Contention-Based Prioritized Opportunistic Medium Access Control in Wireless LANs*

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***Abstract*— In wireless environments, the inherent time-varying characteristics of the channel pose great challenges on medium access control design. In recent years, multiuser diversity and opportunistic medium access control schemes have been proposed to deal with the channel variation in order to efficiently improve the network throughput. In this paper, we propose a novel MAC protocol called Contention-Based Prioritized Opportunistic (CBPO) Medium Access Control Protocol. This protocol takes advantage of multiuser diversity, rate adaptation, which utilizes the multi-rate capability offered by IEEE 802.11, and black-burst (BB) contention to access the shared medium in a distributed manner. In particular, rather than simply measuring the channel condition for a node pair in communications each time, with the help of multicast RTS, the candidate users with qualified channel condition are selected and prioritized. Then the qualified receivers contend to send back prioritized clear-to-send message (CTS) with BB, which is a pulse of energy, the duration of which is proportional to the CTS priority. The user with the best channel quality is always selected to send back CTS and receive packets from the sender. Extensive simulation results show that our protocol achieves much better performance than IEEE 802.11 and other auto rate schemes with minimal additional overhead.**

***Index Terms*— Medium access control (MAC), Multiuser diversity, Rate adaptation, Prioritized CTS, Black burst, Wireless LANs.**

I. INTRODUCTION

IN wireless local area networks (WLANs), providing high data rate and reliable services is an important design goal. However, limited and shared medium, time-varying propagation characteristics, hostile interference, distributed multiple access, and energy constraints impose great challenges on medium access control design.

One of the effective approaches to lessen the influence of channel variation is multiuser diversity, which exploits the fact that different users may have different instantaneous channel gains for the same shared medium [1]. Opportunistic multiuser communication utilizes the physical layer information fed back from multiple users to optimize medium access control. By allowing the user with good link condition to transmit, the overall network performance may be greatly improved.

Another way to exploit the channel variation is to adapt the transmission data rate to the channel state. IEEE 802.11a, 802.11b, and 802.11g provide physical layer capability to support multiple data rates. Higher data rates than the base rate are possible when the signal-to-noise ratio (SNR) is sufficiently high such that channel-resiliency demands of error correcting codes and modulation schemes can be relaxed. In IEEE 802.11b, the possible data rates are 1, 2, 5.5, and 11 Mbps. Auto rate schemes proposed in some previous work [2-3] indicate that significant throughput gains can be achieved by matching the data rate with the channel condition. However, these schemes consider only the time-domain diversity of a single node pair.

In wireless LANs, a node typically communicates concurrently with several neighbors. Since channel condition is time-varying and independent across different neighbors, this provides the node an opportunity to choose the neighbor with the best channel quality to transmit data to, with the highest feasible rate. Existing schemes which exploit multiuser diversity can be divided into two categories. One category focuses on selectively transmitting data to a receiver with the best channel condition. The sender decides which receiver to serve after channel probing with query/reply exchanges [4]. This scheme may incur high overhead because if the sender centrally schedules the transmission, it will need to wait for the sequential transmissions of CTS from each user. After receiving CTS which carry the channel condition information of each channel from the candidate receivers, the sender can determine the node with the best channel condition. In the other category, based on the channel condition information, the sender chooses one of the neighboring nodes with channel quality above a certain threshold to schedule the packet transmission [5]. This scheme may incur lower overhead, but the sender may not transmit to the candidate receiver with the best channel

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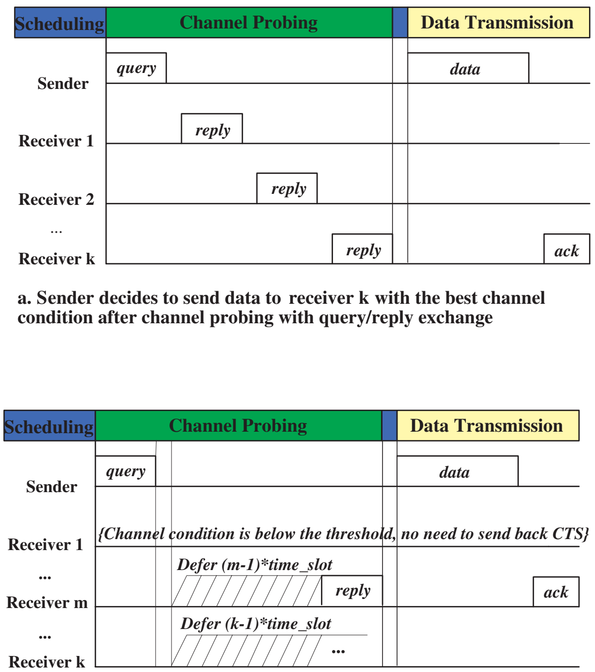
condition, so the overall system throughput improvement may be limited. Fig. 1 shows the basic mechanisms of the two categories.



a. Sender decides to send data to receiver k with the best channel condition after channel probing with query/reply exchange

b. The receiver with the highest priority (The listing order of intended receivers in the RTS announces the priority) among those whose channel condition is above the threshold would reply CTS first

Fig. 1. Basic mechanisms of the two main categories of existing schemes.

These observations provide the key motivation for us to design novel MAC protocols. In this paper, we propose a novel MAC protocol termed Contention-Based Prioritized Opportunistic (CBPO) Medium Access Control Protocol. This protocol exploits multiuser diversity in CMSA/CA based wireless network, data rate adaptation and BB contention. Particularly, based on multicast RTS channel probing, all qualified neighbors contend for the channel with pulses of energy signals called black bursts whose durations are proportional to the channel conditions [6]. Only the neighbor with the highest priority will send back CTS to the sender. Access on the shared medium is managed in a distributed manner. By reusing the collision avoidance handshake, the additional overhead due to utilizing multiuser diversity is very small. It only needs some minor modifications on the frame structure of RTS and there is no need to change the hardware devices. Therefore, we believe our mechanism can be easily deployed in existing WLANs products.

The rest of this paper is organized as follows. The protocol principles are described in Section II. In Section III, we present the simulation results. Conclusions and discussions for future work are presented in Section IV.

II. Methodology

In this section, we present our proposed Contention-Based Prioritized Opportunistic Medium Access Control Protocol (CBPO). Our design is motivated by the following key observations: 1. With multicast RTS probing, multiple candidate receivers can measure the channel quality simultaneously. As the RTS is sent shortly before data transmission, the channel condition measured is relatively accurate. 2. Based on the channel quality, each qualified receiver is prioritized. Black-burst contention resolves in a distributed fashion which candidate receiver will finally access the shared medium. 3. The sender attempts to use higher transmission rates when better channel quality is achieved. Channel coherence times (the durations for which mobile terminals have better-than-average channels) are typically at least multiple packet transmission times. Consequently, when a mobile user is granted channel access, CBPO grants the user a channel access time that allows multiple packet transmission.

A. Protocol Components

There are five main components in our protocol, spanning the physical layer, MAC layer and link layer. Our objective is to optimize the network performance via cross-layer design.

1) Queue Management at The Sender: CBPO maintains several traffic queues and a queue for control packets at each node. In this paper, we focus on the downlink transmissions from an access point (AP) to the receivers. A subset of the candidates for which packets are waiting to be sent are selected and their addresses are sent in a multicast RTS. The selection of this subset may be based on the QoS requirements. For simplicity, in this paper, we use round robin scheduling.

The ultimate objective of the queue management at the sender is to improve the channel utilization while maintaining temporal or long-term fairness among multiple back-logged flows. In our future work, we will present the theoretical analysis of our scheduling policy which aims to maintain fairness and discuss the performance of some approximate scheduling algorithms.

2) Multicast RTS: Common RTS/CTS are widely used in various CMSA/CA based MAC mechanisms for WLANs. We also use four-way handshaking for collision avoidance and channel condition probing in our proposed scheme. As mentioned above, we use multiple candidate receiver addresses in RTS to probe multiple downlinks simultaneously. Fig. 2 shows the format of a multi-addressed RTS. Targeted data rate can be set to a certain threshold, such as the base rate of 802.11b. Each pair $(RA(i), SIZE(i))$ presents the traffic characteristics of each individual receiver. $RA(i)$ is the address of receiver i and $SIZE(i)$ is the total size of all packets destined to the candidate receiver i.

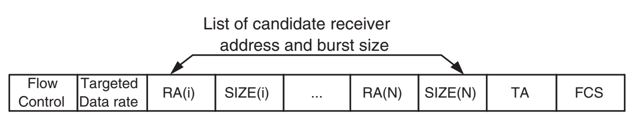


Fig. 2. Format of multicast RTS frame.

3) Channel Condition Awareness and Rate Adaptation: Upon receiving RTS, each candidate receiver evaluates the received signal strength as an indication of channel conditions.

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In this paper, we model the channel [3, 7] by (1) and (2). The signal to noise ratio (SNR) at a given receiver is the most important metric by which we determine the transmission rate.

The received SNR at receiver j for a transmission from sender i at time t is given by

$$SNR_{ij}(t) = \frac{P_i\,(t)\, d_{ij}\,(t)^{-\alpha}\, \rho(t)}{\sigma^2} \tag{1}$$

where $P_i\,(t)$ is the sender's transmission power at time t and it is reasonable to assume that the sender's transmission power is always constant. $d_{ij}\,(t)$ is the distance between sender i and receiver j at time t, α is the path loss exponent, $\rho(t)$ is the average channel gain for the packet at time t, and σ^2 is the variance of the background noise $z(t)$. We use the Ricean distribution for $\rho(\cdot)$, i.e.,

$$p(\rho) = \frac{\rho}{\sigma^2} e^{-(\frac{\rho^2}{2\sigma^2}+K)} I_0(2K\rho) \tag{2}$$

where K is the distribution parameter representing the strength of the line of sight component of the received signal and I_0 is the modified Bessel function of the first kind and zero-order. Specifically, when $K = 0$, the Ricean distribution reduces to the Raleigh distribution where there is no line-of-sight component.

The rate adaptation between sender i and receiver j can be specified as

$$R_{ij}\,(t) = \begin{cases} 0 & if\ SNR_{ij}\,(t) < \beta_0\ or\ NAV_j > 0 \\ R_k & if\ \beta_{k-1} \le SNR_{ij}\,(t) < \beta_k, \\ & k = 1, ..., N-1 \\ R_N & otherwise \end{cases} \tag{3}$$

where R_k is the kth achievable transmission rate, $k = 1, \ldots, N-1$, β_k is the upper bound of SNR for rate R_k.

4) Black-Burst Contention of Prioritized CTS: If the achievable data rate is no less than the targeted rate which is listed in the RTS, the given receiver is qualified to participate in the contention for transmitting CTS. In order to avoid a collision when more than one qualified receiver intends to send CTS, a priority-based service discipline is implemented. Firstly, each qualified receiver calculates its theoretical shortest cycle duration of the data traffic according to the following formula:

$$\begin{aligned} T_c \;\; = \;\; & DIFS + t_{RTS} + SIFS + t_{CTS} + SIFS \\ & + \left(\tfrac{PHY_{hdr}+MAC_{hdr}}{R_{base\_rate}} + \tfrac{L_{pkt\_size}}{R_{achievable}}\right) \cdot N_{pkt} \\ & +(2N_{pkt}-1) \cdot SIFS + N_{pkt} \cdot t_{ACK} \end{aligned} \tag{4}$$

where N_{pkt} is the packet number in the queue for transmission, L_{pkt_size} is the packet length. t_{RTS}, t_{CTS}, and t_{ACK} are the transmission durations for RTS, CTS and ACK, respectively. $SIFS$ represents Shortest InterFrame Spacing and $DIFS$ represents DCF InterFrame Spacing. The physical and MAC headers are transmitted at base rate while the data payloads are transmitted at the achievable data rate $R_{achievable}$. Thus the average efficient transmission rate of a certain traffic burst can be derived as:

$$R_{ave\_efficient} = \frac{L_{pkt\_size} \cdot N_{pkt}}{T_c} \tag{5}$$

For a given candidate receiver, the higher the average efficient rate, the more the throughput gain. It is obvious that a higher efficient data rate corresponds to better channel condition. In addition, if the transmission power does not increase with time, it means less energy is used to achieve the same network throughput. Therefore, we choose $R_{ave\_efficient}$ as the link metric to prioritize each candidate receiver, denoted by P_i:

$$P_i = \left\lceil \frac{R_{ave\_efficient} \cdot n}{R_{peak\_rate}} \right\rceil \tag{6}$$

where n is a constant coefficient for quantization, R_{peak_rate} is the peak rate the system can achieve theoretically. All qualified candidate receivers will then start transmission of BB to contend for channel access. The duration of BB is a function of the CTS priority, i.e. a candidate receiver sends BB for a duration of $P_i \cdot t_{slot}$. After sending its BB, a receiver will listen to the channel to see if the channel is idle. If the answer is negative, it refrains from future transmissions and returns to normal state; otherwise, it knows that it has captured the right to access the channel. The receiver with the highest priority will send the BB with the longest duration, so it has the best chance to capture the uplink channel and reply CTS first. The whole process of our mechanism works as shown in Fig. 3. RTS and CTS messages are always sent at the base rate so that all nodes are informed of the modified data transmission duration to enable them to set their backoff timers accordingly. In order to circumvent the problem of more than one candidate receiver having the same priority, we set priority with a moderate number of levels and add a small random additional priority to each receiver. Optimal BB contention relies on synchronization among different candidate receivers, but our mechanism can tolerate dis-synchronization to some extent because BB contention is evoked after an SIFS and we choose a moderate value for CTS priority so that minor dis-synchronization will not significantly influence the results of BB contention.

To avoid collisions when more than one qualified receiver intends to receive data at a high data rate, we adopt the BB contention rules. Multicast RTS and prioritized CTS with BB contention for channel awareness parallelizes the multiple serial unicast RTS/CTS contention so that the overhead and time cost of channel probing and channel access contention can be significantly reduced. [5] discussed a scheduling mechanism, in which each qualified receiver prepares to reply CTS by employing different InterFrame Spacings (IFSs) (See Fig. 1b). For example, the IFS for the n^{th} receiver equals $SIFS + (n-1) \cdot t_{slot}$, where n is the listing order of the intended receiver in RTS, which is also the announced priority for the corresponding receiver. Data rate derived from SNR will be included in the CTS. The receiver with the highest priority among those who have the capability to receive data transmission at the target data rate or above would reply CTS first. The length of the candidate receiver list is bounded by a certain number, which is a design parameter. A longer receiver list means more diversity, but it also means longer

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waiting time before the sender is able to ensure that there is no qualified receiver. In this scheme, due to the fact that all other candidate receivers would yield the access opportunities to the one transmitting CTS in the first place, i.e., the one with the relatively good channel condition and highest priority (minimum listing order), it does not guarantee that the sender will always transmit to the neighbor with the best channel condition. Hence, it constrains the throughput improvement of the entire system. However, in our protocol, we bind the priority with the channel condition rather than the listing order. With the help of BB contention, an individual receiver will be able to determine by itself whether its priority is the highest or not. The sender always serves the candidate receiver with the best channel condition. This distributed approach not only effectively shortens the sender's waiting time, but also takes full advantage of multiuser diversity.

5) Packet Bursting: Packet bursting is an efficient approach to opportunistically exploit high quality channels when they occur via transmission of multiple back-to-back packets. It is a measure introduced in IEEE 802.11e and enhanced in OAR [3]. With packet bursting, in our mechanism, a selected qualified receiver with the highest priority is allowed to successively transmit multiple data packets in its corresponding traffic queue without contending for the channel repeatedly. We follow the idea in OAR to grant channel access for multiple packets in proportion to the ratio of the achievable data rate to the base rate.

B. Protocol Principles

In this subsection, we present the details of CBPO as follows.

- The sender in WLAN (i.e. the access point) senses the channel condition and transmits a multicast RTS when the channel is idle. Anyone except the candidate receivers identified in the RTS will keep silent to avoid possible collisions before the sender receives the CTS. Once the sender receives the CTS which is sent by the receiver with the highest priority, it will estimate the medium busy duration based on the achievable data rate and include this information in the MAC header of the data burst for the Network Allocation Vector (NAV) setting of other receivers.
- Once the candidate receivers successfully decode RTS, each will conduct channel quality evaluation and data rate adaptation by applying the criteria specified by (3) to get the achievable data rate for the following data burst. If the achievable data rate is higher than the targeted rate which is declared in RTS, the receiver is qualified to participate in the following contention for transmitting CTS.
- Each qualified receiver evaluates its cycle duration and average efficient rate according to the criteria specified by (4) and (5) and obtains its priority by (6). After SIFS, the qualified receivers send out black bursts for a duration proportional to their priorities. After the black burst transmission, the channel will be sensed for an SIFS for verification. If the channel is busy, the receiver simply quits the contention and keeps silent until it receives another RTS; otherwise, it sends back CTS to the sender after SIFS. In this way, the receiver with the highest priority will always have the chance to access the channel because of its longest black burst.
- If the sender successfully receives a CTS within T_{wait_time} (a waiting duration for receiving CTS), it goes to the subsequent step, otherwise it goes to the beginning of the procedure after the waiting timer expires.
- Once the sender successfully decodes the CTS, it sets the data rate as specified in CTS and transmits the data after SIFS. The number of packets allowed to be transmitted back-to-back is set to $\left\lfloor \frac{R_{achievable}}{R_{base\_rate}} \right\rfloor$. If the granted number is greater than 1 and there is more than one available packet in the queue, the "more flag" bit in the MAC header of the data packet is set to 1 and the duration value is set to the time, in microseconds, required to transmit the next data packet, plus two ACK frames, and three SIFS intervals. Otherwise, the "more flag" bit is set to 0.

III. Simulation Results

In this section, we use ns-2 simulations to investigate the performance of CBPO and compare it with the base-rate IEEE 802.11b and OAR. The key mechanism of the OAR protocol is to opportunistically send multiple back-to-back data packets to the same receiver whenever it experiences good channel quality. The base rate for all three protocols is set to $2Mbps$. In both CBPO and OAR, we maintain a separate queue for each active neighbor and schedule data packets in a round robin manner. The maximum length of the candidate receiver list is 4 unless stated otherwise, and the value of the highest priority level is set to 10.

We construct a network with a square area of $300m \times 300m$, within which an access point is located at the center, and 24 other nodes are randomly distributed over the square area. Each traffic flow is UDP traffic following the Poisson traffic model with an average inter-arrival time of $0.005s$, which means that each active queue is almost never empty.

Here we study the performance of our proposed protocol in fully connected topologies in which all nodes are within radio range of each other and all the candidate receivers are within one-hop transmission range of the sender. The wireless LANs we investigated run in the Distributed Coordination Function (DCF) mode. Since most traffic is from the access point to terminals in practice, we configure the network such that all the traffic originates from the access point and all sinks reside at terminals. Each flow is destined to a unique node. The vaues of different SNR thresholds for different rates are set according to $Orinoco^{TM}$ 802.11b card [8]. In order to isolate the effects of certain routing protocol, we use Dumb Routing Agent in ns and the performance metric is the average network throughput.

1) Number of Flows: To study the multiuser gain, in this set of experiments, we vary the number of flows in the network, which indirectly also varies the number of nodes, as each flow is between a unique source-destination pair of nodes. Fig. 4 shows the network throughput of CBPO for different numbers of flows for a Ricean parameter $K = 2$. When the flow number is 1, CBPO also gives a small throughput. It is reasonable

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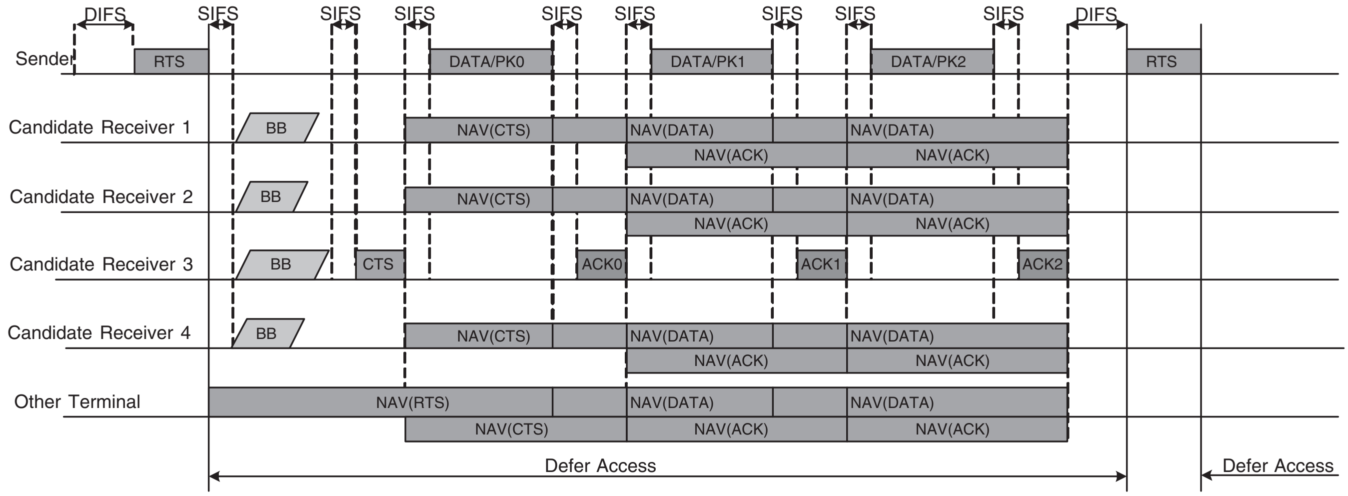

Fig. 3. Illustration of medium access diversity.

because no multi-user gain can be achieved. However, with the increase of flow number, the throughput gain is evident. Our simulation results manifestly show that the number of the candidate receivers, even as small as 4 in our scenario, can effectively achieve significant multi-user diversity. When the number of flows increases beyond 4, the network throughput improvement stabilizes. This is because the maximum number of candidate receiver list is set to 4 in our simulation.

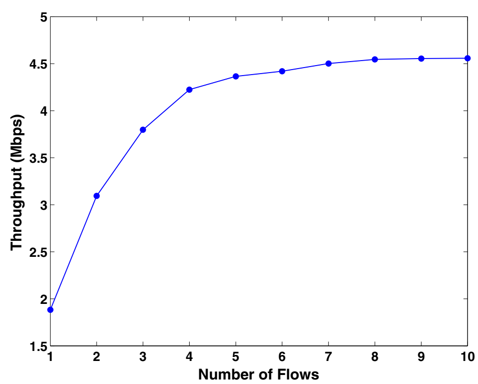

Fig. 4. CBPO throughput as a function of the number of flows.

2) Optimal Value of Receiver List: In this subsection, we attempt to experimentally answer the question of "What is the optimal number of the receivers a sender should query in one transmission dialogue simultaneously?". We consider a network model where the sender is located at the center of a square area $D \times D$. 10 UDP traffic flows originate from the sender to individual terminals. D varies from $50m$ to $300m$ to represent different cases in wireless LANs. The plotted figure is shown in Fig. 5 from which we can make some observations. First, the optimal value of the receiver list increases with D. Second, a larger maximum size of candidate receiver list may mean more multiuser diversity. However, from the simulation results, we can see that the network performance may not improve in some cases. On the contrary, it may introduce some additional complexity to the system such as large RTS messages and some meaningless BB contentions which may degrade the performance of the entire network. For instance, when candidate receivers are all close to the sender ($D = 50$ or $D = 100$), the probability of the sender achieving peak rate for data transmission is high, and as a result, multiuser diversity gain will be overshadowed by additional overhead even with a small value of receiver list.

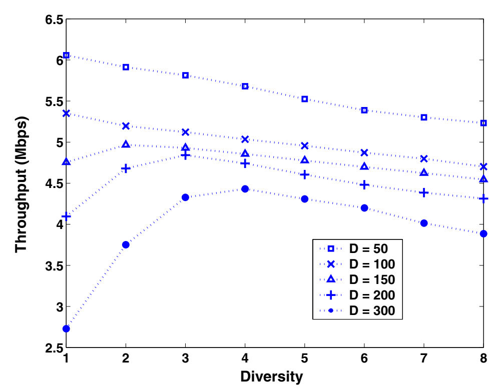

Fig. 5. CBPO throughput as a function of the value of receiver list.

3) Channel Quality: To characterize the channel condition, we vary the distance between the sender and the receiver. In this set of simulations, we evaluate the impact of channel condition on the network throughput. The number of UDP flows is 24. Fig. 6 shows the throughput drops as the channel condition degrades. When the average channel quality is very good and high data rate is always achieved, OAR performs a little better than CBPO. It is reasonable because hardly any multiuser gain can be achieved if channel condition is good and CBPO has a little bit more overhead in RTS/CTS messages and also wastes some time on BB contention. However, as the channel condition gets worse, the performance of CBPO greatly outperforms OAR due to the effects of multiuser diversity. Without multiuser diversity and rate adaptation, the base-rate IEEE 802.11b always performs worst.

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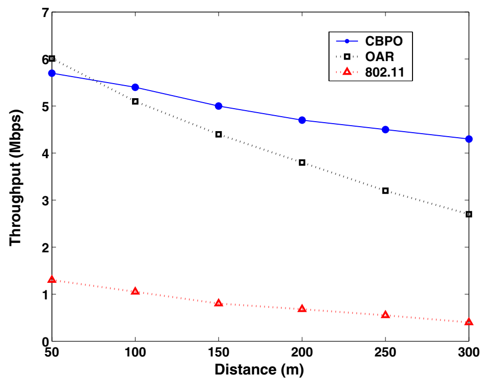

Fig. 6. Throughput as a function of the channel quality.

4) Line-of-Sight Component K: Here, we study the effect of the Ricean parameter K on the performance of CBPO, OAR, and base-rate IEEE 802.11b. For $K = 0$, the channel has no line-of-sight component such that only reflected signals are received and hence, overall channel quality is relatively poor. With increasing K, the overall channel SNR increases and higher data rate is feasible more often. Fig. 7 shows that CBPO achieves much higher throughput than base-rate 802.11b and OAR. It obtains throughput gains of more than 400% over base-rate IEEE 802.11b and 45% or higher as compared to OAR. The line-of-sight component has less influence on CBPO because our protocol forces the candidate receivers with bad channel conditions to yield channel access opportunity to the one with the best channel quality in each round, while keeping the same priority to access the channel for each receiver in the long term.

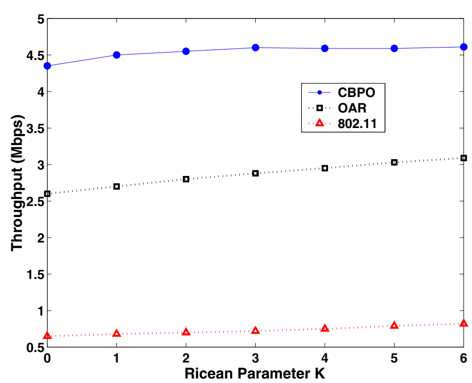

Fig. 7. Throughput as a function of Ricean Parameter K.

5) Node Mobility: A node's mobility will affect its channel in two ways [3]. First, it changes the nodes' location which affects a pair of nodes' line-of-sight Ricean parameter K. Second, it affects the average channel coherence time as a node with higher velocity has a lower average coherence time, hindering the ability to exploit opportunistic scheduling. The throughputs for CBPO, OAR, and base-rate 802.11b are depicted in Fig. 8 for speeds from $1m/s$ to $5m/s$. The number of UDP flows is 24. As can be seen, with the increase of velocity, the performance changes of CBPO are small. This is because within this range of velocities, the coherence time is sufficiently long to extract the full performance gain.

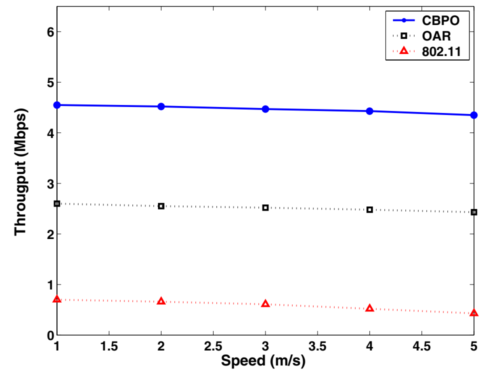

Fig. 8. Throughput as a function of mobile speed.

IV. Conclusions

In this paper, we propose Contention-Based Prioritized Opportunistic (CBPO) Medium Access Control Protocol. In CBPO, with the help of multicast RTS channel probing, multiple users contend to access the channel with BB contention for a duration that allows multiple packet transmissions so that the user with the best channel quality is always selected to send back CTS. Particularly, it takes advantages of multiuser diversity, rate adaptation scheme which utilizes the multi-rate capability of IEEE 802.11, and black-burst contention to access the shared medium in a distributed manner. We have implemented our mechanism in ns-2 with realistic channel conditions. Extensive simulation results indicate that CBPO obtains throughput gains of more than 400% over IEEE 802.11b, and 45% or higher over other auto rate protocol with relatively small overhead. In the future, we will study the performance of our mechanism in multi-hop ad hoc networks.

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