Performance of a Cooperative Relay-Based Auto-Rate MAC Protocol for Wireless Ad Hoc Networks

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Abstract—Cooperative communication is becoming a promising technology for wireless networks by exploiting multipath fading instead of mitigating its impact. To integrate cooperative diversity into practical systems, efficient protocols are needed across the entire protocol stack. This paper presents a Cooperative Relay-Based Auto-Rate MAC protocol (CRBAR) to enhance the multi-rate capability along a long link. By leveraging the broadcast nature of the wireless medium and spatial diversity, a low-rate hop can be replaced by two high-rate hops via adaptive MAC-layer cooperation. To adapt to dynamical channel variation and network topology, the relay candidates adaptively select themselves as the relay nodes and determine the relay scheme and transmission rates based on the instantaneous channel measurements. System-level simulation study shows that CRBAR significantly outperforms traditional rate adaptation schemes in realistic scenarios.

I. INTRODUCTION

Cooperative communication is becoming a promising technology for wireless networks [1] by exploiting multipath fading instead of mitigating its impact. Single antenna devices that are geographically close can share their antennas in a cooperative manner to emulate a Multi-Input Multi-Output (MIMO) system and exploit the spatial diversity benefits traditionally realized by an antenna array hosted on a single device. This idea is particularly appropriate for wireless ad hoc networks since it not only lessens the hardware requirements of small mobile devices but also freely exploits the two key characteristics of wireless medium: spatial diversity and broadcast nature.

Although cooperative communication has motivated extensive research activities in information theory and communications communities, its implication and application to wireless network design receive little attention until very recently [2-6]. Two similar MAC protocols, CoopMAC [2] and rDCF [3] have been proposed to enhance the multi-rate capability of the IEEE 802.11 protocol [7] by taking the advantage of MAC layer relaying. A slow node, instead of sending its packets at a low rate to a destination directly, uses a “helper” that is located between the sender and the receiver and is able to transmit at a higher rate in a two-hop manner. These schemes can significantly improve system performance when the direct link quality is poor. In this case, traditional rate adaptation schemes cannot help. However, a relay is chosen in a proactive manner based on a relay table at the sender, which may not adapt to dynamical channel condition and network topology in wireless ad hoc networks. This proactive relay selection does not consider the real-time interference at the chosen relay and may lead to poor response probability. Furthermore, simple relaying is employed in their schemes which do not exploit the key characteristic of cooperative communication: the receiver can improve its capability to decode the original packet by combining the information from both the source and the relay.

In this paper, we present a Cooperative Relay-Based Auto-Rate MAC protocol (CRBAR) with reactive relay selection. The relay candidates adaptively select themselves as the relay nodes and determine the relay scheme and transmission rates based on the instantaneous channel measurements. Packet combining is adaptively employed at a receiver to combine the copies of the same signal from a sender and a relay such that a high data rate between the relay and the receiver may be possible due to diversity gain. This protocol is backward compatible with the legacy 802.11 Distributed Coordination Function (DCF). We compare the performance of CRBAR and traditional rate adaptation schemes in realistic scenarios via system-level simulations.

The rest of this paper is organized as follows. The related work on rate adaptation in ad hoc networks and cooperative communication are summarized in Section II. In Section III, the proposed CRBAR protocol is presented in details. Simulation model and performance evaluation are discussed in Section IV. Conclusions are given in Section V.

II. RELATED WORK

A. Rate Adaptation in Ad Hoc Networks

The 802.11 protocol supports a physical-layer multi-rate capability to adapt to different channel conditions. For example, the IEEE 802.11b provides four physical layer rates: 1, 2, 5.5 and 11 Mbps using different modulation schemes. A number of MAC mechanisms have been proposed to exploit this capability which can be divided into two classes: sender-based and receiver-based. The Auto Rate Fallback (ARF) protocol [8] is sender-based in which senders use the history of previous transmissions to determine the following transmission rate. To estimate the channel more accurately, a Receiver-Based AutoRate (RBAR) protocol [9] is proposed in which receivers measure the instantaneous channel condition by sensing the signal strength of the control packet for each transmission and set the transmission rate for senders. Due to the fact that almost all routing protocols utilize the lowest-rate broadcasting message to search the shortest path between a
source and a destination, the above schemes are not effective in wireless ad hoc networks where long hops are frequently present.

### B. Cooperative Communication in Ad Hoc Networks

In [4], Jakllari et al. proposed a multi-layer approach employing virtual Multi-Input Single-Output (MISO) link and Distributed Space Time Coding (DSTC) to increase the transmission range of one hop in mobile ad hoc networks. In [5], Moh et al. proposed a cooperative diversity MAC called CD-MAC to enhance the link reliability. Both the source and one proactively chosen partner will jointly retransmit the previously lost packet by utilizing a suitable DSTC. DSTC scheme heavily depends on the physical layer implementation and has a lot of technical challenges to overcome in practice such as channel estimation and synchronization. Instead of improving the transmission range or link reliability, two similar MAC protocols, CoopMAC [2] and rDCF [3] have been proposed to use the multi-rate capability of the 802.11 protocol to increase the data rate by employing a fast relaying between a sender and a receiver. By continuously listening to the packets in the air or periodically accepting a willing list advertised by a potential helper, each sender can maintain a relay table. Before each transmission the sender will proactively choose a “best relay” based on the records of the channel measurements in the relay table. This proactive relay selection scheme may not adapt to dynamic channel conditions and network topology in wireless ad hoc networks since the records in the table may be out of date. And they did not consider packet combing at the receiver. In [6], a distributed relay selection scheme is proposed based on the instantaneous channel estimation and information theoretical analysis is given without considering rate adaptation.

### III. Proposed Protocol

In this section, we give details of the proposed CRBAR protocol that is backward compatible with the legacy 802.11 DCF and RBAR scheme. The key function of CRBAR is to let the relay candidates determine the transmission scheme and data rate based on the instantaneous channel measurements, which is totally different from current sender-based or receiver-based rate adaptation schemes. To fully take advantage of cooperative diversity, Maximal Ratio Combiner (MRC) [10] is used at a receiver to combine the copies from both a sender and a relay. In RBAR, a rate $r_m$ will be chosen if the SNR $\gamma$ at the receiver is above a certain threshold $\theta_m$. With MRC, suppose that a node receives two copies containing the same information with the SNR $\gamma_1$ and $\gamma_2$ respectively, a rate $r_m$ will be chosen for each copy if the following conditions are satisfied:

$$\gamma_1 + \gamma_2 \geq \theta_m \cdot D \quad \text{and} \quad \gamma_1, \gamma_2 \geq \theta_1$$

(1)

$D$ is the diversity gain. With diversity gain, the SNR requirement for a given BER is reduced. To make packet combing possible, the receiver does not need to successfully decode the payload from one copy but does need to sense the transmission and acquire the timing. Hence, in addition to the above data reception threshold $\theta_m \cdot D$, a control reception threshold is introduced which is normally equal to $\theta_1$, i.e. the threshold to support the basic rate. The decode-and-forward scheme is used in this paper and thus the relay has to decode the data packet successfully before forwarding it.

### A. RTS/CTS Channel Probing

The basic rate Request to Send/Clear to Send (RTS/CTS) handshaking is initiated at the beginning of each transmission. The sender $S$ stores the size of the data frame $L$ into the RTS. By sensing the signal strength of the RTS, the receiver $D$ infers the achievable data rate $r_{sd}$ from the sender $S$ as in [9]. Due to the broadcast nature of wireless medium, some neighboring nodes of the sender $S$ can overhear the RTS and estimate the achievable transmission rate $r_{sr}$ between the sender and themselves. Then they will check their Network Allocation Vector (NAV) to determine if their surrounding channels have been reserved by other ongoing transmissions. If not, they will record the source address of the RTS and try to decode the following CTS and estimate the achievable transmission rate $r_{sd}$ between the receiver and themselves by sensing the signal strength of the CTS. Note that we assume a symmetric channel here and hence $r_{sd}$ is equal to $r_{sr}$. The practical supported transmission rate between a potential relay node and the receiver may be higher than $r_{sd}$ since cooperative transmission can be utilized to combine two copies of the data from both $S$ and the relay. The receiver $D$ will incorporate the estimated data rate $r_{sd}$ and the frame size in the CTS.

### B. Relay Self-Rating and Backoff Procedure

The potential relay nodes have obtained all the channel measurements and the data frame size $L$ to determine which transmission scheme will be adopted based on the total transmission duration. There are three schemes available: direct transmission, simple relaying (SR) and cooperative relaying (CR) with packet combining. Their transmission durations are calculated as follows:

- **Direct Transmission:** $D_{DT} = T_{PLCP} + L / r_{sd}$ (2)
- **Simple Relaying:** $D_{SR} = 2 \times T_{PLCP} + L / r_{sr} + L / r_{rd}$ (3)
- **Cooperative Relaying:** $D_{CR} = 2 \times (T_{PLCP} + L / r_{sr})$ (4)

$T_{PLCP}$ is the transmission time for physical layer overhead. Note that in cooperative relaying two copies of the data have to be transmitted using the same modulation technology thus the same rate due to the requirements of combining algorithm. And hence a relay with high $r_{sr}$ is preferred even if its channel to $D$ may be not very good. If the channel between the sender and the receiver is good enough and two-hop relaying cannot help more (e.g. $r_{sd}=5.5$ or 11 Mbps in 802.11b), the protocol is reduced to RBAR. A node will select itself as a relay candidate only if all the following conditions are satisfied:

I. It decodes both the RTS and the CTS successfully;
II. Its NAV indicates its surrounding channel has not been reserved by other ongoing transmissions;
III. Its help can deliver the data packet faster than the direct transmission.
Note that other selection criteria can be easily considered such as remaining energy, congestion level or just the willingness of its own. Since several nodes may wish to be the helper for current transmission, an efficient collision avoidance mechanism is needed to help choose the most appropriate node. Here we adopt a $p$-persistent backoff procedure due to its effectiveness. Each relay candidate $R_i$ calculates a relay probability $P_i$ based on estimated two-way channel conditions:

$$
\begin{cases}
    P_i = 0, & D_{DT} \leq D_{SR}, D_{DT} \leq D_{CR} \\
    P_i = \frac{\delta}{\min(D_{SR}, D_{CR})}, & \text{others}
\end{cases}
$$

(5)

$\delta$ is a constant here. At the end of each backoff slot $\sigma$, $R_i$ will send a Ready-To-Relay (RTR) frame with the probability $P_i$. The relay candidates will withdraw their willingness anytime once it senses the medium busy which means that either the sender has transmitted the data packet or other relay candidate has transmitted the RTR. Since carrier sensing range is much larger than transmission range in current wireless card setting, hidden relay problem can be avoided. In case that relay candidates collide or relay backoff counter reduces to zero, no retransmission attempt is allowed and the sender will transmit the data packet at rate $r_{sd}$ after a SIFS as shown in Figure 1(b).

It can be shown that the relay backoff success ratio can be considerably high if an appropriate relay backoff counter $N$ and $P_i$ are chosen. If an RTR is successfully received by the sender, a two-hop transmission will be initiated after a SIFS. The sender will send the data packet at rate $r_{sd}$ after decoding the data, the receiver $D$ will send an ACK frame directly to the sender $S$.

To avoid unnecessary waiting when appropriate relays are absent, a sender maintains a counter for each receiver to record the consecutive number that no relay responses during the relay backoff. If this number is up to $M$, the sender will enter into RBAR mode and transmit a data packet at rate $r_{sd}$ immediately after receiving the CTS. After a period $T$, the sender will employ CRBAR again to look for new relay help.

C. Frame Format

To promptly deploy CRBAR-enabled stations and consider the backward compatibility with the popular 802.11 protocol, we make the minimal modifications to the standard 802.11 frames. The new frame formats are shown in Figure 2. Similar to [9], the 16 bit duration field in original CTS frame has been replaced by a 4 bit rate subfield and a 12 bit length subfield which is not shown here due to limited space. The rates of both hops are included in the RTR frame. A special subheader, called Identity Subheader (ISH), is introduced in the MAC header of the data frame, which consists of several fields in the original 802.11 MAC header plus an individual CRC to protect and verify its correctness. This subheader is transmitted at the basic rate and has two functions: one is similar to the reservation subheader in [9] which is used to reserve the channel for the data transmission and another is to identify its sender and receiver and notify the receiver that this is one
copy for combining though its body content cannot be decoded at this moment. If a relay is employed, the address field in the original 802.11 is used to indicate the relay address, which is not used in the original 802.11 ad hoc mode.

D. Channel Reservation and Cancellation

The hidden node and exposed node problem have significant negative effect to the performance of wireless ad hoc networks. An effective virtual carrier sensing mechanism is essential to deal with these problems and enhance the spatial reuse. The duration reserved by different packet types are listed in Table 1. In CRBAR, the sender firstly makes the channel reservation for the control packet handshaking only with the RTS. This value accounts for the possible maximum channel reservation significantly constrains the channel utilization in this area. The performance of CRBAR with SR only is a small-scale multi-path fading. The Ricean K factor is fixed to 5 in this paper.

<table>
<thead>
<tr>
<th>Packet Type</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTS</td>
<td>$\text{CTS + N} \times \sigma + \text{RTR} + 3 \times \text{SIFS}$</td>
</tr>
<tr>
<td>CTS (relay unexpected)</td>
<td>$\text{DATA} (t_{\text{dir}}) + \text{ACK} + 2 \times \text{SIFS}$</td>
</tr>
<tr>
<td>CTS (relay expected)</td>
<td>$\text{DATA} (t_{\text{dir}}) + \text{ACK} + \text{RTR} + 3 \times \text{SIFS}$</td>
</tr>
<tr>
<td>RTS</td>
<td>$\text{DATA} (t_{\text{dir}}) + \text{ACK} + 2 \times \text{SIFS}$</td>
</tr>
<tr>
<td>DATA$_{1}$ (first hop)</td>
<td>$\text{ACK} + \text{SIFS}$</td>
</tr>
<tr>
<td>DATA$_{2}$ (second hop)</td>
<td>$\text{ACK} + 2 \times \text{SIFS}$</td>
</tr>
<tr>
<td>ACK</td>
<td>0</td>
</tr>
</tbody>
</table>

The following data packet will update this value using the duration field in its identity subheader. Similarly, a receiver knows if a relay is needed but does not know if there exists a relay. If the channel between the sender and the receiver is good enough and two-hop relaying cannot help more, the receiver will reserve the channel for the exact one-hop data transmission duration. Otherwise, a relay node is expected and the receiver will make a conservative reservation using the CTS. This has to indicate the worst case that RTR frames collide at the last relay backoff slot and the sender has to transmit data directly to the receiver.

The actual data transmission often takes less time if a relay is employed. Since the transmission attempts of other nodes will be deferred until their NAVs expire, this conservative reservation significantly constrains the channel utilization ratio. Here we introduce a key operation of CRBAR: channel reservation cancellation. After the actual data transmission is completed, the receiver will use the ACK to cancel the unnecessary channel reservation and notify its neighbouring nodes that the channel is free now. According to the 802.11 standard, the current NAV can only be updated by a larger value. To comply with this standard, each node maintains a list of the temporary NAVs for each received CTS instead of actually updating the NAV, indexed according to the receiver address of each CTS. Each time that a node overhears a new CTS, it will construct an index in this list. After the corresponding ACK is received, this index will be removed from the list. A node has to defer its transmission until both the NAV and all the temporary NAVs expire.

IV. PERFORMANCE EVALUATION

The performance of the CRBAR protocol is evaluated and compared with RBAR using OPNET simulator 11.5 [11].

A. Simulation Setup

Without loss of generality, the IEEE 802.11b physical layer is considered in this paper which provides four rates: 1, 2, 5.5 and 11 Mbps. The CRBAR protocol parameters used in this simulation are listed in Table 2, the functions of which have been explained above. Their optimizations are beyond the scope of this paper. For simplicity, the diversity gain $D$ is assumed to be 5 dB for all the modulation schemes. We study the performance of CRBAR in a single hop scenario (250m×250m) where nodes can hear each other via at least the basic rate of 1Mbps. To examine the effectiveness of the relay schemes, five sources are set at the left edge of this area and their destinations are set at the right edge. Each flow is saturated with payload size 1000 bytes. Mobile nodes are randomly distributed in this area which may act as potential relays. The random waypoint model [12] is used to model the node mobility. The Ricean fading model is used to model the small-scale multi-path fading [13]. The Ricean K factor is fixed to 5 in this paper.

B. Simulation Results

Due to the limitation of paper length, we only report the throughput and cooperation ratio here. The cooperation ratio is defined as the ratio of the throughput acquired via a relay to the aggregate throughput acquired via both direct transmission and relaying.

1) Impact of the number of potential relay nodes

We increase the number of mobile nodes in this area from 0 to 10. The random waypoint model with a speed uniformly distributed in [0, 5m/s] is used. The maximum speed in this environment is 5m/s. Pause time between moves is set to be 0s which corresponds to continuous motion. As shown in Figure 3, both CRBAR schemes significantly improve the performance compared to RBAR with the increasing number of potential relay nodes. When there is no potential relay node in this area, the performance of CRBAR with SR only is a little worse than RBAR due to periodic relay searching overhead. However, the CR scheme already has cooperation opportunities by cooperating with its neighbouring senders as shown in Figure 4. Even though only a few potential relay nodes exist, the CR scheme can still achieve a high cooperation ratio compared to the SR only scheme since it can effectively utilize the nodes close to a sender but far from a receiver. With the increasing number of potential relay nodes,

<table>
<thead>
<tr>
<th>Table 1. The duration reserved by different packet types</th>
<th>Table 2. The CRBAR protocol parameters used in simulations</th>
</tr>
</thead>
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<td>Duration/Input</td>
</tr>
<tr>
<td>RTS</td>
<td>$\text{CTS + N} \times \sigma + \text{RTR} + 3 \times \text{SIFS}$</td>
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</tr>
</tbody>
</table>
both schemes obtain a similar cooperation ratio. More potential relay nodes cannot help more due to the contention among them.

2) Impact of the mobility of potential relay nodes

Mobility affects not only the location of nodes but also the channel coherent time. In this section, we fix the number of potential relay nodes to 10 and investigate the impact of their mobility. For a typical WLAN environment with nodes moving at walking speeds (e.g. \( \leq 2 \) m/s), channel variations occur slowly and both CRBAR schemes can improve the performance by up to 40\% compared to RBAR as shown in Figure 5. However, as the speed increases, channel variations occur much more rapidly degrading the predictability of the channel. All the schemes encounter a decline in performance with the increasing speeds. The CRBAR schemes outperform RBAR for all the speeds though their performances degrade more quickly. That is because that the potential relay nodes have to estimate the bi-directional channels resulting in a higher estimation error. The cooperation ratios just reduce a little as shown in Figure 6 and thus the degraded performance mainly results from the transmission error and increased retransmission attempts.

V. CONCLUSION

This paper presents a Cooperative Relay-Based Auto-Rate MAC protocol (CRBAR) with reactive relay selection. Preliminary simulation results show that it can significantly improve performance under dynamical channel and network topology via adaptive MAC-layer relaying. Furthermore, cooperative relaying scheme with packet combining increases cooperation ratio and outperforms simple relaying scheme. For future work, we are comparing our scheme with proactive relay selection schemes and combining their respective advantages.

REFERENCES