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CONCURRENT PACKET RECEPTION BOUNDS OF ON-DEMAND MAC PROTOCOLS FOR MULTIPLE BEAM ANTENNAS

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ABSTRACT

Multiple beam antennas can initiate several data communications concurrently by forming spatially separable beams. However, their concurrent packet reception (CPR) capability is largely governed by the underlying medium access control (MAC) protocol. In this paper, we present an analytical framework to calculate CPR upper bounds of multiple beam antennas using on-demand MAC protocols. The model can be used for adaptively changing transmission probability of the nodes so as to achieve optimal performance. We consider both transmitter-initiated and receiver initiated medium access protocols with uniform and random distribution of nodes. Using the developed model, we compute CPR capability of IEEE 802.11 DCF and ESIF based mechanisms for multiple beam antennas. We verify our model using simulations.

I. INTRODUCTION

Recently multiple beam antennas have started gaining acceptance in multihop wireless networks and several protocols have been proposed for them [1]-[5]. A node employing a *multiple beam antenna array* (*MBAA*) can initiate several simultaneous transmissions or receptions with different nodes, thereby efficiently utilizing the available spatial bandwidth. However, the onus of allowing simultaneous data communications by a node depends on the underlying medium access control protocol.

MAC protocols are generally classified into *on-demand or contention-based protocols* and *scheduling or contention-free protocols*. On-demand protocols are also referred to as random or distributed medium access protocols and are well suited for asynchronous traffic. Here, nodes wishing to transmit simultaneously contend for the channel and hence there is no guarantee of successful transmission as two or more nodes can start their transmission concurrently. Scheduling protocols, on the other hand, divide the available time into slots and each node is given a distinct slot to transmit. This ensures that if there is a transmission in a particular slot, then it is successful. The allocation of slots is done either using global information as in centralized schemes or using two-hop information [4]. In an ad hoc scenario, each type of scheme has its own advantages and disadvantages as listed below:

- On-demand protocols dynamically allocate channel resources to a given node and thus are more scalable.
- On-demand protocols are immune to topological changes. Scheduling protocols, however, require new schedules to be generated and propagated as soon as a node joins or leaves the network.
- On-demand protocols do not require any strict time synchronization as required by some of the scheduling protocols. Time synchronization is hard to achieve in an ad hoc network unless GPS is used.
- Scheduling protocols can effectively utilize concurrent transmission (or reception) capability of smart antennas as compared to on-demand protocols.

As is evident, scheduling protocols can inherently allow CPR by multiple beam antennas. However, implementing them in a distributed environment is non-trivial and involves a lot of message overhead. Further they are not suited for mobile environments. Moreover, for the various reasons listed above, on-demand protocols are more preferable for ad hoc networks.

In this paper, we develop an analytical framework to calculate concurrent packet reception upper bounds of MBAA using on-demand MAC protocols. We further use the developed model to calculate the CPR capability of protocols based on IEEE 802.11 DCF [6] and the recently proposed ESIF mechanism [1].

The rest of the paper is organized as follows. In section II, we give an overview of the multiple beam antennas and related on-demand MAC protocols. We develop our analytical model in Section III. In Section IV, we employ the developed model for IEEE 802.11 DCF based protocols, while for ESIF based protocols in Section V. Section VI concludes the paper.

II. MBAA AND MAC PROTOCOLS

A. Multiple Beam Antenna Array (MBAA)

Multiple beam antennas are capable of forming multiple beams and can thus support simultaneous transmission (or reception) of multiple packets on different beams. This requires:

- Synchronizing transmitting nodes to start their transmission for the common receiver at the same time
- Synchronizing transmitter beams of the common transmitter to initiate transmission at the same time

While the former is necessary for concurrent packet receptions (CPR), the latter facilitates a node to have concurrent packet transmissions (CPT). It is noteworthy that such an antenna array can support *either* multiple transmissions *or* multiple receptions, but *not* both at the same time [1].

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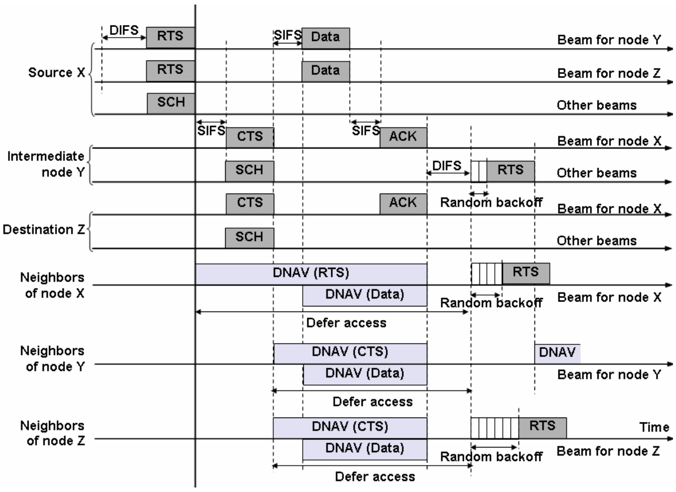

Figure 1. Basic operation of MAC protocols for MBAA based on IEEE 802.11 DCF mechanism

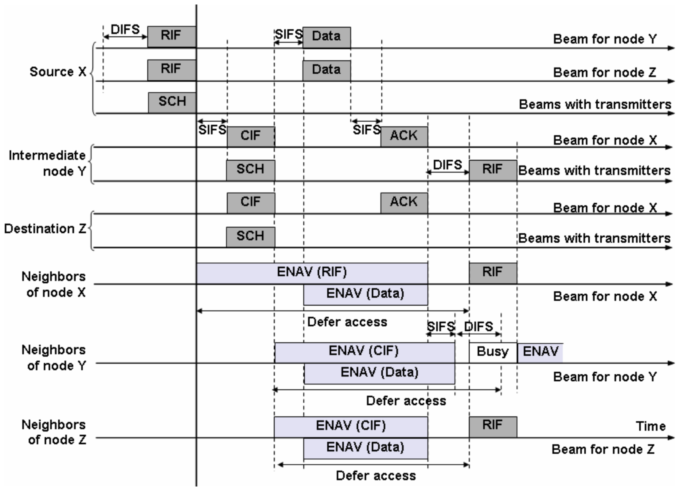

Figure 2. Basic operation of MAC protocols for MBAA based on ESIF mechanism

Multiple beam antennas are generally of two types, viz., *switched beam* and *adaptive beam* antenna array. Switched beam antenna has pre-defined beam patterns while an adaptive beam antenna dynamically forms the beams in the desired directions. Pre-defined beam patterns in switched beam antenna may lead to performance degradation when two interfering nodes lie in the same beam. However, they are simpler in design and implementation than adaptive antenna arrays.

B. MAC Protocols Based on IEEE 802.11 DCF Mechanism

IEEE 802.11 DCF [6] is the de facto MAC standard for wireless LANs and ad hoc networks. Primarily designed for omnidirectional antennas, it provides contention based channel access to the mobile stations (MSs) in the network. A MS wishing to transmit data waits for DIFS duration under idle conditions. If the channel is still idle then the node waits for additional random duration before commencing transmission. If any activity is detected on the channel in the contention window based backoff duration, the node freezes its backoff timer and waits till the channel is idle again. Once the backoff timer expires, the data transmission is initiated. This mechanism mitigates the probability of two nodes transmitting data at the same time. A random deferral by each node also ensures fair channel award in the long term.

IEEE 802.11 DCF based protocols primarily differ in the way control messages are sent (*omni* or *directional*) and contention window is maintained (*beam-based* or *node-based*) [2]. In [2], authors have shown that it is improbable to achieve a high percentage of concurrent packet reception (CPR) in such protocols. However in *node-based* backoff schemes, the same contention window is employed for all the beams, thereby providing a very high percentage of concurrent packet transmission (CPT). This concept is exploited by *Multiple-beam omnidirectional MAC with Node-based Backoff* (*MMAC-NB*) [2]. While RTS and CTS messages are transmitted in respective beams, scheduling (SCH) packets are transmitted in remaining beams. The basic operation of MMAC-NB is illustrated in Fig. 1.

C. MAC Protocols Based on ESIF Mechanism

Explicit Synchronization via Intelligent Feedback (ESIF) [1] is a cross layer protocol where contention window based backoff after DIFS wait is removed. It further uses embedded feedback to synchronize neighboring nodes and thus allows nodes to receive (or transmit) multiple packets simultaneously in different beams. The feedback is piggybacked in the modified control messages, called RTS with Intelligent Feedback (RIF) and CTS with Intelligent Feedback (CIF). In order to mitigate deafness, another control message, SCH, is transmitted in all the remaining beams having potential transmitters. One of the parameters in the feedback is the number of transmitters in that beam of the node. This allows the neighboring nodes to calculate the transmission probability while initiating communication with this node, a mechanism similar to p-CSMA [7]. Thus, the transmitter node transmits in a beam with probability p, where p is the inverse of number of senders in the receiver's beam. Fig. 2 illustrates the basic operation of ESIF protocol.

D. Antenna Model

We consider a wide azimuth switched-beam smart antenna comprised of multiple beam antenna array. Each antenna array with M elements forms non-overlapping sectors spanning an angle of $360/M$ degrees so as to collectively span the entire space as shown in Fig. 3. Beam shape is assumed as conical and benefits of nulling or the impact of side-lobe interference are not considered. Carrier sense is performed directionally. In idle mode, the receiver scans all its beams for valid transmissions. Also, a collision occurs only if a node receives interfering energy in the same beam in which it is actively receiving a packet.

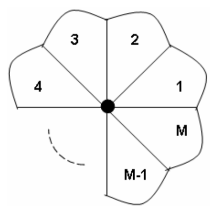

Figure 3. The antenna model

III. Concurrent Packet Reception Probability

In this section, we calculate concurrent packet reception probability (P_{CPR}) for on-demand protocols. Note that for scheduling protocols, we do not need to calculate P_{CPR}, as transmission (or receptions) in all beams are synchronized to commence concurrently. We assume *saturated network conditions*[1] and a node is ready to transmit in any random slot with probability p. We consider two types of distribution of nodes in the network: *uniform* and *random*.

A. Uniform Distribution of Nodes

Consider a node with N neighbors contending to transmit data to this node. The neighbors are uniformly distributed around the node. Assume that each node is capable of forming M non-overlapping beams. Thus, the average number of neighbors lying in each antenna beam is at least

$$\bar{n} = \left\lfloor \frac{N}{M} \right\rfloor, \tag{1}$$

where $\lfloor \ \rfloor$ is the floor function. Then, the probability that a successful reception takes place in a beam is given by

$$P_S = \binom{\bar{n}}{1} p(1-p)^{\bar{n}-1}. \tag{2}$$

The probability that a node receives concurrently in b beams is then calculated as

$$P_{CPR}(b) = \binom{M}{b} P_S^{\,b}(1-P_S)^{M-b}. \tag{3}$$

Therefore, the probability of concurrent packet reception by a node is

$$P_{CPR} = \sum_{b=2}^{M} P_{CPR}(b). \tag{4}$$

B. Random Distribution of Nodes

Now let us consider a more general case where the nodes are randomly distributed. In this case, probability of concurrent packet reception is given by

$$P_{CPR}(b) = P(b,N) \cdot Q(b,M), \tag{5}$$

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

$$P(b,N) = \binom{N}{b} p^b (1-p)^{N-b}. \tag{6}$$

While $Q(b,M)$ is the probability of arranging b nodes in M beams such that concurrent packet reception can happen. Note that for concurrent reception from these b nodes, at least two beams of the receiver should have only one transmitting node. We now calculate CPR for the following two types of on-demand protocols:

- *With receive-initiated protocols*: No more than M nodes start their transmission concurrently and transmitting nodes lie in distinct beams of the receiver node. This happens when a receiver node decides to communicate with a particular node in the next slot.
- *With transmitter-initiated protocols*: Any number of nodes can start their transmission in a given slot. This takes into consideration the case where non-collided concurrent receptions occur in at least two beams, while other beams may have collided or non-collided receptions during that time.

1) CPR with receiver-initiated protocol

For on-demand receiver initiated protocols (RIP), the probability that transmitting nodes lie in b distinct beams is given as

$$Q(b,M) = \frac{M.(M-1)..(M-b+1)}{M^b} = \frac{{}^{M}P_b}{M^b}. \tag{7}$$

Thus, from (5), (6) and (7),

$$P_{CPR\_RIP}(b) = \binom{N}{b} p^b (1-p)^{N-b} \frac{{}^{M}P_b}{M^b}. \tag{8}$$

Then similar to (4), we have

$$P_{CPR\_RIP} = \sum_{b=2}^{M} P_{CPR\_RIP}(b). \tag{9}$$

Further, for any asynchronous on-demand receiver-initiated protocol, if N is large, p is small and $N.p$ is constant, (8) can be approximated by Poisson probabilities as

$$P_{CPR\_RIP}(b) = \frac{(Np)^b e^{-Np}}{b!} \frac{{}^{M}P_b}{M^b}. \tag{10}$$

Now, (9) and (10) can be used together to determine upper bounds on the percentage of CPR for asynchronous on-demand receiver-initiated protocols. These results are presented in Fig. 4 for different values of $N.p$ and M. An important inference that can be drawn is that P_{CPR} reaches its maxima when $N.p$ is greater than two for all cases. This means that a random protocol should ensure that at least two nodes transmit in a given slot. This is in contrast to omnidirectional protocols which try to achieve $N.p$=1 for optimal performance.

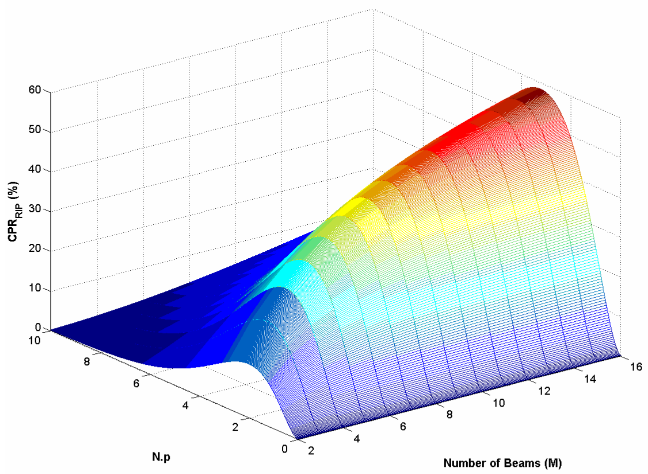

Figure 4. Percentage of CPR for asynchronous on-demand receiver-initiated protocols

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

2) CPR with transmitter-initiated protocol

Now, let us consider a more general case of transmitter initiated protocols (TIP) where at least two beams have non-collided reception, while other may or may not have collisions. In that cases we redefine $Q(b,M)$ as

$$Q(b,M)=\frac{M.(M-1)(M-2)^{b-2}}{M^{b}}=\frac{M-1}{M}\left(\frac{M-2}{M}\right)^{b-2}. \qquad (11)$$

Thus from (5), (6) and (11),

$$P_{CPR\_TIP}(b)=\binom{N}{b}p^{b}(1-p)^{N-b}\frac{M-1}{M}\left(\frac{M-2}{M}\right)^{b-2}. \qquad (12)$$

Then probability of concurrent packet reception is given by

$$P_{CPR\_TIP}=\sum_{b=2}^{M}P_{CPR\_TIP}(b)\cdot \qquad (13)$$

Again, for any asynchronous on-demand transmitter-initiated protocol, if N is large, p is small and $N.p$ is constant, (12) can be approximated by Poisson probabilities as

$$P_{CPR\_TIP}(b)=\frac{(Np)^{b}e^{-Np}}{b!}\frac{M-1}{M}\left(\frac{M-2}{M}\right)^{b-2}. \qquad (14)$$

Now, using (13) and (14) we can determine the upper bounds on the percentage of CPR for asynchronous on-demand transmitter-initiated protocols. These results are presented in Fig. 5 for different values of $N.p$ and M. Again P_{CPR} reaches its maxima when $N.p$ is greater than two for all cases implying that a random protocol should facilitate at least two transmissions in a given slot.

IV. CPR WITH IEEE 802.11 DCF

We use the models developed in Section III for calculating CPR with uniform and random distribution of nodes respectively. IEEE 802.11 DCF is transmitter-initiated protocol and hence we use the transmitter-initiated protocol model for calculating CPR. Now, due to asynchronous nature of the protocol, all neighbor nodes contend for the common receiver. Thus, without loss of generality, the transmission probability of node under saturated conditions can be directly obtained from Bianchi's model [8]. Therefore, the probability p can now be calculated from the following relation

$$p=\frac{2}{1+W+qW\sum_{i=0}^{m-1}(2p)^{i}}=1-(1-q)^{1/(N-1)}, \qquad (15)$$

where W is the minimum contention window (CW_{min}), m is given by ($\log_2 CW_{max}/\ \log_2 CW_{min}$) and q is the conditional collision probability. Note that W and m are fixed, while q is varied such that the above condition holds true, leading to a unique value for p [8].

Fig. 6 and Fig. 7 show the CPR obtained with IEEE 802.11 where nodes are distributed uniformly and randomly, respectively, around the receiving node. Here the neighbor nodes are varied from 5 to 100, while number of beams is varied from 2 to 16. We note that distribution of nodes have no effect on probability of CPR. This is because each node is contending with all the neighbor nodes of the receiver, irrespective of there location. This further implies that we are not fully utilizing the spatial separation of nodes facilitated by multiple beam antennas.

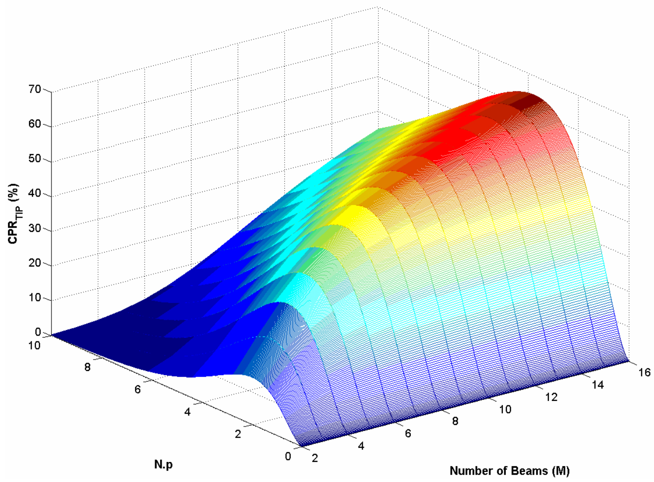

Figure 5. Percentage of CPR for asynchronous on-demand transmitter-initiated protocols

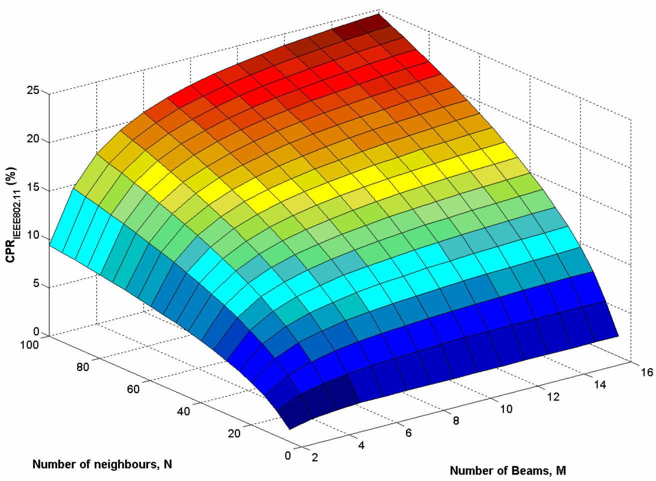

Figure 6. Percentage of CPR for IEEE 802.11 over MBAA with uniform distribution of nodes

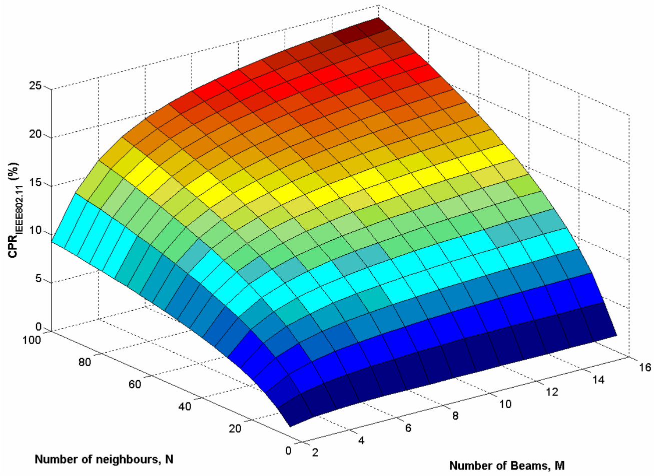

Figure 7. Percentage of CPR for IEEE 802.11 over MBAA with random distribution of nodes

Fig. 8 further shows the CPR obtained from simulation and analysis for four and eight beam antennas when number of transmitting nodes is varied from 5 to 100. These results validate our analytical model for calculating CPR in multiple beam antennas with IEEE 802.11 DCF.

V. CPR WITH ESIF

We use the model developed in Section III for calculating CPR with uniform distribution of nodes. Recall that, in the control messages, a communicating node sends the number of senders in the respective beams. Hence, each transmitting node knows the number of nodes, n, that it is contending with to initiate communication with the intended receiver. Thus, the value of p for p-CSMA [7], with uniform distribution is,

$$p = \frac{1}{n} \cdot \tag{16}$$

Fig. 9 show the CPR obtained with ESIF when nodes are distributed uniformly around the receiving node. The neighboring nodes are varied from 5 to 100, while the number of beams is varied from 2 to 16. We note that as the number of beams is increased, the probability of CPR rises sharply. Also, when the number of nodes is smaller than the number of beams, 100% CPR is obtained because each node transmits with probability one. As the number of neighbors increases, the probability of CPR decreases because this reduces the probability of transmission by each node. However, when number of beams are also increased, we are able to achieve CPR because p-CSMA in each beam ensures that at least one node in each beam transmit at a given time. So, the possibility that more than one beam will have non-collided reception increases with increasing beams. Fig. 10 further shows the CPR obtained from simulation and analysis for four and eight beam antennas when number of transmitting nodes is varied from 5 to 100. These results validate our analytical model for calculating CPR in MBAA with ESIF.

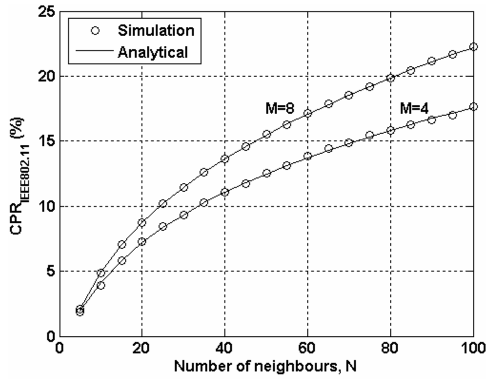

Figure 8. Percentage of CPR for IEEE 802.11 over four and eight beam MBAA

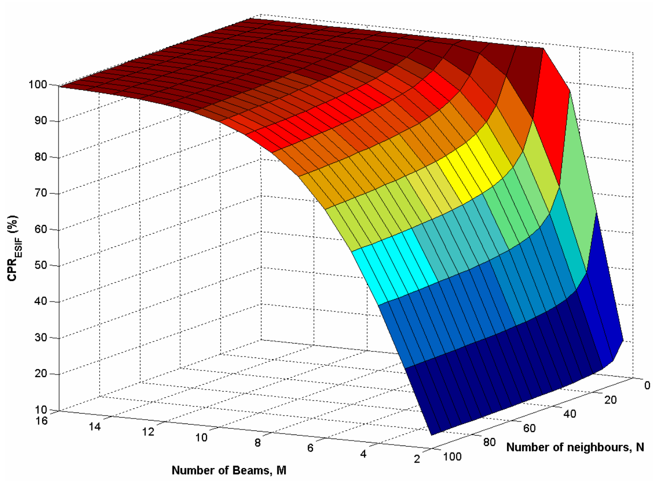

Figure 9. Percentage of CPR for ESIF over MBAA with uniform distribution of nodes

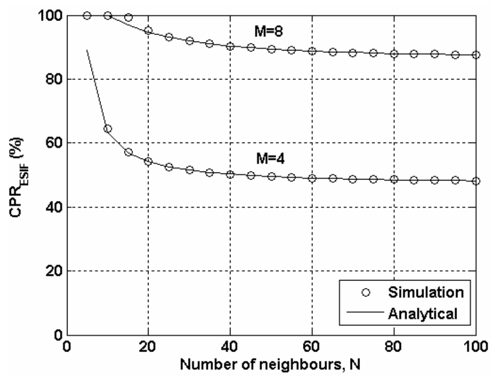

Figure 10. Percentage of CPR for ESIF over four and eight beam MBAA

VI. CONCLUSIONS

In this paper we have derived an analytical model to calculate the concurrent packet reception bounds for on-demand MAC protocols for multiple beam antennas. The model is then used to calculate the CPR bounds for medium access protocols based on IEEE 802.11 DCF and ESIF mechanism for MBAA. The analytical model has been further validated using simulations.

The model can be used to dynamically tune the transmission probability of the nodes so as to achieve optimal network performance with multiple beam antennas. This is done by allowing more than one neighboring nodes to transmit at a given time. This is contrary to the current MAC protocols based on IEEE 802.11 DCF that try to prevent more than one neighboring nodes from transmitting at the same time. Also, the results of ESIF confirm that optimal CPR can be achieved by employing localized synchronization and properly selecting the transmission probabilities.

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