Multichannel Feedback in OFDM Ad Hoc Networks

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***Abstract*—We propose a multichannel feedback protocol to enable local scheduling with channel state information for wireless networks with orthogonal frequency division multiplexing (OFDM). In our proposed protocol, the frequency subcarrier domain is shared by multiple control channels, on which request-to-send (RTS) and clear-to-send (CTS) are exchanged. These control channels are created using random spreading signatures. Channel state information of the simultaneous transmissions, which defines the gains of these channels, is exchanged on these control channels and channel state information tables that contain the channel information of both the desired link and the interfering links are created at the transmit nodes, then scheduling decisions are made based on the channel information tables. We show that the proposed protocol improves the network throughput compared to IEEE 802.11 style protocols for a wireless local area network topology.**

I. INTRODUCTION

Distributed wireless networks, e.g., wireless local area networks (WLAN) and ad hoc networks have received increasing interest. In ad hoc networks, there is no fixed infrastructure as in cellular systems. Traffic may be carried along multiple transmission hops. A well-known medium access control (MAC) protocol for WLAN and ad hoc networks is IEEE 802.11 [1]. In the distributed coordination function (DCF) mode of the 802.11 protocol, the mechanism “carrier sensing multiple access with collision avoidance” (CSMA/CA) [2] is employed to coordinate the distributed communication.

In wireless networks, the channel conditions between different node pairs differ significantly due to path loss, fading and interference in the wireless environment [3]. Further, such variation occurs on a short timescale, i.e., on the order of few packet transmission times. Adaptation of the transmission rate to different channel conditions leverages the network throughput compared to single-rate transmission strategies [4]–[6]. For point-to-point transmissions, this is achieved by selecting a high data transmission rate when the channel condition is favorable and using lower data rate when the channel condition is poor.

When there are multiple simultaneous transmissions in the network, scheduling that utilizes the channel state of these transmissions may benefit the overall system throughput. Earlier work on channel state dependent scheduling focuses on solving the head of line (HOL) problem [7]. In Wang et. al [8], the OSMA (opportunistic packet scheduling and medium access) protocol is proposed. This protocol employs clear-to-send (CTS) messages prioritized based on channel conditions along with multicast request-to-send (RTS) messages to make use of channel diversity among wireless links. In Ji et al. [9], the medium access diversity (MAD) protocol is investigated. By using multicast RTS with multiple CTS’s to feedback channel information, the transmitter can make the optimum decision on packet transmissions. The main focus of the past research is on the point-to-multipoint transmission scenario, however, how to exploit the channel variation on a short timescale for multiple simultaneous flows in the network as illustrated in Fig. 1 has not been realized in these protocols.

The 802.11 MAC protocol uses binary exponential backoff as the mechanism for medium access and collision resolution. In this system, OFDM is a commonly used physical layer technology. The winner of the contention consumes all the OFDM subcarriers. When there are multiple neighboring nodes accessing the media, the binary exponential backoff does not take advantage of the channel conditions of the transmissions. For this scenario, a joint subcarrier allocation that splits the OFDM subcarriers domain for the transmitters based on their channel and traffic conditions can achieve higher throughput.

The joint subcarrier allocation requires the channel information of the transmissions that can interfere with each other. The 802.11 style MAC protocol, however, cannot achieve this goal since the neighboring nodes share a contention period (equivalently one control channel). To resolve this issue, we propose to use multiple control channels to carry RTS/CTS/ACK messages and to exchange the channel information between these links. Our extension to multiple control channels assumes an OFDM based physical layer. Multiple control channels are supported using spreading signatures in the subcarrier domain. We assume that the sum data rate is fixed for each control channel. Thus when a fixed length control packet is transmitted on a control channel, the packet transmission time for the multichannel case is longer. This implies that the control overhead increases for the multichannel case. On the other hand, with multiple control channels,

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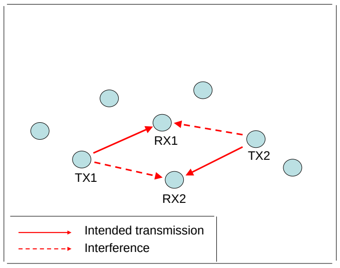


Fig. 1. In an 802.11 style MAC, a collision happens when there are simultaneous transmissions interfering with each other.

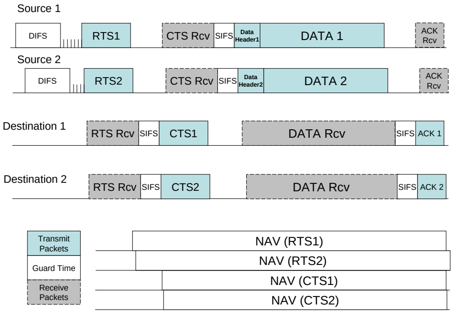


Fig. 2. Operation of the proposed protocol corresponding to the network topology in Fig. 1. Source one and two intend to send a data package to the destination one and two respectively. The destinations measure the channels and feed back the channel quality. The mechanism to support reception of two RTS'/CTS' will be described in Section II-B.

channel state information may be exchanged among the nodes. This facilitates a more flexible allocation of the subcarrier resource and may improve throughput. Therefore, there exists a tradeoff between overhead and resource allocation.

In this paper, we propose a multichannel feedback protocol that uses two control channels to exchange control messages and channel state information. We assume that in this network, all nodes are synchronized in carrier frequency and transmission time. These control channels are created using spreading signatures. Nodes exchange channel state information on the control channels. They create their individual channel information tables by decoding control packets on these control channels. We propose a scheduling algorithm that utilizes the channel state information tables to make scheduling decision at each individual node. We can generalize this protocol to the case of more than two control channels. For simplicity of analysis, this study focuses on the frequency-flat channels, the proposed transmission scheme that supports multiple control channels can also be applied to the frequency-selective channels. The overall system throughput is improved thanks to channel based scheduling compared with the 802.11 MAC protocol.

II. MULTICHANNEL FEEDBACK PROTOCOL

We propose a protocol that enables feedback of channel state information and cooperative scheduling among different simultaneous point-to-point links. This section discusses the basic operation of this protocol. We then present the underlying physical layer technology to support multiple control channels with random spreading signatures. We discuss how channel information is shared among the nodes, further, we propose scheduling algorithms that utilizes the available channel information to make scheduling decisions.

A. Basic Protocol Operation

The proposed protocol has a similar operation procedure to the Opportunistic Auto Rate (OAR) protocol [5]. All nodes perform carrier sensing, binary exponential backoff and contention-based medium access as the standard IEEE 802.11 protocol. The operation of this protocol is shown in Fig. 2.

The control packets are request-to-send (RTS), clear-to-send (CTS) and acknowledgement (ACK) packets. These control packets are transmitted at a fixed base data rate. The data transmission labelled by "DATA" has a fixed duration. The transmission rate in each "DATA" period, however, is adapted to the channel conditions of the wireless links. There may be multiple fixed "DATA" durations, each followed by an ACK message.

We define two control channels to carry the control packets. This is different from the conventional 802.11 style protocol, which uses only one control channel. Details of the control channel configuration and the mechanism for exchanging channel state information are presented in Section II-B and Section II-C. During the data transmission period, the entire OFDM subcarrier domain is used but may be shared by several transmitters. A subcarrier allocation algorithm determines the mapping from the subcarrier domain to the point-to-point links. Details of the scheduling algorithms will be presented. The scheduling decisions are made separately at the transmitters with the channel state information obtained in the RTS/CTS handshaking period. The scheduling algorithm is presented in Section II-D.

The basic system operation is described as the following:

Step 1. A node sends a RTS on one of the control channels after a duration of random backoff when it senses the medium has been idle for a duration of DIFS (distributed interframe space). Here sensing is based on the power level of the received signal, which is the same as the 802.11 style MAC. Each node maintains a backoff timer and a backoff window which is also the same as the 802.11 style MAC. The mechanism to support multiple control channels will be described in Section II-B. The receive nodes perform channel estimation and decoding for the control packets intended to itself. It also tends to estimate the channel and decode control packets for the control packets on the other control channel.

Step 2. Nodes send back CTS messages that contain channel information about the intended transmission and the interferers. If the transmitter that has sent an RTS does not receive an expected CTS from the intended receiver, the transmitter defers its transmission according to the binary exponential backoff.

Step 3. If the transmitter successfully decodes the CTS messages, a channel information table will be created at the transmitter. This table contains the source and destination pairs and their corresponding channel coefficients. This will be described in Section II-C.

Step 4. As discussed in Section II-D, a scheduling decision is made based on the channel information table at each node independently. It determines the subcarrier mapping between the subcarrier domain and the transmitters.

Step 5. The transmitter informs the subcarrier mapping to the intended receiver by sending a data header that contains the subcarrier mapping and other control information on its control channel. Then data packets are transmitted in the data transmission period according to the subcarrier mapping.

Step 6. The receive nodes decode the control headers in the ’DATA’ period. The header contains the subcarrier allocation information. Using the mapping information, the receiver decodes the transmitted data in the ‘DATA’ period. ACK messages are sent back after the data transmission period on the control channels.

B. Capture Using Random Spreading Signatures

This section discusses the mechanism used to create two control channels, i.e., using random spreading signatures. Though having more control channels helps exchange channel information, more control overhead is needed. The spreading signatures consist of two spreading coefficients. We stack the spreading signatures in a vector form as $\boldsymbol{\alpha}_i = [\alpha_i[1], \alpha_i[2]]^T$. In terms of implementation, the vector $\boldsymbol{\alpha}_i$ can be randomly selected for a user i from a set of non-orthogonal signatures denoted by $\boldsymbol{\mathcal{A}}$ [10]. This is different from the multi-carrier CDMA modulation (MC-CDMA) that uses orthogonal spreading codes.

We use an interleaving subcarrier pattern to carry the RTS/CTS messages. The subcarrier mapping function from the k^{th} subcarrier on the l^{th} control channel to a physical subcarrier on the l^{th} control channel is denoted by $\mathcal{I}[k, l]$, where $\mathcal{I}[k, l] = 2 * (k - 1) + l$. The transmitter architecture is illustrated in Fig. 3. The control packets are transmitted using random spreading signatures while the data packets are transmitted according to the subcarrier allocation derived from the subcarrier allocation algorithms.

When a node i sends a RTS message, it randomly selects a signature from the signature set $\boldsymbol{\mathcal{A}}$. The node i sends RTS’s in the subcarrier domain by multiplying the message with coefficients $\alpha_i[1]$ and $\alpha_i[2]$ on the k^{th} logic subcarrier of each of the channels. The control channels are created using spreading signatures. For the case of two control channels, the length of any spreading signature is two in our system. This introduces less amount of control overhead to the system. We first give an example to illustrate the case of having two nodes access the control channels. On the k^{th} logic subcarrier of each of the control channels, we have the following system equation

$$\begin{cases} x[k,1] = H_1[k,1]\alpha_1[1]s_1[k] + H_2[k,1]\alpha_2[1]s_2[k] + n[k,1] \\ x[k,2] = H_1[k,2]\alpha_1[2]s_1[k] + H_2[k,2]\alpha_2[2]s_2[k] + n[k,2]. \end{cases} \tag{1}$$

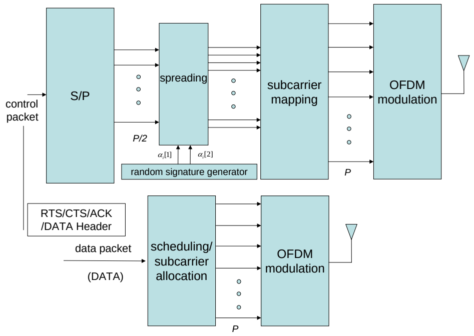


Fig. 3. Block diagram of the transmitter that processes control packets with random spreading and perform subcarrier allocation to the data packets.

where $H_i[k, l]$ denotes the channel between the i^{th} transmitter and the receiver on the k^{th} subcarrier of the l^{th} control channel. The term $s_i[k]$ denotes the signal transmitted by the i^{th} transmitter on the k^{th} subcarrier for both control channels. The signature $\alpha_i[l]$ is the coefficient of a spreading signature chosen by the i^{th} user for the l^{th} control channel. In a vector form, we express it as

$$\mathbf{x}[k] = \mathbf{H}[k]\mathbf{s}[k] + \mathbf{n}[k] \tag{2}$$

where $\mathbf{s}[k] = [s_1[k], s_2[k]]^T$, $\mathbf{x}[k] = [x_1[k, 1], x_2[k, 2]]^T$ and the channel matrix $\mathbf{H}[k]$ is

$$\mathbf{H}[k] = \begin{pmatrix} \alpha_1[1]H_1[k,1] & \alpha_2[1]H_2[k,1] \\ \alpha_1[2]H_1[k,2] & \alpha_2[2]H_2[k,2] \end{pmatrix}. \tag{3}$$

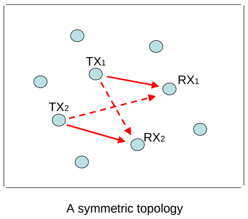
When the channel matrix $\mathbf{H}[k]$ has full rank, the signal $\mathbf{s}[k]$ is separable. This implies that the transmitted signal can be identified at the receiver.

Notice that even for the case that $H_1[k, l] = H_2[k, l]$, since the vector $\boldsymbol{\alpha}_1$ and $\boldsymbol{\alpha}_2$ are linearly independent, the transmitted signals are still separable. When the size of the set $\boldsymbol{\mathcal{A}}$ becomes larger, the probability of choosing the same signature from the set for more than one neighbors in a local area gets smaller.

For a different number of users in the system, the analysis follows in a similar way. However, the transmitted signals are not separable at a receiver if it receives signals from more than two transmitters. The maximum number of control messages that can be separated at a receiver is two. Effectively, this mechanism that uses random spreading signatures creates two control channels.

C. Sharing Local Channel Information

The RTS messages are also used for channel measurement. If the receive node can decode the RTS message and also estimate the channel coefficients of all the interfering transmissions, the receive node feeds back all the channel information to the transmit node. Notice that this happens when the number of interfering transmissions is less than or equal to two. This information is carried in the CTS message. If the transmitter decodes the CTS message, it then knows the channel information of its own channel and also the interferer. Consequently, a channel information table can be created at



Channel Table at TX1

	RX1	RX2
TX1	$H_{1,1}$	$H_{2,1}$
TX2	$H_{1,2}$	$H_{2,2}$

Channel Table at TX2

	RX1	RX2
TX1	$H_{1,1}$	$H_{2,1}$
TX2	$H_{1,2}$	$H_{2,2}$

Fig. 4. The channel information tables created at the transmit nodes based on the feedback information in the CTS'.

the transmitter. An example of the channel table is illustrated in Fig. 4.

The following assumption about information reciprocity is crucial for our local scheduling algorithm. The underlying principle is that if a receive node can decode a RTS message from a transmit node, the CTS message that the receive node sends can also be decoded by the transmit node.

Information reciprocity: Transmit nodes TX$_1$ and TX$_2$ send RTS messages to receive nodes RX$_1$ and RX$_2$ respectively as illustrated in Fig. 4. Assume that the transmit node TX$_1$ decodes the CTS messages from both receive nodes RX$_1$ and RX$_2$. Since node RX$_1$ decodes the RTS from node TX$_2$ and node RX$_2$ decodes the RTS from node TX$_1$, by reciprocity assumption, node TX$_2$ can decode the CTS from node RX$_1$ and node TX$_2$ can decode the CTS from node RX$_2$.

We say that the node TX$_1$ has *the complete channel information table* if it knows all items of $H_{1,1}$, $H_{2,2}$, $H_{1,2}$ and $H_{2,1}$. When the node TX$_1$ has the complete channel information table, by information reciprocity, it is likely that node TX$_2$ will also have the complete channel information table. This, however, may fail when there are hidden transmissions for node TX$_1$. In this case, decoding of the receive messages is not feasible at node RX$_2$.

D. Scheduling Algorithms

We propose algorithms that determine the mapping between the subcarriers and the transmitters based on their channel information tables.

Case 1 (complete channel information): For a node i_1 in the network, after the RTS/CTS exchange, it creates a channel information table. If it finds that there exists a node i_2, such that, the channels H_{j_1,i_1}, H_{j_2,i_2}, H_{j_1,i_2} and H_{j_2,i_1} are all known. The transmit node performs a subcarrier allocation to maximize the sum utility of the transmissions. Utility can be defined as a function of the channel information and the traffic information. By maximizing the sum utility of the network, certain throughput and fairness objectives can be achieved [11]. We first state the general utility maximization scheduling algorithm, then propose two specific choices of utility functions for our system.

Algorithm 1: Formulate a cost function $U_s(\Gamma) = \sum_{t=1}^{N}[U_{i_1\to j_1}[t]I\{\Gamma(t) = i_1\} + U_{i_2\to j_2}[t]I\{\Gamma(t) = i_2\}]$, where Γ determines the subcarrier mapping function, U is the utility function and $i_1 \longrightarrow j_1$ denotes the transmission from node i_1 to j_1.

In this paper, we assume that the channels are frequency flat for simplicity of analysis. In this case, we use equal power distribution to the band that is allocated to each transmitter. The bandwidth allocation is performed for both links in the following fashion (maximizing the sum rate with respect to the parameter β, where β determines the bandwidth sharing factor for both links),

$$\max_{\beta} U_s(\beta) = \max_{\beta}[N\beta U_{i_1\to j_1}(\beta) + N(1-\beta)U_{i_2\to j_2}(\beta))]. \tag{4}$$

Utility Functions: A simple choice for the utility function is the rate function itself. We assume that the total transmit power at both transmit nodes for all OFDM subcarriers is P_t and the noise power at both receivers is σ^2. Therefore, the resource allocation problem is formulated as

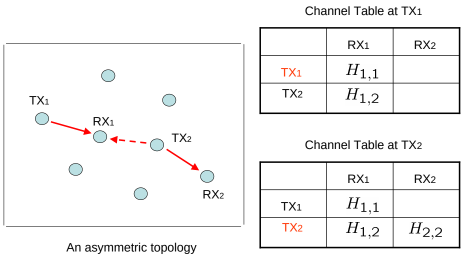
$$\max_{0\le\beta\le1}\left\{N\beta\log_2\left(1+\frac{P_t|H_{j_1,i_1}|^2}{N\beta\sigma^2}\right)+\right.$$
$$\left.N(1-\beta)\log_2\left(1+\frac{P_t|H_{j_2,i_2}|^2}{N(1-\beta)\sigma^2}\right)\right\}. \tag{5}$$

We name this method "Max-Sum-Rate" scheduling. The main problem with this method is that it strongly favors the link with a good channel in bandwidth allocation. Alternatively, the logarithmic of the rate function can be used as the utility function. It can help the point-to-point links with poorer channels. The optimization problem is formulated as the following

$$\max_{0\le\beta\le1}\left\{\log\left(N\beta\log_2\left(1+\frac{P_t|H_{j_1,i_1}|^2}{N\beta\sigma^2}\right)\right)+\right.$$
$$\left.\log\left(N(1-\beta)\log_2\left(1+\frac{P_t|H_{j_2,i_2}|^2}{N(1-\beta)\sigma^2}\right)\right)\right\}. \tag{6}$$

The one-dimensional optimization can be performed by an exhaustive search. We call this method "Max-Sum-Log-Rate" scheduling. For both methods, when the allocation ratio β is computed, the subcarriers are mapped to each transmit node simply based on a subcarrier mapping function which maps the subcarrier indexed from 1 to $\lfloor\beta N\rfloor$ to the transmitter i_1. The rest of the subcarriers are mapped to the transmitter i_2.

A scheduling outage happens when one transmit node has the complete channel information table while the other transmit node does not have the complete channel information table. By information reciprocity, if one transmit node i_1 has the complete channel information table, the other node i_2 is likely to have the complete channel information unless a hidden terminal disturbs the reception of the CTS at that node. For the second case, the node i_2 will not transmit any data to the destination during the data transmission period. The node i_1 transmits data according to the scheduling algorithm that we explained in this paper. This leaves some of the subcarriers unused in the transmission period. The receive node will detect the under-utilization of the system resource and will send back a notification to the source in the ACK message. Essentially, a scheduling outage causes a decrease of throughput.



Channel Table at TX1

	RX1	RX2
TX1	$H_{1,1}$	
TX2	$H_{1,2}$	

Channel Table at TX2

	RX1	RX2
TX1	$H_{1,1}$	
TX2	$H_{1,2}$	$H_{2,2}$

Fig. 5. The channel information tables created at the transmit nodes based on the feedback information in the CTS' in an asymmetric topology.

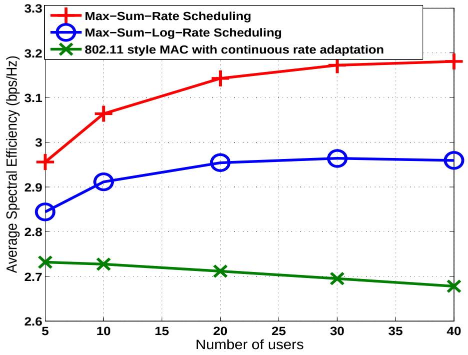


Fig. 6. Comparison of the throughput of the multichannel feedback protocol and the 802.11 style protocol with continuous rate adaptation for a symmetric topology.

Case 2 (incomplete channel information): If a transmit node does not have the complete channel information, scheduling is performed based on the timestamps of the RTS transmissions, instead of the channel information. The transmitter that has the earliest timestamp will be scheduled and it will consume all the OFDM subcarriers for its transmission. In this implementation, the timestamp of the RTS message for the interfering link is carried in the CTS and is fed back to the transmit node. The case of incomplete channel information happens under asymmetric topologies where information reciprocity does not hold, as illustrated in Fig. 5. The proposed protocol falls back to the 802.11 style MAC. Therefore, in this scenario, throughput performance of the proposed strategy is close to the 802.11 style MAC protocol. By having two control channels, the hidden terminal problem is alleviated. This effect has also been observed in [12], where MIMO technology is used along with multiple RTS/CTS handshakes in time.

III. PERFORMANCE EVALUATION

In this section, we evaluate the performance of the proposed multichannel feedback and scheduling framework. The performance analysis is conducted for a symmetric topology where nodes can all decode each other's control messages. For this case, we show that the proposed strategy significantly outperforms IEEE 802.11 style MAC with continuous rate adaptation in terms of saturation throughput defined in [13]. The analysis is based on the analysis model proposed in [13]. The following assumptions are used:

- All nodes can decode the control packets of each other in the symmetric topology. There are total N nodes in the network.
- Continuous data rate is determined using capacity expression ($\log_2(1+\text{SNR}_k)$) on each subcarrier. This simplifies the analysis and characterizes the ideal system performance. This metric can be closely related to the coded system performance with rate adaptation.
- The channel distribution considers both propagation path loss and fading. The path loss model assumes the form of $\frac{1}{d^2}$, where the distance between any pair of nodes, denoted by d, is a random variable depending on the node locations. The fading model follows an i.i.d. Rayleigh distribution. The wireless channel is assumed to be constant over several packet transmission time.
- Random traffic pattern: any node may send a packet to any receiver in the network.

Assuming that the transmission probability of any node is τ, it can be calculated as $P_{tr} = 1-(1-\tau)^N$. We define P_{tr} as the probability that there is at least one transmission in the network. The quantity P_s denotes the probability of successful transmission conditioned on that there is at least one transmission in the network. Let T_s be the average time the channel is sensed busy and T_c be the average time the channel is sensed to be busy during a collision. The parameter σ, called the slot time, is set equal to the time needed at any station to detect the transmission of a packet from any other station [13]. Following the analysis in [5], the throughput of the proposed protocol and the 802.11 protocol with continuous rate adaptation, denoted by S, can be represented by

$$S = \frac{P_s P_{tr} E[P]}{(1-P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1-P_s)T_c} \tag{7}$$

where $E[P]$ is the average payload size transmitted by the nodes in the network.

The base rate of the system is denoted by R_b, which is used to send control packets such as RTS' and CTS'. Assuming that the data units are of the length L, the duration of data packet transmission can be computed as $\frac{L}{R_b}$. Therefore, we have $E[P] = \frac{L}{R_b}E(C)$, where $E(C)$ is the rate of the links based on the wireless channel conditions. The average rate can be obtained by averaging the sum rate for every channel realization that is generated using Monte-Carlo sampling. This can be derived from (4).

For the case of using two control channels, let P_u be the probability of having two successful simultaneous transmissions in the network. Then the probability of having two successful simultaneous transmissions in the network, denoted by P_u, can be written as

$$P_u = P_{tr}P_s = N\tau(1-\tau)^{N-1} + \frac{N(N-1)}{2}\tau^2(1-\tau)^{N-2}. \tag{8}$$

The conditional collision probability p which defines the probability of a collision seen by a packet transmitted on the

TABLE I

PARAMETERS USED FOR THROUGHPUT CALCULATION

DATA duration	8.184 ms
MAC header	272 bits
PHY header	128 bits
ACK	112 bits + PHY header
RTS	160 bits + PHY header
CTS	112 bits + PHY header
Control Channel Data Rate	1 Mbit/s for one control channel 0.5 Mbit/s for two control channels
Propagation Delay	$1\mu s$
Slot Time	$50\mu s$
SIFS (short interframe space)	$28\mu s$
DIFS (distributed interframe space)	$128\mu s$

channel can be expressed as

$$p = 1 - \frac{P_u}{N\tau}. \tag{9}$$

The collision resolution scheme is the same as used for the 802.11 protocol, i.e., binary exponential backoff. When there is no CTS message heard by the transmitters after the period of CTS transmission, the transmitter performs the binary exponential backoff. We can also relates the probability p with τ by

$$\tau = \frac{2}{1 + W + pW\sum_{i=0}^{m-1}(2p)^i} \tag{10}$$

where W is the backoff window size for the binary exponential backoff. By solving (9) and (10), the parameters τ and p can be retrieved.

We compare the throughput performance of the 802.11 style protocol (with continuous rate adaptation) with our proposed protocol that has two control channels. The system parameters in [13] is used to take into account the overhead as shown in Table I. We neglect the overhead increase in the CTS message from the channel information feedback for simplicity.

We first compare the throughput performance of the proposed protocols with the 802.11 style protocol using continuous rate adaptation. The ratio of the transmit power and the noise power is fixed to be 5 dB. The minimum backoff window and the number of backoff stages are set to be 16 and 3 respectively for the 802.11 MAC [13]. The minimum backoff window is set to be 8 for the proposed protocol. The use of two control channels requires twice the length of the transmission time for the RTS/CTS messages. The payload period is chosen to be 8.184 ms [5].

Fig. 6 illustrates the throughput of the proposed protocol and the 802.11 style MAC. As the number of users increases, for both "Max-Sum-Rate" and "Max-Sum-Log-Rate" methods, the throughput of the proposed protocol increases. The scheduling algorithms based on the channel state information table achieves higher throughput than the 802.11 style MAC with the assumption of continuous rate adaptation.

Fixing the noise power at each receiver, we vary the transmit power and illustrate the throughput vs. the ratio of transmit power to the noise power in Fig. 7. Notice that we assume that all nodes can successfully exchange control packets in the SNR region shown in this figure. In the low power region, the performance gain with two control channels is significant compared to the 802.11 style MAC with single control channel.

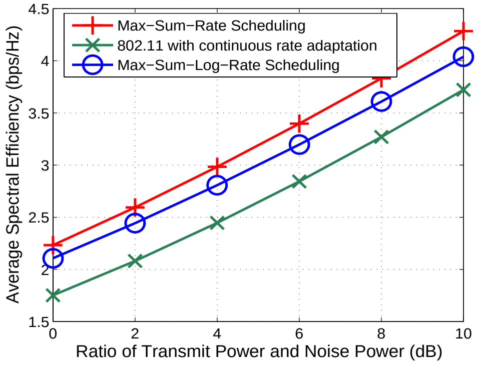


Fig. 7. Comparison of the throughput vs. the ratio of the transmit power to noise power for a symmetric network topology, where there are 40 nodes in the network.

IV. CONCLUSIONS

In this paper, we proposed a multichannel feedback and scheduling solution for OFDM ad hoc networks. Multiple orthogonal control channels are used to carry RTS/CTS messages. This also serves to exchange channel state information between these transmissions. We proposed a scheduling algorithm to allocate the OFDM frequency resource based on the channel state information. Performance analysis showed that the proposed protocol achieves higher throughput than the 802.11 protocol for a symmetric network topology.

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