# Interference Based Multiple Access (IBMA) Protocol for CDMA-Based Ad-hoc Networks

Manish Singh, Puneet Sahni, Krishna Paul and Abhay Karandikar

*ABSTRACT — Efficiency of power controlled* Media Access Control (MAC) *protocols has been established by extensive research for ad-hoc networks. These protocols increase the capacity of the network by improving spatial channel reuse. This paper extends the concept of power controlled MAC protocols and explores the applicability of CDMA based communication for ad-hoc networks. We propose an interference based multiple access protocol, IBMA, that uses receiver specific codes for data communication and accounts for Multiple Access Interference. Power control and code division of IBMA allows for increased number of simultaneous transmissions in the same network area, which otherwise is not possible with fixed transmission range protocols (e.g. 802.11). Transmission power of packets is dynamically determined on the basis of channel-gain information obtained from reception of control packets. This results in enhanced spectrum utilization. The algorithm is completely decentralized and hence, suitable for mobile ad-hoc networks. Our initial simulation results show that IBMA improves throughput and delay performance considerably as compared to non-CDMA based protocols. Finally we discuss in brief the impacts of control overheads on system throughput.*

## I. INTRODUCTION

One of the dominant wireless multiple access protocols for ad-hoc networks is IEEE 802.11 [1] which implements carrier sense multiple access with collision avoidance (CSMA/CA). A Request-to-Send (RTS)/Clear-to-Send (CTS) control packet handshake before data transmission creates a silence zone in which all nodes other than the transmitting one, delay their transmissions for a specified time-interval. The performance of 802.11 degrades sharply with increasing node density and high traffic load on the system. One of the promising approaches to increase the throughput is by constraining the transmission power to the minimum required level, thereby reducing the size of silence zone created by fixed power transmission. Power Controlled Multiple Access (PCMA) [2] is one such *Media Access Control (MAC)* protocol which improves the aggregate channel utilization by a factor of 2 as compared to 802.11.

CDMA has been acclaimed as one of the predominant (MAC) protocol for next generation systems for its effectiveness in high capacity multi-class traffic systems [1] [3,4] and efficient utilization of bandwidth. In this paper, we explore the applicability of CDMA based communication for ad-hoc networks and extend the concept of power controlled MAC protocols so as to successfully exploit the multiple access capabilities of CDMA. We propose an Interference Based Multiple Access (IBMA) protocol for a decentralized ad-hoc network, in which we dynamically limit the transmission power of data packets using channel information obtained from control packets to reduce multiple access interference in the network. Extensive simulations demonstrate that the proposed protocol gives performance improvements over conventional power controlled protocols both in terms of aggregate channel utilization and delay performance of the network.

It is to be noted that IEEE 802.11 has a spread spectrum specification and allows using Direct Sequence Spread

The authors are with Information Networks Laboratory, Department of Electrical Engineering, Indian Institute of Technology, Bombay, INDIA

[1] The capacity of power-controlled reverse link in a CDMA-cellular environment is five-to-six times more than that of FDMA/TDMA hybrid systems[6]

Spectrum (DSSS) technique in physical layer. The 802.11 DSSS system uses baseband modulations of differential binary phase shift keying (DBPSK) and differential quadrature phase shift keying (DQPSK) to provide 1 Mbps and 2 Mbps data rates respectively, hence providing a wireless LAN with both 1 Mbit/s and 2 Mbit/s data payload communication capability. According to FCC regulations, the DSSS system should provide a processing gain of atleast 10 db[2]. But IEEE 802.11 standard uses SS techniques at the physical layer just to mitigate the impact of harsh wireless channel. All transmitted signals are spread using a common spreading code, precluding the possibility of exploiting multiple access capabilities of CDMA and supporting multiple simultaneous transmissions in the neighborhood of the receiver.

Rest of the paper is organized as follows: Section II discusses the related work and motivation for the present work. In Section III, we elaborate on the increase of network capacity through power control and CDMA, followed by discussion of some critical issues in CDMA MANETs in Section IV. Section V discusses our assumptions about channel model and the proposed IBMA protocol. Section VI presents the simulation results and performance analysis. We conclude the paper in Section VII.

## II. Related Work and Motivation

One of the first proposals for multiple access protocol for wireless networks was Media Access with Collision Avoidance (MACA) [7] which improved upon the collision avoidance framework of CSMA/CA for packet radio networks. A similar protocol was proposed in [8]. Some of the basic design choices in MACA were re-evaluated and improvements were suggested in [9] for use in wireless LANs.

All CSMA/CA based protocols suffer from the problem of low throughout. This can be primarily attributed to random access of the medium by the nodes and error-prone wireless channel. The most natural optimization to increase throughput is to dynamically limit the transmission power to a level just sufficient to reach the destination node. This decreases the size of the silence zone and hence, more than one transmissions can be supported in the neighborhood. PCMA [2] is one such variable transmission range based protocol that shows improvement over fixed transmission range based schemes. The notion of collision avoidance in MACA is replaced here with bounded power model, which allows transmissions at minimum power level so that any on-going transmissions are not corrupted.

[2] Due to this specification, we use a processing gain of 10 in the implementation of our protocol

In this work, we extend the concept of power controlled MAC protocols for a CDMA based ad-hoc network so as to successfully exploit the multiple access capabilities of CDMA. Most of the MAC protocols for CDMA based ad-hoc networks in current literature [10], [11], [12], [13] do not use power control. Orthogonal codes are used in all these protocols which inherently assumes perfect synchronization between the nodes. But achieving synchronization in a distributed ad-hoc network is extremely difficult. Multiple Access Interference has been used in [14] to limit the transmission power, but the protocol needs centralized control (base station) for its implementation.

We address these limitations by proposing a decentralized interference-based protocol IBMA for CDMA-based ad-hoc networks that uses non-orthogonal codes for spreading data. We dynamically limit the transmission power of packets using the channel information obtained from control packets in signaling channel to reduce multiple access interference in the network. Multiple transmissions in the same network area become feasible in IBMA by *spreading* the data as this results in an increase in interference tolerance of the nodes. At a radio receiver, Signal-to-Interference ratio, *SIR*, is given by [3]

$$\frac{E_b}{I_0} = \left(\frac{W}{R}\right)\left(\frac{h_{ij}P_i^t}{\sum\limits_{k\neq i,j} h_{kj}P_k^t + N_0}\right) \quad (1)$$

where, $W$ is the spreading bandwidth, $R$ is the data rate, $h_{ij}$ is the channel gain between node $i$ and $j$, $P_i^t$ is the transmission power of node $i$ and $N_0$ is the background thermal noise.

In a non-spreading case, the $W/R$ ratio (also called *processing gain* ) is unity. Any transmission in the neighborhood adds up to the denominator, but it does not obstruct correct reception of the packet at the receiver as long as $SIR$ is within the required limits. In MACA like protocols this adaptability is not exploited as it implements fixed power transmission disregarding the relative position of the destination node. PCMA exploits this by dynamically constraining the transmission power level to the minimum required to reach the destination node.

In the CDMA scenario, however the $W/R$ is greater than unity. From (1), the received signal power to interference ratio is multiplied by the factor of $W/R$. Hence, the tolerance level of the receiver increases, i.e., the receiver is able to decode packets received at lesser power level which otherwise would not have been received correctly. The improvement in interference tolerance facilitates in having many simultaneous transmissions. Thus the throughput as well as the delay performance of the system are expected to improve. CDMA based MAC protocol for ad-hoc network is also expected to perform better in terms of delay jitter and hence such systems will give better performance for real time traffic.

## III. Enhancing Network Capacity through Power Control and CDMA

In Multiple Access Collision Avoidance (MACA) mechanisms (e.g. IEEE 802.11), collision avoidance for data packets is achieved by source-destination handshake before the data transmission starts. The primary sources of collisions in shared wireless channel access are hidden and exposed nodes with respect to source and destination pair. (Scenario explained in figure 1). A handshake with small fixed size packets Request-to-Send (RTS) from source and subsequent Clear-to-Send (CTS) from destination enables hidden nodes and exposed nodes to know the exact duration they are required to remain silent. It is to be noted that for a correct execution of the protocol in MACA, each transmission needs to be done at same transmission power by all nodes, which determines the extent of silenced region. This also leads to the fact that more the density of network, the lesser is wireless channel throughput (assuming every node has data to transmit) since higher density increases the number of silenced nodes for entire duration of data transmission in the neighborhood.

Let us consider a network where node placements are shown in figure 1. By MACA protocol, when $C$ is trans-

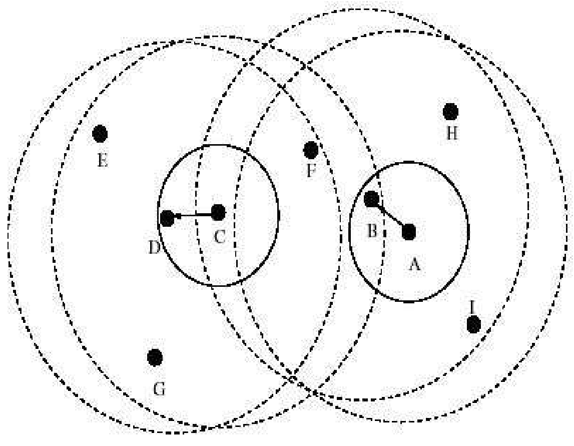


Fig. 1. Motivation for the use of power control

mitting for $D$, $B$ cannot transmit to $A$, since it would be silenced by RTS packet from $C$. In this scenario, the most natural optimization is to make $C$ transmit at a power level (transmission range) that is required to reach node $D$ only. This can allow $B \rightarrow A$ communication in parallel alongwith $C \rightarrow D$, provided B also transmit at a range that is enough to reach only $A$. To implement such a strategy, a power controlled medium access mechanism is required which can provide features similar to collision avoidance and collision resolution. PCMA as well as IBMA is such a variable transmission range based protocol that shows improvement over fixed transmission range based schemes. The mechanism uses two key principles a) Power conservation: nodes must transmit at minimum power level that is required to heard by intended receiver b) Cooperation: no station commences a new transmission at a power that disrupts any ongoing transmission. The notion of collision avoidance in MACA is replaced here with bounded power model, which allows transmissions that obeys the two aforementioned principles.

With such a power control it is possible to initiate communication $C \rightarrow D$ alongwith communication $A \rightarrow B$, provided interference tolerance limit at $B$ can accommodate interference caused by transmitted power $P_{CD}$ of C, where $P_{CD}$ is the minimum power required by C to reach D. IBMA shows better performance as compared to PCMA because of improved tolerances at the receiver nodes and the support for higher number of simultaneous transmissions. Moreover, the throughput of PCMA (in a non-spreading case) decreases drastically in high density and high load systems, while performance of IBMA has been shown to be substantially better since IBMA exploits the multiple access capabilities of CDMA.

We now explain the reason behind performance improvement in the proposed scenario with the help of a numerical example.

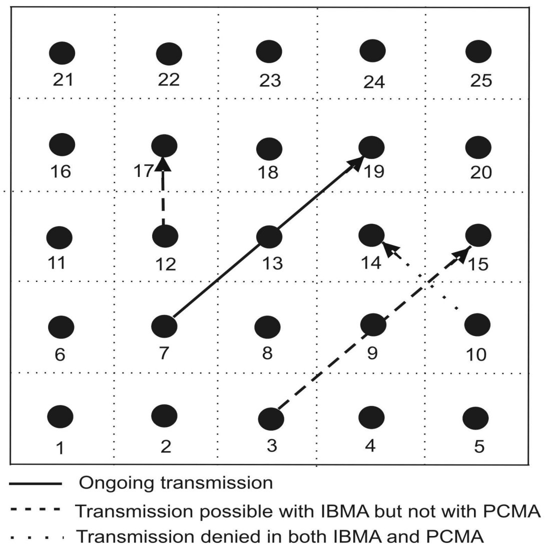


Fig. 2. Comparison of IBMA with MACA and PCMA

Consider the network topology of 500 X 500 $m^2$ area with

25 nodes as shown in Fig. 2. For ease of numerical computation, the nodes are taken to be uniformly distributed over the area and are placed at the center of 100 X 100 $m^2$ square plots. The parameters used in the example are the same as used for simulation results.

Let the medium be free and the following four pair of communications contend for the channel at some instant of time:
Node 7 wants to transmit data to node 19
Node 3 wants to transmit data to node 15
Node 12 wants to transmit data to node 17
Node 10 wants to transmit data to node 14

Assume that the above communications contend for the channel in the above sequence. Suppose the network is running MACA or 802.11. Then node 7 starts transmitting data to node 19 at fixed power level. Now after the initial handshake, node 7 acquires the floor area of the entire network and hence precludes all other communications listed above during the transmission time of the packet. So, in the case of MACA or 802.11, only one transmission will be possible during the packet transmission time.

Now suppose the network is using CDMA-interface with our IBMA protocol (the protocol details have been explained in a later section). Node 7 calculates the minimum power level $P_{minreq}$ required to reach the destination node 19. It then calculates the maximum permissible power level $P_{maxper}$ at which the node is allowed to do transmissions so that the other transmissions do not get disrupted. So, the power level for the desired transmission is calculated as

$$Pt_{data} = \frac{Pt_{minreq} + P_{maxper}}{2} = 0.35\text{W}$$

Now node 3 desires to send data to node 15. It calculates its $P_{maxper}$ and $P_{minreq}$ to be $0.7$ W and $0.141$ W respectively. Now, $Pt_{minreq} < P_{maxper}$ ensuring that the intended transmission will not corrupt the ongoing transmission hence node 5 also commences the transmission at power level $Pt_{data} = 0.42$ W. Similarly node 12 commences transmission at a $Pt_{data} = 0.16$ W.

For node 10, its $P_{minreq}$ turns out to be $0.077$ W while its $P_{maxper}$ turns out to be $0.052$ W which is less than $P_{minreq}$, and hence the transmission cannot happen alongwith the other three communication. Consequently node 10 backs-off. Thus, for IBMA, three parallel transmissions are possible, $7-19$, 3-$-15$ and $12-17$ while the fourth one,$10-14$, is denied.

Now consider the non-spreading case with PCMA protocol. Node 7 starts transmitting data to node 19. It transmits data at the minimum power level required to reach the destination so as to satisfy the *Signal-to-Interference* constraint, allowing a 4dB power compensation. But this precludes the other three transmissions in the network due to interference tolerance level of the destination node.

The improvement in interference tolerance in IBMA stems from the fact that the received *Signal-to-Interference* power gets multiplied by the spreading gain *W/R*, which is 10 from IBMA, while only 1 for PCMA. So the interference tolerance level of the nodes in IBMA will roughly be 10 times that of PCMA, due to spreading of the signal. This facilitates in having many simultaneous transmissions and hence the throughput as well as delay performance of the system are expected to improve.

CDMA based MAC protocol for ad-hoc network is also expected to perform better in terms of average delay and delay jitter and hence such systems will give better performance for non-elastic traffic. It is also expected to provide fair allocation of bandwidth to traffics with regard to source-destination distance, as compared to other power-controlled non-spread spectrum systems.

Our contribution in the present work are a) a power controlled CDMA based MAC protocol (IBMA) for decentralized ad-hoc environment b) Performance analysis of IBMA through simulation to show improvement in network throughput, average delay and delay jitter.

In the next section , we briefly touch upon some of the critical issues involved in implementing CDMA in Mobile Ad-hoc networks.

## IV. Issues related to use of CDMA in MANETs

1. Excess bandwidth requirements

A CDMA-based network demands more resources in terms of bandwidth due to signal spreading as compared to non-spread spectrum based networks. Therefore, a CDMA based protocol should give throughput improvements which should compensate for the additional resource requirements in terms of bandwidth. For fair comparison of throughput, our CDMA-based network can be said to perform better only if the capacity improvement in the network is greater than $\frac{W_{cdma}}{W_{other}}$ times the throughput of systems based on non-spread-spectrum techniques, which operate within lesser bandwidth.

2. Assignment of Spreading Codes

We have made the assumption that each node has a unique spreading code. This allocation of code itself in a real scenario might be a very involved issue. The unique codes can be obtained from the unique MAC addresses by the use of suitable hash functions. We do not address this issue in our paper. This allocation of codes has been addressed in [15,16].

### 3. Issues with orthogonal pseudo-random sequences

The system throughput can be further increased by use of orthogonal pseudo-random (Hadamard-Walsh) codes [17] because in such a scenario, the interference caused by transmissions on other codes is minimal. With processing gain of W/R, the number of users that can be supported by using orthogonal codes is approximately equal to (W/R), hence we either need a much larger spreading bandwidth or a dynamic allocation of codes. Also, use of orthogonal codes in a system needs perfect synchronization of the nodes and this is difficult to achieve in a decentralized scenario such as ad-hoc networks. Moreover, multipath introduces interference that is not orthogonal to the transmitted signal. So, keeping in mind the implementation issues in the real scenario and the bandwidth requirements, we use non-orthogonal codes. This eliminates the need of perfect synchronization and the required synchronization can be achieved using the standard PN-sequence synchronization circuitry, which is used in cellular communication.

### 4. Number of simultaneous transmission in CDMA based MAC

In literature [3,4,5], it has been shown that in a cellular network, the number of users than can be simultaneously supported is directly proportional to the spreading ratio W/R. Now, in a cellular network, the base station tries to normalize powers of all users to the same level using power control. Drawing an analogy form cellular networks, we can argue that the number of simultaneous users that can be supported in our system is roughly proportional to the processing gain $W/R$. The increase would not be directly proportional because the number of parallel transmissions depends on the placement of nodes and the nature of ongoing transmissions. However, for uniformly distributed nodes with uniform traffic generation rate, the deviation from the formula would be less as compared in other distributed scenarios.

## V. THE IBMA PROTOCOL

In this section, we present a brief overview of the system architecture, assumptions and details about the protocol.

### 1. System Architecture

All nodes are assumed to have static and unique spreading codes allocated to them. The wireless channel is assumed to be symmetric between the communicating nodes and is assumed to remain stationary for the entire data transmission period which includes RTS/CTS exchange, data packet transmission and acknowledgment.

The available bandwidth is divided into two distinct non-overlapping channels - A narrow-band *control channel* which is used for the transmission of control packets and a wide-band *data channel* is used for RTS-CTS handshake and the ensuing data transmissions. Only the transmissions in the data channel are spread using the spreading codes. Those in the control channel are transmitted by normal base-band transmission through random access mechanism. All nodes are assumed to be identical and each node has two transceivers, one each for data and control channel. The data channel receiver at each node is tuned to its own spreading code, and all handshake and data transmissions (in the data channel) are done using the intended receiver's spreading code.

### 2. Packet formats

In this section, we describe the packet formats used in IBMA protocol.

*1) Beacons:* This packet has three entries: *node id, corresponding spreading code* and *current noise level* at that node. Beacons are used to broadcast the noise tolerance of the nodes and to calculate the channel gain between the two nodes.

*2) Ready-to-Send (RTS):* This packet has three entries: *node id* of the transmitting node, *power level* at which RTS is being transmitted and *noise level* at the transmitting node.

*3) Clear-to-Send (CTS):* This packet has two entries: *node id* and *minimum power level* required for the packet to reach the destination node correctly.

*4) Data-Send (DS):* This packet contains the *power level* at which the data packet will be sent.

*5) Interference Tolerance (IT):* This packet contains the value of excess interference that the node can tolerate.

Beacons, DS and IT packets are sent in the control channel while RTS, CTS, data packets and ACK are sent in the data channel.

### 3. The Protocol

In IBMA, we use the multiple access capability of CDMA to support more than one simultaneous transmissions in the same area. To a receiving node all other transmissions appear as interference however if the data is being transmitted at an appropriate power level, it can still be decoded properly. The concept of *"collision avoidance"* is generalized in IBMA by deferring only those transmissions which can potentially disrupt any ongoing transmissions, i.e., can cause the interference level on any receiving node to exceed the tolerable limits.

In our protocol, each node maintains a *neighborhood table* which contains a complete "power map" of its first-hop neighbors, i.e., each node has a knowledge of the interference tolerance or the noise level at every other node. The neighborhood table has entries shown in Table 1:

| |
|---|
| Node Id |
| Spreading Code |
| Status |
| Interference Tolerance/Noise Level |
| Gain |

Table 1. Entries in neighborhood table

Every node broadcasts its current noise level in its idle state through beacons. On receiving a beacon, a node updates the corresponding entries in its *neighborhood table* The channel gain in the control channel is calculated as:

$$G_{ij}^{c} = \frac{\text{Received Power}}{P_{beacon}}$$

The gain in the data channel is calculated using the gain in the control channel as follows [17]:

$$G_{ij} = G_{ij}^{c} * (\frac{\lambda_d}{\lambda_c})^2$$

where, $\lambda_d$ and $\lambda_c$ are wavelengths corresponding to the center frequencies of data channel and control channel, respectively.

Whenever a node wants to transmit data, it first determines whether the destined node is free and then calculates the feasibility of sending data to the node from the power values in the *neighborhood table*.

If a node $i$ wants to transmit data to node $j$, it calculates the minimum power required for the desired communication to $j$ as

$$Pt_{minreq} = \left(\frac{R}{W}\right) SIR_{thres} * \frac{\text{Interference Level at j}}{G_{ij}} \quad (2)$$

where $SIR_{thres}$ is the minimum required *SIR* for correct reception.

It is to be noted that this is an approximate value depending on the *"staleness of information"* in the power map. Since this power map is updated frequently enough, this value is a good approximation which can be used to calculate transmission power of RTS.

Similarly, node $i$ calculates the maximum permissible power at which it can transmit without disrupting the ongoing transmissions. This value $P_{maxper}$ is calculated as[3]:

$$P_{maxper} = \min\{\min_{i \in table}\{\text{Interference Tolerance}[i]\}, P_{max}\}$$

The node backs off if $Pt_{minreq}$ turns out to be greater than $P_{maxper}$.

If the transmission is feasible, RTS packet is sent at a power level which is the mean of $P_{maxper}$ and $Pt_{minreq}$. This value is chosen so that we can keep some interference margin for the future transmissions and can also leave some margin for the weakest reception
Thus the transmit power for RTS is calculated as

$$Pt_{RTS} = \frac{Pt_{minreq} + P_{maxper}}{2}$$

On receiving RTS, the node $j$ calculates the actual channel gain as:

$$G_{ij} = \frac{\text{Received Power}}{Pt_{RTS}}$$

Using this channel gain, the receiver now calculates the actual minimum power at which the data needs to be sent by node $i$ as in Equation 2. This calculation is done again as the previous value was calculated on the basis of channel gain in the neighborhood table which may not represent the immediate value and also it involved an approximation conversion of gain from control to data channel, however, the value calculated by the receiver uses the data packets in the data channel only and hence represents an accurate value. This value is communicated to the transmitter through CTS packet. The transmission power level of CTS is calculated similar to that for RTS. On receiving the CTS message the transmitter calculates the maximum permissible power value ($P_{maxper}$) at which it can send data without disrupting any ongoing transmission, as done for RTS. Transmission at value $P_{minreq}$ does not allow for any interference tolerance at the receiver, and thus all its neighbors will have to defer their transmissions during the ongoing reception (i.e., no simultaneous transmissions can take place). Transmitting data at $P_{maxper}$ will consume all the interference margin of the weakest link[4] thereby causing deference of any further transmission in its vicinity. Thus, to have sufficient interference margin for both

[3]Please note that the interference tolerance column in the neighborhood table has transmission power level which creates an interference at the corresponding node equal to its noise tolerance as explained by Eqn 3

[4]which has the least interference tolerance

cases, the data packet is transmitted at a power level which is the mean of the minimum required power and the maximum permissible power :

$$Pt_{data} = \frac{Pt_{minreq} + P_{maxper}}{2}$$

Before transmitting data packet, a special DS packet is sent at power level equal to that of data packet in the network so that all the nodes update their noise tolerances as per the commencing transmission. The channel gain entry is also updated whenever DS packet is received, and the status of the corresponding node is set to TRANSMITTING. With the data packet size being being fixed, the nodes calculate the exact duration of data transmission and correspondingly increase their tolerance level after this duration.

Every receiving node advertises the value of excess interference it can tolerate by placing it in interference tolerance (IT) packets, while an idle node advertises its current noise level with the help of beacons. Interference Tolerance at a node is given by

$$\left(\frac{W}{R}\right)\frac{\text{Received Data Power}}{SIR_{thres}} - \text{Current Interference Level}$$

On receiving an IT packet, the current interference tolerance value of the node is updated using the corresponding entry(Actual Noise Tolerance) in the packet as

$$\text{Interference Tolerance} = \frac{\text{Actual Interference Tolerance}}{G_{ij}} \tag{3}$$

The channel gain is calculated as for beacons. The status flag for the node is set to RECEIVING.

IT packets are sent whenever the noise tolerance at a node changes while beacons are sent periodically. These packets are used by the nodes in one-hop distance to update their neighborhood table.

After successful reception of data, ACK packet is sent at a power level which is calculated in the same way as that for CTS. If the transmitter of data does not receive ACK, then it backs off, and retransmits the data after the back off interval.

# VI. Simulation Results and Observations

## 1. Simulation Setup

In this section, we investigate the performance of IBMA for throughput and delay metrics under varying network conditions through simulations done on OPNET[18]. We have taken an area of 500 x 500 $m^2$ with nodes uniformly distributed. Nodes can transmit up to a maximum distance of 250 meters. Each source generates traffic flow according to independent Poisson process. The rate refers to packets per second. For each source, destinations are chosen randomly within one hop distance. The values of parameters used in simulation are listed in Table 2.

Table 2. Parameters Used for Simulations of the IBMA Protocol

| **Parameter** | **Value** |
|---|---|
| $P_{beacon}$ | $-8.46$ dBm |
| $P_{max}$ | 28.5 dBm |
| Background Noise | 5x$10^{-15}$ W |
| Data Rate(on both channels) | 1 Mbps |
| Center Frequency (Data Channel) | 1805 Mhz |
| Bandwidth(Data Channel) | 10 Mhz |
| Center Frequency (Signaling Channel) | 1799.5 Mhz |
| Bandwidth(Signaling Channel) | 1 Mhz |
| $(E_b/N_0)_{thresh}$ (both channels) | 7 dB |
| Beacon Interval | 2 ms |

Beaconing is done at such a power level (0.1424 mW), that every receiver within a circle of radius 250 meters (one-hop distance) from the sender can receive the beacon correctly in the presence of the background noise. The maximum possible transmission power (Pmax) is chosen to be 28.8 dBm to make it equal to that used by the PCMA protocol to ensure a fair comparison.

We have compared IBMA with PCMA and idealized IBMA (IIBMA). The purpose of comparing with IIBMA is to explore performance penalty for using imperfect information on link gains between two nodes, noise at potential destination from power map generated by potentially delayed control packets. The IIBMA protocol is exactly the same as IBMA protocol with the exception that every node has information about the instantaneous power map of the neighborhood so that it has the exact value of link gains and noise tolerance at any destination. The width of data channel in PCMA is taken to be 1 MHZ. We have also compared IIBMA with idealized version of PCMA (IPC) to explore the actual performance gain of IBMA over PCMA, while ignoring overheads of imperfect information (as explained previously) caused by randomized method of update. We have not evaluated against fixed transmission range protocols like 802.11 specifically, as PCMA has already been shown to improve performance by factor of 2 over 802.11. In our simulation the results on throughput has been normalized by a factor of 10 which is the extra bandwidth required in IBMA so that the performance of the IBMA and PCMA can be compared and thus all the graphs show normalized throughput as opposed to actual throughput.

## 2. Simulation Results

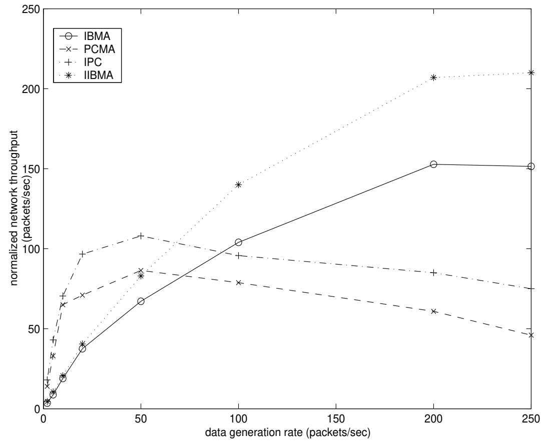


Fig. 3. Normalized system throughput as a function of increasing data arrival rate for a network with 25 flows

Fig 3 compares the performance of IBMA, PCMA, IIBMA and IPC protocols with respect to throughput of the system with varying load (by varying data rate at each node). It can be seen that at lower data rates, i.e., for a lightly loaded system, IIBMA and IPC perform very closely, though the normalized throughput of IIBMA is less than IPC. (It is worth mentioning that the net throughput of IIBMA is still much higher than that of IPC even at these loads). This can be explained by the fact that in lightly loaded systems, there is very less contention for the IIBMA to take advantage of the additional bandwidth to have multiple simultaneous communications. As a result we do not get throughput increase of more than 10 times as compared with IPC. But as the data arrival rate increases, IIBMA's performance improves even in terms of normalized throughput and it gives an increase of more than 200% over that of IPC. This is because as the data rate

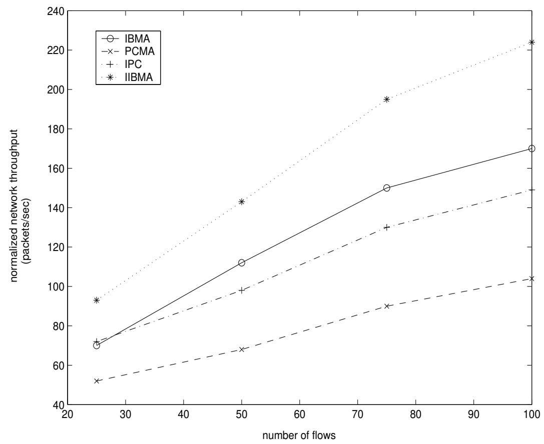


Fig. 4. Normalized system throughput as a function of increasing node density (for data generation rate = 50 packets per sec per node)

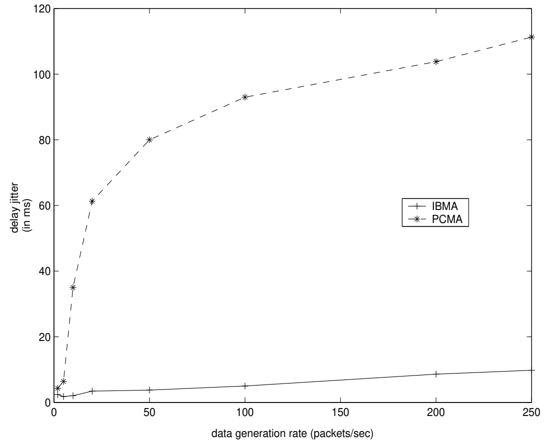


Fig. 5. Delay jitter of the system as a function of increasing data arrival rate

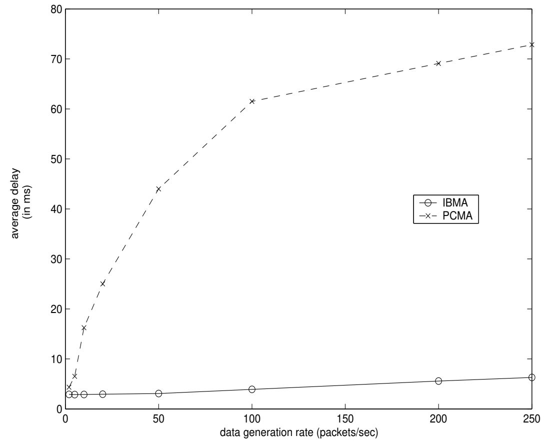


Fig. 6. Average Delay of the system as a function of increasing data arrival rate

increases, the contention in the system increases leading to large back-offs in IPC, however, IIBMA can afford to support multiple parallel transmissions in the same area resulting in increase of normalized throughput as compared to IPC. Similar trend can be seen for comparison of IBMA protocol with PCMA. For high data rates, IBMA achieves substantial performance improvement which compensates for the use of additional bandwidth. Moreover the deviation of performance of IBMA from that of the ideal protocol IIBMA is not much. From this we can conclude that the nodes have fairly correct information about the power map in the current protocol implementation.

The variation of system throughput with varying node density, is shown in Fig. 4. Here also, we can see that the normalized throughput of the system for IIBMA is higher than that of IPC and in particular for dense scenarios, we see that IIBMA performs much better than IPC. This gain can be attributed to the fact that increasing node density increases the contention in the system, and multiple parallel transmissions increase the throughput in our case. The observation is similar for the performance of IBMA w.r.t PCMA.

In Fig. 5 and 6 we compare the delay jitter[5] and the average delay performance of IBMA with PCMA with 25 nodes uniformly distributed in 500 X 500 $m^2$ network area. It can be seen that for lightly loaded networks IBMA performs only slightly better in terms of both average delay and delay jitter, however as the load on the system increases, the performance of PCMA degrades heavily while that of IBMA remains almost constant. Thus it achieves a substantial improvement over the PCMA protocol with respect to delay jitter and average delay performances. The degradation of PCMA's performance can be attributed to the fact that for dense networks with high data arrival rates, the contention resolution results in large back-offs, but the presence of multiple simultaneous transmissions prevents large backoffs in case of IBMA, thereby resulting in a much better performance.

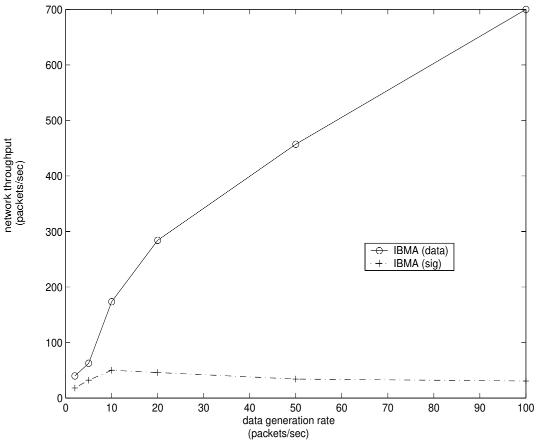


Fig. 7. Comparison of network throughput with RTS/CTS in data and control channels

Control overheads, especially RTS/CTS packets, are a major concern in the working of any MAC protocol. Loss of control packets lead to back-offs in the system, which affect the system throughput. So, apart from protecting data, any efficient MAC protocol should have low probability of loss of RTS/CTS packets. In the original MACA protocol, a correct RTS/CTS handshake avoids collision of data packet due to any other transmission with high probability. But this is not the case with IBMA or with PCMA. In fact, the same is true for any existing variable transmission range protocol. In IBMA or PCMA, even after successful RTS/CTS handshake, a data transmission can get corrupted due to large number of simultaneous RTS/CTS transmissions by other nodes in the network. This happens because all these nodes simultaneously observe the power map to be favorable, and such simultaneous RTS/CTS transmissions result in unfavorable change in system interference level for the ongoing data transmission. An alternative design to avoid such scenarios is to move RTS/CTS to control channel. But in this design, RTS/CTS suffer from lot of collisions and the random access control channel becomes overloaded. Hence, the throughput of the system decreases drastically. Fig.7 shows the comparison of system throughput of IBMA with RTS/CTS in data channel (represented by *ibma(data)*) and in control channel (represented by *ibma(sig)*) for a network with 75 nodes and data generation rate of 50 packets/s at each node. As expected, the throughput for RTS/CTS in control channel is much less as compared to when RTS/CTS is sent in data channel. The loss of throughput due to data packets being corrupted (by multiple access interference) is more than compensated by highly decreased probability of loss of RTS/CTS. Hence, RTS/CTS in data channel gives much better performance as compared to RTS/CTS in control channel, and the improvement is much more at high network loads.

Another impact of control overheads on protocol performance can be seen in the variation of system throughput with respect to data packet size as shown in Fig.8. If the size of data packet is more, lesser control overheads are needed to transmit the same amount of data. Considering the fact that there is a finite probability of loss of RTS/CTS packets, the system throughput increases since the same amount of RTS/CTS handshake transmits more amount of data. This explains the increase in system throughput for the case with 25 nodes and initially for the case with 75 nodes. For the case of 75 nodes, the graph shows a decrease in system throughput at higher packet sizes. This can be explained as follows: at higher node density, the traffic load on the system is higher. In such scenario, the probability of nodes transmitting RTS/CTS simultaneously is higher and the number of nodes doing so is also higher. This leads to higher multiple access interference in the network and the data packet (which has a fixed interference tolerance margin) gets corrupted. In fact, there exists an optimal data packet size for a particular node density and traffic load on the system, and finding the dependence of optimal packet size on these parameters is by itself a complex mathematical problem.

## VII. Conclusion and Future Work

In this paper, we have proposed an interference-based media access protocol for a decentralized ad-hoc network with a CDMA interface and analyzed its performance as compared to other protocols which operate in non-spread spectrum sce-

[5] Delay jitter of the network is calculated as the difference between the maximum and minimum delay experienced by any packet in the network

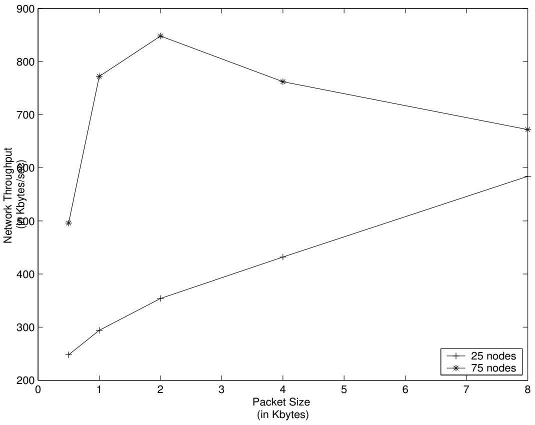


Fig. 8. Throughput of the system vs size of data packet with data generation rate of 50 packets/s at each node

narios. Simulation results demonstrate that the throughput improvement achieved in the CDMA-based network more than compensates for the excess bandwidth requirement. This motivates the use of CDMA as the link layer in ad-hoc networks for efficient use of bandwidth which happens to be a scarce resource. Moreover, the delay performance of our protocol is much better than that of other protocols which is highly desirable for inelastic traffic. We are currently working on stochastic analysis of the protocol to provide performance bounds. We are also investigating the fairness issues of bandwidth allocation for multi-class ad-hoc network and the performance of the protocol in a multihop scenario.

## REFERENCES

[1] International Standard ISO/IEC 8802-11; ANSI/IEEE Std 802.11, 1999 Edn. Part 11: wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications.

[2] V. Bharghavan, J.P. Monks and W. Hwu, "A Power Controlled Multiple Access Protocol for Wireless Packet Networks," *Proceedings of IEEE INFOCOM, pages 219-228-83, 2001.*

[3] Andrew J. Viterbi, "*CDMA: Principles of Spread Spectrum Communication,"* Addison-Wesley Wireless Communication Series,2000.

[4] A. M. Viterbi and A. J. Viterbi, "Erlang Capacity of a Power Controlled CDMA System," *IEEE Journal on Selected Areas in Communication ,* 11(6)pages 892-900, 1993.

[5] Savo G. Glisic, "*Adaptive WCDMA: Theory and Practice,"* Wiley, Inc.,2002.

[6] K. S. Gilhousen, I. M. Jacobs, R. Padovani, A. J. Viterbi, L. A. Weaver and C. A. Wheatley, "On the Capacity of a Cellular CDMA system," *IEEE Transactions on Vehicular Technology,* VT-40(2):303-312, 1991.

[7] P. Karn, "MACA: A new channel access method for packet radio," *ARRL/CDDL Amateur radio* $9^{th}$ *Computer Networking Conference, pages 134-140, September 1990.*

[8] Chane L. Fullmer and J.J. GarciaLunaAceves, "Floor Acquisition Multiple Access (FAMA) for PacketRadio Networks ," *Proceedings of ACM SIGCOMM, 262-273, 1995.*

[9] S. Shenker, V. Bharghavan, A. Demers and L. Zhang, "MACAW: A media access protocol for wireless LANs," *Proceedings of ACM SIGCOMM, pages 212-225, August 1994.*

[10] M-Joa-Ng and I-Tai Lu, "Spread Spectrum medium access protocol with collision avoidance in mobile ad-hoc networks,", *Proceedings of IEEE INFOCOM, pages 776-83, March 1999.*

[11] J. Garcia−Luna−Aceves and J. Raju, "Distributed assignment of codes for multihop packet−radio networks," *Proceedings of IEEE MILCOM Conference,* volume 1, pages 450-454, 1997.

[12] 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 net works.," *Proceedings of the International Symposium on Parallel Architectures, Algorithms and Networks,* pages 232237, 2000.

[13] E. Sousa and J. A. Silvester, "Spreading code protocols for distributed spread-spectrum packet radio networks," *IEEE Transactions on Communications,* 36(3):272-281, March 1998.

[14] P. E. Omiyi and T. Farrell, "A new throughput analysis of a novel MAC protocol for CDMA-based wireless LANs,", *RAWCON'98 Proceedings, pages 23-26, 1998.*

[15] Saurabh Srivastava, Sachee Tripathi, Dheeraj Sanghi and Ajit Kumar Chaturvedi "Resource Optimization in CDMA based Wireless Ad-Hoc Networks," Technical Report *http://www.cse.iitk.ac.in/research/btp2002/98344.html.*

[16] A. A. Bertossi and M. A. Bonuccelli, "Code assignment for hidden terminal interference avoidance in multihop packet radio networks," *IEEE Transactions on Communications,* 3(4):441-449, August 1995.

[17] Jhong Sam Lee and Leonard E. Miller, "*CDMA Systems Engineering Handbook,"* Artech House, 2002.

[18] *www.opnet.com*