Multi-User Diversity in Single-Radio OFDMA Ad Hoc Networks Based on Gibbs Sampling

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Abstract*—Multiuser Diversity Medium Access or MDMA is a new cross-layer channel allocation scheme that exploits channel fading diversity and attains concurrency utilizing OFDMA in single-radio ad hoc networks. Channel throughput is enhanced by enabling concurrent transmissions from multiple nodes to the same receiver or from a single transmitter to multiple receivers over orthogonal Subchannels. Also, concurrency is attained when two hop away neighbors can utilize the same subchannel to transmit data to nodes not neighboring the other two hop neighbor. Each subchannel uses a portion of the available bandwidth and contains a grouping of subcarriers or tones which are orthogonal carriers of lower-rate input data streams. A new subchannel assignment algorithm based on Gibbs sampling is presented. This algorithm operates alongside the proposed MAC signaling to distribute subchannels among nodes to exploit channel fading condition on each communication link and to minimize hidden terminal interference. The new MAC addresses the synchronization requirements of OFDMA and the needs of the subchannel assignment algorithm. We present simulation results on the throughput gains obtained with our design compared to traditional channel assignment techniques for multi-channel networks.

I. Introduction

Attaining high channel throughput is a major goal in the design of medium access control (MAC) and physical (PHY) layer schemes. The objective is to enhance throughput by either (a) enabling *concurrency*, (b) adding *diversity*, or providing (c) *adaptivity* in the allocation of resources.

To achieve concurrency, previous MAC protocols utilize orthogonal multichannel networks [1], [2], CDMA [3], MIMO [4] (also provides spatial diversity), and network coding.

Many multichannel FDMA MAC protocols have been proposed in the past [1], [2], where the entire spectrum is divided into orthogonal channels, and nodes switch between such channels to enable concurrent data transmissions. The drawbacks of these techniques are channel switching delays, restrictions on the number of available orthogonal channels, and the inability to deploy dynamic bandwidth allocation techniques. CDMA-based MAC protocols enable concurrent transmission of data over a wider spectrum by multiplying the transmitted signal with a unique code specified for that transmission. However, the drawback of this approach is the need for complex equalization techniques and inability to transmit more than one packet at a time.

Recent results have demonstrated that the capacity of wireless ad hoc networks can significantly improve as a result of spatial diversity if nodes are endowed with multiple interfaces/radios in the presence of multiple non-overlapping channels [5]. However, it is not realistic to utilize as many radios as the number of non-overlapping channels that may be available in a network. Channel assignment and medium access is an even more challenging problem in such networks [4], [6]. TDMA has also been considered for adaptive adjustment of time slots' length among interfering neighbors, however, there is no concurrency of transmissions around receivers, while the adaptive allocation of time is not efficient.

Orthogonal Frequency Division Multiple Access (OFDMA) has been selected for use in multi-user environments (e.g., IEEE 802.16 [7] and DVB [8]) employing OFDM technology due to its ability to combat the multipath effects of wireless channels, and to facilitate the concurrency of transmissions. In OFDM systems, *subcarriers* or *tones* are orthogonal carriers of lower-rate input data streams that mitigate multipath effects. In OFDMA, a group of non-overlapping tones called a *subchannel* can be assigned to each user, thus enabling simultaneous data transmission while intelligent assignment of subchannels based on wireless channel fading results in *multiuser channel diversity*.

Previous work focusing on channel assignment for OFDMA infrastructure-based networks [9]–[12] focuses on fast heuristics for centralized scheduling, which is not applicable to ad hoc networks. The adoption of OFDMA in ad hoc networks has been explored by a few recent works [13]–[15]. These schemes focus on resource allocation algorithms in a multi-antenna environment, or routing, and do not provide a MAC protocol to attain multiuser diversity using single-radio nodes. Scheduling in time and frequency for mesh networks in which routers are responsible for channel assignment is discussed in [16]. On the other hand, the work reported in [17] focuses on a prototype multiuser dynamic OFDMA in a realtime WLAN testbed and does not address ad hoc networks.

To our knowledge, no previous MAC protocol has been designed for ad hoc networks using an OFDMA physical layer to achieve multiuser channel diversity while exploiting concurrency.

Section II and Section III of this paper presents an overview of OFDMA networks, the synchronization restrictions of OFDMA ad hoc networks, and an overview of Gibbs sampling.

Section IV presents the main contribution of this paper, which consists of a cross-layer channel allocation approach for OFDMA-based ad hoc networks. We propose the Gibbs Subchannel Assignment (GSA) algorithm to achieve diversity and adaptive allocation of the spectrum. GSA selects subchannels for a communication link by sampling a Gibbs distribution that aims to minimize both fading and interference power. The algorithm assigns as many subchannels as necessary based on the transmission rate requirement for the link. A node can be in communication with K of its neighbors at the same time. The proposed Multiuser Diversity Medium Access (MDMA) protocol addresses the synchronization requirements of OFDMA

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and also performs concurrent data transmissions from multiple nodes to the same receiver or from a single transmitter to multiple receivers after a single round of handshaking and by utilizing GSA to select enough subchannels for each of the K communication links to achieve the required transmission rate.

Sexction V presents the results of simulations that illustrate the throughput advantages of our technique compared to traditional MAC protocols based on contention-based avoidance of multiple access interference (MAI).

II. OFDMA OVERVIEW

In OFDM, the input data stream is split into a number of lower-rate substreams and is transmitted using a single carrier frequency over multiple parallel orthogonal *tones*. OFDMA is similar to OFDM technology, but it is designed for a multi-user environment. The idea is to group multiple tones into a subchannel and each user transmits data on the assigned subchannel while sending no information over the rest of the tones. Therefore, all users send data at the same time on different parts of the spectrum, and each user can be assigned the best tone from a selection of possible tones. Hence, each user can experience better channel conditions and can take advantage of fading. This is based on the fact that the probability of facing a deep fade by all users on a specific tone is negligible. Thus *multiuser channel diversity* gain is attained. Furthermore, a node can utilize multiple subchannels at the same time for communication. Hence, the number of utilized subchannels can change based on the network demands. Our approach uses this adaptive allocation of bandwidth to improve performance.

To adopt the OFDMA concept to ad hoc networks in which a multi-transmitter scenario is possible, tone orthogonality must be maintained at all receivers. In this case, transmitters should use non-overlapping parts of the bandwidth to send their data. However, because packets are sent using the same carrier frequency, the received signal at a receiver is the addition of all OFDM symbols transmitted over the air. For the receiver to be able to decode any of the transmissions successfully, a *quasi-synchronous* network is required [18], [19], meaning that all transmitters must start transmitting data at the same time. In this case, the time offsets among received signal is limited to the propagation delay and can be incorporated as part of the channel impulse response. Thus, the offset can be compensated as part of the channel equalization performed at the receiver if the added cyclic prefix to each frame is longer than the channel delay spread plus the relative propagation delay among users. Given that in practice the cyclic prefix is designed to be very long, and the propagation delays between nodes are relatively short in a typical ad hoc wireless network, this assumption is realistic [19]. Hence, we assume that the time for data transmission is divided into time slots, and we address the required signaling to create a *quasi-synchronous* network in Section IV.

III. GIBBS SAMPLING

Let $G = (V, E)$ be an undirected graph with a state variable of $X = \{x_1, x_2, ...x_V\}$ for its V nodes each from some finite set S. Then an energy function $E(X)$ for the configuration X is defined and the goal is to find a configuration of the graph that minimizes $E(X)$. This is an NP-hard problem that can be solved efficiently in some special conditions. Let $P_\Delta(X)$ be a potential defined for the subset of Δ from V. Then the energy function over all subsets of Δ on this graph is said to be:

$$E(X) = \sum_{all \ \Delta \subset V} P_\Delta(X)$$

A *Gibbs Measure* uses this energy function for a probability density function of:

$$f(X) = \frac{e^{-E(X)}}{\sum_{Y \in S^V} e^{-E(Y)}}$$

where S^V is the set of possible graph state configurations.

If a considered potential has non-zero values only for Δ that is a clique, then $f(X)$ leads to a Markov random field. This means that the probability of each state can be calculated based on the states of the neighboring nodes. In addition, as it is apparent from the expression fort $f(X)$, the states with the highest probabilities are associated with the lowest energy functions. In such a case, a Gibbs sampler can be used by node v to find its state when the energy function is calculated locally:

$$E_v(x) = \sum_{\Delta \subset V, v \in \Delta} P_\Delta(x)$$

with probability function of:

$$f_v(x) = \frac{e^{-E_v(x)}}{\sum_{y \in S} e^{-E_v(y)}}$$

The energy function is the sum of potentials over cliques that contain v. The algorithm finds a state of x for node v that minimizes the energy function [20]. Each node can independently calculate its state based on the above sampler and move to the new state.

IV. MDMA

Tones are grouped into non-overlapping subchannels. In our design, each node can use multiple subchannels that are none overlapping to transmit or receive data from a neighbor. The subchannels for each transmission are working together as one *channel*. As shown in Figure 1, a common transmitter (C-Tx) can concurrently transmit data on multiple communication links while subchannels on each link are non-overlapping to the subchannels on the other links. Meanwhile a common receiver (C-Rx) can concurrently receive data from multiple transmitters.

Our goal is to distribute subchannels in both C-Tx and C-Rx scenarios while assuring that diversity, adaptiveness, and interference-free transmissions are attained. To do so, we must make sure that each subchannel along with other subchannels utilized on each transmission link contributes to meeting the transmission rate requirement, while a *quasi-synchronous* transmission is achieved. If a C-Tx aims to send data to multiple receivers (Rx) on some subchannels, the subchannel utilized to send data to each Rx should satisfy the following conditions: (a) face better fading on the link between the Rx and the C-Tx, (b) not be currently in use by any neighbor of Rx for transmission, (c) not be currently in use by any neighbor of C-Tx for data reception, and (d) not be used by C-Tx for transmission to other receivers. Also, if a C-Rx aims to receive data from multiple transmitters (Tx) on some subchannels, the subchannel utilized to receive data from each Tx should satisfy the following conditions: (a) face better fading on the link between the Tx and the C-Rx, (b) not be currently in use by any neighbor of Tx for reception,

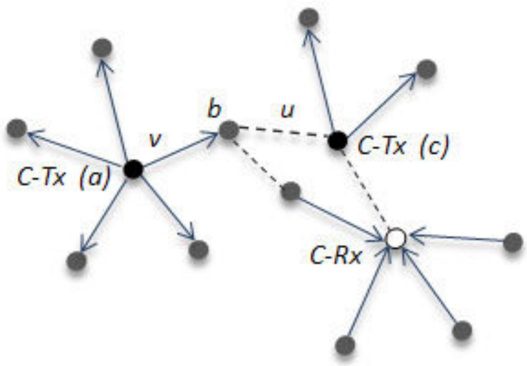


Fig. 1. A sample topology for Common Transmission and Common Reception

c) not be currently in use by any neighbor of C-Rx for data transmission, and (d) not be used by C-Rx for reception from other transmitters.

We assume that each subchannel includes the minimum number of tones possible, and as a result, the maximum number of subchannels are available (802.16, up to 96 subchannels [21]).

The MAC protocol is responsible for: (a) allowing the estimation of the channel gain at receivers by transmission of pilot signals from transmitters to receivers prior to data transmission, (b) exchanging information regarding interference power, (c) exchanging information regarding the allocated subchannels from a C-Tx or a C-Rx to the corresponding neighbors, and (d) performing synchronization to avoid loss of orthogonality in a multi-transmitter situation.

Our goal is to minimize direct interference and hidden terminal interference, and to maximize channel diversity. We propose to use the Gibbsian method with a small twist by defining a new energy model and a MAC protocol that works to select subchannels for each communicating link. Gibbs sampling has been used in the past [21] to distribute channels among multiple 802.11 interfering access points; however, this prior work does not consider hidden terminal interference and is based on self-measuring interference power.

To define the potential function for our design, we model our network with a Gibbs graph in which each directed link in the network is represented by a node in the graph. The edges in the graph connect two nodes together if the associated directed links share the same endpoint. Then the potential function for a node involves the node as one clique, and each clique includes the node and its direct neighbor, v', and the state variables, x, are the subchannels.

$$E_v(x) = P_v(x) + \sum_{v'} P_{v,v'}(x)$$

To maximize diversity, we set $P_v(x)$ to be the inverse of the absolute value of the channel gain on the associated link. Given that we want to minimize interference from neighboring transmitters, $P_{v,v'}(x)$ is set to the channel gain times the transmission power on the interfering links. $\sum_{v'} P_{v,v'}(x)$ can be measured at the sharing endpoint by node b in Figure 1 for link v in the network graph or node v in the Gibbs graph and is equal to interference power, $Pi_v(x)$. This eliminates hidden-terminal interference. If the measured power on a subchannel at node b is very low, there still might be a concurrent transmission from c on the same channel to another neighbor; however, the fading causes a very weak channel gain on link u and as a result node a can select this subchannel for transmission to b. This increases spectrum utilization by means of hidden terminal fading over utilization. The MAC in our design avoids causing interference at a neighbor of a who is receiving data on some subchannel.

A. Gibbs Subchannel Assignment (GSA)

A Gibbs measure is defined for each transmission link in our design when the energy function is calculated locally and is based on the interference power and the channel gain of the link. A C-Tx or a C-Rx is responsible for running the GSA algorithm to find subchannels for transmitting links to their neighbors. During the operation of MDMA, after a C-Tx or a C-Rx had requested multiple transmissions or receptions over links $U = \{1, 2, ..u\}$, the absolute value for channel gain on each subchannel k, $CSI_u(k)$, as well as the interference power at the end point of link u on each subchannel k, $Pi_u(k)$, will be known via MDMA handshaking at the C-Tx or the C-Rx which performs the following:

1) For each link, calculate the energy function for all subchannels with a known CSI_u and Pi_u when

$$E_u(k) = 1/CSI_u(k) + Pi_u(k)$$

.

2) For each link, find the distribution for all subchannels k as

$$f_u(k) = \frac{e^{-E_u(k)}}{\sum_{k' \in K} e^{-E_u(k')}}$$

3) Sample the distributions of links $U = \{1, 2, ..u\}$ when no two links receive the same subchannels and the rate requirement is met for all links. This means that, for each state k, the link with the highest state probability (maximum probability of successful reception) is found and that subchannel is allocated to that link:

$$choose\ link\ u = \arg \max_{u \in U} f_u(k)$$

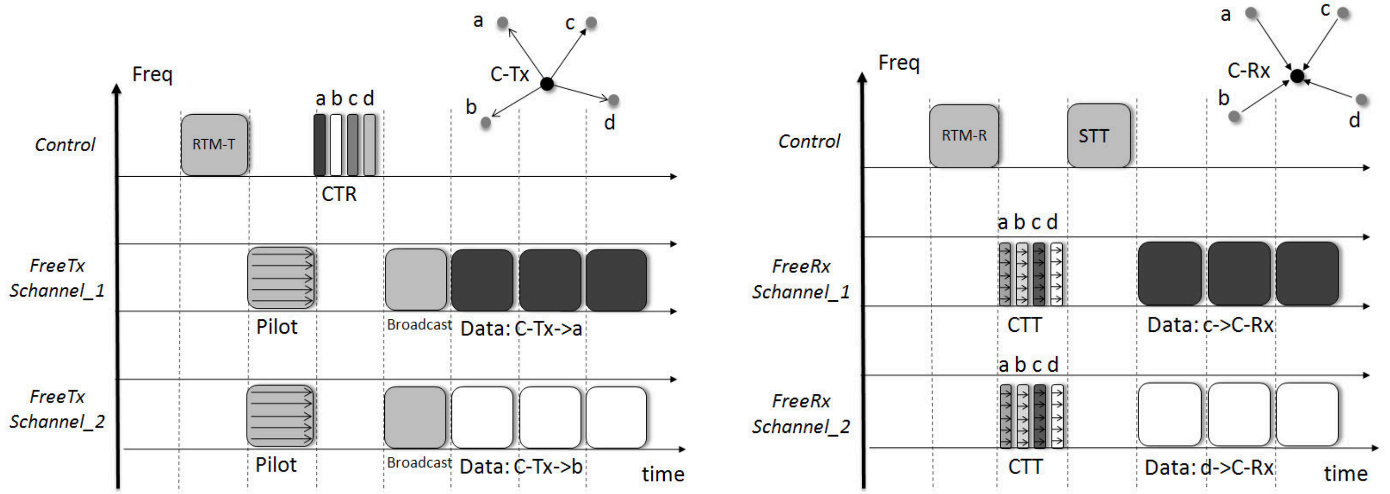
For each subchannel a maximum number of decodable bits is found based on the SINR value of the associated link $SINR_u(k) = \frac{P \times CSI_u(k)}{Pi_u(k) + noise}$, where P is the transmission power. This is done by comparing the minimum SINR required for a modulation (QPSK, 16QAM, 64QAM, 256QAM) to be decodable at the receiver with the value of $SINR_u(k)$. Then a table is created for each link with the accumulated number of bits on all of the assigned subchannels for each link. During the run, if any of the accumulated rates for any of the links meets the rate requirement, GSA eliminates the link from the rest of the assignment.

Based on the rate requirement, all links can be assigned the required rate and some subchannels may still be left unassigned and can be used by the neighboring nodes for concurrent communication. This adaptive allocation of spectrum is an important advantage of this technique as will be discussed in Section V.

B. Common Transmitter (C-Tx)

A Common Transmitter (C-Tx) performs the following steps:

1) C-Tx transmits an RTM-T (Request to Multiple Transmit) over a dedicated control subchannel. The RTM-T contains a clock frequency reference, candidate subchannels for transmission of pilots (*FreeTx list* from stage 7), the addresses



(a) Illustration of MAC signaling when a common transmitter sends to multiple receivers

(b) Illustration of MAC signaling when a common receiver receives from multiple receivers

Fig. 2. Illustration of signaling for MDMA

of the receivers and time reference, as well as the schedule for the transmission of CTR (Clear to Receive).

2) C-Tx sends pilot data over the subchannels that are free for transmission (*FreeTx list*). One pilot is sent for every m tone, and each receiver estimates the channel gain via interpolation. m is set by the physical layer detection algorithm. The channels that are free for transmission are known to C-Tx from stage 7 of this protocol.
3) Receivers that successfully receive the RTM-T message, estimate the average channel gain for each subchannel.
4) The same receivers measure the interference power on the subchannels in *FreeTx list*.
5) Each receiver transmits a CTR (Clear To Receive) message based on the schedule sent by the C-Tx to avoid interference.
6) The CTR message from node b contains a table that includes the calculated channel gain, $CSI_{(C-Tx,b)}(k)$, for each subchannel k and the measured power of interference or $Pi_b(k)$ for each subchannel k, as well as time reference information originally sent by the C-Tx.
7) All nodes neighboring the receivers would be aware of the clock reference time of the C-Tx and can fix their time to avoid loss of orthogonality in a multi-transmitter scenario. Neighbors of each receiver (e.g., b) would also be able to use the CTR table to calculate the subchannels that with high probability will be chosen by the C-Tx for transmission to node b. These subchannels are then eliminated from the *FreeTx list* of neighbors of b.
8) C-Tx then runs the GSA algorithm and assigns the resulting grouping of subchannels to each neighbor.
9) The first OFDM frame is a broadcast frame and contains the list of the assigned subchannels for each neighbor.
10) C-Tx starts sending data to multiple nodes using the allocated subchannels.
11) The receivers obtain an OFDM frame that contains the null value on some subchannels. Each node would decode the entire frame and after the FFT module filters the assigned subchannels, it detects its own data.

Figure 2(a) illustrates an example for the above scenario when a C-Tx is attempting to transmit data to nodes a, b, c and d. After the transmission of the RTM-T, all neighboring nodes can adjust their clock frequency and their time reference. Therefore, if any of the one-hop neighbors of a, b, c, or d is about to start transmitting data, it can adjust its time to the C-Tx to avoid causing multi-transmission loss of orthogonality at a, b, c, or d. The pilot signals sent by the C-Tx are known signals that are sent for every m tone of the subchannel to enable the estimation of the channel gain at the receiver side (for instance, $m = 4$ in DVB design [8]). After $CSI_{(C-Tx,a)}(k)$, $CSI_{(C-Tx,b)}(k)$, $CSI_{(C-Tx,c)}(k)$, and $CSI_{(C-Tx,d)}(k)$ is calculated and $Pi_a(k)$, $Pi_b(k)$, $Pi_c(k)$, $Pi_d(k)$ is measured by a, b, c and d on the subchannels, the common transmitter is informed about them via reception of the CTR. Then the GSA algorithm is run at the C-Tx and the first broadcasting packet informs the receivers about the allocated subchannels. Data transmission from C-Tx to a and b is shown in the figure.

C. Common Receiver (C-Rx)

In this case, a Common Receiver (C-Rx) performs the following:

1) A C-Rx transmits an RTM-R (Request to Multiple Receive) over the control subchannel. The RTM-R contains clock frequency reference, candidate subchannels for data reception and transmission of pilots (the *FreeRx list*, which can easily be sensed from the channel), the intended transmitter addresses, a time reference, and a schedule for transmission of pilots from each transmitter.
2) Nodes that successfully receive the RTM-R message transmit a CTT (Clear to Transmit) message based on the schedule sent by the C-Rx over the specified subchannels. The CTT message contains pilot data to facilitate fading estimation at the receiver, as well as the time reference of

the C-Rx node. Note that each transmitter only sends CTS on a subchannel if the subchannel is part of its *FreeTx list*.

3) C-Rx performs channel estimation, measures interference power $Pi_u(k)$, and runs the GSA algorithm to assign a grouping of subchannels to each link.
4) C-Rx transmits a STT (Start to Transmit) message on the control subchannel that contains the list of the assigned subchannels for each neighbor.
5) Nodes start transmitting data over the assigned subchannels at the same time according to the clock and time reference of the C-Rx, and C-Rx would be able to separate them based on the assignment.

Figure 2(b) illustrates an example for the C-Rx scenario. In this scenario, to facilitate channel estimation, after reception of RTM-R message, nodes a, b, c and d should send pilots over the subchannels specified by the C-Rx via RTM-R message. The CTT message also includes the C-Rx time reference information. Therefore, one-hop neighbors of a, b, c and d receive the message and would be able to make sure that, if they are about to be receiving data on any subchannel, the timing of the other transmitter is aligned with the timing used by a, b, c and d. The C-Rx in this case, has to run the GSA algorithm, assign subchannels to the neighbors, and sends an STT message to inform the neighbors about the assigned tones. Data transmission from c and d is shown in the figure.

V. Simulations

Qualnet [22] and MATLAB simulations were carried out to study the performance of GSA and MDMA. Given that Qualnet does not offer bit level simulations, we used MATLAB to find the average achievable bit rate per transmission link and fed that information to Qualnet to obtain the average throughput.

A sample topology in MATLAB with seven C-Txs is shown in Figure 3. We simulated for C-Txs attempting to transmit data to K randomly selected neighbors (out of the six in this scenario). To evaluate GSA we only consider common transmitters and assume the same result applies for common receivers. Each link is modeled to be facing a Rayleigh distributed channel. Random seeds were selected to simulate the rate under different fading channel conditions. We compared the performance of GSA with channel selections of traditional multichannel networks that utilize adaptive rate selection (McH) so that QoS is considered in our comparison [23]. Also, we considered a channel-based diversity technique, CBD, when each OFDMA node is assigned periodically multiple subchannels unique to the subchannels of its interfering nodes. The selection is based on some priority order such as node ID [24]. The more the traffic requirement, or K, the more number of subchannels is assigned to each node. Then fading is only considered when a C-Tx or a C-Rx distributes the tones within the assigned subchannels among the K communicating neighbors.

Figure 4 presents the total received bit rate (throughput) for various rate requirements (R) per link when 2k subchannels are available and $K = 4$. Throughput is saturated when the entire spectrum is utilized. The improvement from McH to CBD is apparent. However, there is a large improvement when subchannel selection is done adaptively by minimizing interference power and fading over the entire spectrum, as it is done with the GSA algorithm. In this case, a two hop neighbor of a C-Tx can use the same subchannel to transmit data to a neighbor that is not in the

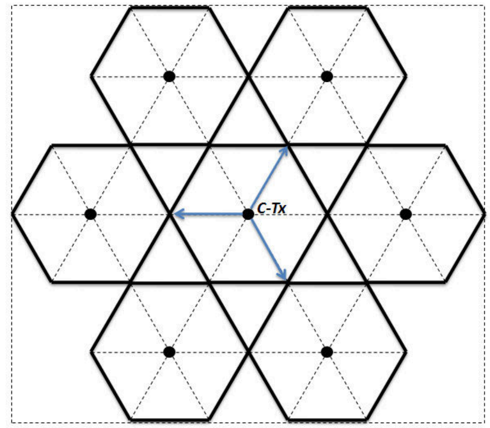


Fig. 3. Topology for MATLAB simulations

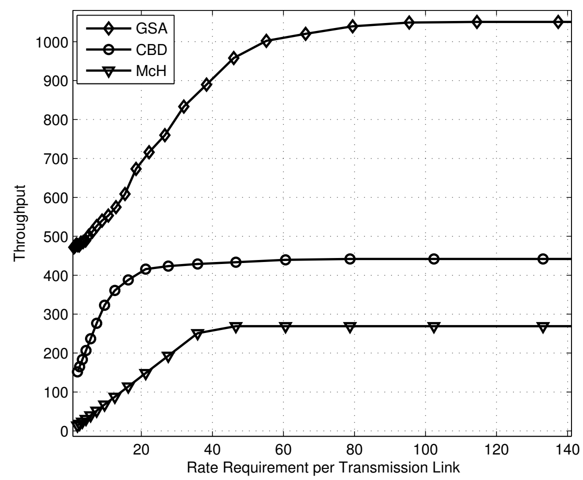


Fig. 4. MATLAB results comparing the proposed GSA scheme with a MultiChannel (McH) technique and an algorithm using Channel Based Diversity (CBD)

range of the C-Tx if the receiver of the C-Tx is not neighboring this two-hop transmitter. Therefore, more concurrency is attained with MDMA. Based on the results from our simulations, the ratio of improvement for different K is the same.

In Qualnet simulations, 50 nodes were distributed uniformly in an area that changed depending on network degree or the average number of nodes' direct neighbors (Ne.) Throughput is the total number of successfully received data bits (not any of the control data bits) in the network divided by the simulation time and the number of nodes in the network. This provides an insight on the performance of the simulated protocols considering all overhead. Packets have an MTU of 512B, and we averaged our experimental values over 10 different random stationary topologies. The signal attenuation is assumed to be based on an indoor environment by delay spread of 200ns. Figure 5 shows the throughput per node in bit/sec versus normalized K, K_N, or percentage of direct neighbors in communication with a C-Tx or a C-Rx. Each node randomly chooses a number from 0 to 1 and if the number is less than 0.5, the node becomes a C-Tx; otherwise, it acts as a C-Rx. The simulations were carried out for MDMA, and other techniques such as CTRMA [25], CBD, and a channel-switching MAC. For a channel switching MAC, we simulated MMAC [2] which is a multi-channel MAC based

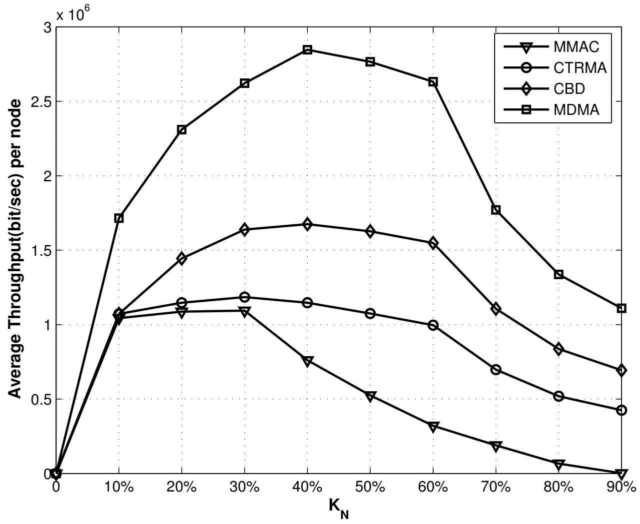


Fig. 5. Simulation results for MDMA, CTRMA, CBD, MMAC

on exchanges of requests over a control channel but only utilizes a single orthogonal channel per transmission and tries to avoid interference based on the first available free channel(same overall bandwidth as MDMA for the sake of comparison). CTRMA also uses OFMDA at the physical layer; however, it focuses on adaptive distribution of subchannels among links based on network traffic and node IDs, and channel fading is not a factor in its assignment of subchannels.

With a channel-switching scheme, only a fixed number of channels can be utilized as K_N increases. As K_N goes up from 0 to 30%, the throughput increases because more communication can take place in the network. However, the number of channels is not enough to support all the traffic, and throughput declines as K_N continues to increase due to contention. The number of channels is equal to 5 in this simulation. For the case of a channel-switching scheme, the fewer channels available, the larger the throughput is at lower K_N but the faster it declines as traffic increases. With CTRMA, CBD, and GSA, as the number of communicating neighbors increases, the schemes assign more subchannels to the nodes, and although contention does exist, the reduction in throughput is much slower than with a channel-switching scheme. In thse three approaches, the more spectrum wide diversity that is incorporated, the higher the achievable rate on a link is, which means that the resulting throughput is higher. As shown in Figure 5, MDMA has the best performance as traffic demand increases and provides the highest bit rate for all traffic needs.

VI. Conclusion

We presented a new spectrum allocation technique based on multi-user diversity for single-radio OFDMA ad hoc networks using Gibbs sampling. Previous cross-layer MAC protocols for ad hoc networks fail to utilize OFDMA at the physical layer to achieve diversity over the entire spectrum. The novelty of this work is the Gibbs Subchannel Assignment (GSA) algorithm, which uses Gibbs sampling to minimize interference power and fading, and a new MAC protocol using GSA that enables concurrent initiation of data transmission and adaptive distribution of the channel. The results from simulations illustrate the performance improvement due to concurrency, the added diversity rate, and the adaptive allocation of bandwidth to nodes.

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