Smart-802.11b MAC protocol for use with Smart Antennas

Harkirat Singh and Suresh Singh
Email: {harkirat, singh}@cs.pdx.edu
Department of Computer Science
Portland State University
Portland, OR 97207

***Abstract*— Smart antennas enable a receiver to determine the Direction of Arrival (DOA) of multiple transmissions as well as to form *nulls* in some number of directions to maximize SINR (Signal to Interference and Noise Ratio) of the received signal. We utilize the benefits of these capabilities to develop a simple modified version of the popular 802.11b protocol. This protocol exhibits *high throughput* under a variety of network conditions and is *fair*. The performance of the protocol is examined exhaustively using joint simulation in OPNET and Matlab.**

I. Introduction

Smart antennas (or adaptive array antennas) have some unique properties that enable us to achieve high throughputs in ad hoc network scenarios. A transmitter equipped with a smart antenna can form a directed beam towards its receiver and a receiver can similarly form a directed beam towards the sender, thus resulting in very high gain. A receiver can also identify the direction of multiple simultaneous transmitters by running DOA algorithms and use this information to determine the directions in which it should place the *nulls*. Placing nulls effectively cancels out the impact of interfering transmitters. In this paper we develop a simple 802.11b based MAC protocol called Smart-802.11b that explicitly uses these three properties of smart antennas (beamforming, DOA, and nulling) to achieve high throughputs.

The two protocols developed in this paper are called *Smart-Aloha*([1], [2]) and *Smart-802.11b*, and, as the name implies, these two protocols are modifications to the well-known Aloha and 802.11b protocols. In both cases, we have added functionality at the MAC layer to allow it to directly control the antenna: *the MAC layer controls the direction of the beam and the direction of the nulls*. In addition, the antenna provides the MAC layer with DOA information for all transmissions it can hear along with signal strength information. The *main results* of our paper are that our protocols show a *very high throughput* while *maintaining fairness. The conclusion is that by appropriately exploiting the benefits of smart antennas, the capacity of wireless networks can be increased dramatically.*

We use smart antenna model similar to our previous work [1], [2]. The remainder of this paper is organized as follows. In the next section we summarizes the previous work in this and related areas. In section III we describe the two protocols called Smart-Aloha and Smart-802.11b. Section IV presents our OPNET-based simulation results and we provide a comparison with the omnidirectional case. We also analyze the fairness of our protocol in section IV-C. Finally, we summarize the main results in section V.

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II. Literature Review

Table I presents the main throughput results of the MAC protocols designed for directional antenna equipped nodes. It is important to note that, most of the MAC protocols summarized in the Table I do not fully exploit the *nulling and beamforming* capabilities of the smart antenna.

The salient features of our work are:

1) We use realistic antenna model, we develop liner array of antenna elements in Matlab and interface it with OPNET simulation.
2) We use nulling as well as DOA capabilities of the smart antennas.
3) We do not use additional channel for the tones.
4) Smart-802.11b does not use combination of omnidirectional/directional RTS and CTS as used by previous MAC protocols.

III. Description of the Protocols

Consider the case when a node a needs to transmit a packet to node b which is its one-hop neighbor. We assume that a knows the angular direction of b (as in [3]) and it can therefore form a beam in the direction of b. However, to maximize SINR, b should also form a beam towards a and form nulls in the direction of 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. The two protocols we discuss answer these two questions somewhat differently as we describe next.

A. Smart-Aloha

Smart-Aloha is a slightly modified version of the standard *Slotted-Aloha* protocol. To transmit a packet, a transmitter forms a beam towards its receiver and begins transmission. However, it prefaces its packet transmission with the transmission of a short (8-byte) *pure tone* (this is a simple sinusoid).

Prior Work	Characteristics of Simulation Expts.	Maximum Throughput					
[3]	Switched beam antenna	Random Topology			Mesh Topology		
	45^0 beamwidth, 10dB gain, 250m	(N=25, 4 hops)					
	range for omni, 900m directional	MMAC	DMAC	802.11	MMAC	DMAC	802.11
	4 CBR sources, 75kbps–2Mbps each	1000 kbps (5x)	400 (2x)	200 (1x)	800 (4x)	300 (1.5x)	200 (1x)
[4]	Multi-beam antenna (1, 2, 4 beams each)	Fully connected (20 nodes)			Multi-hop (100 nodes, 5 hops)		
	30^0 beamwidth, 2Mbps channel	1 beam	2	4	1	2	4
	slotted (8ms slot), 16Kbit packet	12Mbps	30	60	60	150	300
	(Throughput converted to bps from pkts/slot/net)	(Max over ROMA, UxDMA)					
[5]	Adaptive antenna; 4x4, 8x8	4x4			8x8		
	planar arrays, TDMA-802.11, 1-hop	(55 nodes)					
		8 pkts/packet time			9 packets/packet time		
[6]	Switched beam	Proposed		DRTS/DCTS		CSMA/CA	
	60^0 beamwidth	(50 nodes)					
		3.5 Mbps		2.5		2	
[7]	Circular adaptive antenna array	25 nodes (grid)			225 nodes (grid)		
	beamwidth 64^0, 8dB gain	No PC	Global PC	Local PC	No PC	Global PC	Local PC
		(PC – Power Control)					
	(Improvement over 802.11)	1.3x	1.7x	2.1x	2.6x	4.75x	5.25x
[8]	Ideal adaptive antenna	*Protocol*		*Beamwidth*			
	20 nodes, no nulling	O – Omnidirectional		(20 nodes, degree = 7.5)			
		D – Directional		90^0	60^0	30^0	10^0
	(Improvement over omni case)	ORTS/DCTS		35%	57%	100%	142%
		DRTS/DCTS		64%	107%	143%	186%
	Packet transmission is	DRTS/OCTS		28%	43%	n/a	57%
	directional at sender/receiver	ORTS/OCTS		29%	50%	86%	121%
		STDMA		n/a	400%	n/a	400%
[9]	6-element circular antenna array	(No Mobility)					
	(10 fixed patterns – no adaptation)	Omni	Rx directional		DVCS	DVCS–Ideal	
	45^0 beamwidth, 100 nodes, $1500m^2$		Tx Omnidirectional		Tx,Rx Directional		
	2-ray propagation model, no nulling	400kbps	800kbs		1.4Mbps	2.2Mbps	

TABLE I

SUMMARY OF DIRECTIONAL MAC PROTOCOL PERFORMANCE.

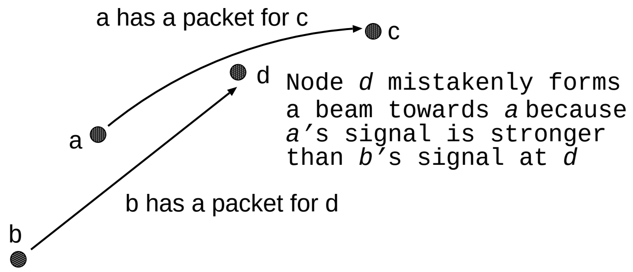

Fig. 1. False beamforming.

Idle nodes remain in an omni-directional mode and receive a complex sum of all such tones (*note that the tones are identical for all nodes and thus we cannot identify the nodes based on the tone*) and run a DOA algorithm to identify the direction and strength of the various signals . An idle node then *beamforms in the direction of the maximum received signal strength and forms nulls in other directions* and receives the transmitted packet. If the receiver node was the intended destination for the packet, it immediately sends an ACK using the already formed directed beam. On the other hand, if the packet was intended for some other node, then the receiver discards it. A sender waits for an ACK immediately after transmission of the packet and if it does not receive the ACK, it enters backoff in the standard way. Thus, the Smart-Aloha protocol follows a *Tone/Packet/Ack* sequence.

The intuition behind the receiver beamforming in the direction of the maximum signal is that, because of the directivity of the antenna, there is a high probability that it is the intended recipient for the packet. However, we note that in cases, as in Figure 1, the receiver d incorrectly beamforms towards a because a's signal is stronger than b's. While this is not a serious problem in most cases, we can envision scenarios where the $b \longrightarrow d$ transmission gets starved due to a large volume of $a \longrightarrow c$ traffic. An optimization we have therefore implemented is a *single-entry cache* scheme which works as follows:

- If a node beamforms incorrectly in a given timeslot, it remembers that *direction* in a single-entry cache.
- In the next slot, if the maximum signal strength is again in the direction recorded in the single-entry cache, then the node ignores that direction and beamforms towards the second strongest signal.
  - If the node receives a packet correctly (i.e., it was the intended recipient), it does not change the cache.
  - If it receives a packet incorrectly, it updates the cache with this new direction.
- If there is no packet in a slot from the direction recorded in the cache, the cache is reset.

This simple mechanism ensures that in cases similar to Figure 1, connections are not starved. However, we can construct more complex scenarios where a single-entry cache will fail to prevent starvation. In these cases, more sophisticated multiple-entry caching schemes are required. However, in our simulations, we only use the single-entry caching scheme because the probability of more complex scenarios resulting in starvation are very rare.

B. *Smart-802.11b*

The second protocol we have developed, *Smart-802.11b*, is based on the 802.11b standard with some changes as noted below. As in the case of the Smart-Aloha protocol, transmitters beamform towards their receivers and transmit a short *sender-tone* to initiate communication. However, unlike Smart-Aloha, the transmitter does not immediately follow the tone with a packet. Instead, it waits for a *receiver-tone* and only then transmits its packet. After transmission of a packet, it waits for the receipt of an ACK. If there is no ACK, it enters backoff as in 802.11b. Figure 2 provides a state diagram of our tone-based protocol. The behavior of the protocol in various states can be summarized as follows:

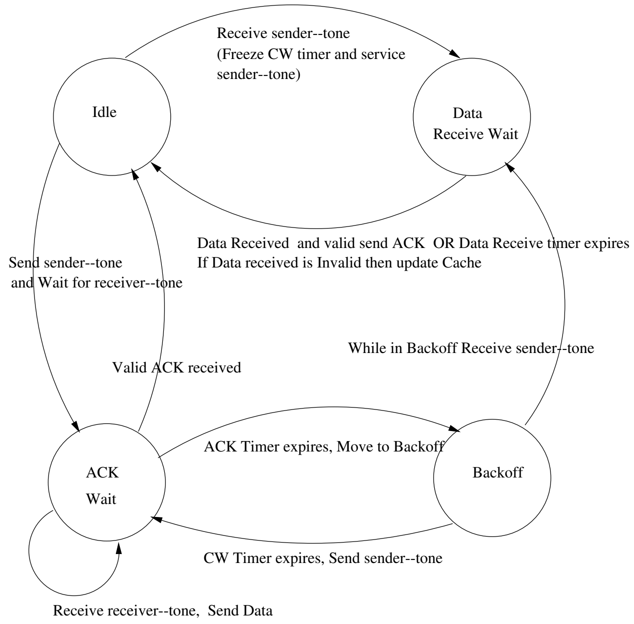

Fig. 2. State diagram of the Smart-802.11b protocol.

Idle: In case a node has no packet to send, it will remain in the Idle state and set its antenna to operate in the omni-directional mode. If it receives a sender–tone from some other node, it will move into the Data Receive Wait state. On the other hand, if it wishes to send data, it will beamform in the direction of the receiver. It chooses a random number between [0..CW] and sets the CW (Contention Window) timer[1]. When the CW timer expires, it sends a sender–tone in the direction of the receiver and moves to the ACK Wait state. If, before the CW timer expires, the node receives a sender–tone from another node, it will freeze its CW timer and move to Data Receive wait state.

Data Receive Wait: A node will move to this state in the event it receives a sender–tone. The node will beamform towards the sender and then randomly defer transmitting the receiver–tone by choosing a random waiting period between $[0..32]\times 20\mu$sec. The reason for deferring the reply is to minimize the chance of several receiver–tones colliding at the sender[2].

After transmitting a receiver–tone, the node remains in this state for 2τ (twice the maximum propagation delay+tone transmission time). If it does not hear a transmission, it returns to the Idle state. If it hears the start of a transmission, it remains in this state and receives the packet. It then discards the packet if the packet was meant for some other node If, however, the packet was meant for it, then it sends an ACK.

Ack Wait: If the sender node receives a receiver–tone before the tone RTT timer goes off (which is twice the tone transmission time plus propagation delay) it will transmit the data packet. Reception of a valid ACK will move the node to the idle state, and if packets are there in the queue then it will schedule the one at the head of the queue. The node will move to Backoff state under two conditions 1) a receiver–tone did not arrive, 2) an ACK was not received following transmission of the data packet.

Backoff: The node computes a random Backoff interval (as in 802.11) and remains in backoff for this time period (it also resets its antenna to omni-directional mode). If, however, a sender-tone is received, it freezes the backoff timer and enters the Data Receive Wait state. If the node is in backoff, upon expiration of the timer, it retransmits the sender–tone, increments the retransmit counter, and enters the ACK Wait state. A packet is discarded after the retransmit counter exceeds Max_Retransmit= 7, as in the IEEE 802.11 standard.

The reception of a data packet by a node may be interfered with transmissions of sender–tones, receiver–tones, or other data packets (since our protocol does not take care of hidden terminals). A node engaged in receiving a data packet can dynamically form nulls towards new interferers, but this process takes some time (*we model this time as the length of a sender–tone*). Thus, the data packet will have errors due to this interference. We combat this error by relying on FEC (Forward Error Correcting) codes as used in IEEE 802.11e, where (224, 208) shortened Reed Solomon (RS) codes are used. In 802.11e, a MAC packet is split into blocks of 208 octets and each block is separately coded using a RS encoder. A (48,32) RS code, which is also a shortened RS code, is used for the MAC header, and CRC-32 is used for the Frame Check Sequence (FCS). Note that any RS block can correct up to 8 octet errors.

[1]The random number selected is multiplied with 20μsec.

Simulation Parameters	
Background Noise + ambient Noise	-143 dB
Propagation model	Free space
Bandwidth	1,000 kHz
Min frequency	2,402 MHz
Data Rate	2000 kbps
Carrier Sensing Threshold	+3dB
Minimum SINR	9 dB
Bit Error	Based on BPSK Modulation curve
Maximum radio range	250 m
Packet Size	16KB
Simulation time	200sec
Single Hop	
Number of nodes	20
Area	100x100 m
Multihop	
Number of nodes	100
Area	1500X1500

TABLE II

OPNET SIMULATION PARAMETERS.

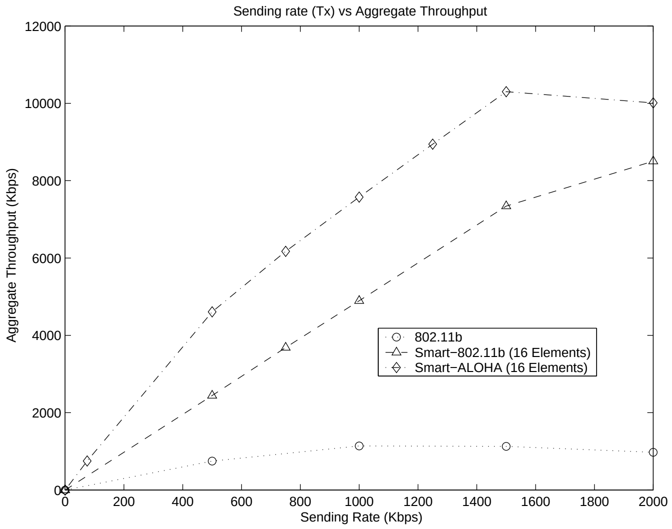

Fig. 3. Single-hop case with 20 nodes.

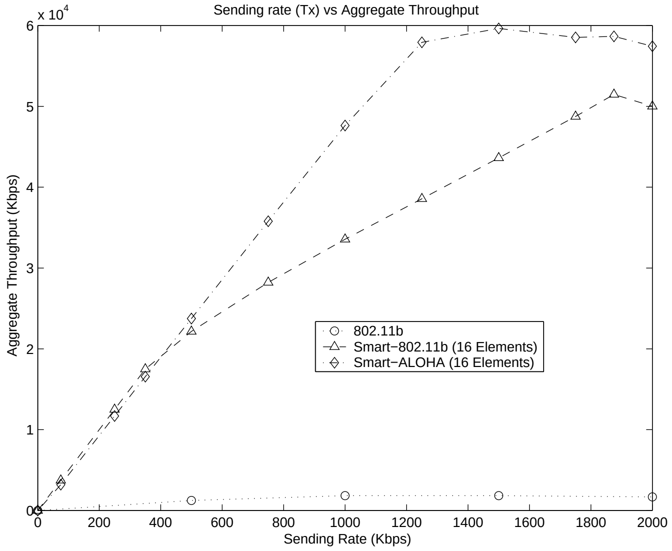

Fig. 4. Five-hop case with 100 nodes.

IV. Performance Study

A. Simulation Model

For our simulation, we built linear array antenna in Matlab and interfaced it with the *radio pipe line stage* of OPNET. We implemented Smart-Aloha into OPNET and modified the existing 802.11b implementation in OPNET to create Smart-802.11b. The modifications included adding the two-tones (sender and receiver) as well as changing the FEC to the 802.11e specification. The remainder of the simulation parameters are detailed in Table II. For every new packet that is generated at the node, a destination is chosen from the set of logical neighbors. Logical neighbors are those nodes which are within the transmission range of the radio.

B. Simulation Results

We studied the performance of our protocol for a single-hop case with 20 nodes and 5-hop case with 100 nodes using of 16KB packets. We used 16 antenna elements (for an effective beamwidth of 40^0). Figure 3 plots the aggregate one-hop throughput as a function of arrival rate for the one-hop case. We note that 802.11b achieves a maximum throughput of 1Mbps while Smart-802.11b achieves a high of 8.5Mbps and Smart-Aloha achieves a high of approximately 10.5Mbps. In fact, the throughput of Smart-802.11b and Smart-Aloha increases with arrival rate because of good spatial reuse of the channel. Figure 4 plots the aggregate throughput of our protocol for the 100-node 5-hop case. 802.11b reaches a maximum throughput of well below 0.5Mbps while Smart-802.11b reaches a maximum of 50Mbps and Smart-Aloha reaches a maximum throughput of 60Mbps. Again, the better spatial reuse of the channel given the directivity of the antenna is the reason for this performance improvement.

[2]Note that our tones do not carry information about the sender and the receiver so if all the nodes who receive a sender–tone (and are in idle state) respond immediately then the sender will detect a collision.

C. Fairness of Smart-Aloha and Smart-802.11b

We performed a study of the *fairness* properties of the two new protocols and 802.11b presented here using prior work [10], [11], [12] as a guide. Since our goal was to examine the fairness of the MAC protocol (as opposed to the fairness of TCP flows), we considered the single hop flows illustrated in Figure 5. The dotted lines between two nodes in the figures indicates that the two nodes can hear one another. The arrows indicate the direction of flows and we used 2Mbit/sec CBR traffic for each flow with 512 byte packets. The maximum channel capacity is also 2Mbit/sec and the remaining parameters were set as per Table II.

Table III shows the data rate achieved by each flow in each of the three topologies from Figure 5. In Topology 1, nodes 1 and 2 are within range of one another and node 1 is in fact in the second symmetric lobe formed by node 2 towards node 3. In the case of Smart-802.11b, this causes node 2 to

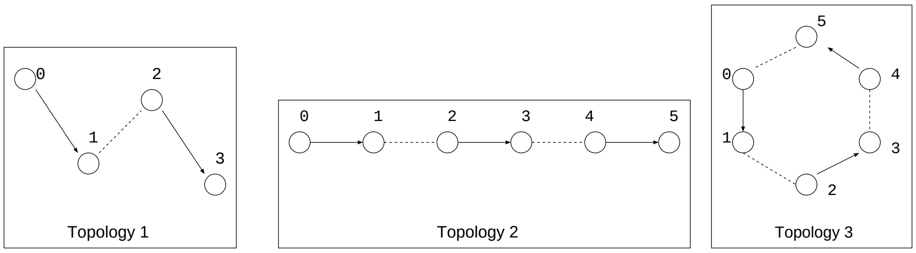

Fig. 5. Topologies used for fairness study.

Topology 1			
Flow	*802.11b* (Mbps)	*Smart-802.11b* (Mbps)	*Smart-Aloha* (Mbps)
$0 \longrightarrow 1$	0.661	0.919	1.957
$2 \longrightarrow 3$	0.663	1.282	1.978
Topology 2			
Flow	*802.11b*	*Smart-802.11b*	*Smart-Aloha*
$0 \longrightarrow 1$	0.089	0.871	1.958
$2 \longrightarrow 3$	0.108	0.908	1.827
$4 \longrightarrow 5$	0.567	0.860	1.931
Topology 3			
Flow	*802.11b*	*Smart-802.11b*	*Smart-Aloha*
$0 \longrightarrow 1$	0.427	0.745	1.573
$2 \longrightarrow 3$	0.433	0.914	1.459
$4 \longrightarrow 5$	0.430	0.924	1.896

TABLE III
AVERAGE DATA RATES OF DIFFERENT FLOWS.

sometimes incorrectly send a receiver-tone to node 2 resulting in lower throughput for the $0 \longrightarrow 1$ flow. Smart-Aloha is not affected by this because node 1 is closer to node 0 and forms a bean towards 0 while forming a null towards 2 using the DOA information. In the case of Topology 2, the three flows are equally sharing the channel because, unlike in Topology 1, the second lobe of a transmitter (such as node 2) does not face unintended receivers (node 1). Finally, due to the symmetry of Topology 3, all the flows are equally affected by the second lobe and thus exhibit similar throughputs. In addition to the topologies discussed above, we studied other topologies including the star topology with four transmitters sending to one common receiver (as in [12]). We note that all the flows shared the channel equally in this case as well.

V. CONCLUSION

This paper presents two simple tone-based protocols for use with smart antenna systems. These protocols do not explicitly combat hidden terminals yet they show very high throughput, exceeding that of many other protocols. We also demonstrate that our protocols share the channel fairly among multiple competing flows. In many ways our approach here is contrary to the current trend of designing increasingly complex MAC protocols for directional antenna systems. The overall conclusion is that smart antennas can indeed be used to great benefit in ad hoc networks and can enhance the performance of the popular slotted-aloha and 802.11b protocols.

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