Opportunistic Media Access Control and Rate Adaptation for Wireless Ad Hoc Networks

Jianfeng Wang, Hongqiang Zhai, and Yuguang Fang
Department of Electrical and Computer Engineering
University of Florida
Gainesville, FL 32611, USA
E-mail: jfwang@ufl.edu, zhai@ecel.ufl.edu, and fang@ece.ufl.edu

Maria C. Yuang
Department of Computer Science and Information Engineering
National Chiao Tung University
1001 Ta Hsueh Road, Hsinchu, Taiwan
E-mail: mcyuang@csie.nctu.edu.tw

***Abstract*— Many rate adaptation schemes at the medium access control (MAC) layer have been proposed to utilize the multi-rate capability offered by the IEEE 802.11 wireless MAC protocol through automatically adjusting the transmission rate to best match the channel conditions. In this paper, we present the Opportunistic packet Scheduling and Auto Rate (OSAR) protocol to exploit the channel variations. The basic idea of OSAR is as follows: rather than just matching the channel condition for a node pair in communications, our protocol takes advantage of the multi-user diversity as much as possible and adapt the rate accordingly, i.e., based on the channel conditions to its neighboring nodes, the sender chooses the neighboring node with channel quality better than certain level to schedule the transmissions of packets in its queue, then the overall system throughput may be increased. The key mechanisms of OSAR are channel aware media access, rate adaptation and packet bursting. We carry out several sets of ns-2 simulations and evaluate the impact of various factors such as channel condition, network topology and traffic load on the throughput of OSAR. Simulation results show that our proposed protocol can achieve much better performance than other auto rate schemes.**

Keywords- Rate adaptation, Medium access control (MAC), Multiuser diveristy, Ad hoc networks

I. INTRODUCTION

In wireless ad hoc networks, especially in mobile environments, channel conditions are time-varying. For a given node pair, the link quality may be too poor to transmit any data even at the lowest data rate or may be so good that a high data rate can be achieved.

One of solutions to deal with the channel variations in wireless ad hoc networks is to adapt the transmission rate to the channel state. The IEEE 802.11a, 802.11b and 802.11g provide physical layer capability to support multiple data rates. Auto rate schemes proposed in [1-3] showed significant throughput gain by matching the data rate with the channel condition. However, these schemes considered only the time-domain diversity of a single node pair.

Another interesting way to deal with the channel variations in wireless networks is to exploit the multiuser diversity. Opportunistic multiuser communications have been extensively explored in wireless cellular networks [4-6]. A scheduling algorithm, which exploits the inherent multiuser diversity while maintaining fairness among users, has been implemented as the standard algorithm in the Qualcomm's HDR [7] (High Data Rate) system (1xEV-DO).

In wireless LANs or mobile ad hoc networks, it is usual that a node concurrently communicates with several neighbors. Since channel quality are normally time-varying and independent across different neighbors, this provides the node a opportunity to choose one of its neighbors with good channel quality to transmit data before those with bad channel quality, if the FIFO (First-In-First-Out) service discipline is not strictly enforced. Thus, it is interesting to know how we can schedule the transmissions of packets to its neighbors to improve the performance and find out the significance of such multiuser diversity in contention-based ad hoc networks. All previous schemes on multiuser diversity are based on wireless cellular networks where a base station acts as the central controller and control channels are available for channel state feedback. The methodology to design MAC protocol in the contention-based wireless ad hoc networks is much different from that in wireless cellular networks. To exploit the multiuser diversity in the distributed fashion, Qin and Berry[8] proposed the channel-aware ALOHA. The work considered an uplink model where a group of users are all communicating to a single receiver, such as an access point in a wireless LAN or a base station in a cellular setting.

To exploit the mulituser diversity in the CSMA/CA based wireless ad hoc networks, in this paper, we present a new MAC protocol, i.e., the opportunistic packet scheduling and auto rate (OSAR) protocol. This protocol takes advantage of both multi-user diversity and rate adaptation. Specifically, based on Multi-RTS channel probing, only one of the backlogged users with channel quality better than certain level is allowed to access media. By reusing collision avoidance handshake, the overhead to utilize diversity is very small.

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The rest of the paper is organized as follows. The protocol is presented in the next section. Simulation results considering various factors are given in section III. Finally, section IV concludes our work.

II. OSAR PROTOCOL

A. Protocol model

Given that a node sends RTS and no collision occurs, the signal to noise plus interference ratio (SINR) and the network allocation vector (NAV) at a given receiver are major factors to determine whether the following data transmission is allowed or not and which data transmission rate can be achieved. We model the channel [11] as (1). The rate adaptation between sender i and receiver j at time t is given in (2).

$$\begin{aligned} Pr_{ij}(t) &= P_i(t)g(d_{ij}(t))r_{ij}^2(t) \\ SINR_{ij}(t) &= \frac{P_i(t)g(d_{ij}(t))r_{ij}^2(t)}{\sigma^2 + \sum_{k\in\Omega_j(t)} P_k(t)g(d_{kj}(t))r_{kj}^2(t)} \\ g(d) &= \frac{G_t G_r \lambda^2 d_0^{\alpha-2}}{(4\pi)^2 L d^{\alpha}} \end{aligned} \tag{1}$$

$$R_{ij}(t) = \begin{cases} 0 & \text{if } SINR_{ij}(t) < \beta_0 \text{ or } NAV_j > 0 \\ R_k & \text{if } \beta_{k-1} \le SINR_{ij}(t) < \beta_k, \\ & \quad k = 1,\ldots,N-1 \\ R_N & \text{Otherwise} \end{cases} \tag{2}$$

where R is the data rate, β is the threshold of SINR, $P_i(t)$ is the transmission power of the sender at time t, $P_k(t)$ is the transmission power of the interfering node k at time t, $d_{ij}(t)$ is the distance between the sender i and the receiver j at time t, $d_{kj}(t)$ is the distance between the interfering node k and the receiver j at time t, $r_{ij}(t)$ is the small-scale fading parameter from the sender i to the receiver j at time t, $r_{kj}(t)$ is the small-scale fading parameter from the interfering node k to the receiver j at time t, $\Omega_j(t)$ is the set of nodes interfering the receiver j at time t , σ^2 is the power of the background noise, G_t and G_r are the transmit and receive antenna gains (assuming they are the same for all nodes), α is path-loss exponent, d_0 is the reference distance, and L is a system loss factor (L = 1 in our simulations). The rate adaptation scheme is based on signal to noise ratio[1].

According to the Ricean fading model and the Clarke-Gans model, the channel coherence time may be on the time scale of several packet transmissions. By granting the channel access for transmission of multiple back-to-back packets in proportion to the ratio of the achievable data rate to basic rate, more throughput gain can be obtained from the reduction on the overhead of channel contention and channel probing (i.e., the exchange of RTS/CTS). Moreover, the time-share fairness can be ensured [3].

B. Protocol components

Four main components spanning over the link layer, the MAC layer and the physical layer are employed in our scheme to achieve the benefits of cross-layer design.

1) Link layer queue management

Before the transmission of RTS from a sender, one of its address lists of candidate receivers with bounded length is chosen according to specific scheduling policy if the sender has several packets in its queue waiting for transmissions. OSAR maintains several queues in each node and one queue is for one next-hop. Considering the significance of control packets in comparison with data packets, a separate queue is maintained for network layer control packets. Another separate queue is maintained for broadcast packets other than network layer control packets. According to the routing protocol used, appropriate scheduling policy should be designed to achieve optimal cross-layer interaction effects. In this paper, we focus only on the scheduling among unicast data flows. Specifically, the round robin scheduling (RR) is adopted in our scheme to address the fairness between different links. We believe that the fairness and QoS can be enhanced by more complex scheduling such as Earliest Timestamp First (ETF).

2) Multicast RTS

Recognizing that RTS/CTS is a common mechanism for wireless local area networks and multihop ad hoc networks, we propose to use RTS/CTS handshake procedure for collision avoidance and channel probing in our scheme. RTS used by 802.11 is unicast in that only one receiver is targeted. In our protocol, we use multiple candidate receiver addresses in RTS and request those receivers in the receiver list to receive the RTS and measure channel quality simultaneously. The wireless share media with omni-directional antenna makes this mechanism possible without incurring much overhead. The motivation using multicast RTS is to probe the channels among the selected candidate receivers. Thus, the receivers with channel quality better than certain level can be targeted. Fig. 1 shows the format of RTS frame. Targeted data rate is added to the RTS for the declaration of the data rate that the sender wants to achieve. We dynamically set targeted data rate according to the recent measured channel conditions among those candidate receivers in the list. Each node monitors the transmissions of its neighbors and records the received power. In addition, considering both packet size and data rate are variable, we use the packet size rather than the duration into RTS for each candidate receiver so that the correspondent receiver can derive duration according to the selected data rate based on the channel condition.

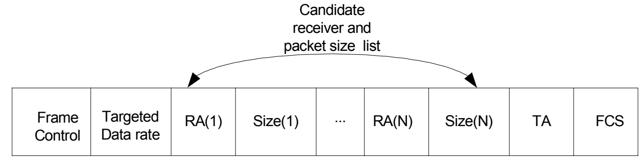


Figure 1. Format of Multicast RTS fame

[1] Achievable data rates as a function of received power and signal to noise ratio are available from http://www.swisswireless.org/, which includes parameters in several implemented WLAN systems such as Orinocco cards PCMCIA Silver/Gold and CISCO cards Aironet 350.

3) Prioritized CTS with channel awareness

After receiving RTS, the candidate receivers evaluate the channel condition and apply the criteria specified by (2) to calculate the appropriate data rate. If achievable data rate is higher than the targeted data rate announced in the RTS, it is allowed to transmit CTS.

To avoid collision when two or more intended receivers are qualified to receive data at the targeted data rate, a service rule is applied. The listing order of intended receivers in the RTS announces the priority of the media access among candidate receivers. To prioritize the receivers, different Inter-Frame Spacings (IFSs) are employed. For example, the IFS of the n^{th} receiver equals to *SIFS + (n-1) * time_slot*. The receiver with highest priority among those who have capability to receive data packet at targeted data rate or above would reply CTS first. The length of candidate receiver list is bounded by a certain number, which is a design parameter. Bigger receiver list means more diversity, but also means the longer waiting time before the sender makes sure that there is no qualified receiver. Fortunately, it has been shown by our simulations that the number of the intended receivers, even with as small as 4, can achieve significant multi-user diversity.

Since all candidate receivers are within one-hop transmission range of the sender and the carrier sensing range are normally larger than two hops of transmission range no matter what data rate is used to transmit (if transmission power is kept the same), the CTS should be powerful enough to reach all other qualified candidate receivers that can hear or sense. These receivers would yield the opportunity to the one transmitting CTS in the first place, i.e., the one with the good channel condition and highest priority.

Multicast RTS and prioritized CTS with channel awareness parallelize the multiple serial unicast RTS/CTS messages, so the overhead of channel contention and channel probing can be reduced significantly. Another important benefit is alleviation of the Head-of-the-Line (HOL) problem. P. Bhagwat et al first presented the HOL problem for wireless LAN in [10]. We take a much different approach from [10] to address the HOL problem for both WLANs and ad hoc networks.

4) Rate adaptation and packet bursting

Equation (2) is provided as the criteria to choose the modulation rate setting. We use rate adaptation and packet bursting to opportunistically utilize the high quality channel for multiple packet transmission at an appropriate rate matching channel condition. Packet bursting is a measure introduced in IEEE 802.11e and enhanced in the OAR[3] to better utilize the medium and improve the performance. With packet bursting, a station is allowed to transmit multiple packets successively without contending for the media again after accessing the channel, as long as the total access time does not exceed a certain limit. We follow the thought of OAR to grant channel access for multiple packets in proportional to the ratio of the achievable data rate over the basic rate.

C. Protocol operation

Here we present the detailed OSAR protocol operations in the following few steps.

Step 1: A node neither in transmission state nor receiving state monitors the channel and transmits a multicast RTS if the channel is IDLE. Anyone except the candidate receiver who receives the RTS should tentatively keep silent to avoid possible collision before the sender receives the CTS. After a qualified receiver is selected and transmission duration is determined and fed back by CTS to the sender, the sender will include the duration in the subheader of DATA for the final NAV setting. The subheader is referred to as the Reservation SubHeader (RSH), which has already been employed in the MAC header of data packets by IEEE 802.11, RBAR [2] and OAR [3]. RSH is sent at the basic rate so that all overhearing nodes can decode.

Step 2: Not all the candidate receivers may correctly decode the RTS because of poor channel quality. Those who can correctly decode the RTS and have zero NAV will conduct channel quality evaluation and judge if they are qualified to receive successive data packets at the data rate targeted by the sender. If yes, they will prepare to reply CTS by deferring the duration of *SIFS + (n-1) * time_slot,* where n is the index in the candidate receiver list for the corresponding candidate receiver. Data rate derived from (2) will be included in the CTS for the following DATA transmission and ACK transmission. Duration to be advertised in the CTS is set to 2*SIFS plus transmission time for DATA and ACK. If channel is idle during the deferring period, the corresponding candidate receiver will transmit the CTS at the basic rate, otherwise it just cancels replying CTS and returns to the normal state.

If the sender receives a CTS successfully, it goes to Step 3, else goes to Step 1.

Step 3: Once the sender receives a CTS, it would set data transmission rate as specified in the CTS and transmit DATA after SIFS. The number of data packets granted to transmit back-to-back is set to the floor function of transmission rate/basic rate. If the granted number is greater than 1 and there is more than 1 packet in the queue intended for the receiver, the More Fragments bit in the MAC header of DATA is set to 1 and the duration value in the MAC header of DATA is set to the time, in microseconds, required to transmit the next data packet, plus two ACK frames, and plus three SIFS intervals. Otherwise, the More Fragments bit is set to 0, the granted number is set to 1 and the duration value is set to the time, in microseconds, required to transmit one ACK frame, plus one SIFS interval. Upon receiving ACK, the sender would decrease the granted number and check if the granted number is still greater than 0. If so, it transmits DATA and applies the rule indicated above to set the More Fragments bit and the duration value in the MAC header of DATA. Otherwise, it goes to Step 1.

Step 4: The receiver replies with ACK after receiving DATA successfully. The duration value included in ACK is set to the duration specified in the received DATA minus SIFS and ACK. If the sender receives ACK correctly, it goes to Step 3, otherwise it goes to Step 1.

III. Simulation and Analysis

In this section, we use the ns-2 simulation package to evaluate the performance of our protocol and compare it with

OAR. The available rates for both OAR and OSAR, based on IEEE 802.11b, are set to 2 Mbps, 5.5 Mbps and 11 Mbps. The values for SINR thresholds for different data rates were chosen based on the settings of Orinoco™ 802.11b card[2]. Our approach attempts to isolate the impact of each performance factor as much as possible and then study the joint effects of numerous factors.

In both OAR and OSAR, we maintain a separate queue for each active neighbor and schedule data packets in the manner of round robin. The maximum length of the candidate receiver list is set to 4 and the corresponding DIFS is set to 90 us. The Ricean fading channel model in ns-2 module we use is originally developed by CMU ARC group [9] and enhanced later by Rice Networks Group [3]. To characterize the channel condition, we use the Average Fade Probability, which is the probability that the received power is less than the received power threshold for basic rate defined by 802.11. The background noise power is set with 100dBm.

The data packet size is set to 1000 bytes in all simulations and each reported result is the average over 10 or above 200-second simulations. Moreover, to isolate the effect of routing protocol on performance and study more clearly the performance of OSAR at the link layer and the transport layer, we adopt the Dumb Routing Agent defined in ns-2 as the routing agent. Finally, all throughput results we provide are end-to-end data throughput.

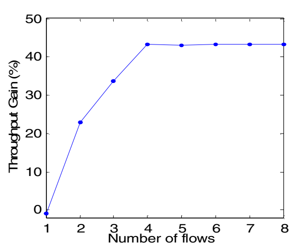


Figure 2. OSAR throughput gain as a function of the number of flows in WLANs

A. *Wireless LANs*

The Wireless LANs we are simulating here run in the DCF mode. Since most of traffic is from an access point to terminals in practical scenarios, we configure the networks in the way that all the traffic sources originate from the access point and all sinks reside in terminals. Each flow is destined to a unique node.

1) *The Number of Users*

To explore the multi-user gain, we vary the number of flows with the setting that the channel condition of each link is identical and independent. The Average Fade Probability is set to 10%. Traffic is from UDP flows with interval 0.001, which means each active queue is almost not empty at any time.

Fig. 2 shows the throughput gain of OSAR over OAR for different number of flows. We observe that when the number of the flows is 1, OSAR actually gives smaller throughput, say, about 1.5% lower than OAR. This is reasonable because no multi-user gain can be achieved in case there is only one user while OSAR has longer DIFS than that of OAR. When the number of flows increases, throughput gain due to the opportunistic scheduling is manifested. When the number of flows increases to 3 or above, the multiuser gain maintains relatively stable, about 43%. The reason is that the maximum number of candidate receivers is bounded by 4 in our simulation.

2) *Location distribution and channel variations*

Location distribution affects path loss factor and the line-of-sight Ricean parameter K, while the node velocity affects the average channel coherence time, i.e., the speed of the channel variations. We conduct this set of simulation to investigate the overall WLAN throughput considering both diversities of location distribution and channel variations.

We evenly distribute 24 nodes over a 500m*500m square area. The access point is put at the center. Each traffic flow is UDP traffic with interval of 0.05. Fig. 3 indicates that OSAR achieves approximately 52%-78% overall throughput gain over OAR. Besides, each flow by OSAR has higher throughput than OAR. The key reason is that OAR cannot avoid bad channel condition even though it can exploit high quality channel duration. Thus, the HOL problem is still serious with OAR. Our protocol let the candidate receiver in the bad channel state yield channel access opportunity to the one with better channel while keep the same priority to access channel for each candidate receiver in the long term. The simulation time is long enough to let each flow take chance to catch good channel state so each flow achieves much higher throughput.

We also notice that the performance of OSAR degrades while the performance of OAR increases when the velocity is changed from 0.5m/s to 5m/s. This result is due to two effects introduced by the change of the channel coherence duration: the increase of the average channel duration of good quality and the increase of that of poor quality. The former results in more benefits of packet bursting. The latter leads to the more serious HOL problem. In this scenario, because of the diversity of channel quality, the performance of OSAR depends more on channel duration of good quality, but the performance of OAR relies more on channel duration of poor quality because of the HOL problem.

3) *Interaction with TCP*

In this set of simulations, the number of TCP flows is 16 and each link quality follows i.i.d distribution. The simulation time is 3600s. Fig. 4 shows the throughput and the fairness as the channel quality changes. When the average channel quality is very good and data transmission rates can be achieved at 11Mbps almost each time, the OAR performs a little bit better than OSAR. The reason is that the trivial multiuser gain can be achieved if channel is always good and OSAR has more overhead than OAR. With the average channel quality gets worse, the throughput gain for OSAR over OAR increases up to 125%. That is obvious because the HOL problem gets more serious for OAR when the channel becomes worse. It is surprised to see that the fairness is enhanced by our scheme rather than weakened. The fairness index we use is shown as (3), which was proposed by R. Jain et al.[12]. The reason for enhancement of fairness could be as follows. The packet loss,

[2] For 802.11b, we use the specifications for the Orinoco™ wireless NIC which can be found at http://www.orinocowireless.com.

especially the burst packet loss, is the key reason in this scenario leading to instability and unfairness of TCP. Data dropping at the MAC level due to exceedance of maximum allowable RTS retransmission limit or the data retransmission limit is deceased in our scheme.

$$f = \left(\sum_{i=1}^{n} x_i \right)^2 / \left(n \sum_{i=1}^{n} x_i^2 \right) \quad (3)$$

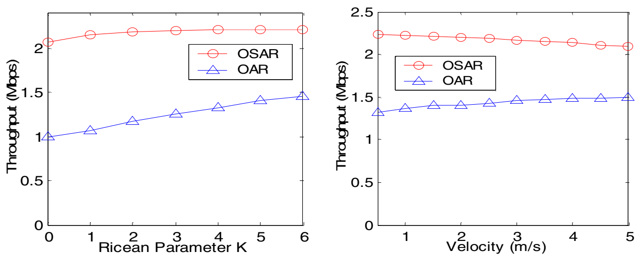


Figure 3. Throughput as a function of Ricean Pamameter K and mobile speed in WLANs

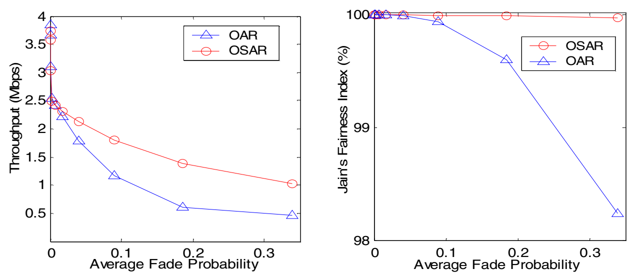
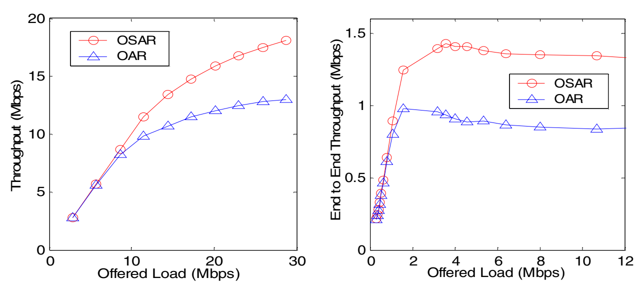


Figure 4. TCP throughput and the fairness as a function of the channel quality in WLANs



5.a One hop flows 5.b Multihop flows

Figure 5. Throughput of one-hop flows and multi-hop flows in the ad hoc networks with grid topology

B. Multihop ad hoc networks

Our final experiment addresses the performance of OSAR in multihop ad hoc networks. We use the grid topology with 100 nodes. One hop distance is set as 200m. We conduct two sets of simulations. First is for one-hop flows and the other is for multihop flows. In the first scenario, each node has a UDP flow destined to each neighboring node. Fig. 5.a shows the simulation results for the first scenario. We observe that when the offered load is light, the throughput gain is not so significant. However, with increasing offered load, OSAR achieves much higher throughput than OAR. Throughput gain results from the increasing spatial reuse. The HOL blocking in this scenario for OAR is mainly due to the fact that a receiver is within the physical or virtual carrier sensing range of other ongoing transmission when the RTS is sent. OSAR enables sender to choose a candidate receiver with clean channel so that the spatial reuse can be greatly improved. In the second scenario, there are 40 UDP flows. Each flow is of 10 hops length. It is shown in Fig. 5.b that OSAR achieves 56% higher throughput than OAR in the saturated state.

IV. CONCLUSIONS

In this paper, we presented an opportunistic media access and rate adaptation protocol (OSAR), whereby multiuser diversity and high quality channel duration can be significantly exploited in CSMA/CA based WLANs and multihop ad hoc networks. Ns-2 simulation results indicate that OSAR normally obtains throughput gains of 40% or higher as compared to the other auto rate adaptation protocols. Since the design of OSAR is based on CSMA/CA, it can be easily incorporated into IEEE 802.11 MAC standard.

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