Opportunistic Packet Scheduling and Media Access Control for Wireless LANs and Multi-hop Ad Hoc Networks

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Abstract— **In the wireless LANs or mobile ad hoc networks, a node with multi-packets in its queue waiting for delivery to several neighboring nodes may choose to schedule a candidate receiver with good channel condition for transmission. By choosing a receiver with good channel condition, the Head-of-Line (HOL) blocking problem can be alleviated and the overall system throughput can be increased. Motivated by this observation, we introduce the Opportunistic packet Scheduling and Media Access control (OSMA) protocol to exploit high quality channel condition under certain fairness constraints. We base our design on CSMA/CA so that it can be simply incorporated into the 802.11 standard.The key mechanisms of OSMA protocol are multicast RTS and priority-based CTS. In the OSMA protocol, RTS includes a list of candidate receivers. Among those who are qualified to receive data, the one with the highest order would be granted to catch the channel by replying CTS in the first place. The ordering list will be updated dynamically according to certain scheduling policy such as Round Robin (RR) and Earlier timestamp First (ETF), so other performance metrics, e.x., fairness and timeliness, can be enhanced. To the best of our knowledge, this is the first paper to exploit the multiuser diversity in the CSMA/CA based wireless networks. We evaluate the OSMA using ns-2 and our simulation results show that this protocol can improve the network throughput significantly.**

I. INTRODUCTION

In the wireless ad hoc networks, especially in mobile environment, whether a packet can be transmitted successfully or not relies on time-varying and location-dependent channel condition, which can be characterized by the path loss, the short-term fading, and the noise plus interference level. For specific MAC protocols such as CSMA/CA, another condition for successful packet transmission is that the receiver should not be within either virtual or physical carrier sensing range of any other ongoing transmissions even the channel is good enough.

If the sender has the knowledge of all these aforementioned factors and the channel state would maintain stable on the order of data transmission, the sender can choose a receiver with good condition for successful transmission.

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However,if all packets are queued in a single queue and the sender transmits data packets using FIFO, it would result in the Head-of-Line (HOL) blocking problem. The HOL packet transmission failure prevents other packets in the FIFO queue from being transmitted. Note that since channel gains from the sender to different neighboring receivers and the interference plus noise level at those receivers may be independent, FIFO service discipline may forbid us to take advantage of the fact that some of the blocked packets in the queue destined to other receivers can be successfully transmitted during this time interval when their channel conditions are good. Thus, all flows passing this node suffer from throughput degradation with FIFO scheduling. Because the HOL packet may fail in retransmission of RTS or DATA many times for various reasons such as short fading, the interference and the collision, the HOL problem would be more serious. In the MANETs, the MAC protocol regards this situation as a link breakage and reports to the routing layer if the number of retransmissions exceeds a certain limit. The routing layer will then initiate rerouting process even if the receiver is still in its transmission range. Misrouting not only introduces a large amount of overhead for the route re-discovery but also results in unnecessarily discarding packets in the upstream along the path. The HOL blocking problem together with the random nature of the contention-based MAC protocols may result eventually in serious instability and unfairness problem at the transport layer, especially when TCP is applied [1] [2].

One of the first few papers that address the HOL blocking effects imposed by the wireless variations is [4]. Bhagwat et al. proposed the Channel State Dependent Packet Scheduling (CSDPS) to deal with the problem in the wireless LANs. The basic idea of CSDPS is that, when a wireless link experiences bursty errors, it defers transmission of packets on this link and transmits those on other links. The link state is evaluated at the sender by observing the outcome of the last packet transmission. Since it is too costly to test the states of wireless links by the data packet and acknowledgement pair, Fragouli et al. [8] used RTS and CTS to check the channel state and the retransmission number of RTS to estimate the channel condition. In addition, [8] attempted to solve the unfair bandwidth sharing in CSDPS by combining the class-based queueing (CBQ).

In comparison to the above two solutions, a much different but more efficient approach to deal with the HOL blocking problem is the opportunistic multiuser communications, which exploits the channel fluctuations rather than mitigates their effects. Knopp and Humblet [5]presented a scheme to maximize the single-cell capacity by allowing only the user with the best channel condition to transmit at any time. A scheduling algorithm, which exploits the inherent multiuser diversity while maintaining the fairness among users, has been implemented as the standard algorithm in the Qualcomm's HDR [6] system (1xEV-DO). In [11], Liu and Knightly provided a general formulation for the wireless opportunistic fairness scheduling over multiple channels.

However, to enable the opportunistic multiuser communications, timely channel information of each link is required for an effective scheduling. Just as all the mentioned schemes have assumed, timely channel information is possible in cellular networks where the base station acts as a central controller and control channels are available for channel state feedback. When it comes down to ad hoc networks, it is difficult to utilize the multiuser diversity because of the single share medium and distributed MAC protocol. Qin et al. [7] presented the channel-aware ALOHA to exploit high quality channel in a distributed fashion. Since the model they targeted at assumes each user has knowledge of its own fading level based on the analysis of periodic pilot signal broadcasted at the base-station, the scheme cannot be directly applied into wireless LANs or multihop ad hoc networks. Most of recent work [12] [13] [14] on diversity in CSMA/CA based ad hoc networks is limited to the path diversity. Multiuser diversity is still under investigation. Especially, there is little work that provides comprehensive and realistic study on multiuser diversity with desired goals in protocol design.

To alleviate the HOL problem and exploit the multiuser diversity in wireless LANs and multihop ad hoc networks, we propose the Opportunistic packet Scheduling and Media Access control (OSMA) protocol and present its evaluation results. The rest of the paper is organized as follows. Section II presents the framework and detailed design. Simulation results are provided and discussed in section III. Finally, section IV concludes our work.

II. OSMA Protocol

A. Overview

In mobile ad hoc networks, where the single available channel is shared, it is impossible for the sender to get all channel information updated before making scheduling decision. For example, if the sender probes the channel one by one, the overhead of handshake is very high. More importantly, the time taken to probe channels is unpredictable because the MAC is contention-based. After the sender completes channel probing, the channel state probed may be stale. Thus, it is hard to target the best. However, we can still exploit the channels whose instantaneous conditions are better than a certain level without introducing too much overhead.

The basic idea of our protocol is as follows. The sender multicasts a channel probing message to a selected group of candidate receivers. Each candidate receiver evaluates the instantaneous link quality based on the received channel-probing message. The candidate receiver with channel quality better than a certain level is granted to access the medium. Considering more than one candidate receiver may have good channels and are ready to receive data, a coordinating rule should be applied to avoid collision. The channel-probing message will include a list of the media access priority of each candidate receiver. According to the announced channel access priority list, the qualified candidate receiver with highest priority is ensured to access the channel in the first place.

Since the opportunistic media access may lead to unfairness among all links, we provide a framework to deal with both throughput and fairness. In other words, we decouple the throughput optimization and fairness guarantees, two conflicting goals. Two separate components, namely packet scheduling and channel aware media access control, are provided to exploit high quality channel and enforce fairness. The major concern of our protocol design is simple and practical, i.e., can be easily incorporated into the popular 802.11 MAC protocol.

The scheduling we discuss here is local scheduling. Recall that, in the multihop ad hoc networks, topology related issues such as location dependent channel contentions and channel state need to be taken into account. The solution of the problem can be divided into two steps, i.e., global scheduling and local scheduling. We focus only on the latter in this paper. Similarly, we leave the scheduling among unicast data packets, control packets and broadcast packets for future work and focus on the scheduling of unicast data packets only in this paper.

B. Framework of OSMA

In this section, we provide a general framework for opportunistic packet scheduling and media access control with imperfect channel information. Recognizing the throughput optimization and the fairness guarantees can be decoupled, we provide two modules, scheduling and channel aware media access control, to deal with fairness and throughput, respectively. The fairness is enforced by scheduling at the sender and the good channel condition is exploited by distributed channel aware media access control at the side of receivers. Fig. 1 shows the framework. One separate queue is maintained for each next hop at each node. Whenever a node prepares to transmit data, based on the weight of HOL packet in each queue, $\overrightarrow{w(k)}$=[$w_1(k)$,...,$w_N(k)$], the scheduler chooses a candidate receiver list from receivers toward which there are packets queued in the corresponding queue and assigns media access priority to each candidate receiver. The sender then multicasts a channel probing message with media access priority list to those chosen candidate receivers. After physical-layer analysis of channel probing message, each candidate receiver can determine instantaneous link quality, $c_i(k)$, from the given sender to itself. The candidate receiver with channel condition better than certain level is allowed to access channel. It is possible that more than one candidate receiver is qualified to receive data. To avoid collisions, the media access priority list in the received channel probing message announces the order of media access among qualified candidate receivers. The output of channel aware media access controller is $\overrightarrow{X(k)}$=[$X_1(k)$,...,$X_N(k)$] for time slot k where $X_i(k)$ can be normalized as the transmission rate of each link in slot k. We provide the general formulation of OSMA so that packet bursting and rate adaptation technique [3] can be easily incorporated into our proposed framework.

Opportunistic media access will easily lead to short-term deviations from the ideal fairness. To ensure long term fairness among links, the weight adjustor is used to update the weight of each link after each time of data transmission. Let $\overrightarrow{\Phi}$=[Φ_1,...,Φ_N]denote the objective weight of each link and $Y_i = E[X_i(k)]$ denote the expected throughput for link i. If the deterministic fairness is targeted, (1) should be satisfied:

$$\frac{Y_i}{\Phi_i} = \frac{Y_j}{\Phi_j} \tag{1}$$

According to the definition of weight and specific scheduling policy applied, not only fairness but also QoS can be enforced. Many scheduling algorithms reviewed in the literature [10], such as Round Robin (RR) and Earliest Timestamp First (ETF), can be applied into our framework without much modification. Considering there are many constraints for portable wireless device such as CPU and energy consumption, one of the crucial requirements for the scheduling algorithm is the simplicity. We do not go into the details about the design of scheduling algorithms in this paper and leave this issue for the future research. The only scheduling policy discussed in our simulation is the Round Robin. We show from the simulation study that both throughput and fairness can be significantly enhanced even by this simple scheduling method. We believe the fairness and QoS can be further enhanced by more complex scheduling algorithms.

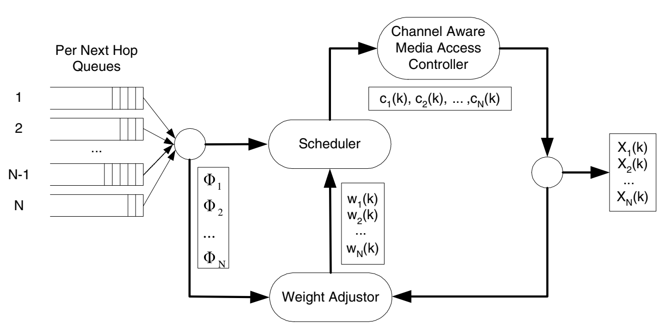

Fig. 1. Framework of OSMA

C. Design of channel aware MAC

In this section, we discuss the design of channel aware media access module in the real context, in particular, for the basic rate CSMA/CA networks. The objective of channel aware MAC design is to achieve as high throughput as possible given that the candidate receiver list has been determined. It is well known that RTS and CTS handshake is the common mechanism used in the CSMA/CA networks. The handshake of RTS and CTS has to be done before the data transmission if the packet length is greater than a certain threshold. RTS/CTS is also used to probe the channel. If a channel is too bad for the receiver to decode the RTS correctly, CTS will not be sent to the sender, thus the sender will defer the data transmission and avoid unnecessary data packet errors. Based on the RTS and CTS exchange, we introduce the Multicast RTS and Prioritized CTS to exploit the multiuser diversity as well as collision avoidance in our scheme.

1) Multicast RTS: RTS used in 802.11 MAC is a unicast message in that only one receiver is targeted. In our protocol, we use multiple candidate receiver addresses in the RTS and request those receivers in the receiver list to receive the RTS and measure the channel quality simultaneously. The wireless shared media with omni-directional antenna makes this mechanism possible without incurring much overhead.Fig. 2 shows the format of RTS frame.

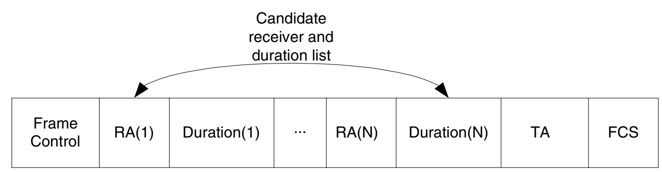

Fig. 2. Format of Multicast RTS fame

2) Prioritized CTS: The candidate receivers evaluate the channel condition based on the physical-layer analysis of the received RTS message. If the channel quality is better than certain level and its NAV is zero, the given receiver is allowed to transmit a CTS. To avoid collision when two or more intended receivers are qualified to receive data, a service rule is applied. The listing order of intended receivers in the RTS announces the priority of the media access among the candidate receivers. The closer the receiver address to the top of the receiver list, the higher the priority to access media. 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 would reply CTS first. 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, the CTS should be powerful enough for all other qualified candidate receivers to 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.

One design issue is how the maximum candidate receiver list should be if there are enough data packets targeting them. Longer receiver list means more diversity can be exploited, but also means the waiting time would increase before the sender can make sure there is no qualified receiver. This will also increase the length of DIFS if DIFS is set to $SIFS + M * Time\_slot$, where M is the maximal number of intended receivers which can be included into the multicast RTS. Fortunately, even with small M, e.g., 4, significant multi-user diversity can be achieved. Here is an illustrative example. Assume that the probabilities for candidate receivers to successfully receive the intended data packet are identical and independent, say, p, then the probability that there is one or more receivers qualified to receive the targeted data is $P = 1 - (1 - p)^n$, where n is the number of intended receivers. Given p equals to 0.5, the P is 0.75, 0.875 and 0.9375 when n is 2, 3, and 4, respectively. In addition, because the time slot is rather small, with the time scale of μs (20 μs used in 802.11 MAC), M is allowed to be quite big without introducing too much overhead by comparing DIFS to the data packet transmission time. In our simulation, we use only 4 and find it already yields significant throughput gains.

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. More importantly, the HOL problem can be alleviated significantly.

III. Simulation and Analysis

In this section, we use ns-2 as simulation tool to evaluate the performance of our protocol and compare it with the base rate IEEE 802.11 scheme. The methodology we follow in our simulation is to isolate the impact of each performance factor as much as possible and then study the joint effects of numerous factors. We begin with WLAN and study effects of number of users, channel conditions and interaction with TCP respectively. We then consider grid topology in which both channel condition and receiver blocking affect successful data transmission.

The physical propagation model we use is Ricean fading model.The Ricean fading ns-2 module is originally developed by CMU ARC group [15] and enhanced later by Rice Networks Group [3]. The background noise power is set at 100dbm. To characterize channel condition, we introduce Average Fade Probability. It denotes the probability that the received power is less than the received power threshold defined by 802.11 MAC.

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

A. Wireless LAN

The Wireless LAN we simulate runs on DCF mode. Since most of traffic is from access point to terminals in real scenarios, we configure it in such a way that all the traffic sources originate from access point and all sinks reside in terminals. Each flow is destined to a unique node.

1) Number of Users: To explore the multi-user diversity gain, we vary the number of flows with the setting that channel condition for each link is identical and independent. The Average Fade Probability is set as 25%. Traffic is UDP with interval 0.001, which implies that each active queue will not be empty at any time.

Fig. 3 shows the throughput gain of OSMA over 802.11 MAC for different number of flows. Observe that when the flow number is 1, OSMA is actually a little bit, about 1.5%, worse than 802.11 MAC, which is reasonable because no multi-user diversity gain can be achieved in case there is only one user while OSMA has longer DIFS than that of 802.11 MAC. When the number of flows increases, the throughput gain benefited from opportunistic scheduling starts to show. When the number of flows increases to 3 or above, the multiuser gain maintains relatively stable, about 44%. There are two reasons for this result. The first is that the maximum number of candidate receivers is bounded by 4 in our simulation. The second is that the probability of all the 3 or above candidate receivers are not satisfied to receive a packet at any given time is very low, i.e., when the number of flows goes up to 3, almost each time access point sends an RTS, it would receive CTS to continue data delivery.

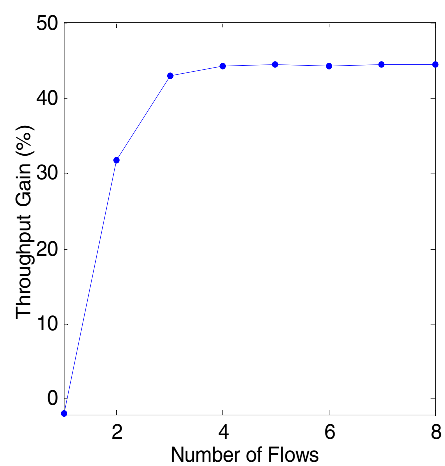

Fig. 3. OSMA throughput gain as a function of the number of flows in WLANs

2) Location distribution and Channel varations: Location distribution affects path loss factor and the line-of-sight Ricean parameter K of a node pair, while the node velocity affects the average channel coherence time, i.e., the rate of channel variations. We conduct this set of simulations to investigate the overall WLAN throughput considering both diversities of location distribution and channel variations.

We distribute 24 nodes over a 500m*500m square area. The access point is put at the center. Each traffic flow is UDP with interval of 0.05. Fig. 4 shows that OSMA achieves approximately 52%-78% overall throughput gains over 802.11 MAC. Besides, each flow in OSMA has greater throughput than 802.11 MAC. The key reason is that OSMA holds the priority for HOL packet in the head of candidate receiver list while allowing others to use the channel if it cannot be delivered due to the bad channel condition. The simulation time is long enough to let each flow take chance to catch good channel state so each flow achieves a higher throughput.

We also notice that the performance of OSMA is nearly independent of velocity while performance of 802.11 MAC gets better when the velocity increases. The reason for the difference is that the HOL problem is almost eliminated in OSMA while becomes serious in 802.11 MAC. The lower the node velocity, i.e., the longer the channel coherence time, the higher probability of burst packet error for each link, the larger the contention window size, and the longer the average backoff time in 802.11 MAC. When the velocity increases, the HOL problem becomes weaker, so throughput increases.

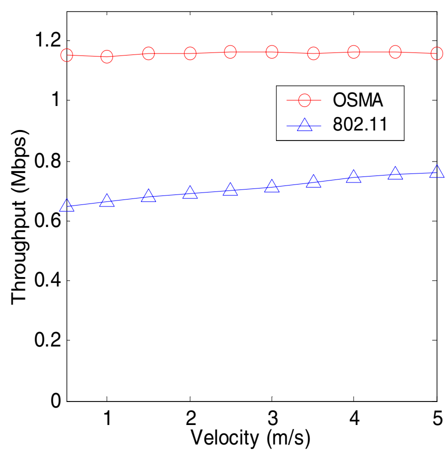

Fig. 4. Throughput as a function of mobile speed in WLANs

3) Interaction with TCP: Next, we need to answer two questions. One is whether the throughput gain due to OSMA at the MAC layer can be exploited by TCP at the transport layer. The other is whether the fairness is enhanced. In this set of simulations, TCP flow number is 16 and each link quality follows the independent and identical distribution. The simulation time is 3600s. Fig. 5 shows the throughput as the channel quality changes. The throughput gains achieved by 802.11 MAC range from approximately 12% to 87%. The worse the channel, the larger the throughput gains. This is reasonable because the HOL problem gets worse for 802.11 MAC when the channel becomes worse. As shown as Fig. 6, the fairness is also enhanced. The fairness index we use is shown as (2), which was proposed by R. Jain [9], where x_i is the flow rate for flow i. The reason could be as follows. Packet loss, especially burst packet loss, is the key reason in this scenario leading to instability and unfairness observed at TCP. Data dropping at MAC level due to exceedance of the maximum allowable RTS retransmission times or data retransmission times is deceased by our scheme.

$$f = \frac{(\sum_{i=1}^{n} x_i)^2}{n \sum_{i=1}^{n} x_i^2} \tag{2}$$

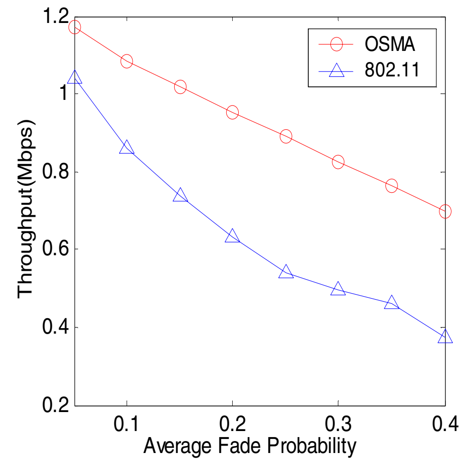

Fig. 5. TCP throughput as a function of channel quality in WLANs

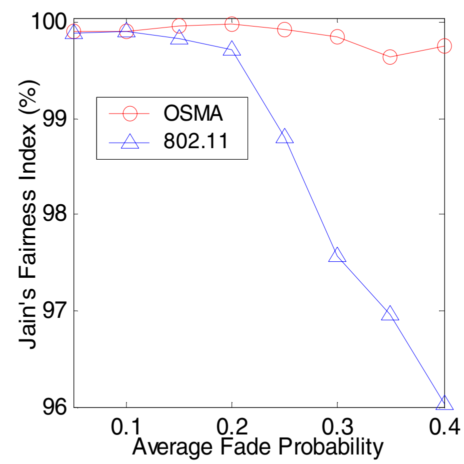

Fig. 6. TCP fairness as a function of channel quality in WLANs

B. Multihop networks

Our final experiments address the performance of OSMA in multihop ad hoc networks. We use grid topology with 100 nodes. One-hop distance is set as 200m. We conduct two sets of simulation. First is for one-hop flows. Second is for multihop flows. In the first scenario, each node has a UDP flow destined to each neighboring node. Fig. 7 shows that OSMA achieves about 20%-29% higher throughput than 802.11 MAC. Besides the channel fading, the HOL blocking problem is also caused by the fact that the receiver is within the carrier sense range of other ongoing transmissions when RTS is sent.

OSMA enables sender to choose a candidate receiver with clean floor so the spatial reuse is greatly increased.

In the second scenario, there are 40 UDP flows. Each flow is of 10-hop length. Fig. 8 shows the simulation results for the second scenario. It shows that, when the offered load is light, the throughput gain is not so significant. With the increase of the offered load, OSMA achieves much higher throughput than 802.11 MAC. When the network becomes heavily loaded, the performance of 802.11 MAC drops very fast while OSMA maintains stable.

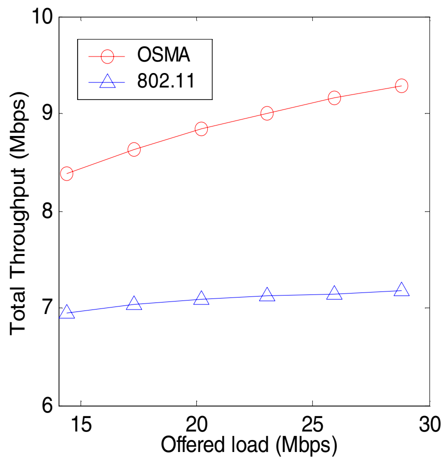

Fig. 7. Throughput of onehop flows in Grid Topology

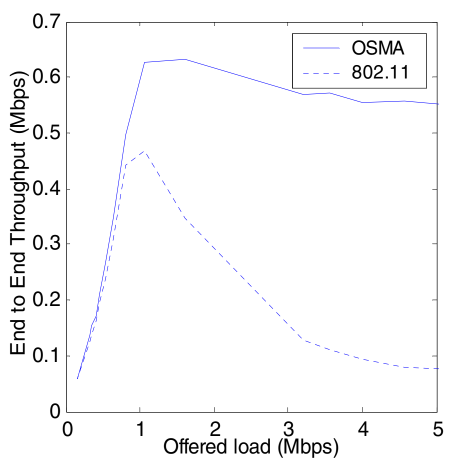

Fig. 8. Throughput of multihop flows in Grid Topology

IV. Conclusion and Future Work

In this paper, we present OSMA, an opportunistic scheduling and channel aware media access protocol for WLANs and multihop ad hoc networks. By using multi-cast RTS and prioritized CTS, OSMA explores the multiuser diversity and alleviates HOL blocking problem significantly. Ns-2 simulation results show that OSMA normally obtains throughput gains of 50% or above in WLANs and several times better in multihop ad hoc networks as compared to 802.11 MAC. To the best of our knowledge, this is the first paper to address multiuser diversity by opportunistic scheduling in the CSMA/CA based wireless networks. Furthermore, the general framework introduced in this paper can easily incorporate power control, rate adaptation and directional antenna. Detailed design and extensive simulation study for these joint schemes are left for future work.

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