A MAC protocol based on Adaptive Beamforming for Ad Hoc Networks

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***Abstract*— This paper presents a novel slotted MAC (Medium Access Control) protocol for nodes equipped with adaptive antenna array in ad hoc network. The protocol relies on the ability of antenna to uses DOA (Direction-Of-Arrival) information to beamform by placing nulls in the direction of interferers thus maximize SINR (Signal to Interference and noise ratio) at the receiver. We studied the performance of the protocol using joint simulation in OPNET and Matlab. We studied the impact of variable number of antenna elements, DOA algorithm, and nulling. The performance of our new protocol is compared against one of the recent directional MAC protocols [5]. We observe that despite the simplicity of our protocol it achieves high throughput.**

I. INTRODUCTION

Recently, there has been increasing interest in developing MAC protocols for use in ad hoc networks where nodes are equipped with directional antennas. Antenna models used include sectored fixed beam antennas, idealized adaptive array antennas, and steerable directional antennas. As previous researchers have shown, using directional antennas increases throughput because of better spatial reuse of the spectrum (see [1], [5], [2], [3]). However, we note that these previous works have not fully exploited the benefits of adaptive array antennas (or smart antennas) such as the ability to form nulls in the direction of interferers (resulting in high SINR) and the ability to determine the direction of transmitters (Direction of Arrival). We show that by exploiting these capabilities of smart antennas, a simple protocol can yield throughputs that are 2x – 4x higher than one of the recent protocols [5]. We also note that our simulations use realistic antenna models unlike the idealized models used in many (with the exception of [2]) papers and, despite this, our protocol out performs most of these existing protocols.

There are two key capabilities of antenna arrays that we exploit in developing DOA-MAC: the ability to form directed beams and place nulls in given directions, and the ability to determine the direction of arrival of signals from multiple transmitters. In DOA-MAC, a small initial portion of the slot is used for finding the direction of various transmitters (all of which transmit directionally). This is done by requiring each transmitter to transmit a pure tone [1] (no source and destination id) towards its intended receiver for a short interval prior to transmitting the packet. The receiver runs a DOA algorithm which provides information about the received signal strength and direction of the different transmitters. This information is then used at each receiver to guide beamforming (beam and nulls) for the remaining duration of the slot. Upon correct packet reception, a receiver sends an ACK using the already formed beams.

Our work here differs from all of the above papers in the following ways: our adaptive array antenna model is made up of a linear array of antenna elements and we exploit DOA information as well as the nulling capability of the antenna to maximize SINR at the receiver. This gives us the ability to develop a simple protocol (DOA-MAC) that performs very well.

The remainder of the paper is organized as follows: in the next section we describe our system model and provide a brief overview of adaptive array antennas. Section III describes related work. Section IV illustrates our protocol DOA-MAC in more detail. Section V presents results of the simulation.

II. SYSTEM MODEL

We assume that each node is equipped with an adaptive array antenna system which is composed of a linear array of M elements. For simplicity, we assume that the antenna array is perpendicular to the x-y plane in which the nodes lie. The reason for this assumption is that the beam formed by the antenna is symmetric about the antenna axis and is thus independent of the direction in which a node is "facing". Figure 1 provides a schematic of an adaptive array antenna system. As illustrated in the figure, the antenna consists of M antenna elements separated from each other by a known distance d. We can assume that a transmitter is located far enough away from the receiver that all the signals $S_i(t)$ arriving at the different antenna elements are parallel. However, since the elements are separated by distance d, the phase of the different signals is different. Let w_i denote the phase and gain that is added to each signal $S_i(t)$. Then $z(t)$, the output sent to the receiver, can be written as,

$$z(t) = A\sum_{i=1}^{M} w_i S_i(t) = A\sum_{i=1}^{M} w_i S_0(t) e^{-j\beta i d \cos\theta}$$

where $\beta = 2\pi/\lambda$ is the phase propagation factor, λ is the wavelength, and A is an arbitrary gain constant. The weights

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[1] The tone format is a combination of the DSSS PLCP Preamble and PLCP header as given in IEEE 802.11.

w_i used in this paper only shift the phase of the signal and leave the amplitude untouched. The representation for the weights is,

$$w_i = e^{j\beta i d sin\theta_i}$$

For a more comprehensive discussion, please see [4].

As we noted in the introduction, a beneficial feature of adaptive array antennas is the ability of these antennas to form nulls in given directions. In fact, given M elements, an antenna can form upto $M-1$ nulls. However, the shape of the desired beam can change depending on the number of and the direction of the nulls. Figure 2 illustrates two cases when using $M = 8$ antenna elements with $\theta = 45^o$ being the desired direction. In the first case, we are forming only two nulls whereas in the second case we are forming six nulls. As can be seen, the shape of the beam and side lobes changes. *In this work we are using MMSE (Minimum Mean Square Error) algorithm to determine weights w_i to form nulls appropriately* [4].

We implemented the adaptive array antenna model in MATLAB and interfaced it with the physical layer of OPNET. In our study we use realistic antenna patterns with the side lobes.

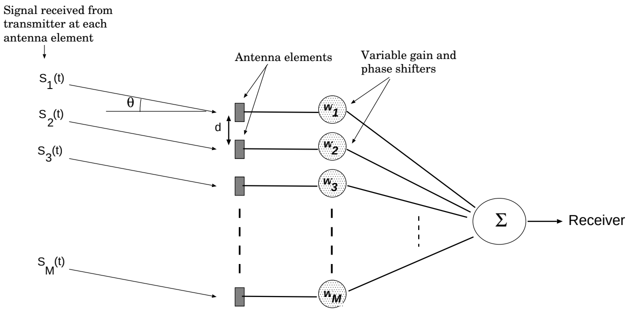

Fig. 1. Schematic of a adaptive array antenna.

III. Related Work

[6] focuses on design the design of Smart antennas for mobile devices with operating frequency of 20 Ghz. The authors examine the impact of the antenna design on network throughput and the impact of mutual coupling[2] on the performance of adaptive algorithms. The paper presents results of detailed OPNET simulations using a TDMA version of the 802.11 protocol as the MAC layer.

[7] presents a scheduling-based MAC protocols for nodes equipped with directional antennas. The directional antenna considered is a multi-beam adaptive array antenna (MBAA) which is capable of forming multiple beams. The key contribution of the paper is the development of a neighbor tracking scheme that is then used to schedule transmissions by each node in a distributed way.

[1] proposes a MAC protocol where nodes are equipped with M directional antenna elements. Each of the antenna elements has a conical pattern, spanning an angle of $2\pi/M$ radians. The M antennas at each node are fixed with non-overlapping beam directions so as to collectively span the entire plane. The MAC protocol is assumed to be capable of switching any one or all the antennas to active or passive modes. The paper did not examine the benefits of nulling or the impact of side-lobe interference. Furthermore, the propagation model was rather simplistic because of the assumption of complete attenuation outside the conical pattern.

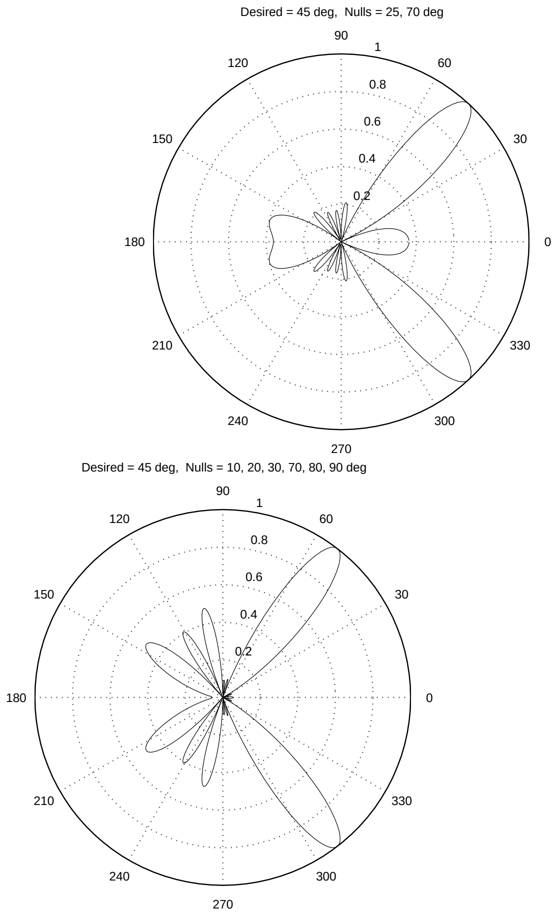

Fig. 2. Antenna patters with 8 antenna elements and 2 or 6 nulls.

[5] studies MAC protocols for Ad hoc network for nodes equipped with directional antennas where the main beam is modeled as a cone and the sidelobes as a sphere. They develop a novel multi-hop RTS to establish links between distant nodes and G_d (directional gain) is assumed to be higher than G_o (omni directional gain). The direction in which the main lobe is to be oriented is determined by the MAC protocol (which in turn is provided this information by the network layer which is assumed to be neighbor-aware). Beamwidth of the antenna is assumed to be a constant. They show that their protocol has a 4-5x throughput as compared with 802.11.

In [2] a node in promiscuous mode caches AOA information based on signals received and uses this information for sending RTS. A circular antenna with 6 elements is assumed, and a node is capable of electronically steering the boresight towards a specific direction. A constant beamwidth of 45 deg assumed.

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[2] Mutual coupling results in radiation patterns that have shallower and shifted nulls, and less accurate AOA, thus deteriorating overall network throughput.

However, it was observed that as the boresight changes the side lobe pattern changes drastically. *They also observe that using realistic antenna patterns as opposed to a ideal patterns results in a 36% degradation of throughput.*

There have been several other papers that look at the benefits of using smart antennas in cellular environments see, for instance, [8], [9], [10], [11], [12]. These papers look at models where the base station is equipped with one or multiple adaptive antenna arrays.

IV. PROTOCOL DESCRIPTION: DOA-MAC

In this section we describe the behavior of our protocol. However, before doing this, we need to make the following assumptions: (1) We assume that nodes are aware of the *angular location* of each of their neighbors (as in [5]) since this information is needed at transmitters to form directed beams towards receivers; and (2) For simplicity, we assume that all nodes use the same constant transmit power.

Consider the case when a node a needs to transmit a packet to node b which is its one-hop neighbor. Since a knows b's angular direction it can form a directed beam towards b. However, in order to maximize SINR at b, b needs to form a beam towards a and form nulls towards all other transmitters. In order to do this, b needs to know two things – first, that a is attempting to transmit to it, and second, the angular direction of all the other transmitters that interfere at b. Our protocol is based on the slotted ALOHA model with the addition of a component that enables receivers to form beams and nulls as described.

Each slot in DOA-MAC is broken into three minislots. The protocol then works as follows:

1) The first minislot in a slot is called the DOA-minislot and it is here that a node identifies the angular direction of all transmitters that it can hear. All transmitters transmit a simple tone (i.e., a sine wave) during the DOA-minislot towards their intended receivers. The signal received at some receiver is thus the complex sum of all of these tones. The receiver runs a DOA algorithm to determine the angular direction of each of the transmitters and the received power from each transmitter.

   There are several different DOA algorithms that can be used and the primary difference between them is fidelity versus computational complexity. For this work we chose to use MUSIC (MUltiple SIgnal Classification) [4] which lies somewhere in between all the other algorithms in terms of complexity and fidelity. Figure 3 shows an example of running MUSIC at the receiver when there are three transmitters (all using the same transmit power). As we can see, nodes a and b are close to one another in angle w.r.t. the receiver whereas c is quite distinct. The output of the MUSIC algorithm shows that the receiver is unable to distinguish between a and b because they are close in angle. This can result in a higher SINR at the receiver because the receiver's beam could include both transmitters.

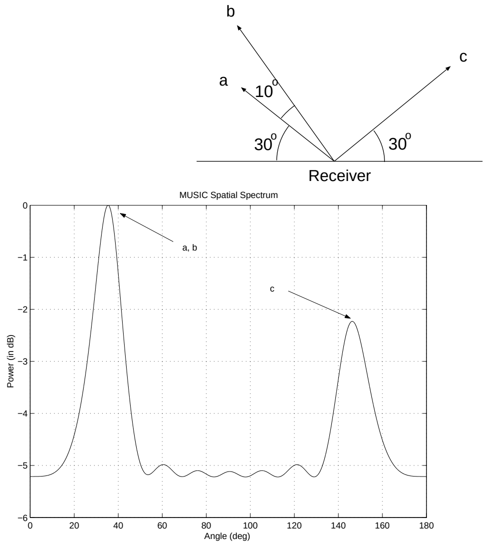
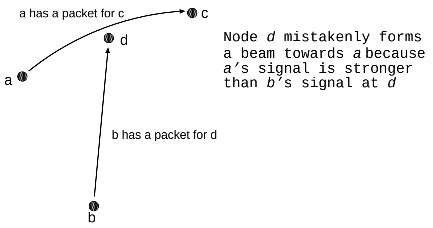


Fig. 3. Example of computing DOA using MUSIC.

2) Once a receiver determines the DOA of all transmitters it can hear, *it forms its directed beam towards the one that has the maximum power and forms nulls in all the other identified directions.*
3) The second (and largest) minislot is the packet transmission slot and it is here that the packets are transmitted. After the receiver has formed its beam and nulls as described above, it receives the packet from the transmitter. After receiving the packet, it looks at the header and *rejects* the packet if it was not the intended destination. An example of this happening is illustrated in Figure 4 where we see that nodes a and b are transmitting to nodes c and d respectively. However, node d incorrectly chooses to receive a's transmission because that transmission is stronger!



Node *d* mistakenly forms a beam towards *a* because *a*'s signal is stronger than *b*'s signal at *d*

Fig. 4. An example of incorrect beamforming leading to a rejected packet.

4) The last minislot is the ACK slot where the receiver transmits an ACK using the already formed beam to the sender (if the packet was not rejected and correctly received). In Figure 4 node d will not send an ACK to node a or to node b because it did not receive b's packet but rather mistakenly received a's packet.
5) When a transmitter does not receive an ACK, it retransmits the packet at a later time (as in slotted ALOHA).

TABLE I

OPNET SIMULATION PARAMETERS.

Simulation Parameters	
Background Noise + ambient Noise	-143 dB
Propagation model	Free space
Bandwidth	1,000 kHz
Min frequency	2.4 GHz
Data Rate	2000 kbps
Packet Size	512 bytes
Packet Generation	CBR
Carrier Sensing Threshold	+3dB
Minimum SINR	9 dB
Bit Error	Based on BPSK Modulation curve
Maximum radio range	250 m

V. PERFORMANCE STUDY

In our simulation study, we examined three questions:

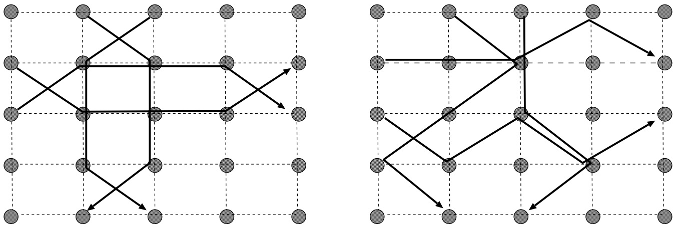
- Does increasing the number of antenna elements improve throughput?
- What is the impact of using a realistic DOA algorithm (MUSIC) as opposed to an optimal algorithm with an arbitrary resolution (i.e., in Figure 3 it would correctly discriminate between nodes a and b)?
- Does nulling have any benefits?

The simulation parameters we selected are displayed in table I. We evaluate the performance of DOA-ALOHA using a 5x5 mesh (as used in [5]) with four pre-defined flows. Figure 5 shows the network topology and flows used for two of these experiments. For the third experiment, we used a random node placement on the grid where a node's position is shifted in the x-axis and y-axis by adding a displacement randomly selected from [-150m , +150m] and the flows are as in Figure 5(b). The traffic is CBR (Constant Bit Rate) which increases (per flow) from 75kbps to 2Mbps. The packet size is 512 bytes.

In order to examine the impact of the number of antenna elements on throughput, we plot the aggregate throughput as a function of data rate of one flow, for the case shown in Figure 5(a), in Figure 6. We plot the same data for the random topology case in Figure 7 as well. As we can see, using 16 antenna elements as opposed to 8 does improve throughput in both cases. This result in not surprising because larger number of antenna elements results in narrower beams and hence better spatial reuse. Interestingly, the throughput is higher for the random topology case when compared with Figure 5(a). This is because, in Figure 5(a), the flows are aligned and need to share bandwidth at the second hop whereas in the random topology case, there is greater potential for spatial reuse since flows are not aligned.

In order to determine the impact of using MUSIC instead of optimal DOA and to answer the question about the benefits of nulling, we focus on the case shown in Figure 5(b). Figure 8 plots the aggregate throughput as a function of data rate of a single connection for the case when we have 16 antenna elements (Figure 9 does the same when we use 8 antenna elements).

We observe that using 16 antenna elements as opposed to 8 elements makes a big difference in aggregate throughput. This is because the beamwidth when using 16 elements is smaller than when using 8 elements which results in more simultaneous transmissions/slot. For the flows in Figure 5(a), (when flows are aligned), we did not notice much difference in the performance of 16 and 8 antenna elements but for Figure 5(b) and for random topologies we do see a significant difference. The reason is that when flows are not aligned, there is a greater potential for spatial reuse with 16 antenna elements (due to its smaller beamwidth).



(a) Four flows (some alignment)

(b) Randomly selected flows

Fig. 5. 5x5 grid topology used to compare performance with [5].

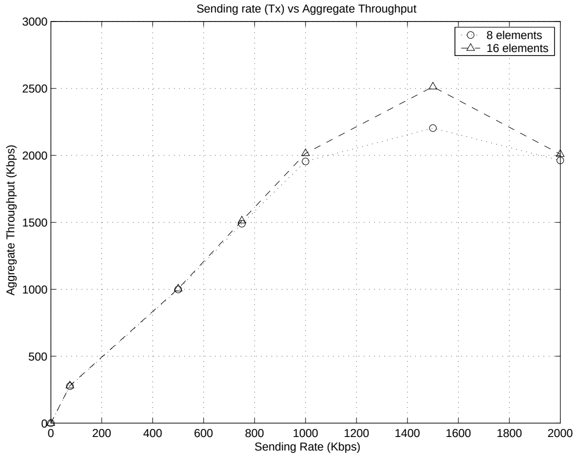


Fig. 6. Performance of our protocol with optimal DOA in 5(a).

We notice that MUSIC results in poor performance (approx. 8% reduction in throughput with 8 elemenst and 5% reduction with 16 elements) in comparison to optimal DOA, this is for the reason as explained in Figure 3 and 4 that MUSIC fails to distinguish between two nodes located in close proximity. A high-resolution algorithm will be able to discriminate between these two nodes, however, it will require more training sequences and its computation cost will be high. We are currently studying the trade-off between DOA algorithm complexity and its computation cost. Finally, we observe that Nulling has greater impact on 8 elements (improvement of approx. 11%) than 16 elements (improvement of approx. 5%).

Table II summarizes our results and compares them with [5]. We provide the maximum throughput when using the optimal DOA as well as when using MUSIC. We observe that our protocol is 2x – 3x better when we use 8 elements and is much better (3x – 4x) for 16 elements. We note that the beamwidth

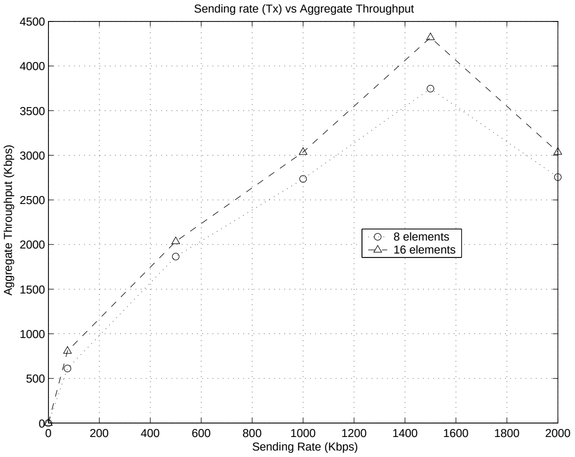


Fig. 7. Performance of our protocol with optimal DOA in random grid topologies.

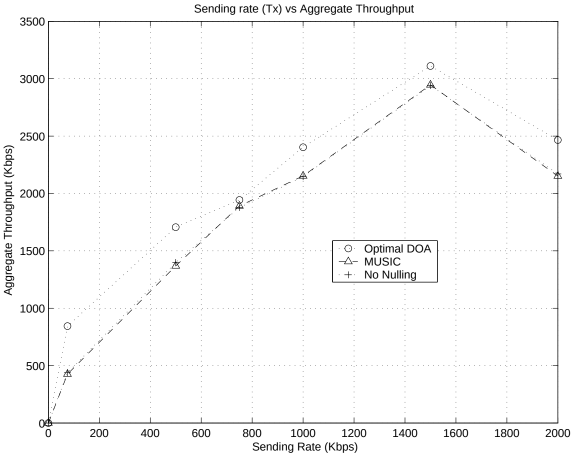


Fig. 8. Performance of our protocol with 16 elements in 5(b).

used in [5] is 45^0. In our case, the linear array creates two symmetric beams and we define beamwidth for our protocol as the sum of these two beams.

VI. Conclusion

In this paper we have presented DOA-MAC, a slotted MAC that uses DOA information at the receiver to beamform in a way that maximizes SINR. We notice that by exploiting the benefits of smart antenna a simple protocol like DOA-MAC can achieve very high throughput. We studied the impact of using a realistic DOA algorithm as well as the benefits of nulling. Finally, we compare the performance of our protocol against [5] and show that our protocol has a throughput of 2x – 4x higher than the [5].

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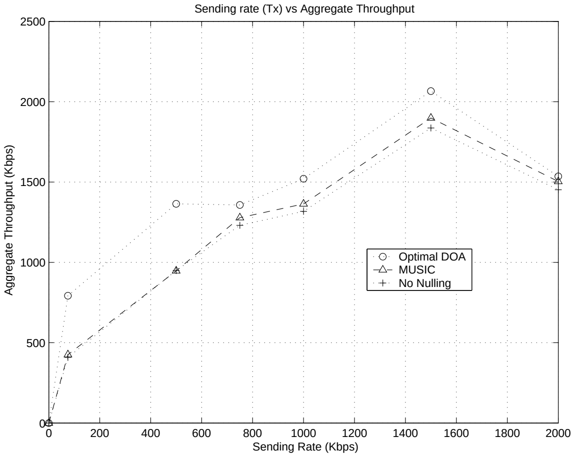

Fig. 9. Performance of our protocol with 8 elements in 5(b).

TABLE II

	Mesh Figure 5(a)	
	16 Elements $(\sim 40^0)$	8 Elements $(\sim 70^0)$
Our Protocol (optimal DOA)	2500kbps	2200
[5]	800kbps	
	Mesh Figure 5(b)	
	16 Elements	8 Elements
Our Protocol (optimal DOA)	3100kbps	2065
Our Protocol (MUSIC)	2940kbps	1900
[5]	1000kbps	
	Random Mesh	
	16 Elements	8 Elements
Our Protocol (optimal DOA)	4300kbps	3700
[5]	1000kbps	

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