

UC Santa Cruz

UC Santa Cruz Previously Published Works

Title

Parallel Interaction MediumAccess for Wireless Ad Hoc Networks

Permalink

<https://escholarship.org/uc/item/743776g8>

Author

Garcia-Luna-Aceves, J.J.

Publication Date

2008-08-03

Peer reviewed

Parallel Interaction Medium Access for Wireless Ad Hoc Networks

Marzieh Veyseh[†]
marzieh@soe.ucsc.edu

[†]Computer Engineering Department,
University of California, Santa Cruz
Santa Cruz, CA 95064, USA

J.J. Garcia-Luna-Aceves^{†*}
jj@soe.ucsc.edu

*Palo Alto Research Center (PARC)
3333 Coyote Hill Road
Palo Alto, CA 94304, USA

Abstract—The Parallel Interaction Medium Access (PIMA) protocol is introduced to orchestrate channel access in a wireless ad hoc network when nodes are endowed with a single half-duplex radio, and can either transmit multiple packets to multiple destinations in parallel or receive multiple packets from multiple transmitters in parallel using OFDMA. Analytical and simulation results indicate that PIMA attains tremendous improvements in channel throughput compared to MAC protocols aimed at attaining concurrency via traditional channel switching techniques proposed in the past for multi-channel networks.

Index Terms—OFDMA, MAC protocol, multichannel MAC, Ad hoc networks, OFDMA synchronization.

I. INTRODUCTION

Prior work on attaining concurrency in medium access control (MAC) has focused on channel switching, network coding, multiple antenna (MIMO), and few works on OFDMA. In multichannel MACs designed for channel switching networks, e.g. 802.11 [1], each radio is assigned to receive or transmit on a single channel by means of different mechanisms, including [2]–[8]: scheduling, negotiations and reservations taking place on a dedicated common channel accessed concurrently or alternately with data channels, the use of a common channel-hopping sequence, or the use of channel-hopping sequences assigned to nodes randomly and learned over time. However, since nodes are limited to transmitting or receiving on a single channel, many problems such as *multichannel hidden terminal problem* are very obstinate to overcome.

Different schemes have been proposed to improve network throughput by using network coding (NC). However, concurrency in NC is still limited, because a receiver must receive one packet at a time [9], and the gains observed in some schemes (e.g., analog network coding [9]) can be attributed to the ability of a receiver to decode multiple concurrent transmissions under very strict assumptions.

Multiple antennas (MIMO) introduce concurrency by enabling nodes to receive n data streams in parallel [10] or

eliminate interference on the same channel from as many as $(n - 1)$ neighbors [11] if the nodes are endowed with at least n antennas for the price of higher energy consumption.

Orthogonal Frequency Division Multiple Access (OFDMA) [12] has been selected for use in multi-user infrastructure-based environments (e.g., IEEE 802.16 [13] and DVB-RCA [14]). OFDMA joins OFDM with FDMA (frequency division multiple access) to enable concurrency while avoiding collisions. In OFDM systems, *subcarriers* or *tones* are orthogonal carriers of lower-rate input data streams that result in longer symbol duration compared to channel delay spread to mitigate multipath effects. In OFDMA, a group of non-overlapping subcarriers called *subchannels* are assigned to each user to enable simultaneous data transmission to a base station.

Centralized schemes for scheduling in time and frequency for mesh networks where mesh routers are responsible for channel assignment are discussed in [15], and [16]. Although Kulkarni and Srivastava [17] and Venkataraman [18] propose resource allocation algorithms in terms of power, bit, and subcarriers in ad hoc networks, they do not discuss a complete MAC protocol.

This paper demonstrates that using OFDMA at the physical layer constitutes a viable alternative to achieving concurrency. The attained concurrency is much more flexible compared to techniques like channel switching, network coding, and MIMO. Section II introduces the Parallel Interaction Medium Access (PIMA) protocol, which is the first MAC protocol that permits a sender to transmit multiple packets concurrently and a receiver to decode multiple packets concurrently by orchestrating channel access over time and frequency based on OFDMA in ad hoc networks where nodes are equipped with single half-duplex antennas. Section III presents an analytical model and simulation results showing that PIMA provides substantial benefits compared to prior multichannel MAC protocols based on channel switching.

II. PIMA: A NEW APPROACH TO CONCURRENCY IN AD HOC NETWORKS

A. Physical Layer Synchronization in Time and Frequency

In OFDMA networks, a transmitter puts together the data streams for all users after passing them through subcarrier

¹This work was partially sponsored by the U.S. Army Research Office under grants W911NF-04-1-0224 and W911NF-05-1-0246, by the National Science Foundation under grant CNS-0435522, by DARPA through Air Force Research Laboratory (AFRL) Contract FA8750-07-C-0169, and by the Baskin Chair of Computer Engineering. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the U.S. Government.

assignment unit and creates one block of frequency-domain samples. Afterward, the block is passed through an Inverse Discrete Fourier Transform (IDFT) module and a Cyclic Prefix (CP) is added to avoid Inter Block Interference (IBI). The received signal at the receiver is the addition of all OFDM symbols transmitted over the air. The synchronization task in MANETs entails much higher complexity compared to general OFDM transmission, because the signals come from different transmitters and they pass through different channels. In general, as a consequence of L_m channel taps, the length of each OFDM block is extended up to $L_m - 1$ samples of the next OFDM block. If the inserted CP is longer than L_m , no IBI is presented in the received signal and the timing offset only causes a phase shift that can be detected and compensated by channel equalizer. This is of great interest in OFDMA networks, because the receiver cannot align its Discrete Fourier Transform (DFT) window to all transmitters at the same time; therefore, it needs to acquire time and feed back for the estimates to each neighbor to adjust their DFT window and their oscillators to create a rather *quasi-synchronous* scenario.

PIMA attains time and frequency synchronization as follows: First, a potential receiver attaches a pilot signal to a control message called ready to receive (RTR). This message serves the purpose of coarse synchronization as well as a marker for the initiation of transmissions in PIMA as it's important for channel assignment purposes. The RTR is sent to potential transmitters right before they start their transmissions so that they can adjust their DFT (Discrete Fourier Transform) window as well as their local oscillator. The technique proposed by Moose [19] for OFDM systems exploits training sequences to acquire frequency offset in the uplink scenario. In PIMA, assuming subband based subcarrier assignment, which assigns continuous subcarriers to each user, two successive identical training sequences are transmitted along with each OFDMA block, and the phase shift is measured in the frequency domain at the receiver when N subcarriers are used per OFDM symbol:

$$\hat{\epsilon} = \frac{1}{2\pi(N + L_m)/N} \arg \left\{ \sum_{k=0}^{N-1} u_2(k) u_1^*(k) \right\}$$

$u_2(k)$ and $u_1(k)$ are the consecutive blocks assuming the channel is flat for two successive blocks, and $(\hat{\epsilon})$ is the estimated Carrier Frequency Offset (CFO).

For frequency compensation, after the separation of data streams and the estimation of $(\hat{\epsilon})$, prior to each DFT block, a direct multiplication of $e^{-j2\pi\hat{\epsilon}k/N}$ compensates for frequency offset. However, this technique requires a separate DFT block for each user and greatly increases the complexity of the receiver especially when the number of transmitters increases. Jihoon et al. proposed a method called CLJL [20] that performs compensation after the DFT block using circular convolution. Note that the complexity of this design decreases as the number of users increases.

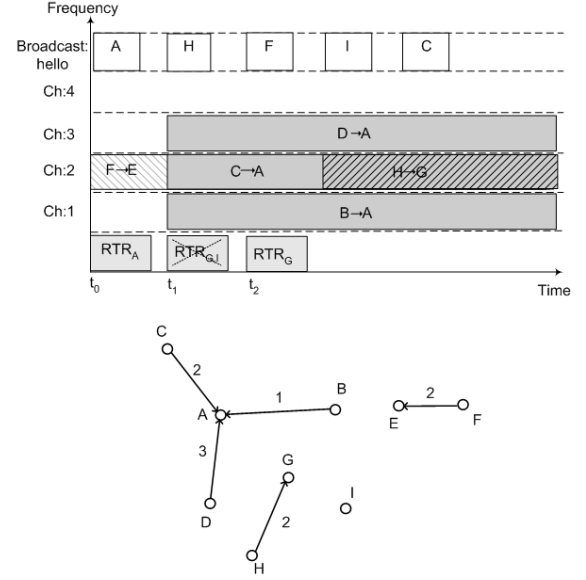


Fig. 1. Illustration of the operation of PIMA

B. Subchannel Assignment

The design of PIMA takes advantage of two basic principles. First, if the collision-avoidance handshake is initiated by the receiver, the throughput is greatly improved [21]. Second, By exchanging busy channel lists, receivers can make smart decision in avoiding hidden-terminal interference.

A channel is dedicated for control message exchange. The receiver is responsible for choosing non-overlapping channels for multiple transmitters in one round of collision avoidance handshake by sending a message called *ready to receive* (RTR) on the control channel and given that nodes can receive data on all channels at the same time, a node is able to decode messages from the control channel even when it is busy receiving data on other channels. This message contains a list of the receivers' neighbors and a channel assignment for each of them. These channels are distinct and they should be chosen in such a way that no collision occurs if the neighbors start to send messages on the assigned channels.

Two basic factors are required to make sure that the channel assignment procedure is carried out successfully: (a) No other transmitter in the one-hop vicinity of the receiver should send messages on the channels that the receiver is going to assign to its neighbor, and (b) the channel that the receiver is going to assign to Node A should not be used by Node A's neighbors for data reception. With respect to the first factor, each node is capable of listening to all channels and due to the usage of OFDMA, each node can detect which channels are being occupied by the neighbors' transmissions and create a list of channels that are Clear to Receiver (CR). Regarding the second factor, a receiver needs to be informed of the list of prohibited channels for each one-hop neighbor prior to channel selection.

The *Prohibited for transmission list* (PTL) is the list of the channels currently being used by the two-hop neighbors for transmitting data packets. This list is created by each node and

is updated when a new RTR is received on the control channel. Because an RTR includes a list of the channels that the neighbors of the transmitter of the RTR are using, the recipient of the RTR adds all the channels listed in the RTR to its PTL to keep it updated. Meanwhile, each node needs to be informed of the consistent PTL list belonging to each one-hop neighbor. To do so, routing protocol control messages are the perfect carriers of these lists. Every time a node broadcasts a *hello* message or a similar update message belonging to the routing protocol to its one-hop neighbors, it appends its updated PTL list to the message. To make sure that the broadcast messages will be received clearly, we dedicate a channel for transmission of *hello* messages. This channel is periodically used by nodes to broadcast their neighbor discovery messages. The intervals between the transmission of *hello* messages need to be a function of the network degree, N_n (average number of on-hop neighbors), as: $I = N_n + \text{rand}(\text{seed}) \times N_n$.

The collision avoidance handshake of PIMA operates as follows: The receiver (node j) transmits an RTR on the control channel with rate λ/N_n when the packet arrival rate is Poisson distributed with rate λ . The RTR contains a list of the neighbors and the channels assigned to each of them. Node j chooses a distinct channel, c_i , for neighbor i while $c_i \notin PTL_i$ and $c_i \in CR_j$. PTL_i is the PTL list belonging to neighbor i , and CR_j is the CR list belonging to receiver j . A training sequence is appended to the message RTR, to make sure that the neighbors adjust their clocks and their DFT windows to create a quasi-synchronous environment. Transmitters start sending messages immediately after successful reception of RTR if they have data ready to be sent.

Fig. 1 illustrates the operation of PIMA for the drawn topology. Node A sends an RTR on the control channel at time t_0 . Note that channel 2 is being used by Node F to transmit data to Node E, since Node A had received the PTL list of Node B through the transmission of *hello* messages, it knows that channel 2 is prohibited for Node B. So Node A selects channel 1 for Node B. After the successful reception of RTR by Nodes B, C, and D, they immediately start sending messages on the assigned channels. At time t_1 both Nodes G and I attempt to access the control channel by sending RTR, however collision occurs and no transmission takes place. At time t_2 , only Node G sends an RTR and I assigns channel 2 to Node H. This is due to the fact that channel 1 and 3 are occupied by one-hop neighbors of G.

III. PERFORMANCE EVALUATION

A. Numerical Analysis

We analyze the throughput improvement achieved via OFDMA concurrency compared to existing multi-channel MAC protocols based on channel switching and single-channel MAC schemes. To take hidden terminals into account in our analysis, we assume that there are a total of n nodes randomly distributed on a unit sphere surface that is divided into square cells with area $a(n)$ as described by Gamal, et al. [22]. They prove that, if $a(n) = \Theta(\log n/n)$, each cell contains at least one node with very high probability. A node can communicate

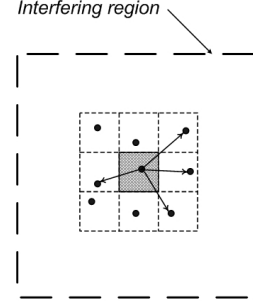


Fig. 2. Model used in the analysis

with any other node in its cell and the 8 neighboring cells and the transmission range is $r(n) = \sqrt{8a(n)}$ to insure connectivity. Based on the relaxed protocol model [23], a successful transmission of data from node i to node j on a specific channel is possible if for any other node k transmitting data on the same channel:

$$d_{kj} = (1 + \Delta)r(n)$$

where d_{kj} represents the distance from node k to node j . The *guard interval* Δ has a direct relationship with the minimum signal-to-interference ratio (SIR) necessary for the physical layer to successfully receive data bits. Therefore, two transmitters sending data on the same channel should be at least $(2 + \Delta)r(n)$ away from each other. As a result, for a node located in a cell, any other node located in a square with side of $(4.35 + 2\Delta)r(n)$ surrounding this node could be a potential interferer. We focus on the performance of the nodes located inside one interfering region because the performance of MAC primarily is bounded by the behavior of the protocol in a two-hop neighborhood. Fig 2 shows a cell, its eight neighboring cells and the interfering region. The number of cells in an interfering region is found to be:

$$N_{ce} = \frac{[(4.35 + 2\Delta)r(n)]^2}{a(n)} = 8(4.35 + 2\Delta)^2$$

$N = N_{ce}na(n)$ is the number of nodes in this region.

1) *PIMA*: Nodes try to attempt the channel with rate λ/N_n to receive data from their one-hop neighbors at the same time. Therefore, each polled one-hop neighbor has data packet addressed to the polling node with probability 1, because every N_n/λ time units, a node has data packets waiting to be transmitted for all of its neighbors. Due to OFDMA concurrency, each node can simultaneously receive data from $N_n = (9na(n) - 1)$ of its neighbors. Hence the maximum achievable communication links is bounded by the number of nodes in the region and c , the number of available data subchannels is $l_{max} = \text{Min}(c, \lceil N_{ce}/9 \rceil \cdot N_n)$.

The behavior of the MAC protocol is modeled using a Markov chain when the packet length is assumed to be geometrically distributed with parameter q and the average packet length is $L = 1/(1 - q)$. We also assume that the time is slotted with perfect synchronization at slot boundaries.

The length of each time slot is assumed to be equal to the transmission time of an RTR plus two propagation delays. At any given point in time, the state i is represented by (k_i, l_i) where k_i is the number of nodes transmitting data and l_i is the number of nodes receiving data in the region. A transition from one state to another takes place if a new RTR is successfully received by one or multiple idle nodes, or an existing active link between a transmitter and a receiver is terminated. The state transition probability p_{kl}^{mn} from state (k, l) to state (m, n) can be expressed as follows:

$$p_{kl}^{mn} = \sum_{(\alpha, \beta, \mu, \eta) \in S_t} \{R_k(\alpha) \cap T_{k,l}(\mu|\alpha) \cap RT_{k,l}(\eta, \beta|N^a)\} \quad (1)$$

where $R_k(\alpha)$ is the probability that α links are terminated when k transmitters are actively transmitting data in the region:

$$R_k(\alpha) = \binom{k}{\alpha} (1-q)^\alpha q^{k-\alpha} \quad (2)$$

and $T_{k,l}(\mu|\alpha)$ is the probability that μ receivers stop receiving data from all of their transmitters given that α links have been terminated. Based on our analysis and its comparison with the simulation's results, the probability distribution function of μ is expressed as:

$$T_{k,l}(\mu|\alpha) = \mu^{(\kappa-1)} \frac{e^{\mu/\theta}}{\theta^\kappa \Gamma(\kappa)}$$

Assuming μ is gamma-distributed, $\mu \sim \Gamma(\kappa, \theta)$, with shape parameter $\kappa \propto \alpha$, and scale parameter $\theta \propto l$.

$RT_{k,l}(\eta, \beta|N^a)$ is the joint probability that η new receivers start to receive data and β new transmitters start to transmit data given that N' nodes are available in the new state. Only one successful RTR can be transmitted in the interfering region, therefore, only one new receiver can be added to the system. There are a total of $l_{av} = c - (k - \alpha)$ links left to be used in the region. To add β new transmitter, this request must be aimed for β idle neighboring nodes and the assigned channels must be available to the transmitters. Accordingly, β cannot be more than l_{av} . Also β can not possibly be larger than average number of nodes' one-hop neighbors, N_n . N^a is the total number of available nodes and is equal to $N - ((k+l) - (\alpha + \mu))$.

$$RT_{k,l}(\eta, \beta|N^a) =$$

$$\begin{cases} \delta(\eta-1) T_e \left(\frac{N^a}{N_n}\right)^\beta + \\ \delta(\eta) ((1-T_e)^+)^{\beta-1} & \text{if } \beta \leq l_{av}, \beta \leq N_n; \\ T_e \left(1 - \left(\frac{N^a}{N_n}\right)^{\min(m, N_n)}\right) & \\ 0 & \text{if } \beta > l_{av}, \beta > N_n; \end{cases}$$

T_e is the probability that one successful RTR has been transmitted in the interfering region:

$$T_e = \binom{N^a}{1} p (1-p)^{N^a-1} \quad (3)$$

Note that N_n^a is the average number of idle nodes among the nodes' one-hop neighbors: $N^a \cdot N_n / N$.

S_t represents all possible values for the set $(\alpha, \beta, \mu, \eta)$ when $l = 0$ to $(l_{max}+1)/2$, $k = l$ to $(l_{max}+l-1)$, and $n = 0$ to $(l_{max}+1)/2$, $m = n$ to $(l_{max}+1-n)$.

$$S_t = \begin{cases} (\alpha, (m-k) + \alpha, (l-n) + \eta, \eta) : & \text{if } n-l \leq 1, \\ \forall \alpha, \eta \in N, (1 \leq \alpha \leq k, \eta=1) & m-k \geq 1; \\ ((k-m) + \beta, \beta, (l-n) + \eta, \eta) : & \text{if } n-l \leq 1, \\ \forall \eta, \beta \in N, (\eta=0, \beta=0) \text{ or } (\eta=1, 1 \leq \beta \leq m) & m-k < 1; \\ 0 & \text{if } n-l > 1; \end{cases}$$

After finding S_t depending on the value of (k, l) and (m, n) , we can numerically calculate the transition probabilities. If the states are numbered from 1 to $M = \frac{l_{max}(l_{max}+1)}{2} + 1$, π_i represents the steady state probability of state i and $P_{(ij)}$ represents the transition probability from state i to state j . To find π_i for all i , we need to solve the global balance equations as follows:

$$\sum_{i=1}^M \pi_i = 1, \quad \pi_j = \sum_{r=1}^M \pi_r P_{(rj)} \text{ for } j = 1 \text{ to } M$$

Throughput as the average number of packets received per time slot per node is:

$$S = \frac{\sum_{i=1}^M k_i \pi_i}{N}$$

where k_i is the number of communication links in state i .

2) *Channel Switching MAC*: We compare the performance of PIMA with a generalized MAC protocol using a dedicated control channel, a specific common-hopping MAC protocol called RICH [5] because of its good performance among channel switching MACs, and a single-channel MAC employing RTS-CTS collision avoidance handshake.

a) *MAC with dedicated control channel*: In a MAC based on a dedicated control channel, a node transmits an RTS on the common control channel with probability $p = \lambda$. The receiver of the RTS replies with a CTS that includes the agreed channel number and both the transmitter and the receiver switch to the channel to carry on the communication. Given that each node can communicate with only one of the nodes in a neighboring cell, the maximum number of achievable simultaneous links is bounded by:

$$l_{max} = \text{Min}(c, \lceil Nce/9 \rceil \cdot \frac{N_n + 1}{2})$$

At any given point in time, the state of the system is represented by the number of pairs of nodes engaged in data transmission, denoted by k . Note that the average packet length is multiplied by $\frac{(c+1)}{2(c+2)}$ because the bandwidth is divided by $c+1$ channels. The length of a time slot equals the length of an RTS plus CTS plus four propagation delays. This by itself increases the vulnerability period comparing to PIMA, because we assume that the length of an RTS or CTS is equal to the length of an RTR proposed for PIMA. Note that the extra information carried by an RTR is negligible compared to the typical size of each packet. To find the transition probability,

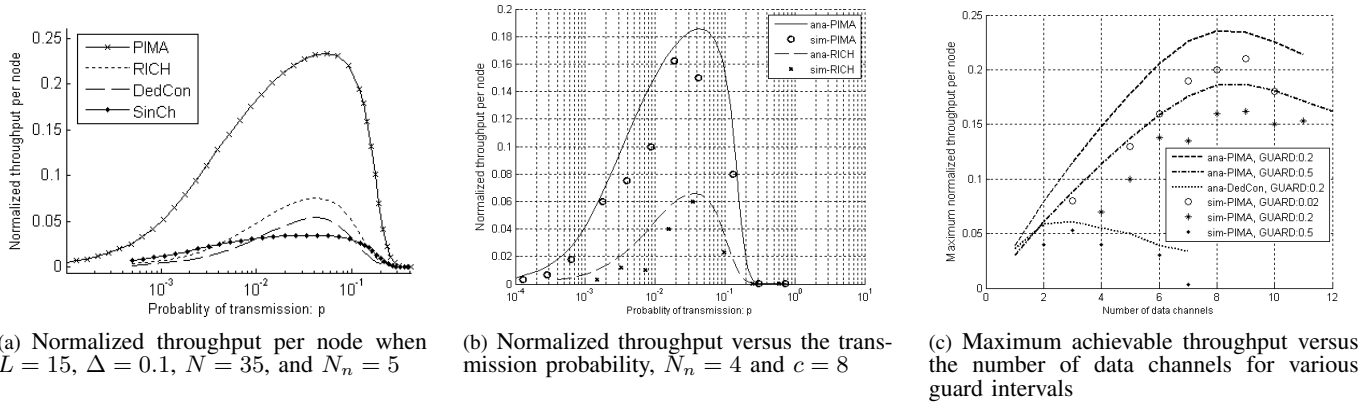


Fig. 3. Analytical and simulation results

$R_k(\alpha)$ is the probability that α links are terminated, as shown in Eq. 2. The probability of adding η links in the new state, $T_k(\eta|N^a)$, is found to be:

$$T_k(\eta|N^a) = \begin{cases} \delta(\eta-1) T_e \left(\frac{N^a}{N_n} \right) + & \text{if } c - (k - \alpha) \geq 1; \\ \delta(\eta) \left((1 - T_e) + T_e \left(1 - \left(\frac{N^a}{N_n} \right) \right) \right) & \\ 0 & \text{if } c - (k - \alpha) < 1; \end{cases}$$

where $N^a = N - (2k)$ represents the total number of available nodes. T_e is calculated as Eq. 3 shows. The transition probability from state k to state m is:

$$P_k^m = \sum_{(\alpha, \eta) \in S_t} R_k(\alpha) \cdot T_k(\eta|N^a)$$

The space S_t includes all the possible values for the set (α, η) when $\{k = 0 \text{ to } l_{max}\}$ and $\{m = 0 \text{ to } l_{max}\}$:

$$S_t = \begin{cases} ((k-m) + \eta, \eta) : \forall \eta \in N, (0 \leq \eta \leq 1) & \text{if } m - k \leq 1; \\ 0 & \text{if } m - k > 1; \end{cases}$$

Assume that the steady-state probabilities are denoted by π_k and derived from solving the global balance equations. The throughput is given by

$$S = \frac{\sum_k k P_k}{N}$$

b) Common-hopping MAC: In RICH, all nodes follow a common frequency hopping sequence. Nodes dwell on the same channel long enough to carry on a receiver-initiated hand-shake and start a new transmission while other nodes move on to the next channel. To initiate the hand-shake a receiver sends an RTR with rate λ while the polled node has data aimed to the polling node with probability $1/(N_n - 1)$. The length of a time slot is equal to the transmission time of an RTR plus two propagation delays.

c) 802.11 collision avoidance: Because a single channel is available, the number of active links in the interfering region can be either 0 or 1. Therefore, the Markov chain can have two possible states. Given that each node can use the entire bandwidth compared to PIMA, the average packet length is

equal to $L = \frac{1}{2(c+2)(1-q)}$ and for the same L , q is increased to $1 - \frac{1}{L \cdot 2(c+2)}$.

B. The Simulation Method and Scenario

To validate the results obtained analytically, Qualnet [24] simulations were carried out after distributing 30 nodes uniformly in an area of 800 by 800 meter. To obtain the most topology-independent results, we averaged our experimental values over 10 different random stationary samples. An OFDMA transceiver was modeled in Qualnet, operating on a center frequency of 2.4Ghz. The modeled transceiver is based on a simple OFDM receiver and the overhead caused by multi-user CFO estimation and synchronization is not taken into account. The total transmission rate is set to 11Mbps, while the available BW is divided into the applicable number of channels. Packets are generated according to a Poisson distribution with parameter $\lambda(\text{packet/sec})$. Each packet has a length of $256B$ and the signal attenuation is assumed to be based on the two-ray path loss model embedded in the simulator. Qualnet uses a BER function that maps each Signal to Interference plus Noise (SINR) value to a bit error rate number. At the receiver side, if two transmitters are using the same channel, based on their relative distance to the receiver the signal and interference power is calculated. Therefore, the guard interval (Δ) necessary to avoid reception error is a function of receiver sensitivity, two-ray path loss model and BER mapping.

C. Performance Comparison

To investigate the effects of number of channels, network degree, and guard interval on the achievable throughput, we plotted the channel throughput for various values of c , N_n , and Δ . Fig 3(a) and Fig 3(b) show the best achievable normalized MAC layer throughput per node versus the probability of transmission in a time slot. The performance of PIMA at its best is more than three times better than RICH and approximately five times better than a dedicated control channel MAC. Although in PIMA the data rate on each channel is smaller, more links can be added to the system with less control overhead.

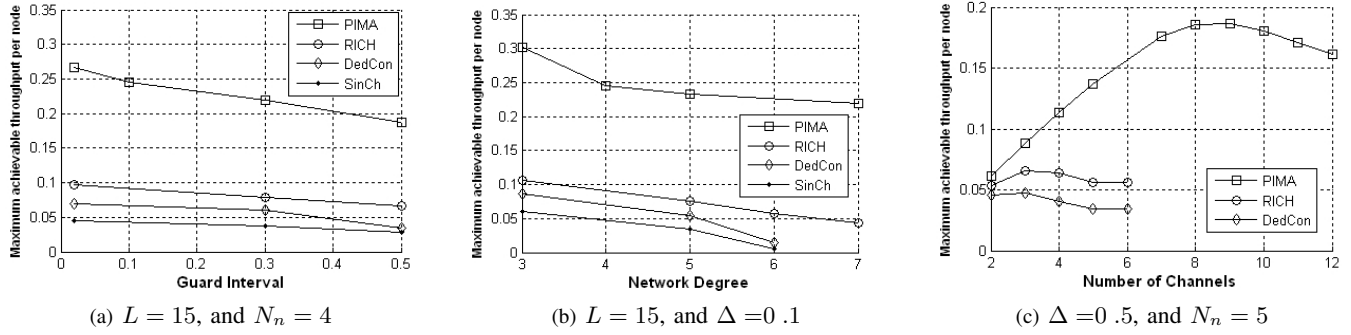


Fig. 4. Maximum achievable throughput under various conditions

1) *Effects of Guard Interval and Network Degree:* Fig 4(a) demonstrates the maximum achievable throughput per node versus different values of guard interval (Δ) while Fig 4(b) shows the normalized throughput for various average number of nodes' one-hop neighbors. For any value of Δ or network degree, PIMA outperforms other protocols substantially because even when interference range is very large, a successful handshake in PIMA leads to more communications comparing to other protocols.

2) *Effects of Number of Channels:* An important observation from the analysis is the optimum number of channels that result in the best channel throughput. As more channels are available, more simultaneous transmissions can take place. However, the available bandwidth on each channel becomes smaller, and as a result q is reduced. Due to the contention on RTRs, there is a limit to how many links can become active even if an infinite number of channels is available. Therefore, after some optimum number of channels, the bandwidth on each channel gets so small that the performance starts to decay. This can be observed in Fig 4(c). For this specific example, PIMA performs at its best when number of data channels c is 8, and RICH and dedicated control channel MAC perform at their best when c is 3. This is due to the fact that PIMA can efficiently utilize the available channels and add links with higher rates.

Fig 3(c) shows that the analysis gives an upper limit of the protocol's actual performance obtained through simulations. In this figure, the maximum achievable throughput is plotted versus the number of data channels for various guard intervals.

IV. CONCLUSION

We presented the Parallel Interaction Medium Access (PIMA) protocol, which exploits the concurrency available through the adoption of OFDMA at the physical layer. The results of our analysis as well as simulations indicate that PIMA attains a 500% improvement in channel throughput compared to the protocols employing channel switching techniques with a dedicated control channel, and 300% improvement over common hopping channel switching techniques. PIMA was implemented in Qualnet and tested for the same conditions assumed for the analysis.

REFERENCES

- [1] *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications*, IEEE 802.11 Working Group Std., 1997.
- [2] J. So and N. H. Vaidya, "Multi-channel mac for ad hoc networks: handling multi-channel hidden terminals using a single transceiver," in *MobiHoc '04*, 2004, pp. 222–233.
- [3] N. Jain, S. Das, and A. Nasipuri, "A multichannel csma mac protocol with receiver-based channel selection for multihop wireless networks," *Proc. IEEE IC3N*, 2001.
- [4] S.-L. Wu, C.-Y. Lin, Y.-C. Tseng, and J.-P. Sheu, "A new multi-channel mac protocol with on-demand channel assignment for multi-hop mobile ad hoc networks," in *ISPAW '00*, 2000, p. 232.
- [5] A. Tzamaloukas and J. J. Garcia-Luna-Aceves, "A receiver-initiated collision-avoidance protocol for multi-channel networks," in *INFOCOM*, 2001, pp. 189–198.
- [6] J. Mo, H. W. So, and J. Walrand, "Comparison of multichannel mac protocols," *Proc. ACM MSWiM05*, 2005.
- [7] V. Rajendran, K. Obraczka, and J. J. Garcia-Luna-Aceves, "A dynamic multi-channel medium access framework for wireless ad hoc networks," in *Proc. IEEE MASS 2007*, vol. 1, october 2007.
- [8] J. J. Garcia-Luna-Aceves and J. Raju, "Distributed assignment of codes for multihop packet-radio networks," in *MILCOM 97 Proceedings*, Nov. 1997, pp. 450–458.
- [9] S. Katti, H. Rahul, D. Katabi, W. H. M. Mard, and J. Crowcroft, "Xors in the air: Practical wireless network coding," in *Proc. of ACM SIGCOMM*, 2006.
- [10] K. Sundaresan, R. Sivakumar, M. Ingram, and T.-Y. Chang, "A fair medium access control protocol for ad-hoc networks with mimo links," *INFOCOM 2004*, vol. 4, pp. 2559–2570, 7–11 March 2004.
- [11] R. R. Choudhury, X. Yang, R. Ramanathan, and N. H. Vaidya, "Using directional antennas for medium access control in ad hoc networks," in *MobiCom '02*, 2002, pp. 59–70.
- [12] D. Kivanc, L. Guoqing, and H. Liu, "Computationally efficient bandwidth allocation and power control for ofdma," *IEEE Transactions on Wireless Communications*, vol. 2, pp. 1150–1158, 2001.
- [13] *IEEE Standard for Local and metropolitan area networks - Part 16: Air Interface for Fixed Broadband Wireless Access Systems*, IEEE Std., 2002.
- [14] *Digital Video Broadcasting (DVB): Interaction channel for Digital Terrestrial Television (RCT) incorporating Multiple Access OFDM (MAC) and Physical Layer (PHY) specifications*, ETSI Std., 2002.
- [15] H. Shetiya and V. harma, "Algorithms for routing and centralized scheduling in ieee 802.16 mesh networks," *WCNC 2006. IEEE*, pp. 147–152, 2006.
- [16] K.-D. Lee and V. Leung, "Fair allocation of subcarrier and power in an ofdma wireless mesh network," *Selected Areas in Communications, IEEE Journal on*, vol. 24, no. 11, pp. 2051–2060, Nov. 2006.
- [17] G. Kulkarni and M. Srivastava, "Subcarrier and bit allocation strategies for ofdma based wireless ad hoc networks," *GLOBECOM '02. IEEE*, vol. 1, pp. 92–96 vol.1, 2002.
- [18] J. Vishwanath Venkataraman; Shynk, "Adaptive algorithms for ofdma wireless ad hoc networks with multiple antennas," *Signals, Systems and Computers*, 2004, vol. 1, pp. 110–114 Vol.1, 7–10 Nov. 2004.
- [19] P. H. Moose, "A technique for orthogonal frequency division multiplexing frequency offset correction," *IEEE Trans. Commun.*, pp. 2908–2914, 1994.
- [20] C. Jihoon, L. Changoo, W. J. Hae, and L. Y. Hoon, "Carrier frequency offset compensation for uplink of ofdm-fdma systems," *IEEE Communications Letters*, vol. 4, pp. 414–416, Dec. 2000.
- [21] J. J. Garcia-Luna-Aceves and A. Tzamaloukas, "Reversing the collision-avoidance handshake in wireless networks," in *Proceedings ACM/IEEE MobiCom 99*, 1999.
- [22] A. Gamal, J. Mammen, B. Prabhakar, and D. Shah, "Throughput-delay trade-off in wireless networks," in *Proc. 2004 INFOCOM*, 2004.
- [23] P. Gupta and P. Kumar, "Capacity of wireless networks," *IEEE Trans. Inform. Theory*, vol. 2, pp. 388–404, March 2000.
- [24] S. N. Technologies, "Introduction to qualnet, qualnet user's manual," 2004.