An Overview of Cross-Layer based Design of Media Access Control (MAC) for CDMA Ad-Hoc Networks

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Abstract

Decentralized ad-hoc networks are plagued with the problem of low network capacity at high traffic load or high node density. Recent proposals on CDMA ad-hoc networks propose to alleviate this problem and in addition, provide benefits of Spread Spectrum (SS) communication. These proposals follow a cross-layer based approach to *Media Access Control (MAC)* layer design, and exploit the link-layer properties in conjunction with dynamic power control to enhance system capacity. These protocols provide a promising solution to increase throughput in a *single hop neighborhood* as compared to widely accepted CSMA/CA based protocols like 802.11. A *cross-layer* design framework which uses spread spectrum/CDMA and power control techniques in physical layer as well as in link layer provides a more optimized approach to increase network capacity. Multiple simultaneous transmissions in such protocols are supported on the basis of *interference level* considerations in the network. In this review article, we discuss some proposals on issues of power control and CDMA based MAC in ad-hoc networks with a greater focus on interference measurement problems in a distributed scenario. We provide a qualitative comparison of the approaches and investigate opportunities for future research.

I. INTRODUCTION

Mobile ad-hoc networks (MANETs) have been a subject of extensive research for the past few years. These ad-hoc networks consist of autonomous nodes that collaborate in data transfer, acting both as end-systems and as routers simultaneously. Such self-organizing networks, which do not require any pre-established infrastructure, are extremely useful in areas where deployment of infrastructure is difficult such as battlefields, disaster areas or remote terrains. Apart from such scenarios, the widespread availability of mobile computing and handheld devices like palmtops, portables and personal digital assistants have increased the user base of Wireless Local Area Network (WLAN) which has typical features of ad-hoc networks.

The design of efficient Media Access Control (MAC) protocols for such self-organizing networks is fraught with many challenges. Due to lack of any centralized controlling entity, the channel access in such networks is contention based leading to a low throughput under high traffic load on the system. One of the most commonly used mechanisms for MAC is Distributed Coordination Function (DCF) mode of IEEE 802.11 standard [1], which follows the "Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)" paradigm.

One of the fundamental challenges in wireless networks is to develop efficient media access protocols which maximize aggregate spectrum utilization. It has been observed that the throughput of a network is significantly low in CSMA/CA based MAC. The low throughput is attributed to the error prone characteristics of the radio channel combined with the contention-based nature of CSMA/CA access. In CSMA/CA with fixed transmission power based schemes (e.g. 802.11's DCF mode), the protocol executes a handshake mechanism to reserve the channel in order to avoid collision from nodes located within the transmission range of transmitter and receiver. This results in a *"silence zone"* around the source and the destination, where no node can transmit or receive packets until the data transmission between a pair of nodes is complete. This class of protocols do not take cognizance of the relative distance between the transmitter and the receiver, resulting in transmissions which are done with excess power than that required for correct reception at the destination node.

Power controlled MAC protocols for ad-hoc networks such as [2] exploit this aspect by transmitting at a power level sufficient for correct reception. The authors, therein, generalize the concept by introducing *"interference limited access"* to the channel so as to bound the Multiple Access Interference (MAI) in the system.

Power control or interference limited access has been effectively used in cellular wireless systems to increase capacity and performance, especially in CDMA networks. Extensive research and deployment has fortified CDMA as the perfect candidate for power controlled multiple access systems providing high network capacity [3]. In cellular networks, the base station normalizes the received uplink powers from all the mobile stations. However, in ad-hoc scenarios, no such normalization of transmit power is possible. Hence, to realize the same benefits of CDMA in ad-hoc networks, novel media access schemes need to be designed which exploit the multiple access capabilities of CDMA in conjunction with retaining the non-coordinated and decentralized architecture of ad-hoc networks.

Much of the current literature on power control in ad-hoc networks addresses the issues of power efficient routing and topology control in multi-hop scenarios. Topology control in wireless multihop networks with variable transmission range is motivated by the fact that the use of optimal power while accessing the channel can improve the aggregate channel utilization by about a factor of $O(\sqrt{n})$, where n is the density of nodes in the region [4].

However, in this article, we present the issues in using power controlled spread spectrum techniques at the physical layer combined with CDMA as the media access control with a view to optimize spectral efficiency and enhance system capacity in the single hop region. We investigate the feasibility of cross-layer design of MAC and physical layers, involving spread spectrum techniques in a dynamic distributed environment. While we do not present an exhaustive survey, we discuss the related problems in detail and present representative research reported in the past in these directions. We also point out unexplored issues in power controlled MAC for future research direction.

The remainder of the article is structured as follows: We explain the basic principles and motivation for the use of power control and CDMA in ad-hoc networks in Section II, followed by Section III on challenges in power controlled CDMA MAC for ad-hoc networks In Section IV, we discuss the design component of CDMA based MAC protocols and present briefly the relevant literature. The article is concluded in Section V where we outline the fairness issues in power controlled MAC.

II. WHY POWER CONTROL AND CDMA FOR AD-HOC NETWORKS?

A. *The case of fixed transmission power based CSMA/CA protocols*

CSMA/CA protocol necessitates each sender-receiver pair to *"acquire floor area"* around its neighborhood to avoid any collisions for data packets from other nodes in the shared wireless channel [1], [5]. The floor acquisition is done as follows: Consider the four nodes shown in Figure 1. The transmission range of individual nodes is shown by the dashed lines. Let C want to transmit data to B. Since D is in the listening range of sender C (i.e., D can hear transmissions from station C) but not of receiver B, D is an "Exposed Node". Node A is in the listening range of B (receiver) but not of C (sender). Hence, A is a "Hidden Node". Before data transmission, C senses the channel to determine if it is free. Then C sends an Request-to-Send (RTS) message to B. If D hears the RTS, it defers transmission until C can hear B's Clear-to-Send (CTS). If node B is not occupied with any other transmission, it responds back with a CTS. On hearing the CTS, node A also defers its transmissions until C finishes sending data to B. This solves the hidden terminal problem. To solve the exposed terminal problem, D defers transmission if it hears both the RTS and the corresponding CTS. If it doesn't hear the CTS, it continues with its transmission. Node B send an acknowledgment (ACK) after it receives the data packet correctly.

The RTS/CTS handshake (as described above) creates a *silence zone* due to floor acquisition in which the nodes have to defer their transmissions till the ongoing data transmission is complete. This is one of the primary reasons for low throughput in CSMA/CA based protocols. Variable

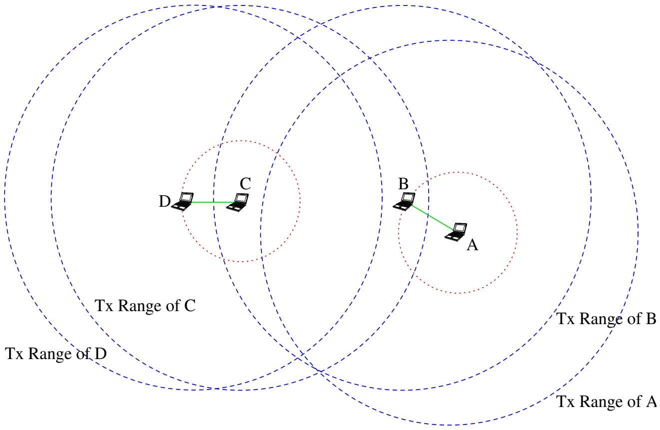


Fig. 1. Motivation for power control and variable transmission range protocols

transmission range power controlled protocols try to minimize this silence zone and thus propose to enhance spatial channel reuse resulting in increased capacity.

Consider again the scenario of Figure 1. Suppose A wants to transmit to B and C wants to transmit to D. In the CSMA/CA MAC implementation, if C is sending to D, then A cannot send to B since B would hear the RTS from C and sense the ongoing transmission. However, if C reduces its transmission power such that it would be sufficient to reach the destination node D, then it acquires a lesser floor area and in this case, node A can also proceed with its transmission. Such a protocol closely packs the source-destination pairs, thereby improving spatial channel reuse and hence increasing the network capacity.

Apart from the above mentioned scenario, power controlled protocols exploit the *"soft capacity"* of receivers. Soft capacity refers to the fact that simultaneous transmission of two packets in the network does not necessarily cause collisions as assumed by CSMA/CA. At any radio receiver, whether a packet is received correctly or not is decided by the ratio of received Bit Energy (E_b)-to-Total Interference power per unit bandwidth (I_0) called Signal-to-Interference ratio (SIR). The *SIR* at a receiving node j is given by [3]

$$\frac{E_b}{I_0} = \left(\frac{W}{R}\right)\left(\frac{h_{ij}P_i^t}{\sum\limits_{k\neq i,j} h_{kj}P_k^t + N_0}\right) = \left(\frac{W}{R}\right)\left(\frac{\text{Received transmitter power}}{\text{Total Interference Power at receiver}}\right) \tag{1}$$

where, W is the bandwidth occupied by the signal, R is the baseband data rate, h_{ij} is the channel gain between the nodes i and j, P_i^t is the transmitted power of node i and N_0 is the background thermal noise. The W/R ratio (called *processing gain* in spread spectrum system) is unity for non-spreading cases.

For correct reception, the received *SIR* should be greater than the minimum threshold level SIR_{thres}. For any ongoing transmission, the interference tolerance at a receiver j is given by (rearranging Equation 1 wth $W/R = 1$)

$$IT_j = \left(\frac{h_{ij}P_i^t}{SIR_{thres}}\right) - (\sum_{k \neq i,j} h_{kj}P_k^t + N_0)$$

where, IT_j is the interference tolerance of node j.

So, even while C is transmitting to D, A can transmit to B. If D is able to listen to transmissions from A, the receiver D can still decode the packet from C correctly if A limits its own transmission power level by considering the interference tolerance of node D. Thus, A makes its decision of transmission power level using two limiting factors: power level should be lower bounded by the value needed to reach destination B, and should be upper bounded by the value which does not disrupt the ongoing transmission from C to D.

This enhancement in the protocol increases the spatial channel reuse and spectral efficiency of the network. But implementation of this idealized protocol in decentralized ad-hoc networks has many challenges as discussed in the later sections. From the previous discussion, it is apparent that the basic principle in designing such a protocol would be to determine an efficient mechanism that can most accurately update the intending transmitter about

- The minimum transmission power requirement from the source that can satisfy the SIR requirement of the receiver under the current noise level at the receiver, taking into consideration the channel gain properties,
- The interference tolerance level at all other nodes in the neighborhood.

Based on these two information, a transmitter can make a local decision on whether it can progress with the transmission or should defer since commencing its transmission can increase the interference level in the neighborhood and thus could potentially disrupt any ongoing transmission. Also, a RTS/CTS handshake mechanism would be beneficial to indicate the transmitting and receiving state of a particular source and destination pair. The challenging part in this strategy is to keep track of the interference level at each node and the distance of a receiver from a particular source.

B. The case of power controlled CDMA in medium access control for ad-hoc networks

The previous section has outlined the advantages of using power control in single hop at the MAC layer, with regard to throughput enhancement as compared to CSMA/CA based protocols. In this section we present the motivation to use CDMA technique at the MAC layer.

CDMA is based on spread spectrum techniques in which each user's packet transmission uses the entire spectrum. In CDMA, a baseband signal is spreaded by multiplying it with a *pseudo-noise (PN)* sequence. Thus in CDMA we have $W \gg R$ in Equation 1. The PN sequence is a sequence of binary digits which satisfies certain statistical properties of random sequences [3]. Ideally one needs a perfectly random noise, but this will be impossible to generate at the transmitter and replicate at the receiver. So, the pseudo-random sequences are the next-feasible option which satisfy Golomb's properties and approximate the binary random noise closely [6]. These PN sequences can be easily generated by Linear Feedback shift Registers (LFSRs). Spreading the transmissions provides multi-faceted benefits and the transmitted signal is more *"robust"* than ordinary baseband pulse transmissions. Benefits of CDMA include improved received quality due to protection against multipath fading, protection against jamming, frequency diversity, interference cancellation and better performance with regard to mobility of the nodes. In cellular networks, CDMA has also been shown to improve capacity upto five to six times compared to that provided by FDMA or TDMA based solutions.

If CDMA is employed in power controlled based variable transmission range ad-hoc network, the tolerance level of the receiver increases because the signal power is now multiplied by the processing gain. Hence, the receiver is able to decode packets which otherwise would not have been received correctly. This allows for increased number of simultaneous transmissions to be packed in the single hop neighborhood resulting in increased system capacity. Thus power controlled CDMA MAC for ad-hoc networks can combine the advantages of both variable transmission range protocols as well as spread spectrum multi-access communication.

The above discussion highlights that the media access protocol design requirements would be same as non-spread spectrum power control MAC for single hop ad-hoc networks with an additional requirement: another handshake mechanism would be required to exchange receiver and transmitter codes between nodes so that receiver and transmitter know which CDMA code to use for data and control packet reception and transmission respectively.

III. Issues in CDMA based MAC for Ad-hoc Networks

In this section, we discuss some issues involved in designing CDMA based MAC for ad-hoc networks.

A. Excess bandwidth requirements

It is to be noted that the benefits of CDMA come at the expense of additional requirement of bandwidth because of signal spreading. Therefore CDMA based protocol should give a throughput improvement commensurate with the additional resource requirements. To compare throughput, a CDMA-based MAC protocol 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 in lesser bandwidth.

B. Code allocation and spreading protocol Issues

In CDMA based ad-hoc networks, allocation of distinct codes to different nodes is required (to be able to do simultaneous transmission in a neighborhood) and this necessitates a code assignment protocol. For small networks, static allocation of unique code can be assumed for the nodes and node to code association information can be disseminated in the initialization period. For large scale self-configuring networks, reuse of codes is required and the local uniqueness of codes should be ensured with a dynamic distributed protocol [7], [8], [9] and [10].

C. Issues with orthogonal pseudo-random sequences

The use of orthogonal codes in a system needs perfect synchronization of the nodes which is difficult to achieve in a decentralized scenario such as ad-hoc networks [3]. Non-orthogonal codes with small cross-correlation factor would be a better design choice. This would eliminate the need for perfect synchronization. With the use of non-orthogonal codes the problem of nonzero cross-correlation of the PN codes will generate a certain amount of Multiple Access Interference (MAI) in adjacent receivers, which should be handled by the distributed power controlled MAC protocol [11].

IV. Power Controlled CDMA based MAC Protocols

From the above discussions, we note that power controlled CDMA based MAC for ad-hoc networks would employ non orthogonal codes with a dynamic distributed protocol for code assignment. Since near far effect is unavoidable due to the use of non-orthogonal codes, an interference controlled access to medium is required. For this the interference level measurement at neighborhood nodes and disseminating this information to all other nodes need to be executed in a distributed fashion.

Lot of research has been carried out on CDMA based packet radio networks (PRN) in late 80's and early 90's especially for distributed code allocation and spreading protocols, whereas interference control protocols in ad-hoc networks are more recent. Though our primary focus is on the recent works on improving MAC protocol using power control and CDMA, we briefly outline some of the spreading protocols proposed in literature.

A. *Spreading Protocols*

In CDMA ad-hoc networks, the code assignment scheme determines the code to be used for transmission. There are four basic types of code assignment [12]:

a) Common code: Here all the nodes are assigned a common code, and hence all transmissions are done on a single spreading code. In this case, multiple simultaneous transmissions are not feasible. Such protocols use spreading mainly to counter the harsh wireless channel conditions.

b) Receiver based: In this scheme, each node is assigned a code. The transmitter uses the code of the intended receiver to spread the packet, while in an idle state, a terminal constantly monitors its own code for reception. This approach simplifies the receiver's circuitry because the receiver does not have to monitor the whole code set for the network. Collisions may occur at the receiver, when two transmitters transmit at the same time using the receiver's code. Another disadvantage of the receiver-based approach is that a broadcast requires the transmitter to unicast the message to each receiver.

c) Transmitter based: In a transmitter-based protocol, a transmission code is assigned to each terminal, and receivers must be able to monitor the activity on the whole set of PN codes. The advantage of this approach is that collisions cannot occur at the receiver. In addition, broadcast is inherently supported. However, the drawback is that the receiver circuitry becomes very complex and expensive.

d) Hybrid Schemes: Various hybrids of the above two approaches are also possible where headers of data packets containing destination and source address can be sent in common code or in receiver code and the data in sender's code. This helps receiver to tune to the particular sender code in next time slot.

One of the issues, which can be observed in aforementioned schemes, is that receivers and transmitters are required to know the spreading code associated with another node and this information can be obtained statically (information conveyed when node enters the network) or dynamically (through beacons). In ad-hoc network's self-configuring mode, dynamic approach is suitable as new nodes are expected to join and leave arbitrarily.

The protocols [12] do not use any handshake mechanism before sending the data to avoid collision for data packets. This issue can be addressed by incorporating RTS/CTS based mechanism. Here, a RTS /CTS handshake between sender and receiver can be done on common code to reserve the channel from contention by other sender for data transmission in next slot. Data can be sent on either transmitter's or receiver's code. This technique can increase the performance in networks with high contention (load).

B. *Interference measurement based MAC protocols for ad-hoc networks*

Power Controlled Medium Access (PCMA) Protocol

Though PCMA was designed for non-spread spectrum based networks, it also exploits the interference measurement based access to increase the number of simultaneous transmission in a single hop ad-hoc network. It is a variable transmission range protocol which uses the principle of cooperation and interference controlled access to the medium [2]. It uses two channels: one for data packets and one for control packets. A request-power-to-send (RPTS)/acceptable-power-to-send (APTS) handshake between the sender and receiver is used to determine the minimum transmission power needed for successful packet reception at the receiver. The RPTS/APTS handshake occurs in the data channel and precedes the data transmission. After the successful reception of the data, the receiver responds with an ACK packet confirming its reception. A noise tolerance advertisement is used by each active receiver to advertise the maximum additional noise power it can tolerate, given its current received signal and noise power levels. The noise tolerance advertisement or busy tone is periodically pulsed by each receiver in the control channel, where the signal strength of the pulse indicates the tolerance to additional noise. A potential transmitter first "senses the carrier" by listening to the busy tone for a minimum time period to determine the upper bound of its transmit power level for all its transmissions. This prevents any new sender from disrupting other on-going transmissions in the network.

Controlled Access CDMA (CA-CDMA) Protocol

CA-CDMA uses spread spectrum (SS) technique at the physical layer as well as the MAC layer for better throughput performance and resource utilization in single hop ad-hoc networks [13]. CA-CDMA is based on interference-limited access to channel while data communication occurs by spreading packets using separate non-orthogonal codes. The protocol has in-built mechanism to take care of MAI generated by non- orthogonal codes and the near-far effect between source-destination pairs. An admission control strategy similar to PCMA is applied to bound the system interference level for all current ongoing communication at a given point of time. The system architecture includes a control channel and a data channel. The control channel is a random access channel and the transceiver has carrier sensing mechanism for control channel. Transmissions in data channel are controlled by handshake mechanisms. Transmission in control channel is done on a common code whereas transmission in data channel is done with distinct receiver based code. The transceiver for control channel at any node is always tuned to the common code. The protocol first executes a RTS/CTS based handshake mechanism between source and destination in the control channel. The RTS packet updates the destination on the maximum possible power that the sender can transmit with, CTS packet updates the sender and all other possible interfering neighbors about the interference tolerance level at this particular destination, so that the neighborhood nodes can update their perception of noise tolerance level at any particular node before they commence any transmission. The transmission power levels of RTS/CTS are determined on the basis of interference levels in the neighborhood to prevent disrupting any ongoing transmissions. Once the RTS/CTS exchange is successful the receiver gets tuned to the receiver code, and the sender transmits the data with the power and receiver code specified in CTS packet. For more detailed discussion the reader can refer to [13]. This protocol shows improvement in throughput over 802.11 based schemes.

Interference Based Multiple Access (IBMA) Protocol

This protocol is similar to CA-CDMA in the sense that it has similar goals, but the protocol is different and more optimized [14]. The channel architecture implements a dual channel paradigm - a narrow-band control channel used for the transmission of control packets and a wide-band data channel. Only the transmissions in the data channel are spread using the spreading codes, those in the control channel take place through random access mechanism. The primary difference with CA-CDMA is that the data and RTS/CTS handshake both are done in data channel, the control channel is random-access as compared to spread-spectrum in CA-CDMA and the system does not require carrier-sensing hardware. 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. Each node in a single hop neighborhood broadcasts its data channel receiver code using beacons in the control channel. Similar to PCMA and CA-CDMA, 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 node to exceed the tolerable limits. In this protocol, each node maintains a neighborhood table, which contains a complete power map of its first-hop neighbors, i.e. each node has knowledge of the interference tolerance or the noise level at every other node. Whenever a node wants to transmit data, it first checks whether the destined node is free and then calculates the feasibility of sending data to the desired node from the power values in the neighborhood table. The information in neighborhood table gets updated as follows. Every receiving node advertises the values of excess interference it can tolerate by placing it in Interference Tolerance packets, while idle nodes advertise their current noise level periodically with the help of beacons. These short packets are sent in control channel and these control packets are used by the nodes in one-hop distance to update their neighborhood table.

If a transmission is feasible, the transmitter sends an RTS to the receiver, which is used by the receiver to calculate the current channel gain and hence, the minimum power required for data transmission to occur. This value is communicated to the transmitter by placing in the CTS message. Once the handshake is completed successfully, data is transmitted using receiver code. The throughput improvement in IBMA for high traffic load-high node density systems is shown to be more than commensurate for the increased bandwidth requirements.

Performance Comparison

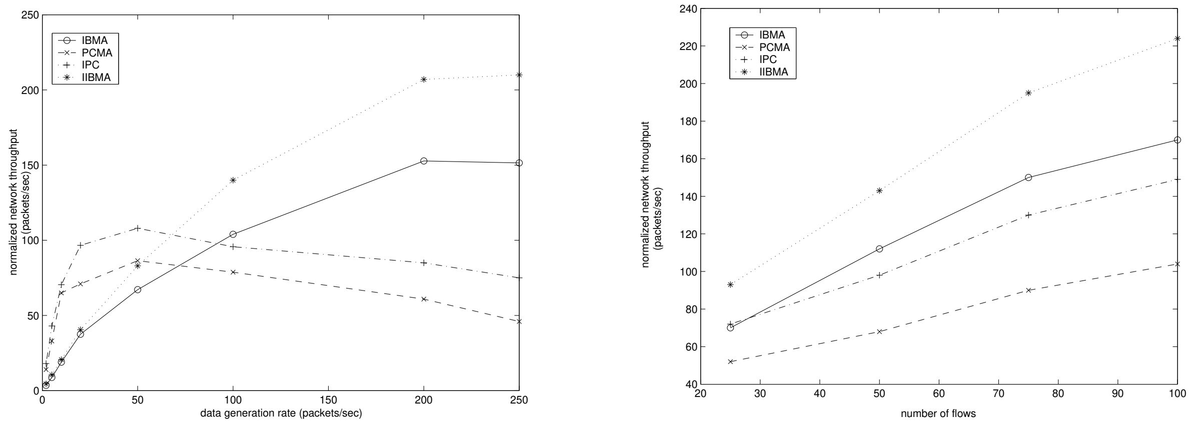
Simulation results from various literature validate that power control and CDMA are able to enhance network capacity as compared to CSMA/CA systems. In [2] the authors have compared the throughput performance of PCMA and 802.11. It has been observed that at low data rates, PCMA gives same performance as 802.11, but as the load on the system increases, PCMA gives higher throughput than 802.11. The throughput of PCMA has been observed to be about two times as that of 802.11 in clustered topologies. In [13], the performance comparison of CA-CDMA protocol with 802.11 in a larger network with higher node density has been reported. CA-CDMA gives much higher throughput as compared to 802.11 for high data rates.

In [14], the authors present a performance comparison between PCMA and IBMA. IBMA, being more optimized and exploting both power control as well as CDMA, gives much higher system throughput than PCMA at high traffic load as well high load density, as shown in Figures 2(a) and 2(b) respectively[1]. IBMA also provides marked improvement in terms of delay performance. As can be seen from Figures 3(a) and 3(b), the delay jitter and average delay suffered by data in IBMA are an order of magnitude less than those suffered in PCMA. Such a performance improvement is critical for ad-hoc systems supporting non-elastic (delay-sensitive) traffic. In a more recent work [15], the authors have argued that IBMA is much more optimized than CA-CDMA and is simpler in implementation.

Observations

The protocols PCMA, CA-CDMA, IBMA, all have the common aspect of interference limited access through power-control. They implement distributed mechanism of interference level measurement at each node caused by noise in the surrounding and simultaneous transmissions in the neighborhood, with different degree of accuracy. The later two also exploit CDMA to enhance spectral efficiency. Due to multipoint to multipoint communication in a decentralized ad-hoc network the challenge is to devise a mechanism to measure the interference level in single hop neighborhood nodes in a distributed fashion, and a mechanism to disseminate this information as immediately as possible to all single hop nodes. Inaccurate or stale information about interference tolerance level at each node and channel gain values, may lead to incorrect

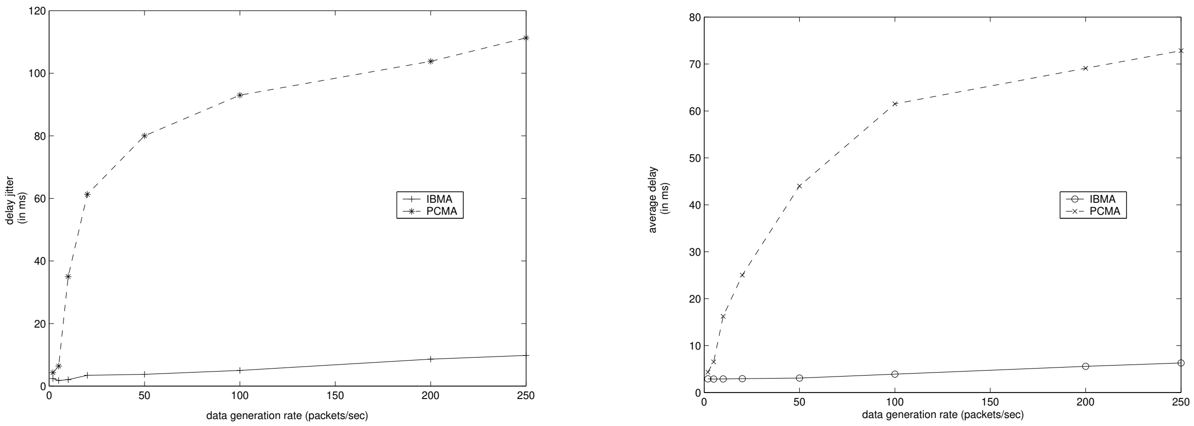
[1]The IPC and IIBMA are idealized versions of PCMA and IBMA, respectively, which use actual network state information rather than information obtained through control packets. For details refer [14].



(a) With increasing data rate

(b) With increasing node density

Fig. 2. Throughput performance of IBMA and PCMA



(a) Delay Jitter

(b) Average Delay

Fig. 3. Delay performance of IBMA and PCMA

conclusions about viability of an intended transmission, which in turn can lead to corruption of ongoing transmissions. This transmission of interference information leads to control overheads which compete with data packets for bandwidth. Updating interference-level-information is very critical aspect of the protocol, since any lapse in update (due to loss or delay of update control packets) can potentially disrupt other ongoing transmission due to incorrect computations. Hence, even if the concept might show improved network performance, it needs to be practically implemented in hardware and the trade-off needs to be optimized.

V. Conclusions and Future directions

In this tutorial article, we have explored the applicability of power controlled CDMA based media access in ad-hoc networks. We have discussed issues arising out of its inherent distributed nature, which were earlier not present in case of cellular networks. We have outlined the various components of the design of cross-layer MAC protocol for CDMA-based ad-hoc networks. We, then, presented representative research work in these directions with an overview of spreading protocols and power controlled CDMA based protocols. In [2], [13], [14], it has been observed that though power controlled protocols lead to increase in system capacity, in ad-hoc environment these protocols favor transmissions over short ranges [2] and traffic with lower SIR requirements in systems supporting heterogeneous traffic classes. Hence, this approach introduces new kinds of unfairnesses, which were not present in fixed transmission range based CSMA/CA protocols. An important future direction is to design power control CDMA protocols which address these fairness issues. Apart from this, providing Quality of Service in such networks is a very critical issue and needs to be addressed appropriately.

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