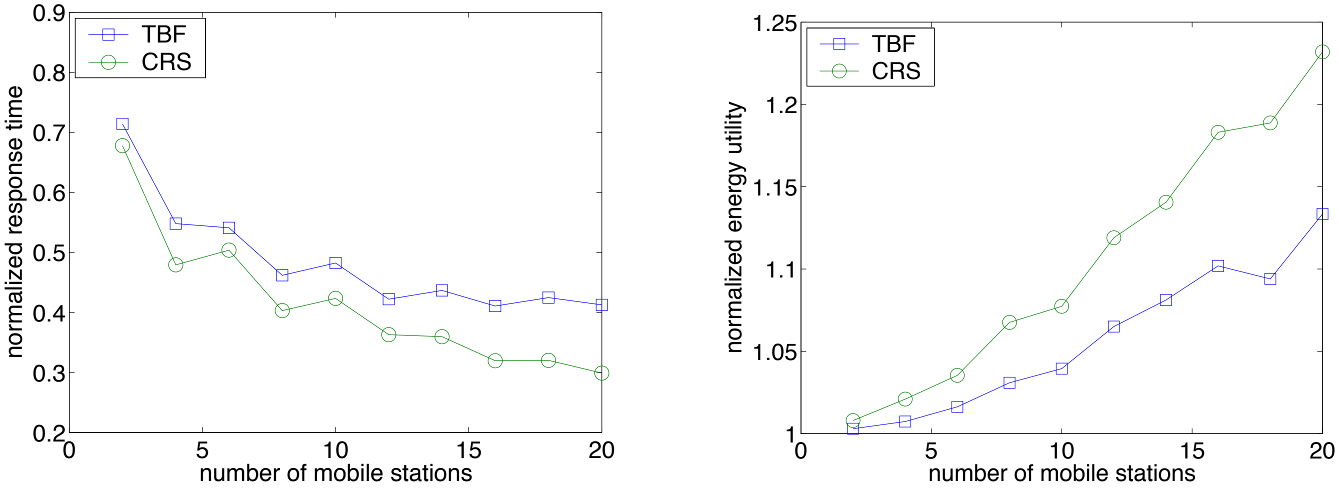
(a) Average response time per request (b) Energy utility

Fig. 10. Average response time per request and energy utility in BU Web client traces



(a) Average response time per request (normalized) (b) Energy utility (normalized)

Fig. 11. Normalized client performance in synthetic Web workloads



(a) Average response time per request (normalized)

(b) Energy utility (normalized)

Fig. 12. Normalized proxy performance in synthetic Web workloads

and proxies in these synthetic workloads, respectively, which are normalized in the same way. These figures show a clear trend of performance improvement for both response time and energy utility when the number of stations is scaled up. With 20 stations in a WLAN, CRS can reduce Web request response time by 57% for clients and 28% for proxies compared with the performance under TBF. The energy utility is also improved noticeably, by 29% for clients and 9% for proxies compared with the performance under TBF, because of the heavier traffic and more active stations than those in BU Web client traces.

The Web workloads we used above are old and the network activities in the workloads are not intensive (The BU Web client traces were collected in 1994, while the parameters of the Surge generator reflect the Web traffic of its implementation date, 1998). However, CRS still achieves significant performance improvements on these workloads. We believe that a real workload collected in current 802.11 hotspots will show a much better performance of CRS.

VII. CONCLUSION

In this paper, we aim to (1) address the throughput degradation induced by low channel rate stations in a WLAN, and (2) exploit the inevitable energy waste in channel listening during a communication session for improving network performance and energy efficiency. We characterize energy efficiency as energy per bit, instead of energy per second. Utilizing idle communication power, we present CRS, a Cooperative Relay Service, which consists of a data forwarding mechanism and an energy-aware token rewarding mechanism to supplement the IEEE 802.11 protocols. In data forwarding, a high channel rate station forwards data for a low channel rate station, resulting in a significant improvement of its throughput. To give high channel rate stations an incentive to be proxies, we design an energy-aware token rewarding scheme, in which low channel rate stations compensate proxies for additional time slots. Thus, a proxy can improve its own throughput without compromising its energy efficiency.

We have presented a mathematical model to guide the protocol design, and have proposed algorithms for proxy selection, channel allocation and scheduling, and data forwarding in IEEE 802.11 WLANs. To evaluate the performance of CRS, we first implemented a prototype of CRS and conducted experiments in a small-scale testbed comprising one Access Point and six mobile stations. The experimental results show that CRS significantly improves the overall system performance. To study CRS in a more generic environment with much more mobile stations and short-file transfers, we also implemented CRS in ns-2 simulator. Through extensive simulations driven by both real and synthetic Web workloads, we observed that CRS also remarkably improves Web access performance.

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APPENDIX

A. An Auction-based Mechanism for Proxy Selection

We model the price negotiation and proxy selection as a *sealed-bid procurement auction*. In this procurement auction, a client that is willing to trade its channel access time for data forwarding service is a *buyer*, the stations that can provide forwarding service by charging channel access time are *sellers*, and the AP works as the *auctioneer*. The sealed-bid means all bidders submit bids simultaneously, and the bidding is single round. In this auction, a client would always like to pay less and get more, while a proxy would always like to being paid more and serve less. Our purpose is to have all bidders to bid with the cost prices of their services, which should be the *dominant strategy*—the "best" strategy that bidders can expect—of this auction. Assuming all bidders are risk neutral, the *Vickrey auction* [19], also known as the *second price auction*, can be used as the auction rule. It works as follows.

All bidders submit their bids with the cost prices of their services. The auctioneer selects the bidder that offers the highest throughput gain to the client as the winner. If two bidders can offer the same throughput gain to the client, the one that offers higher energy utility gain wins. Meanwhile, the buyer (the client) will pay the bidder the price at which it can achieve the throughput gain that the second bidder offers (this is why the auction rule is called second price auction). As a result, the winner may get more benefit than that can be archived at its cost price. If two or more bidders offer the same highest throughput gain and energy utility gain to the client, the auctioneer can randomly select one of them or favor the one with smaller/smallest throughput to be the winner, and the client only needs to pay the cost price. As proved in game theory, in the second price auction, any deviation from the cost price of a bidder cannot increase its benefit, in case that all other bidders bid with their cost prices. In other words, the *Nash equilibrium point* of the auction is the state on which all bidders bid with their cost prices.

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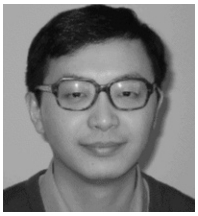

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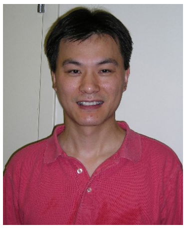

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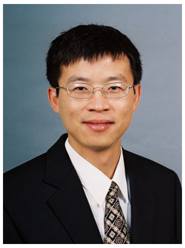

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