IEEE 802.11 DCF Based MAC Protocols for Multiple Beam Antennas and their Limitations

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Abstract – **Multiple beam antennas can receive (or transmit) data on multiple beams simultaneously. The aim of this paper is to show the limitations of using IEEE 802.11 distributed coordination function (DCF) based schemes for medium access control (MAC) in such antennas. We provide four different variants of IEEE 802.11 DCF based on-demand protocols to study this phenomenon. Our simulation results and analyses emphasize the need to develop a novel MAC protocol to fully exploit the capabilities of multiple beam antennas. We further provide some embryonic guidelines for the development of such a protocol.**

Keywords - Concurrent packet reception, medium access control, multiple beam antennas

I. INTRODUCTION

It has been emphasized in the literature that omni-directional communication suffers from poor spatial reuse, thus adversely affecting the network capacity in multihop networks [1]. Directional antennas on the other hand, are known to provide increased range, better spatial reuse and reduced interference as compared to omni-directional antennas [2]-[8]. Recently the research community has started exploring the use of multiple beam antennas with distributed protocols for asynchronous traffic in wireless networks [9]-[11]. Using complex DSP technologies an antenna array can support either multiple transmissions or multiple receptions simultaneously thereby considerably enhancing the system capacity. Such an antenna array is referred to as multi-beam adaptive array (MBAA) [12].

IEEE 802.11 distributed coordination function (DCF) [13] on the other hand is a de-facto medium access control (MAC) standard for wireless LAN and wireless ad hoc networks. Almost all asynchronous on-demand protocols are based on this standard. However IEEE 802.11 DCF, which is designed for omni-directional antennas, may not leverage all the benefits of multiple beam antennas. Ideally, if the offered load is high, then an M times increase in throughput should be achieved, where M is the number of beams that can be simultaneously formed by the antenna system, i.e., a measure of its spatial resolution. This requires *concurrent packet receptions* or *transmissions (CPR/CPT)* on different beams of a node. Moreover, in IEEE 802.11 DCF, after sensing the channel idle for *DCF interframe space* (DIFS) duration, each node waits for a random duration till its backoff timer expires. For multiple beam antennas, this creates the possibilities for disparate backoff timers for different beams.

In this paper, we investigate the performance of different protocol variants based on IEEE 802.11 DCF for multiple beam antennas. We examine these protocols using various metrics like throughput, end-to-end delay, percentages of total packets received and transmitted concurrently, and energy used. We also develop scenarios to explore and contrast the effects of design decisions on different protocols. The paper then examines the patterns in simulation results to deduce right practices for using multiple beam antennas.

The rest of the paper is organized as follows. In Section II we give an overview of multiple beam antennas and existing MAC protocols. We propose variants of IEEE 802.11 DCF for multiple beam antennas in Section III. The performance evaluation and discussion of simulation results is carried out in Section IV. In Section V we provide some elemental guidelines for an optimal MAC protocol for multiple beam antennas. Section VI concludes the paper.

II. OVERVIEW

A. *Multiple Beam Antennas*

Single beam antennas have been explored for multihop wireless networks primarily as a means to extend the range of communicating nodes beyond omni-directional capability by reducing the number of hops traversed in a multihop route. While these antennas are likely to enhance performance when considering a route in isolation, the simultaneous existence of many routes in a loaded wireless network is likely to produce adverse effects. This may occur if multiple routes share some intermediate nodes. The common nodes can forward traffic on only one route at a time thereby increasing the delays on other routes. This phenomenon is called *coupling effect.* Multiple beam antennas have the ability to transmit (or receive) more than one packet in parallel. Thus multiple beam antennas may have the desirable effect of ensuring that throughput

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performance of individual routes is not degraded by coupling effect.

Directional antennas are derived from an array of omni-directional antenna elements. In practice, a smart directional receive beam is formed by applying a complex weight vectors to a received signal vector, which is the set of signals received at different omni-directional elements of the antenna array [14]. A reciprocal of this process is used for transmission. Since each element of the antenna array is involved in the formation of a directional beam, all the elements of the array must be kept simultaneously in either transmission or reception. Hence, the different beams cannot operate independently, making it impossible to achieve an M times increase in throughput. However, while in either transmission or reception, a node may maximize throughput by simultaneously employing as many beams as possible. This constraint is referred as collective *time-division-duplex (TDD)* requirement of the system. This basically states that TDD between transmission and reception, and the ability to form multiple beams, cannot be viewed orthogonally for throughput enhancement. On the contrary, their interdependence causes a significant decrease in throughput as compared to the ideal case [11].

A single beam antenna system typically requires one signal processing unit for formation of transmit or receive beam. In contrast, a multiple beam antenna would require more signal processing units, as each beam of the system would need a dedicated DSP for applying a steering vector to the outgoing or incoming signal. Hence, more hardware cost is incurred. Also, multiple beam antennas require high performance beamforming techniques to ensure that there is negligible interference between simultaneous multiple beams that are active.

B. IEEE 802.11 DCF

IEEE 802.11 MAC [13] is a distributed coordination function (DCF) (also referred as CSMA/CA) which tries to avoid collisions in a contention based channel access to the nodes. Once the channel is sensed idle for DIFS duration, a transmitting node waits for a random duration based on its contention window before starting transmission. If any activity is detected on the channel in that duration, the node freezes its backoff timer and waits till the channel is idle again and repeats the above process. Otherwise, it initiates data transmission. This mechanism minimizes the possibility of two neighboring nodes starting their transmission at the same time. If the frame size exceeds certain threshold, a four-way handshake mechanism involving control messages viz. *request to send (RTS)* and *clear to send (CTS)* preceding the data communication is used in addition to carrier sensing. This is to minimize the data packets collisions. A node hearing RTS or CTS sets its network allocation vector (NAV) to defer channel access until the end of the corresponding data transmission. This is termed as virtual carrier sensing and avoids collision with any ongoing transmission.

C. Directional Protocols Based on IEEE 802.11 DCF

There are several variants of protocols for directional antennas based on IEEE 802.11 DCF [2]-[8]. Broadly they differ in the way control messages are exchanged. While some protocols prefer directional transmission for RTS/CTS messages, some prefer omni-directional transmission. Omni-directional transmission of control packets greatly reduces hidden terminal and deafness problems [4], [8]. While directional communication increases the network connectivity by enhancing the range of the nodes. As in IEEE 802.11 DCF, here also each node maintains a directional network allocation vector (DNAV) based on directional virtual carrier sensing (DVCS) which holds the information regarding deferring transmission in a particular direction until the end of corresponding data communication [4], [6].

D. Antenna Model

In this paper, we consider a wide azimuth switched-beam smart antenna comprised of multiple beam antenna array [11]. Each antenna array with M elements forms non-overlapping sectors spanning an angle of $360/M$ degrees so as to collectively span entire space as shown in Fig. 1. Beam shape is assumed as conical and benefits of nulling or the impact of side-lobe interference are not considered. Also, our focus is on gains obtained from spatial reuse rather than range extension. Hence the range of omni-directional antenna and that of directional antenna is considered same. Carrier sense is performed directionally, i.e., the medium is sensed only for an angular range (a beam) before transmission in a particular direction. In idle mode, the receiver scans all its beams for valid transmissions. Smart directional antennas use the direction of incident energy to determine the appropriate beam for reception of data and can precisely calculate the Angle of Arrival (AoA) of the received signal [15]. Hence, a collision occurs only if a node receives interfering energy in the *same beam* in which it is actively receiving a packet.

III. PROPOSED PROTOCOLS

In this section, we propose four variants of IEEE 802.11 DCF based MAC protocols for multiple beam antennas.

A. Multiple Beam Directional MAC with Beam-Based Backoff (MDMAC-BB)

MDMAC-BB involves directional communication of control packets and beam-based backoff. This implies that RTS and CTS messages are sent only in those beams where data communication takes place. Further, the term beam-based backoff means that contention window is maintained independently for each directional beam of the node and is managed in the same way as in IEEE 802.11 DCF.

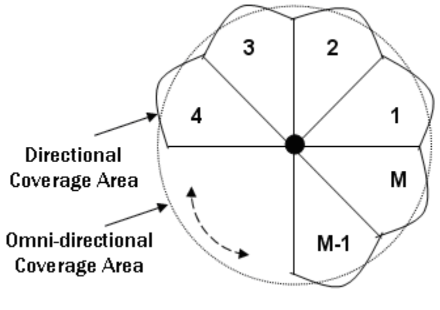

Figure 1. The antenna model

Note that the contention windows for different beams of the same node may be different. The beam, whose random backoff timer expires first, begins transmission. Further, in idle mode after waiting for DIFS duration, if a carrier signal is detected in any of the beams, the node goes into reception mode freezing the backoff timers of the beams waiting to transmit.

B. Multiple Beam Directional MAC with Node-Based Backoff (MDMAC-NB)

The primary difference here from MDMAC-BB is that MDMAC-NB employs only one backoff counter for all its beams. The same contention window is used for all the beams of a node ready for transmission. After the backoff timer expires, data transmission is initiated on all beams that are not blocked by DNAV and where the channel was sensed idle. The backoff timer is usually governed by the beam with maximum number of retransmission attempts as each retransmission increases the contention window. However, the moment there is successful transmission in any one beam, the contention window is reset to the minimum value.

C. Multiple Beam Omni-Directional[1] MAC with Beam-Based Backoff (MMAC-BB)

This protocol differs from MDMAC-BB in that here the control messages RTS/CTS are exchanged in all the available beams and not just in the beams employed in data communication. In beams where no data is available, control messages are sent to inform neighbors about the intended communication so that they can set their respective DNAVs. Data is still transmitted only in the appropriate directional beam.

D. Multiple Beam Omni-Directional MAC with Node-Based Backoff (MMAC-NB)

MMAC-NB combines the features of MDMAC-NB and MMAC-BB. This implies that a single unified backoff timer is maintained for all the beams in the node. Moreover, the RTS/CTS control messages are exchanged in all available beams.

IV. PERFORMANCE EVALUATION

A. Analysis of Proposed Variants of IEEE802.11 DCF for Concurrent Packet Reception and Transmission Probabilities under Saturated Conditions[2]

1) Concurrent packet reception probability: Consider a node with N neighbors contending to transmit data to this node. The neighbors are randomly distributed around the node. Let p be the probability that a node is ready to transmit in any random slot time. This probability under saturated traffic conditions has been calculated for omni-directional communication by Bianchi [16]. Further each node is capable of forming M non-overlapping beams of angular width $360/M$, thus spanning the whole area. The probability that a node receives data in b beams concurrently is given by

$$P_{CPR}(b) = P(b,N) \cdot Q(b,M)\,, \tag{1}$$

where $P(b,N)$ is the probability that b out of N neighbors transmit in a slot concurrently and is given as

$$P(b,N) = \binom{N}{b} p^b (1-p)^{N-b}\,. \tag{2}$$

Note that for concurrent reception from these b nodes, it is required that they lie in b distinct beams of the receiver node. This probability, $Q(b,M)$ is given as

$$Q(b,M) = \frac{\binom{M}{b}}{M^b}\,. \tag{3}$$

Thus from (1), (2) and (3),

$$P_{CPR}(b) = \binom{N}{b} p^b (1-p)^{N-b} \frac{\binom{M}{b}}{M^b}\,. \tag{4}$$

Thus the probability of concurrent packet reception by a node is then given by

$$P_{CPR} = \sum_{b=2}^{M} P_{CPR}(b)\,. \tag{5}$$

Further, if N is large, p is small and Np is constant, (4) can be approximated by Poisson probabilities as

$$P_{CPR}(b) = \frac{(Np)^b e^{-Np}}{b!} \frac{\binom{M}{b}}{M^b}\,. \tag{6}$$

Now, (5) and (6) can be used together to determine upper bounds on the percentage of CPR possible. These results are presented in Fig. 2 for different values of Np and M. For M=8, it can be seen that no more than approximately 14% of packets can be received concurrently.

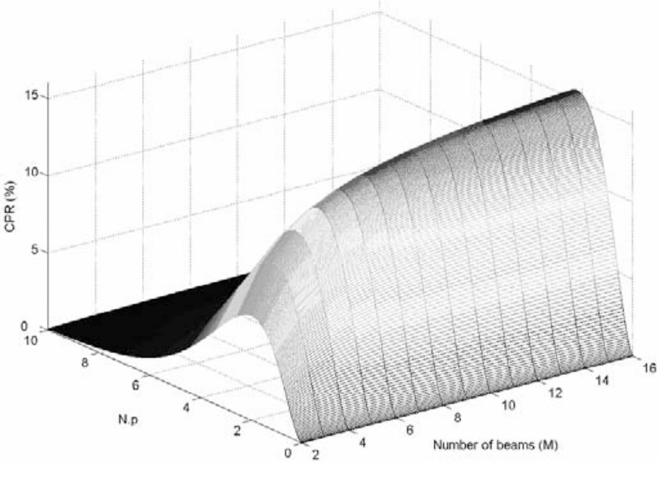

Figure 2. Percentage of CPR

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[1] The term implies that the control messages are sent in all available beams simulating an omni-directional behavior.

[2] A node always has a packet in its transmission queue.

Note that the results remain unaffected whether the backoff is node-based or beam-based. In both the cases the probability to transmit data in a random slot remains p under saturated traffic conditions. However, the choice of backoff scheme does affect the concurrent packet transmission probability of a node.

2) Concurrent packet transmission probability: The Concurrent packet transmission probabilities are relatively simple to calculate. Again, let us consider a node with N neighbors distributed randomly in M beams. In beam-based backoff, each beam is ready to transmit in a given slot with probability q. Also, we assume that the receiver nodes are ready to receive the data packet. Therefore the probability q is given by [16]

$$q = \frac{2}{CW_{\min} + 1}, \tag{7}$$

where CW_{min} in the minimum contention window. To acheive concurrent packet transmissions, two or more beams must start transmission at the same time. The probability for b beams to start transmission concurrently is given by

$$P_{CPT\_BB}(b) = \binom{M}{b} q^b (1-q)^{M-b}. \tag{8}$$

Thus concurrent packet transmission probability for a node with beam-based backoff can be calculated as

$$P_{CPT\_BB} = \sum_{b=2}^{M} P_{CPT\_BB}(b), \tag{9}$$

$$\Rightarrow P_{CPT\_BB} = 1 - (1-q)^M - qM(1-q)^{M-1}. \tag{10}$$

As an example, for a node with eight beams and minimum contention window of 32, P_{CPT_NB} is about 8.1 percent.

While for CPR and CPT with beam-based backoff, P_{CPR} and P_{CPT_BB} are the sums of the probabilities that concurrent packets are received or transmitted respectively in two or more beams. For node-based backoff scheme the probability of CPT is the probability that two or more beams transmit a packet, given that there was a transmission. This is because the backoff timer expires for all the beams at the same time. Thus given the fact that receiver nodes are ready to receive, the minimum value of concurrent packet transmission probability for node-based backoff schemes in saturated conditions is given by

$$P_{CPT\_NB} = \sum_{b=2}^{M} \binom{M}{b} \Big/ \sum_{b=1}^{M} \binom{M}{b}, \tag{11}$$

$$\Rightarrow P_{CPT\_NB} = 1 - \frac{M}{2^M - 1}. \tag{12}$$

Thus for a node with eight beams (i.e., M=8), minimum P_{CPT_NB} obtained is about 97 percent.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Data rate	2 Mbps
Data packet size	2000 bytes
Sensing power	0.07 mW
Reception power	1.45 mW
Transmission power	1.75 mW
Total Beams	8

B. Evaluation Methodology and Considerations

In our simulation we compare the MAC performance of the omni-directional, directional and the four proposed variants of IEEE 802.11 DCF for multiple beam antennas. The range of multiple beam/directional antennas used is the same as that of omni-directional antennas. This isolates the gains obtained exclusively by spatial reuse and ignores those offered by range extension. As in several earlier studies [2], [3], [8], we compare the performance of different MAC protocols under static topological conditions. To ensure fair comparison between the protocols, we use same routes and free space path model in all cases. For directional and multiple beam antennas each node maintains a separate queue for each beam to avoid *head-of-line (HOL)* blocking [17]. Since each beam has its own queue, protocol for single beam directional antenna also has two variants, viz. Directional–BB (Beam-Based Backoff) and Directional-NB (Node-Based Backoff).

C. Simulation Setup

The simulation is written in PARSEC [18], a C-language based discrete event simulator. Some important simulation parameters are given in Table I. For other MAC parameters, the default values as in IEEE 802.11 DCF are used. We maintain DNAV for directional communication. The power levels indicated for reception and transmission modes are for omni-directional wireless LAN cards [19]. These power levels can be divided by the total number of beams, eight, to obtain the nominal values for each beam in different modes. Packet generation at each source node is modeled as Poisson process with specified mean arrival rate. In case there are multiple source nodes, the same arrival rate is used for all of them. This effectively has a multiplicative effect on the traffic generation rate for the entire network. The simulations are run for disparate random seeds and the results statistically averaged out for five iterations each running for hundred simulation seconds. Each node has a maximum buffer of 30 packets after which arriving packets are dropped. Further, each packet has a *lifetime* of 30 packet durations[3] after which it is considered as dead and is dropped. This places an upper bound on the network delays in all protocols.

D. Scenarios

We study the performance of various protocols by activating a subset of routes shown in Fig. 3 so as to form the following topologies:

> *Star:* Routes 5, 6 and 7 are activated together to examine the concurrent packet reception and transmission capability of multiple beam protocols at node C.

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[3] One packet duration is the time required to transmit one data packet at the given data rate.

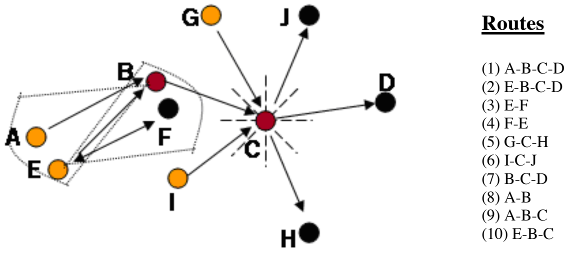


Figure 3. A sample scenario

Linear: This topology investigates the possibility of concurrent data communication between node pairs A-B and C-D for various protocols for the route 1.

Couple: Two routes 3 and 8 are activated together. In this topology both the destination nodes fall in the same beam of each sender; and both the sender nodes lie within the same beam of each destination node. The topology illustrates the effect of deafness and route coupling on each protocol.

Deaf: Routes 9 and 10 are activated simultaneously. This is one of the rare topologies where gains due to deafness are clearly seen at higher loads.

Random: All the routes from 1 to 6 are simulated together to form a random scenario. This is to illustrate the combined effect of the above topologies on network performance.

Complete-5: A topology where five nodes form a completely connected graph, i.e. any two nodes can directly communicate with each other. Each node transmits data to all other nodes. This topology tests the protocols under heavy traffic conditions.

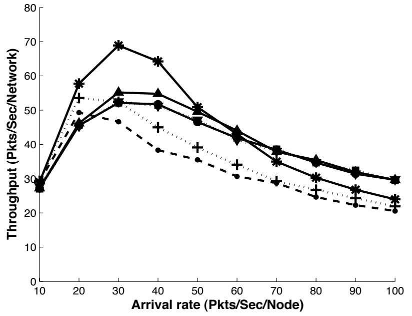
E. *Results and Observations*

We evaluate the throughput, end-to-end delay, concurrent packet reception and transmission percentages and the total energy expended. These metrics are presented for omni-directional, directional protocols with beam-based and node-based backoff timers, and for the four protocol variants discussed in Section III. Using the scenarios defined earlier we make the following observations:

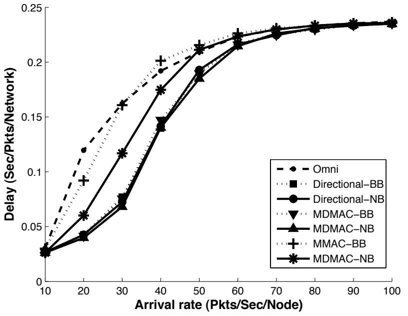
Star Topology: None of the protocols are able to fully capitalize on multiple transmission/reception capability of multiple beam antennas. For example, in Fig. 4 throughput should have been thrice the arrival rate (until the breakdown of the network, which occurs at arrival rates of about 60 Pkts/Sec/Node). However, it can be seen clearly that even in an unsaturated network (arrival rate 50 Pkts/Sec/Node), no protocol is able to extract throughput of more than 33% of the maximum possible value.

Linear Topology: Both the MMAC-BB and MMAC-NB are able to achieve concurrent data communications between node pairs A-B and C-D (Fig. 5). This is due to omni-directional transmission of control messages. Directional protocols on the other hand suffer from deafness problem while omni-directional antenna from poor spatial reuse.

Couple Topology: As is evident from Fig. 6, all protocols perform equally well in this topology. Deafness and route coupling do not affect omni-protocols, but directional protocols experience performance degradation at higher loads.

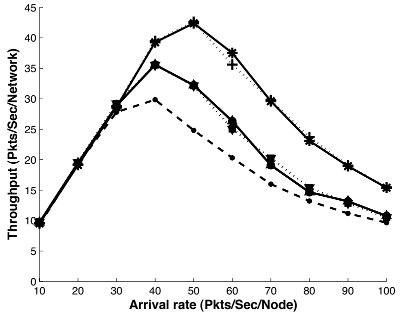


(a) Network throughput vs. packet arrival rate per source node

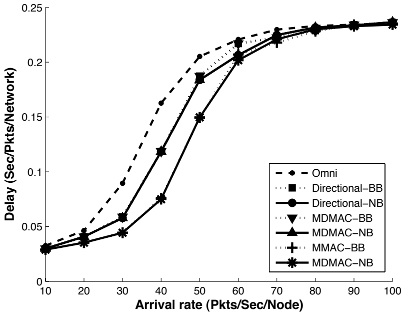


(b) Network end-to-end delay vs. packet arrival rate per source node

Figure 4. Throughput and delay for star topology (G-C-H, I-C-J and B-C-D)

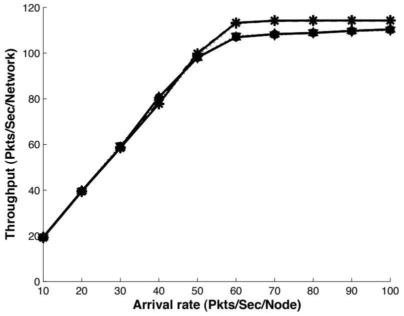


(a) Network throughput vs. packet arrival rate per source node

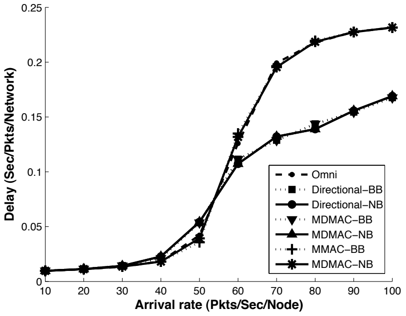


(b) Network end-to-end delay vs. packet arrival rate per source node

Figure 5. Throughput and delay for linear topology (A-B-C-D)



(a) Network throughput vs. packet arrival rate per source node



(b) Network end-to-end delay vs. packet arrival rate per source node

Figure 6. Throughput and delay for couple topology (A-B and E-F)

Deaf Topology: Directional protocols outperform omni-directional protocols in this topology (Fig. 7). In case of a directional antenna the RTS messages from the two source nodes frequently collide with each other due to deafness. This increases the size of contention window of these nodes. As a result, the intermediate node operates in almost a hot-potato routing manner, attempting to buffer no more than one data packet at any given time. On the other hand, in an omni-directional protocol, deafness is mitigated and the source nodes synchronize their NAV/DNAVs accordingly. But this leads to an overwhelming transmission of data to the intermediate node without giving latter a fair chance to forward the traffic. Most data loss occurs at this node when the packet *lifetime* expires. A similar trend can be observed at higher loads in the star topology.

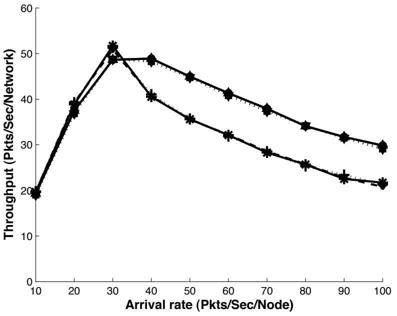
Random Topology: All directional protocols perform equally well in random scenario (Fig. 8). While some gains from omni-directional communication of control packets are obtained at medium loads, directional protocols perform better at higher loads because of better spatial reuse.

Complete-5 topology: This topology clearly shows the gains from concurrent packet transmissions obtained by multiple beam antennas and node-based backoff protocols as compared to other antennas and beam-based protocols (Fig. 9).

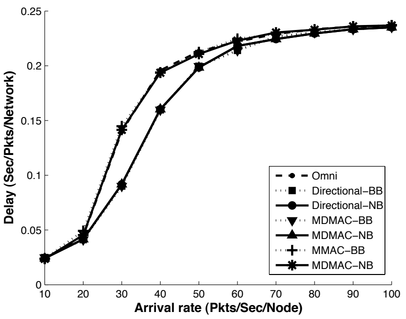
Energy: There is no appreciable difference in the amounts of energy spent by all protocols with the exception of omni-direction scheme (Fig. 10). This follows directly from the observation that most energy is spent during actual data communication. Omni-directional protocol conveys this traffic in all directions. All other protocols use only one directional beam for data communication thereby expending only a fraction (1/M) of the energy used by omni-directional scheme. Similarly, multiple beam omni-directional protocols expend more energy as compared to multiple beam directional protocols due to omni-directional transmission of control messages by the former.

Concurrent Packet Reception: No protocol variant achieves any significant CPR. The average number of packets received concurrently by intermediate node in star topology is less than 1% of the total packets received by that node, as evident in Fig. 11(a). Similarly, in Fig. 12(a), in complete-5 topology none of the nodes is able to achieve even 0.5% CPR. Further, in Fig. 13, we observe that when every beam has one transmitter node, a receiver node achieves a CPR less than 2%. Viewing these results in light of the analytical curves in Fig. 2, we note a fundamental drawback of IEEE 802.11 DCF based MAC protocols for multiple beam antennas – inability to provide any meaningful CPR.

Concurrent Packet Transmission: Node-based backoff schemes are able to achieve fairly high shares of CPT. This reaches up to 80% in case of star topology, as in Fig. 11(b), and 70% in complete-5 topology, as in Fig. 12(b). Beam-based backoff protocols, on the other hand, provide negligible CPT. This is because each beam maintains an independent backoff timer and a node cannot begin transmission in all beams at the same time. As evident from Fig. 14, in saturated conditions and when every beam has a single receiver, we are able to achieve nearly 100% CPT for node-based backoff schemes. While for beam-based backoff schemes CPT obtained is 8-10%.

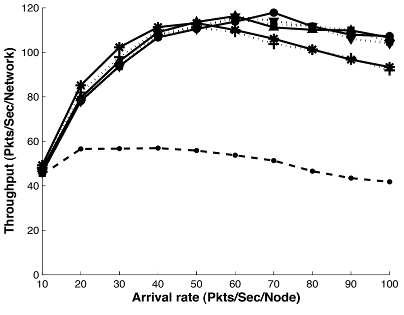


(a) Network throughput vs. packet arrival rate per source node

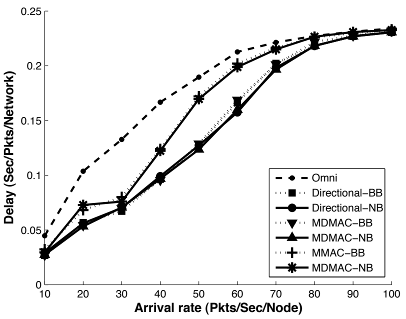


(b) Network end-to-end delay vs. packet arrival rate per source node

Figure 7. Throughput and delay for deaf topology (A-B-C and E-B-C)

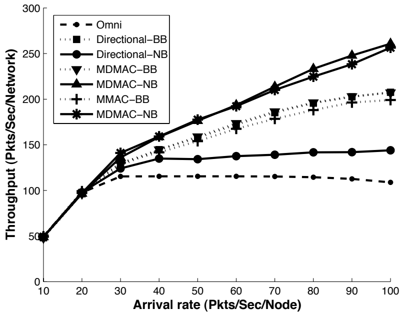


(a) Network throughput vs. packet arrival rate per source node

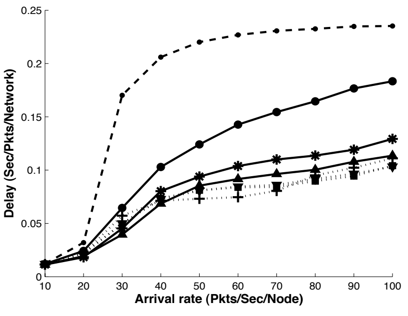


(b) Network end-to-end delay vs. packet arrival rate per source node

Figure 8. Throughput and delay for random topology
(A-B-C-D, E-B-C-D, E-F, F-E, G-C-H and I-C-J)

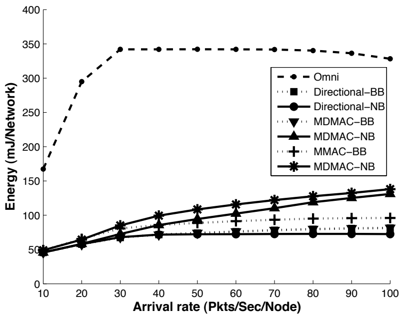


(a) Network throughput vs. packet arrival rate per source node

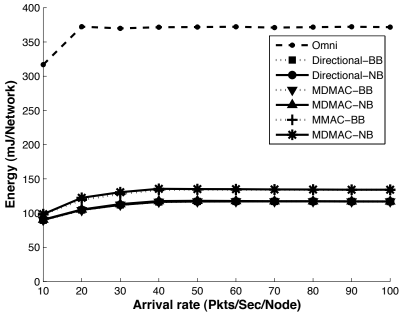


(b) Network end-to-end delay vs. packet arrival rate per source node

Figure 9. Throughput and delay for complete-5 topology

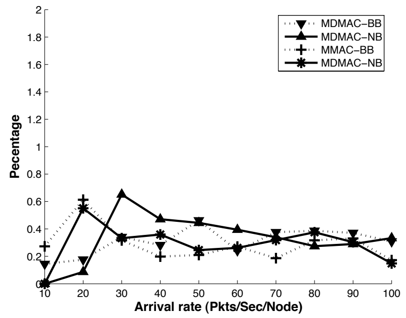


(a) Energy expended vs. packet arrival rate per source node in random topology

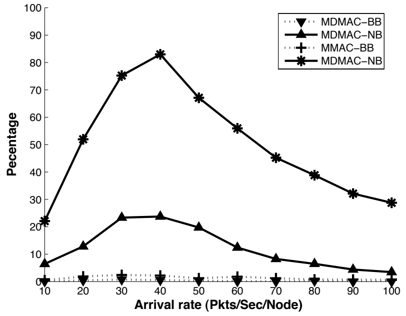


(a) Energy expended vs. packet arrival rate per source node complete-5 topology

Figure 10. Energy expended in random and complete-5 topologies

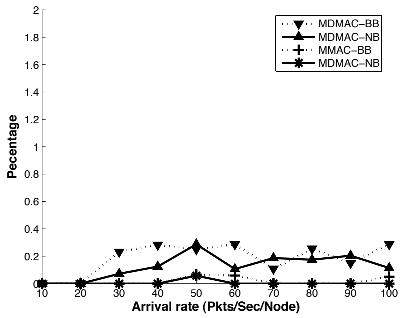


(a) CPR vs. packet arrival rate per source node

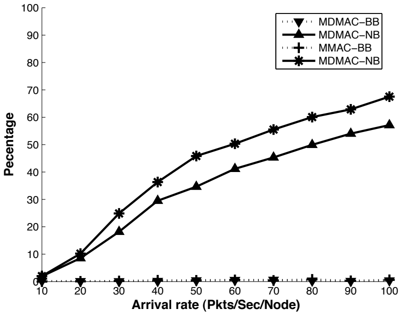


(b) CPT vs. packet arrival rate per source node

Figure 11. Percentage of CPR and CPT obtained at intermediate node (C) in star topology



(a) CPR vs. packet arrival rate per source node



(b) CPT vs. packet arrival rate per source node

Figure 12. Percentage of CPR and CPT obtained at any node in complete-5 topology

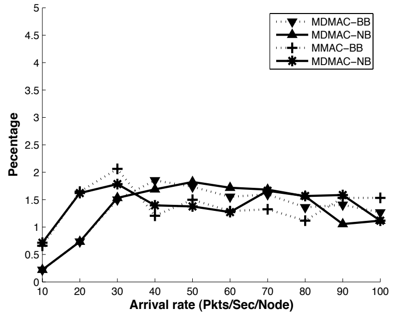


Figure 13. Concurrent packet reception percentage for a node with one transmitter node in every beam

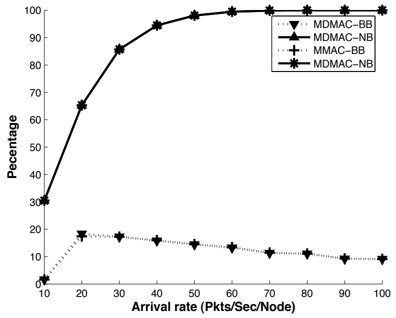


Figure 14. Concurrent packet transmission percentage for a node with one receiver node in every beam

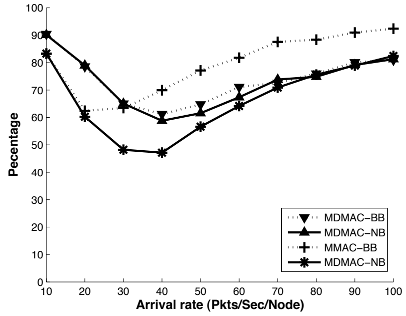


Figure 15. Percentage of total packets received and transmitted successively by intermediate node in star topology

Successive Reception and Transmission (SRT): Intuitively, immediate transmission of just received (concurrent) data packets would best results. However, as can be seen from Fig. 4 and 15, even at very high rates of SRT, star topology provides poor throughput and network delays. This can be explained by results in Fig. 11, which shows inconsequential CPR and CPT, and hence renders our multiple beam antenna to work essentially like a single beam directional antenna.

V. PROTOCOL GUIDELINES

From the results and observations in the previous section, we draw the following inferences that form the framework for development of an optimal MAC for multiple beam antennas.

The control messages (RTS/CTS) must be transmitted in all beams to suppress problems due to deafness and hidden terminals. This is also supported by results presented in [4] and [8] for single beam directional antennas. At higher loads, however, directional MAC yields better results as it avoids unnecessary capturing of neighboring nodes to listen to the control packets. Hence depending on the network load, protocol can switch from omni-directional transmission of control packets to directional communication and vice-versa.

The intermediate node should use a mechanism similar to hot-potato routing, which implies that the protocol should attempt to minimize the temporary storage of data at intermediate nodes. After receiving a data packet, a node must try to transmit it to the next hop with the highest priority. The classic store-and-forward scheme can lead to a queue buildup at the intermediate nodes thereby increasing end-to-end delays and creating possibilities of buffer overflow.

The protocol must use a single backoff timer for all available beams of the given node. This is the only way a node can achieve CPT.

CPT can achieve its maximum potential only if packets are actually received concurrently. This is especially true for intermediate bottleneck nodes. Bottleneck nodes are those which forward traffic from multiple routes. These nodes offer the most promising use of multiple beam antennas. An optimal protocol must attempt to maximize the probability of concurrent packet reception.

Multiple beam antennas require a high degree of synchronization among neighboring nodes to achieve CPR. However, due to the random nature of DCF it is highly improbable that a node receives multiple packets concurrently in different beams. An optimal MAC thus needs to be developed orthogonal to the DCF proposed in IEEE 802.11 and should employ synchronization in the node neighborhood.

The optimal protocol must try to combine the successive reception and transmission scheme with CPR and CPT in order to achieve best results. With synchronous schedules multiple source nodes can begin transmission towards a common node at the same time. The latter can in turn concurrently forward all the packets it has just received.

VI. CONCLUSIONS

In this paper we have investigated employing IEEE 802.11 DCF based MAC protocols for multiple beam antennas. We have used several different variants of such protocols and studied their performance over multiple beam antennas. Our analysis shows that no more than 16% of packets can be received concurrently with such protocols even after using as many as 16 multiple beams. Simulation results further illustrate that CPR, a conduct essential to optimum utilization of the antenna capabilities, is highly improbable with DCF based protocols. We conclude that asynchronous protocols are not suited for medium access control over multiple beam antennas.

We have shown tangible gains by employing unified backoff counters and omni-directional transmission of control messages. We have also provided guidelines for the development of a new MAC protocol which can make best use of the antenna array. We believe that substantial performance improvements can be obtained for multiple beam antennas when nodes synchronize their NAVs with their neighbors. However, this needs to be further investigated and is left as future work.

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