Multi-rate relaying for performance improvement in IEEE 802.11 WLANs

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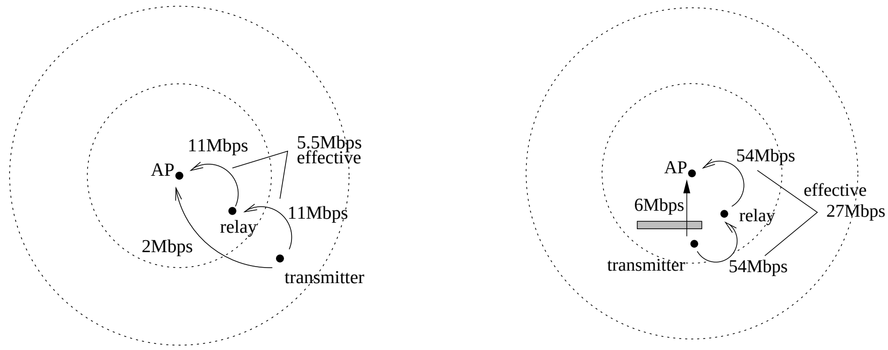
Abstract. It is well known that the presence of nodes using a low data transmit rate has a disproportionate impact on the performance of an IEEE 802.11 WLAN. ORP is an opportunistic relay protocol that allows nodes to increase their effective transmit rate by replacing a low data rate transmission with a two-hop sequence of shorter range, higher data rate transmissions, using an intermediate node as a relay. ORP differs from existing protocols in discovering relays experimentally, by optimistically making frames available for relaying. Relays identify themselves as suitable relays by forwarding these frames. This approach has several advantages compared with previously proposed relay protocols: Most importantly, ORP does not rely on observations of received signal strength to infer the availability of relay nodes and transmit rates. We present analytic and simulation results showing that ORP improves the throughput by up to 40% in a saturated IEEE 802.11b network.
Keywords: IEEE 802.11; cooperative communication protocols; rate adaptation; multi-hop wireless networks; wireless LAN

1 Introduction

The so-called IEEE 802.11 "performance anomaly" [1] implies that the presence of a node using a low data transmit rate significantly degrades the performance of an IEEE 802.11 BSS. Each node has an equal opportunity to access the channel, but nodes with a low data transmit rate occupy the channel for a disproportionately long time each time they transmit. The mean data transmit rate of the BSS – the harmonic mean of all the nodes' transmit rates – is dominated by the lowest transmit rate.

In [2–6], it has been shown that the effective transmit rate of a node may be improved by replacing a single transmission at a low data transmit rate with a sequence of two higher data rate transmissions, via an intermediate relay node. Figure 1 shows a simple example of a 2 Mbps transmission being relayed using a sequence of two 11 Mbps transmissions, for an effective transmit rate of 5.5 Mbps (less some overhead).



(a) Relaying increases the effective transmit rate.

(b) Non geometric variation in transmit rate, due to obstacles.

Fig. 1. Examples of relaying.

ORP is an Opportunistic Relay Protocol for IEEE 802.11 WLANs. Its most significant advantage over previously proposed protocols is that it does not depend on observing other nodes' transmissions to infer relay availability, considerably simplifying implementation and evaluation. In addition, ORP largely preserves the sense of the IEEE 802.11 DCF and MAC headers, allowing ORP and non-ORP nodes to co-exist. Simulation results show that in an IEEE 802.11b BSS where all low transmit rate frames are potentially eligible for relaying, the overall throughput of the BSS increases about 40%.

In the sections that follow, we first define the basic uplink relay discovery mechanism of the ORP protocol and study its performance analytically. Then we extend the basic ORP mechanism to include both uplink and downlink transmission and examine its performance in simulation. Finally, we define the contribution of our work relative to existing relay protocols.

2 Basic ORP Uplink

The basic ORP uplink mechanism allows frames to be relayed from a node (the source) to the access point (AP). To discover a relay, the source optimistically makes a frame available for forwarding, using the duration field in the MAC header to protect the forwarding transmission. If an intermediate node successfully decodes the frame and believes that it can forward it to the AP within the time constraint implied by the duration value, it is a potential relay for the frame. Because there may be more than one potential relay for the frame, a short backoff is used to reduce the risk of relay collision. If exactly one potential relay forwards the frame, the AP sends an ACK directly to the source. Otherwise, the relay fails and the source must retransmit the frame.

Using the duration field to indicate the end-to-end transmit time preserves the sense of the IEEE 802.11 MAC header, making relaying largely transparent to non-ORP nodes. ORP relaying also preserves the IEEE 802.11 DCF contention behavior. Relaying does not affect the relay's own traffic, because the source has already successfully contended for the channel, nor does relaying affect the relay's contention backoff values in the next contention round. The protocol is presented in more detail below:

Consider a network with transmit rates: R_0, R_1, and R_2, where $\frac{1}{R_1}+\frac{1}{R_2}<\frac{1}{R_0}$. A source node whose current transmit rate is R_0 attempts to send a frame of length L to the AP using an intermediate node as a relay. The first transmission (from the source to the relay) uses rate R_1 and the second (from the relay to the AP) is intended to use rate R_2.

The total time for the transmission is:

$$
\begin{aligned}
T_{\text{relay}} = T_{R_1}(L) + & \\
\text{relay\_backoff} + SIFS + T_{R_2}(L) + & \quad (1)\\
SIFS + T(ACK) & \quad (2)
\end{aligned}
$$

where $T_R(L)$ is the transmit time for a MAC frame of size L bits at rate R, relay_backoff is a constant discussed below and $T(ACK)$ is the transmit time for the ACK frame. $T(ACK)$ is a constant based on the AP transmitting the ACK directly to the source at the lowest available rate.

The source does not know whether there are any nodes that can act as a relay. Nevertheless, it sets the duration field in the MAC header assuming the frame will be forwarded using rate R_2. As in conventional IEEE 802.11, the duration value reflects the remaining transmit time: the relay backoff, relay transmission and ACK (terms 1 and 2 above). The source then transmits the DATA frame using transmit rate R_1.

Non-ORP nodes that receive the frame set their network allocation vector (NAV) according to the duration field as in IEEE 802.11 DCF and will not attempt to access the channel during the relay process. Keeping the meaning of the duration field this way allows ORP and non-ORP nodes to co-exist in the same BSS.

ORP nodes examine the frame's duration value. If the frame is a direct transmission, the duration shows that the AP will immediately return an ACK. Otherwise, the duration includes the time allocated for the relay transmission. All of the components of the duration value are known constants except for the frame length L (given in the frame's PLCP header) and R_2. Each receiver can therefore determine R_2, the transmit rate intended by the source for the forwarding transmission.

Each receiver is assumed to know the transmit rate that it currently uses to communicate directly with the AP. A receiver is a potential relay only if its direct transmit rate is at least R_2. Because there is no coordination among potential relay nodes, more than one node may determine that it is a potential relay. To avoid simultaneous relay transmissions, ORP uses a simple backoff. Each potential relay sets a random backoff timer

$$\text{backoff} = \text{Random}() * \text{slotTime},$$

where Random() is uniformly distributed over [0..relayCW]. To allow for the worst case backoff, the value of relay_backoff used in the duration calculation is relayCW $*$ slotTime.

When its backoff timer expires, a potential relay checks the channel. If the channel is clear, the relay sends the frame to the AP, using transmit rate R_2. The duration value gives the transmit time for the ACK, just as with any direct transmission. If the channel is busy, the potential relay assumes that another node is already relaying the frame and drops it.

If exactly one relay wins the backoff and the AP successfully receives the relay transmission, the AP transmits an ACK directly to the source. Because the relay transmission begins with the first backoff timer to expire, the ACK is usually transmitted before the time specified in the duration value (which assumed the maximum backoff). The duration value in the ACK is 0, allowing the next contention period to begin.

If there is no relay node or if two potential relays select the same backoff value and transmit during the same slot, the AP will not receive the frame. If the relay transmission fails, the source times out waiting for the ACK and eventually retransmits the frame using direct transmission.

Relaying will also fail if another node begins transmitting during the relay backoff. This situation can occur if a node can sense the originating transmission, but cannot obtain the duration value from the frame header. The node will defer during the originating transmission, then begin the IEEE 802.11 DCF backoff procedure. However, the case is biased in favor of the relay backoff, which is not proceeded by the DIFS and ends as soon as any potential relay begins to transmit.

3 Analysis

We present two results that will be useful in further discussion of ORP: the probability of successfully relaying and the effective transmit rate obtained using given combination of transmit rates. In this section, we assume that there is a fixed transmit distance for each transmit rate and there are no packet errors.

3.1 Relay success

A source at distance x from the AP attempts to relay using transmit rates R_1 and R_2, with transmit ranges r_1 and r_2 respectively. The attempt succeeds if there is at least one potential relay and exactly one relay wins the backoff. The probability relaying successfully is:

$$P_{\text{success}}(x) = \sum_{n=1}^{N-1} P(\text{no collision}|\text{relays} = n)P(\text{relays} = n) \quad (3)$$

where N is the total number of nodes in the BSS.

The first term in equation 3 is the probability that there is no collision, given that there are n potential relays participating in the relay backoff. Each potential relay chooses a backoff uniformly distributed on $[1..S]$ where $S = \text{relayCW}$. The relay backoff ends successfully at slot i if one relay selects slot i and the other $n-1$ relays select any later slot in $[i+1..S]$, so

$$P(\text{no collision}|\text{relays} = n) = \sum_{i=1}^{S} \frac{n}{S} \left(\frac{S-i}{S} \right)^{n-1} . \tag{4}$$

The second term in equation 3 is the probability that n nodes in the BSS are potential relays for the transmission. We find this probability geometrically, by computing the area of the relay region, in which a relay node must be located to satisfy transmit range constraints (Figure 2). A closed form for $A(x)$, the area of the relay region for a source at distance x from the AP is found in [2, 7].

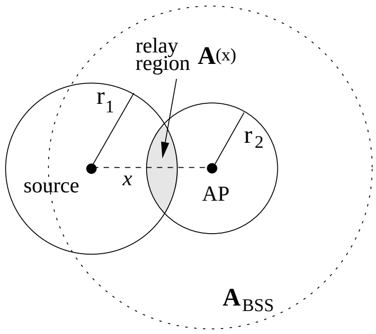


Fig. 2. Area of the relay region $A(x)$ for a source at distance x from an AP with coverage area A_{BSS}.

We assume N nodes are distributed according to a spatial Poisson process over area A_{BSS}, the coverage area of the AP. The probability that a source at distance x from the AP has n potential relays is the probability that there are exactly n of $N-1$ nodes in a region of area $A(x)$.

$$P(\text{relays} = n) = \binom{N-1}{n} \left(\frac{A(x)}{A_{BSS}} \right)^n \left(1 - \frac{A(x)}{A_{BSS}} \right)^{N-1-n} \tag{5}$$

Multiplying equations 4 and 5 gives equation 3, the probability that a node at distance x from the AP successfully relays using transmit rates R_1 and R_2.

3.2 Effective rate

The effective transmit rate R_{eff} of a relayed transmission is its apparent transmit rate when viewed as a direct transmission. The time required for a direct transmission is:

$$T_{\text{direct}} = PLCP + \frac{L}{R_{\text{direct}}} + SIFS + T(ACK), \tag{6}$$

where PLCP is the fixed time required for the physical layer convergence protocol (PLCP) preamble and header. The worst case time required using relaying is:

$$T_{\text{relay}} = PLCP + \frac{L}{R_1} + \text{relay\_backoff} + SIFS + PLCP + \frac{L}{R_2} + SIFS + T(ACK). \quad (7)$$

Setting equations 6 and 7 equal and defining R_{eff} by analogy with R_{direct} gives

$$\frac{L}{R_{\text{eff}}} = \frac{L}{R_1} + \text{relay\_backoff} + SIFS + PLCP + \frac{L}{R_2}.$$

Because of the constant terms, R_{eff} depends on the frame length. In general, it is not cost effective to relay short (¡ 200 byte) frames. In this work, we assume 1500 byte frames, which are representative of TCP traffic.

	IEEE 802.11b	IEEE 802.11g (ERP-OFDM)
frame length L	1500 bytes	1500 bytes
PLCP	96 μs	24 μs + 6 μs
SIFS	10 μs	10 μs
slotTime	20 μs	9 μs
relayCW	15	10
relay_backoff	300μs	90μs

Table 1. Parameters used for computing effective transmit rates.

To compute specific values of P_{success} and R_{eff}, we assign values to the various constants as in table 1. The nominal transmit ranges are taken from the published data sheet[8] for the Cisco Aironet 1200 IEEE 802.11b/g AP.

Using the results above, figure 3 shows the probability $P(x)$ of a node at a distance x from the AP successfully relaying and obtaining a given R_{eff}. Note how the probability of obtaining a 5.5 + 5.5 Mbps relay does not decrease with distance from the AP, because the decreasing size of the relay region $A(x)$ is offset by the reduced risk of relay collision.

4 Further discussion

In this section, we present two aspects of ORP in more detail: the rate selection process and downlink relaying.

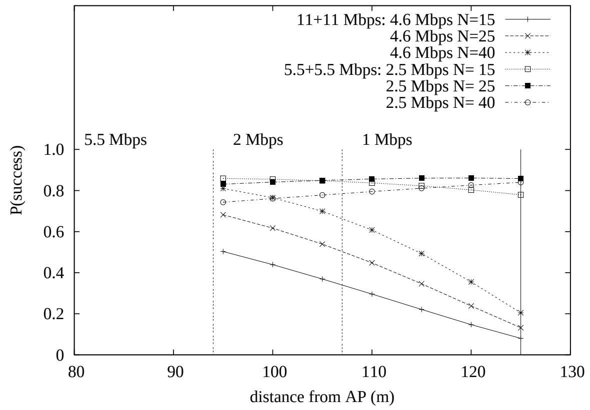


Fig. 3. IEEE 802.11b: Probability of successfully relaying for various BSS sizes. In some cases, the probability of success increases with distance, as the decreasing size of the relay region is offset by a lower risk of relay collision.

4.1 Rate selection

ORP assumes that each node maintains an estimate of its current direct transmit rate to the AP, but does not presuppose any particular rate adaptation mechanism. Because shorter frames are generally transmitted without relaying, the direct rate adaptation mechanism is assumed to operate in parallel with multi-rate relaying.

For each relay frame, the source needs to determine whether or not to use relaying and with what combination of transmit rates. Currently, we prescribe a single relay rate combination for each direct transmit rate. The source periodically attempts to relay using this combination. If consecutive relay attempts fail, the source reverts to direct transmission until the next relay attempt. (This mechanism is essentially Auto Rate Fallback(ARF)[9].)

This strategy does not provide the best possible performance, because there will generally be more than one feasible relay rate combination for a given direct transmit rate. Each relay rate combination will provide a different effective transmit rate and will have a different probability of success.

In general, for a given direct transmit rate, only a relatively small number of relay rate combinations will provide a higher effective transmit rate. Unlike direct transmit rates, however, there is not a simple relationship between the effective transmit rate and the probability of the corresponding uplink relay succeeding. A single luckily positioned relay node may make a rate combination feasible when a more conservative one is not, particularly in complex propagation environments.

Nevertheless, the analytic tools provided in section 3 can be used to compute (offline) a plausible ordering of rate combinations for each direct transmit rate, noting that a successful relay transmission provides information about feasible combinations. The decision to attempt to relay must balance the cost of a failed attempt against the benefits of success. Further development of a rate selection mechanism is future work.

4.2 Downlink relaying

The basic ORP mechanism cannot be used for downlink relaying, because the mechanism relies on potential relays knowing the transmit rate at which they communicate with the destination, i.e. the AP. However, current network traffic patterns reflect download traffic and are characterized by a sequence of large downlink frames and short uplink frames. To obtain significant benefit from relaying, it is necessary to relay downlink traffic.

To provide downlink relaying, uplink relaying is used as a *relay discovery* mechanism. The AP records the uplink relay node used by each source and uses this relay for the corresponding downlink transmission. In this case, the address of the relayer must be specified in the frame. We follow CoopMAC II [3] in using the `Address4` field in the MAC header.

The duration value continues to reserve the channel for the complete relay sequence. Because the relay is specified in the MAC header, the relay backoff is unnecessary and the relay forwards the frame immediately. The total time for the relayed transmission is:

$$T_{\text{relay}} = T_{R_2}(L) + SIFS + T_{R_1}(L) + SIFS + T(ACK), \tag{8}$$

and the corresponding effective rate R_{eff} is slightly higher.

The AP does not not know the transmit rate R_1 that was used between the source and the relay on the uplink path, but it does know the direct transmit rates R_0 and R_2 that it uses to communicate with the source and the relay, respectively. As with uplink relaying, there is currently a single prescribed pair of rates, so R_1 is known.

Even in the case where multiple rate combinations are permitted and R_1 is not known, given R_0 and R_2, there are (in practice) at only a few reasonable options for transmit rate R_1, so the AP can begin with the lowest rate and later attempt to increase it.

Currently, we assume assume an even balance of uplink and downlink relay traffic, so the AP simply records the identity of the relay, which is renewed (and possibly changed) with each uplink transmission.

In more realistic traffic scenarios, relaying short uplink frames is inefficient due to overhead. However, if relay information is cached at the AP, then the cost of using a short uplink frame for relay discovery can be amortized over several downlink transmissions. This approach require more careful cache management, as the cache may be invalidated due to node mobility, requiring the AP to revert to direct downlink transmission. The design of such a caching mechanism is future work, though we believe that such caching is feasible, particularly in common low mobility scenarios such as offices, conferences and internet cafes.

5 Simulation experiments

We did simulation experiments to investigate the throughput performance of ORP. The results show that ORP provides significant improvement. To focus on the impact of relaying, we use a simple traffic model and exclude issues of rate adaptation and selection by fixing direct transmit rates and permitting only a single, fixed combination of relay rates. Other parameters are as in Table 1.

The experiments investigate the case of a saturated IEEE 802.11b BSS with an equal mix of uplink and downlink traffic with a "ping-pong" pattern. All nodes in the BSS are assumed to have an infinite number of frames to transmit: each node sends a frame of length 1500 bytes to the AP and the AP responds with a frame of the same length. Each uplink frame provides relay discovery for the corresponding downlink frame.

The direct transmit rate of each node is assigned based on its distance from the access point, providing a bit error rate of 10^{-5} in the absence of interference. Nodes with a direct transmit rate of 1 Mbps use $R_1 = R_2 = 5.5$ Mbps for an effective transmit rate of 2.5 Mbps. Nodes with a direct transmit rate of 2 Mbps use $R_1 = R_2 = 11$ Mbps for an effective transmit rate of 4.6 Mbps. If three consecutive relay transmission fail, the source reverts to direct transmission for 40 transmissions, then attempts to relay again.

The simulation experiments used Omnet++ 3.2[10] and mobility-fw 1.0a4[11], to which we added support for 802.11b multi-rate communication. The mobility-fw package uses a propagation model similar to that used in ns-2, but provides a somewhat more detailed model of the air frame. As usual in IEEE 802.11 BSS environments, RTS/CTS is not used. Following [12], the bit error rate (BER) for 1 and 2 Mbps and for 5.5 and 11 Mbps transmissions respectively are given by:

$$BER = 0.5\exp\left(\frac{-\mathrm{SNIR} * \mathrm{BW}}{\mathrm{bitrate}}\right) \quad \text{and} \quad BER = C_{5.5,11}\ \mathrm{erf}\left(\frac{-\mathrm{SNIR} * \mathrm{BW}}{\mathrm{bitrate}}\right).$$

We record the total goodput of the BSS (i.e. frames successfully transmitted to and from the AP) over a simulation time of 50s, for each of 50 randomly generated static topologies for network sizes ranging from 15 to 50 nodes.

Figure 4 compares the total traffic sent or received at the AP in the case of no relaying, uplink-only relaying, and both uplink and downlink relaying. The impact of nodes using a low data transmit rate is clear: With no relaying, the goodput is less than 2 Mbps, even though about half of the nodes transmit at either 5.5 or 11 Mbps. Uplink relaying alone results in a goodput about 20% higher over a range of node densities, while both uplink and downlink relaying results in about a 40% increase.

6 Related work

The authors used geometric arguments to analyze the feasibility of relaying and outlined a relay mechanism in [2]. In this section, we highlight key contributions

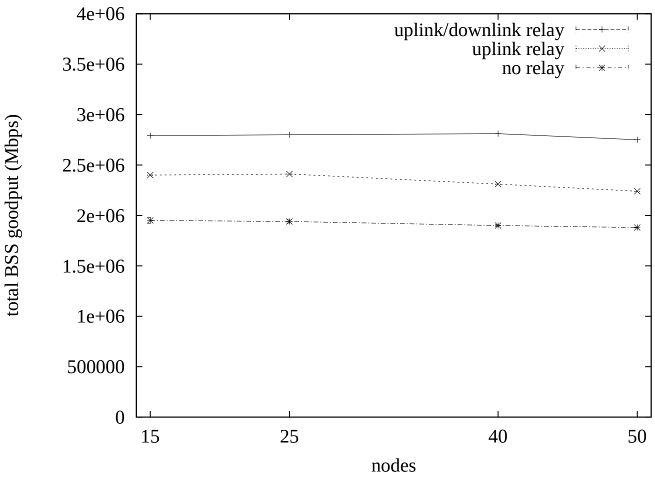


Fig. 4. IEEE 802.11b: Overall AP throughput as a function of BSS size. (The 95% confidence interval is approximately the size of the data point.)

made in this work relative to previously proposed protocols, including CoopMAC [3], RAAR [6], rPCF [4], and rDCF[5].

Any relay protocol must obtain two data: the transmit rate between the source and each potential relay and the transmit rate between the potential relay and the AP. The structure of each protocol is determined by which entity (source, relay or AP) collects this data and selects and assigns relays. Table 2 summarizes protocols according to these criteria.

In Cooperative MAC (CoopMAC), nodes use received signal strength (RSSI) measurements to estimate the transmit rates needed to communicate with potential relays and directly observe the transmit rates used potential relays to communicate with the AP. Relay selection is distributed, each source uses its rate information to select a relay node. CoopMAC I uses an RTS/"HTS"/CTS negotiation to inform the intended relay of its role. Like ORP, CoopMAC II uses the Address4 field in the MAC header to indicate the selected relay.

The Relay-based Adaptive Auto Rate (RAAR) protocol is a centralized protocol in which nodes observe the RSSI of their neighbors' transmissions and estimate the appropriate transmission rate for communicating with each neighbor. The estimates are forwarded to the AP, which computes relay assignments distributes them via its periodic beacon transmission.

rPCF is intended for IEEE 802.11 PCF networks. Nodes forward RSSI observations to the AP, which explicitly assigns relays. rDCF is intended for ad hoc networks. Nodes observe the transmit rates used by their neighbors to determine node pairs for which they might act as a relay. Nodes periodically announce their relay capabilities to their neighbors. ORP uses a similar volunteer relay approach, but does not require an explicit advertisement.

	source-relay	relay-AP	relay selection	relay assignment	uplink downlink	backwards compatibility
CoopMac I	RSSI	snoop	source	RTS-HTS	uplink only	no
CoopMac II	RSSI	snoop	source	Address4	uplink only	no
RAAR	RSSI	AP	AP	AP	both	potentially
rPCF	RSSI	AP	AP	AP	both	PCF only
rDCF	n/a	n/a	relay	Address4	n/a	ad hoc only
ORP (uplink)	exp't	relay	relay	none	uplink only	non-ORP nodes
ORP(downlink)	exp't	relay	relay	Address4	both	non-ORP nodes

Table 2. Comparing relay protocols.

ORP differs from previous work in discovering relay nodes experimentally, by optimistically making frames available for relaying and allowing nodes to select themselves as relays. This approach has three advantages:

First, ORP does not rely on RSSI data to discover relay nodes, avoiding the overhead of maintaining RSSI observations for each potential relay. We believe that transmit rate estimation based on RSSI is less straightforward than suggested in previous work. Computing an SNIR from the RSSI depends on the noise floor estimate, because the RSSI measurement reflects only the total power received at the antenna. This functionality is not provided by default in IEEE 802.11 hardware: the transceiver tries to synchronize whenever the RSS exceeds the receive sensitivity.

As a result, accurate transmit rate estimation may not be feasible in a noisy environment. Moreover, the performance of an RSSI-based approach can be difficult to evaluate in simulation. To infer transmit rates from RSSI data, the relay protocol must incorporate some channel model. The simulator also uses a channel model to approximate the behavior of a real wireless network. If these models are too closely aligned, the simulation results may not provide a good indication of performance.

Second, ORP nodes select themselves as relays, avoiding the overhead of communicating rate information and relay assignments found in other protocols. ORP also provides greater flexibility in managing relays. If relays are not self selecting, then the selector has to determine which nodes support ORP and track node battery levels. An ORP node with a low battery simply does not participate in the relay backoff, while non-ORP nodes need only follow IEEE 802.11 rules to avoid collision.

Third, ORP does not incur a significant performance penalty despite its simple design. Although it is difficult to compare performance results reflecting different simulation environments and experiments, ORP appears to achieve performance comparable to more complex protocols (e.g. [3]).

7 Conclusions and future work

We introduce ORP, an opportunistic relay protocol that differs significantly from previously proposed protocols in not using RSSI information for relay selection.

We derive the probability that a node successfully uses relaying to obtain a given effective transmit rate and present simulation results showing that in a saturated IEEE 802.11b network with both uplink and downlink relaying, the total throughput of the BSS increases about 40%. In addition, because ORP preserves IEEE 802.11 DCF semantics, ORP and non-ORP nodes can co-exist in an ORP BSS.

These results are promising and there is considerable scope for further performance improvement, particularly though the use of rate selection and relay caching discussed in section 4. We also plan to transition ORP to IEEE 802.11a/g, which provides more and faster relay rates. Finally, we hope to implement and test ORP in realistic environments. In non line-of-sight environments, such as buildings or offices, relaying effectively enables routing around obstacles (figure 1(b)). This non-geometric variation in transmit rate provides opportunities to obtain even greater advantages from ORP relaying.

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