Modeling Smart Antennas in Synchronous Ad Hoc Networks Using OPNET's Pipeline Stages

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Abstract
Smart antennas have been proposed as a physical layer device that can increase the capacity of ad hoc networks. The effectiveness of smart antennas depends on whether access mechanisms create the conditions that enable receivers to adapt to both desired signals and interfering signals and enable transmitters to discern where they must avoid causing interference. The ease of implementing solutions and modeling the antennas are both affected by whether the access schemes are asynchronous or synchronous. Asynchronous access mechanisms are more difficult since they allow new transmitters to begin transmissions during ongoing exchanges. Thus, past adaptation becomes irrelevant and current adaptation is done with insufficient information. Arbitrating the effects in simulation requires detailed models of antenna adaptation and the resulting power patterns. Synchronous access mechanisms, however, overcome these shortcomings because they force ongoing exchanges to conclude before new exchanges start and because they cause all new exchanges to occur simultaneously. Receivers can sample both the desired signals and the interfering signals to arrive at a weighting solution. Since conditions do not change after adaptation, the adaptation is more effective and simulation models can be more abstract. In this paper we describe how we built models of adaptive antennas in OPNET using a radio process model and the radio pipeline stages. We use this model in conjunction with our Synchronous Collision Resolution (SCR) medium access control protocol and evaluate the relative merits of different antenna technologies and capabilities. We found that those technologies that improve capture soonest in an exchange most improve the capacity.

Introduction
Directional and smart antennas have been proposed as a means to enhance performance of wireless ad hoc networks including increasing capacity, increasing the range of communications, reducing the susceptibility to detection, interception, and jamming, conserving energy, and resolving collisions. Properties of antennas that have been identified to support these benefits include: antenna directivity, increased gain, and a host of capabilities enabled with arrayed antennas and signal processing techniques including beam forming, null steering, diversity, spatial processing, and multiple input multiple output (MIMO). Direct modeling of these effects and the algorithms that make them work is prohibitive requiring detailed models of the environment, the antennas, and the scenario, their effect on the bit streams that are transmitted and then the results of the algorithms that operate on the bit streams. This level of detail is difficult to create for just the analysis of algorithms let alone to combine it with a comprehensive network model with multiple transceivers transmitting and receiving simultaneously. Abstractions that can capture the effectiveness of these techniques are necessary to assess their contribution to the performance of mobile ad hoc networks (MANETs). In this paper, we propose a modeling abstraction that accounts for directional and smart antenna effects when using synchronous access. We build these models into a radio process model and OPNET's radio transceiver pipeline stages.

Our presentation of this material begins with an overview of directional and smart antenna technologies. Next, we describe how smart antennas are modeled abstractly and then how we model them in OPNET. We describe the Synchronous Collision Resolution (SCR) approach to access and identify how it creates the conditions that enable smart antennas to be exploited and the models we described earlier to be valid. We conclude with a description of simulation experiments we conducted to study the effect of smart antenna performance on SCR capacity.

Directional and Smart Antennas
The mobility of nodes in ad hoc networks will cause the relative direction between nodes to change. Exploiting directional antennas in mobile ad hoc networks (MANET) will involve intelligence to discern where to point an antenna and mechanisms to subsequently point it in that direction. Antennas that can do this are considered smart. Smart antennas have varying levels of intelligence. This intelligence is frequently divided into three levels: switched beam, dynamic phased array, and adaptive array [1]. A review of the differences and the types of intelligence follows.

Switched Beam Antennas
In switched beam antennas, there is a predefined set of directions in which an antenna can be pointed. Use of these antennas in ad hoc networks requires MAC and possibly routing protocols to track which antenna sectors point toward other nodes.

Dynamically Phased Arrays
An array of antenna elements can be pointed in a direction by changing the phase of the signals emitted from each element so that they arrive on the wavefront in the preferred direction at the same time thus constructively interfering in the pointing direction and destructively interfering elsewhere. Any arrangement of antennas can be used; however, they must be calibrated to support beamforming. Weighting of the excitation signal at each antenna can be used to affect the shape and amplitude of the mainlobe and sidelobes.

The enhancement in intelligence that comes with dynamically phased arrays is the ability to determine the direction of the arrival (DOA) of signals so that the antennas can adapt and immediately point toward the source. This capability does not require protocols to track network state.

Adaptive Antenna Arrays

The increased intelligence of adaptive arrays includes algorithms for reducing interference by steering nulls or spatially whitening it. These techniques adapt to the environment accounting for the multipath arrival of signals. We broadly separate environmental adaptation techniques into two different types those that are implemented in reception only, environmental adaptation in reception (EAR), and those that are implemented in both reception and transmission, environmental adaptation in reception and transmission (EART). Use of these techniques puts no requirement on MAC and routing protocols to track state.

Smart Antenna Modeling

The different levels of antenna intelligence have different modeling requirements. Switched beam technologies are the easiest to model. Higher level protocols direct the radios where to point their antennas. Modeling only requires consideration of the power pattern of the antenna, the direction it is pointed and then its relative direction to the transmitter or receiver of interest. At the time antenna gain is assessed the relative direction from the mainbeam is used to lookup or calculate the gain from the antenna power pattern. The intelligence to point the antenna resides in the protocols and the only requirement to model the gain at the physical layer is to provide a means for the protocol pointing the antenna to communicate the pointing direction to the part of the model where antenna gain is assessed..

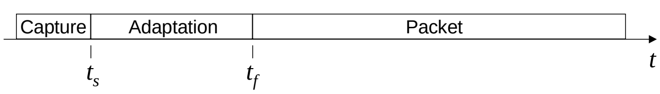


Figure 1: Packet Frame Format for Antenna Adaptation

Smart antennas that adapt to incoming signals are more complex to model since an assessment must be made to determine whether the smart antenna is able to adapt to a desired incoming signal in the presence of interfering signals. We use a modeling approach first proposed in [2]. Figure 1 illustrates the timeline of a received packet. A training sequence at the front end of a packet is used by the antenna to adapt. Adaptation occurs in two parts. First the antenna must capture the desired signal which occurs at the beginning of the sequence and then the antenna optimizes reception of that signal in the adaptation period that follows. Several criteria must be met for adaptation to be successful. There are five parameters:

t_s – the time after the first arriving bit of the training sequence that it takes for a transceiver to capture a desired signal,

SIR_c – the minimum signal interference ratio (SIR) required to capture a signal,

t_{sm} – the minimum time required by a smart antenna to adapt to an interfering signal,

t_f – the end of the training sequence used for adaptation,

SIR_a – the minimum SIR required to adapt to a signal either for enhancing or nulling.

Let t_a be the time an interfering signal arrives at the receiver. The antenna can determine the DOA if $SIR > SIR_c$ when $t_a < t_s$, $SIR > SIR_a$ when $t_s \le t_a \le t_f$, and $\forall\ t_a > t_f$. An adaptive antenna can reject interfering signals if $SIR > SIR_c$ when $t_a < t_s$, $SIR > SIR_a$ when $t_s \le t_a \le t_f$, and $t_a \le t_f - t_{sm}$.

In this sort of model, the ability to capture one signal in the presence of many is enhanced by using unique training sequences for each destination. If the access approach makes this possible and these sequences are used by the antennas, then the model above would have lower values for the parameters SIR_c and SIR_a.

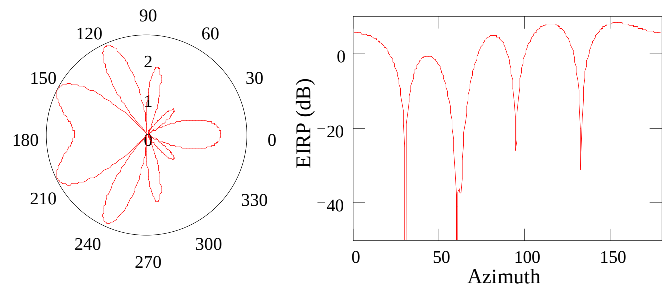


Figure 2: Example Max SINR Adaptation Solution to Receive a Signal from the 100° Direction and to Null Signals from the 30° and 60° Directions Normalized to 0 dB at the 100° Direction

Detailed modeling adaptation effects is complicated and not easily abstracted since adapting to a particular transmitter, receiver, and interferer scenario may result in gain in other directions that exceeds that in the direction towards the source. Figure 2 illustrates the problem. In this example, the Max SINR algorithm was used to optimize reception of a signal in 100° direction when there were interferers in the 30° and 60° directions. This solution provides better than 200 dB SIR. However, we see that the source direction is on the side of sidelobe and that there is high gain (up to 14 dB) in extraneous directions. This high gain in ad hoc environments can increase the number of transceivers that can interfere with ongoing receptions. Accurate modeling of smart antenna use in ad hoc networks must take this into account.

The gains that occur in extraneous directions can vary widely from adaptation to adaptation. In real environments signals not only follow line of sight paths but may traverse many paths that through reflections arrive at the same receiving antennas. It is this complex combination of arriving signals to which antennas adapt. Modeling the exact effects requires an explicit model of the environment, the adaptation algorithm and the resulting array factor. This complex interaction of the environment with the propagating signals makes adaptive antenna modeling impractical and suspect if attempted.

Abstracting the effects of adaptation is possible if the access scenario causes all transmissions to be synchronous. The justification is that the adaptation occurs with knowledge of all transmitters and receivers. Receiving antennas are able to optimize reception of a source while rejecting the interfering transmissions. The models do not have to account for high gains in extraneous directions since there will be no transmitters or receivers in those directions. The models simply assess appropriate antenna gains for each transmitter-receiver pair.

Evaluating the contribution of a particular adaptive antenna technology to the performance of an ad hoc network requires an understanding of the technology. Factors that normally affect the ability of a particular technology to adapt are congestion and directional diversity. Antennas can null out no more interferers than one less the number of antenna elements they use. They can not distinguish between the line of sight components of the transmitters that are directionally coincident. These factors must be assessed in characterizing the antenna and tracked in the simulation unless the access protocol can guarantee that congestion and coincidental directions to multiple transmitters will not occur. The latter is the case with the access protocol with which we have designed our models to be used.

Smart Antenna Models in OPNET

We model smart antennas using a radio process model that is used to track radio state and with various modifications to the radio transceiver pipeline stages. Figure 3 illustrates the radio process model. The illustrated states in this model track whether a transceiver is transmitting, receiving, dozing, or transitioning between those states. Although not illustrated, this process model also tracks other physical layer states including frequency, bandwidth, data rate, modulation, transmit power, forward error correction rate, and antenna parameters. These values are stored in a single data structure that is a state variable. The model is designed to be flexible. It allows the attached MAC model at the node to pass values of each of these parameters. In turn, as part of transitioning between states, it will change the parameters to its attached transmitter and receiver modules. In the case of the antenna parameters, which are not attributes of the transceiver modules, values are simply stored but then accessed by the pipeline stages as necessary. When adaptation is used, the pipeline stages can change these values. Table 1 lists the specific parameters that are used to track the state of directional and smart antennas.

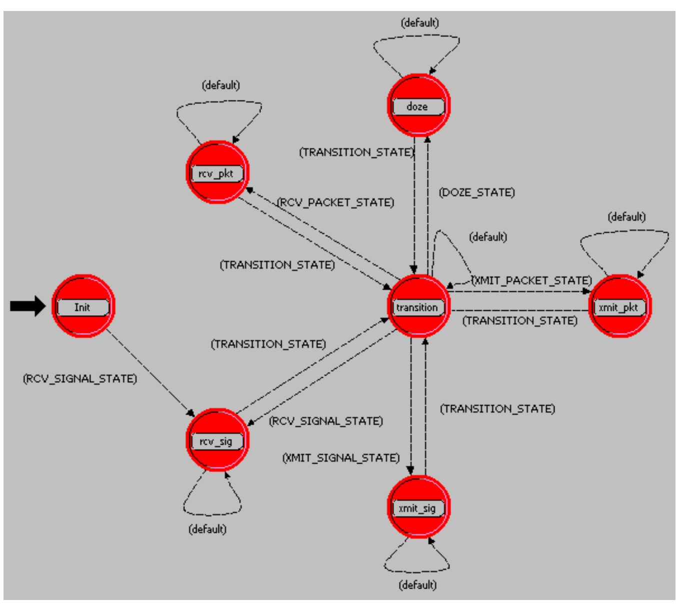


Figure 3: Ad Hoc Radio Process Model

Parameter	Function
ant_dir	Antenna pointing direction
omni	Boolean specifying if the transceiver is using an omnidirectional or directional antenna.
doa_adapt	Boolean specifying if a transceiver is supposed to adaptively point its antenna
already_doa_adapted	Boolean that identifies if the transceiver has adapted and has the direction towards a transmitter or receiver
pkt_dest	This is the destination of a packet. This ID is used to identify if the EAT gain should be applied. EAT gain is a negative gain applied to transmissions towards all nodes that are not the destination
sig_info	Data structure that records pipeline stage observation including the direction toward a received signal.
sig_dir	Vector that points toward the last received signal

Table 1: Parameters Used to Track Smart Antenna State

We model multiple antenna pointing and adaptation strategies. The strategy used at a radio can be selected through the setting of model attributes. Table 2 lists the attributes and their effect on the models used. Adaptive pointing is not used in conjunction with EAR and EAT and EAT is not used without EAR. By convention we assume the default gain in the mainbeam direction is 0 dB and that if the out of beam gain is less than 0 then directional antennas are being used.

Attribute	Function
antenna beam width	Beamwidth between first nulls of the mainbeam
out of beam gain	Gain with respect to the mainbeam for directions outside the beamwidth. Assumes a beam and ball model as illustrated in Figure 5.
Adaptive antenna	Toggle set if adaptive pointing is used
EAR gain	Attenuation applied by receivers to signals that interfere with a signal to which it has adapted.
EAR enabled	Boolean set if EAR is used
EAT gain	Attenuation applied to signals transmitted to receivers that are not the destination
EAT enabled	Boolean set if EAT is used
Minimum time to adapt	t_s
Minimum window SIR to adapt	SIR_a
Maximum time to adapt	$t_f - t_{sm}$
Minimum early SIR to adapt	SIR_c

Table 2: Model Attributes for Antenna Models

The performance of directional antennas is quantified by the directivity of the mainbeam, i.e. its beamwidth. Beamwidth can be specified between half power points, half-power beamwidth (HPBW), or the beamwidth between first nulls (BWFN). Both are illustrated in Figure 4. The second measure of performance is selectivity. This measures the average gain in out of beam directions. The specific patterns can be quite complex and will vary based on the specific design of an antenna. We use a more generic model in our simulation called a beam and ball which is illustrated in Figure 5. It accurately models the characteristics of a mainbeam but blurs the variation of the sidelobes as a single gain in all directions. This model is very general and provides a computationally simple means to access gain in a direction. The calculation occurs in two steps. First, the angle between the mainbeam and the direction to a receiver is determined and then this angle is used to assess the gain. Let **m** be the unit vector that points in the direction of the mainbeam. Let **r** be the unit vector toward the receiver. The vector **r** can be calculated using

$$\mathbf{r} = \frac{\mathbf{d}-\mathbf{s}}{\left|\mathbf{d}-\mathbf{s}\right|} \tag{1}$$

where **s** and **d** are the coordinates of the source and destination locations. The angle between these directions, θ, is easily calculated using the inner product

$$\theta = \arccos\left(\mathbf{m}^{\mathrm{T}}\mathbf{r}\right) \tag{2}$$

and the gain is calculated using

$$g = \begin{cases} g_{mb}\dfrac{\sin(\theta)}{\theta} & \theta \le \dfrac{BWFN}{2} \\ g_{mb} - g_{oob} & \theta > \dfrac{BWFN}{2} \end{cases} \tag{3}$$

Where g_{mb} is the maximum gain in the mainbeam direction and g_{oob} is the difference in gain from the mainbeam in the ball directions. In the beam and ball model g_{oob} = MSLL

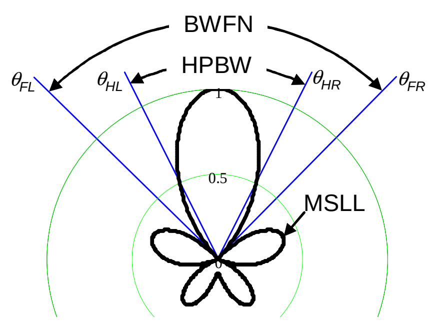


Figure 4: Example Antenna Power Patterns

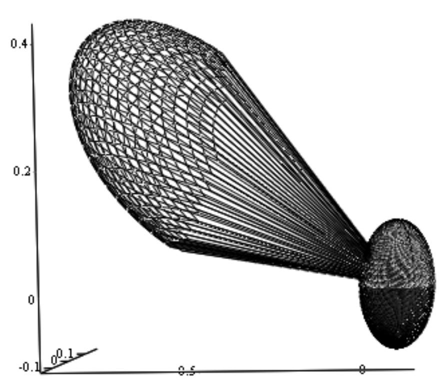


Figure 5: Beam and Ball Antenna Model

Multiple pipeline stages contribute to the assessment of smart antenna effects. Table 3 lists the pipelines stages, the actions that are modeled in those stages and identifies with which antenna pointing and adaptation strategies the actions are used.

Stage	Action	Antenna Technology			
		PP	AP	EAR	EAT
Closure	Calculates pathloss and adjusts received power.	X	X	X	X
Channel Match	The spreading code attribute of the channel is used to identify the training sequence used by the transmitter. Receivers will only adapt to a specified code. In-spectrum packets with other codes are classified as noise.		X	X	X
Transmit Antenna	Looks up the pointing direction of the transmitter's antenna	X	X	X	X
	Calculates antenna gain based on angle between the antenna pointing direction and the receiver direction	X			
	Applies EAT attenuation towards non-destination receivers				X
Receive Antenna	Looks up the pointing direction of the receiver's antenna	X	X	X	X
	Determines the direction from the receiver toward the transmitter and stores it as a packet attribute.	X	X		
	Calculates antenna gain based on angle between the antenna pointing direction and the transmitter direction.	X			
Power	Applies protocol pointing antenna gains to the received power of transmissions	X	X	X	X
	Determines if a receiver locks onto a packet. If so, the node adapts to this packet if other criteria is met.		X	X	X
Interfer-ence noise	Determines if adaptation criteria is met		X	X	X
	Applies adaptive pointing gain to all receptions		X		
	Applies adaptation attenuation to interfering signals			X	
ECC	Writes the adaptation direction for a received packet to the radio states so it can be used in subsequent transmissions.		X		
	Writes the ID of the adapted receiver for use in specifying EAT adaptation				X

Table 3: Modeling Actions by Pipeline Stage

There are four different approaches to pointing and adapting antennas:

Protocol Pointing (PP) – Assumes a protocol decides where to point the antenna. The model considers the antenna to be pointed in the direction specified in the radio state variables. The transmit and receive antenna pipeline stages look up the direction that an antenna is pointed and assess the gain in the direction to the distant transceiver.

Adaptive Pointing (AP) – Assumes the radio uses a DOA algorithm when receiving the preamble of a packet and then points the antenna in the direction determined by the algorithm. The criteria for adaptation is as specified previously. The direction between a receiver and a transmitter of a valid packet is calculated in the receiver antenna pipeline stage and is stored as a packet attribute. At the power stage a decision is made whether this packet is the packet to which the receiver locks. This decision is made by whether the packet exceeds a detection threshold and whether the receiver has not already locked onto another arriving packet. At the interference noise stage, the adaptation criteria are checked. If met, the directional antenna gain is applied to the interfering signal. If not, a flag is set in the valid packet's attributes that prevents adaptation with any other interferer. If a packet is successfully received the antenna pointing vector of the receiving transceiver is pointed toward the direction of the source transceiver. This direction is used in subsequent transmission and receptions as allowed by the protocol. For subsequent exchanges, the antennas return to omnidirectional receiving mode and the process repeats.

Environmental Adaptive Reception (EAR) – Assumes the radio uses an adaptation algorithm when receiving the preamble of a packet and then rejects interfering signals by some specified attenuation. The modeling methodology is similar to AP, however, interfering signals are attenuated by the EAR gain set for the node in its model attributes. Also adaptation has no effect on subsequent transmissions or receptions by the node unless EAT or adaptive pointing is enabled. If adaptive pointing is enabled together with EAR then EAR has precedence during a reception and adaptive pointing is applied in subsequent transmissions. Similarly if EAT is enabled it is used after an adaptive reception. The antenna pointing vector is set for adaptive pointing and the destination ID is set for EAT.

Environmental Adaptive Transmission (EAT) – Assumes that if a radio has adapted to receive a signal it can use the same information to transmit and thus reduce the gain in the direction of the previously interfering transmitters. Transmissions received at these interfering nodes from the adapted transmitters are attenuated. The reduction in gain at these receivers is applied in the transmit antenna pipeline stage. This mechanism assumes the access protocol caused all the receivers to be transmitters during the receive adaptation.

Model Limitations

As we have described them, our models of adaptive antenna effects assume the access protocols with which they are used will create the conditions necessary for their validity. We now clarify these conditions

It is necessary that the cumulative SIR be below the capture and adaptation thresholds. As we have modeled these effects they are assessed with each packet. If there is a congested environment where the sum of interference from multiple interferers exceeds a threshold but where no one interferer does then this model will not behave correctly. This is not as much of an issue in cases where the number of interferers is kept low. It can be mitigated by using larger thresholds.

The reduction in gain caused by adaptation is applied to the power added to the accumulated noise in the interference noise stage. The pipeline stages automatically decrement the power of an interferer from the accumulated noise when the interferer stops transmitting. It uses the received power calculated in the power stage which is not adjusted and so exceeds the power that should be decremented. This deficiency is not a large issue if the packets line-up well due to synchronization of their transmission.

Adaptive antennas do not perform well when the interfering transmitters are in the same direction as the source. Our EAR model treats all interferers the same regardless of location. The model assumes the protocols prevent such coincident transmissions.

As described earlier, EAR can result in large gains in directions where there were no signals considered in the adaptation. If a new transmission starts in one of these directions the interference would be exacerbated. Our models do not explicitly model gain by direction and so do not model this effect. Our models assume the protocols prevent these new transmissions and so the high gain is not necessary to model.

The EAT gain is applied toward non-destination receivers in the transmit antenna stage. It assumes that all these receivers were considered in the adaptation. Receivers that did not send packets in the adaptation window would not have been considered. Our models assume the protocols prevent such receivers from being present.

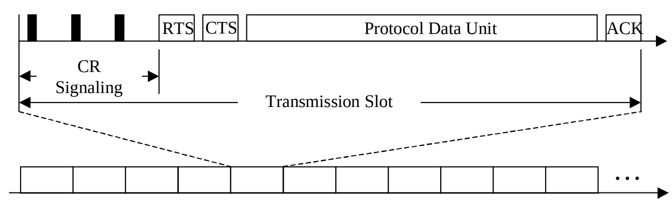


Figure 6. The Synchronous Collision Resolution Protocol

The Synchronous Collision Resolution MAC[1]

We use our antenna models together with the Synchronous Collision Resolution (SCR) MAC. SCR is ideally suited to exploit directional and smart antennas. The SCR protocol is illustrate in Figure 6. It has four main characteristics:

1. The communications channel is time slotted.
2. Nodes with packets to send contend in every slot. There are no backoff mechanisms.
3. Signaling is used to arbitrate contentions.
4. Packet transmissions occur simultaneously.

The transmission slot consists of three activities, collision resolution signaling (CRS) to select a subset of all possible contending nodes, a request-to-send (RTS) – clear-to-send (CTS) handshake used to verify capture and to assist physical layer adaptation, and finally the data exchange.

The goal of CRS is to select a subset of contenders from among all contending nodes in the network so that the nodes in the subset are physically separated from each other by at least the range of their radios. Figure 7 illustrates the starting and ending condition of this process. The desired separation occurs with high probability, >0.99. Details about the design of signaling to cause physical separation of contenders can be found in [3].

[1] Patent pending

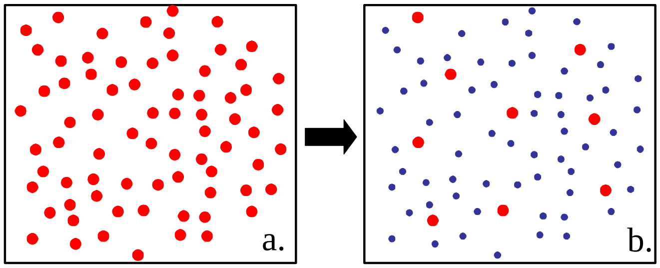


Figure 7: The effects of signaling. All nodes are contenders in panel a and then signaling resolves a subset of these contenders in panel b, where all the surviving contenders are separated from each other by at least the range of their signals. Large nodes are contenders.

CRS is followed by a request-to-send (RTS) – clear-to-send (CTS) handshake. If the destination hears an RTS then it responds with a CTS and if the source hears the CTS it sends the payload. This mechanism causes source destination (SD) pairs suffering too much interference to drop out. The separation shown above is ambitious for the purpose of allowing physical layer capabilities, in this case smart and directional antennas, to make more of these exchanges successful by improving the capture conditions between the SD pairs. The physical layer can use the RTS – CTS transmissions to adapt and can use the RTS-CTS packets to convey information that enhances adaptation or can be used by the protocol to support protocol pointing.

SCR creates four conditions that we believe are necessary for antenna adaptation. Those conditions are:

1. It enables the adaptive antennas to acquire the conditions for determining the weighting of the antenna elements. Changing conditions mean weights will have a short lifetime and so the MACs must enable weight determination in close proximity to the time they are used. With SCR, weights can be determined with each reception. This condition is most important for EAT. Weights determined during the reception of the RTS, CTS, and PDU can be applied to each of the subsequent transmissions. The nice feature of SCR is that these weights are derived in the presence of interfering signals from the transceivers that will be receivers during the subsequent transmission. SCR creates the conditions that allow EAT solutions to point nulls toward these receivers.
2. The CRS prevents congestion. Antenna arrays have limited degrees of freedom to cancel out interfering nodes and so the access mechanism must limit the number. At the conclusion of CRS receivers will be in range of no more than 2 or 3 interfering transmitters.
3. CRS prevents coincident transmission. Adaptive antennas have an angular resolution and cannot differentiate transmitters in the same or near same direction. CRS causes separation of contenders that results in a nice angular separation between transmitters.
4. SCR preserves the condition. MAC protocols must keep the weighting relevant for the duration of its use. The synchronous nature of SCR may not be able to prevent movement of nodes and of objects in the environment but it prevents new interference from within the network.

Since SCR creates these conditions, it simplifies the demands in modeling and so also enables us to use the model abstractions we described earlier.

SCR enables many useful capabilities including energy conservation [4], quality of service [5], channelization [5], and the use of CDMA [6]. The latter two together with smart antenna use could enable us to support a packet multiplexing capability like what occurs at the base stations used with wireless telephony. Figure 8 illustrates the concept. Transmitters may be able to transmit different packets to different destinations simultaneously and receivers may be able to receive multiple packets simultaneously.

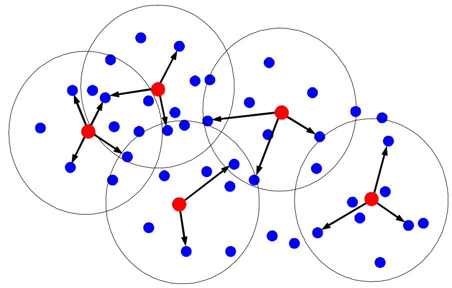


Figure 8: Smart antennas, channelization, and CDMA may be used in combination in SCR to enable instantaneous packet multiplexing both in transmission and in reception.

Model Application

We used our antenna models to evaluate the effect of different antenna technologies on the performance of networks using SCR. The following is a description of the experiments and the results

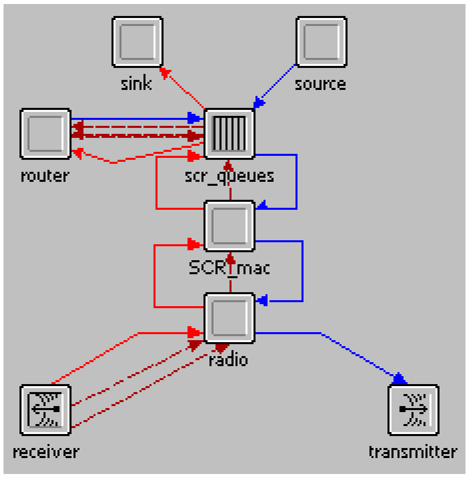


Figure 9: SCR Node Model

Simulation Environment

Our model of each node included an explicit representation of the SCR protocol together with a perfect router, see Figure 9. All transmitters used the same transmit power. The perfect router assumes links exist between pairs of nodes if the arriving signals can achieve a specified SNR when there is no interference. Routes were minimum-hop. Pathloss was determined using the 2-ray propagation model with vertical polarization on flat earth without terrain features. 156 nodes were randomly placed on a square surface, seven transmission ranges[2] on a side, which we toroidally wrapped. Figure 10 illustrates node layout. This results in an average node density of 10 nodes per transmission area. Nodes were stationary throughout the simulation. Packet arrivals at each node were exponentially distributed at the same rate and each arrival was randomly routed to one of the other nodes in the network. The radio is assumed to have transmission capabilities similar to those of an 802.11 modem using its 1 Mbps DSSS modulation scheme, so we use the bit error rate curves of binary phase shift keying.. We sized the transmission slots to send 512 byte payload packets and assume headers sizes and RTS, CTS, and ACK packet sizes the same as those used in the 802.11 MAC. Signaling, handshake packets, headers and interframe spaces account for 34% of a transmission slot's duration and there were approximately 163 transmission slots per second. We used a single scenario, i.e. identical node placement and traffic, and observed the effects of changing smart antenna techniques and their performance parameters. This network was fully connected with a 10 dB SNR criteria for links.

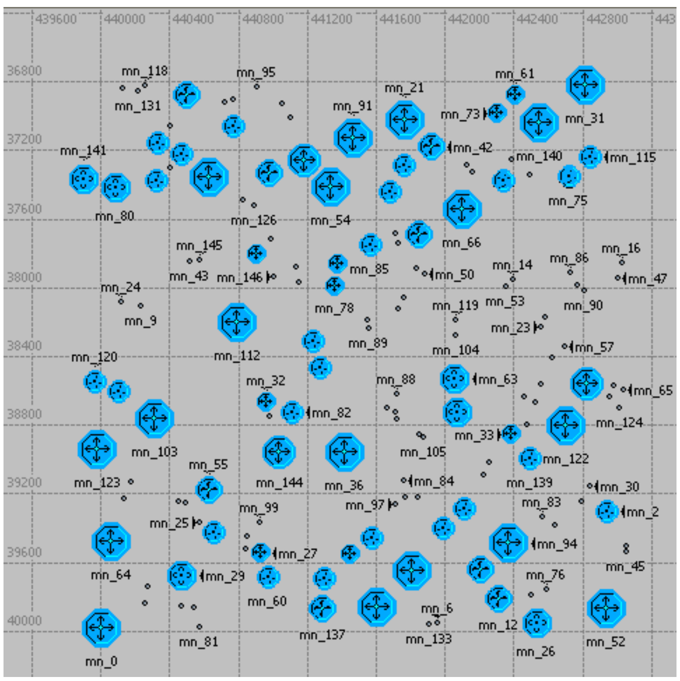


Figure 10: Node Layout for Simulation Experiments

The best measure of the MAC performance in this scenario and the measure that we use is MAC throughput which is the rate packets are exchanged with neighbors. All other performance measures are correlated with this rate. The following information is provided to help the reader interpret the results. The spatial reuse of the channel in the scenario is the MAC throughput (pkts/sec) divided by the slots in a second, ~163. The total area of the network is 15.6 transmission areas so a MAC throughput of 2543 pkts/sec corresponds to a throughput of one packet per transmission slot per transmission area.

[2] We define the transmission range as the distance that a signal has propagated when its strength drops to 10 dB above the thermal noise.

Experiments

We conducted several sets of experiments comparing the effects of varying the directivity (i.e. BWFN) and selectivity (i.e. MSLL) of antennas, and the effectiveness of the adaptation techniques. The standard experiment used a 10 dB SNR for signal and link detection. Table 4 lists the details of the modifications for each experiment. The ID numbers in this table are used to identify the experiment performances in the graphs.

ID	Tech	BWFN	MSLL (dB)	SIR_c (dB)	t_s (µs)	SIR_a (dB)	t_f - t_{sm} (µs)	AG (dB)
1	omni		0					
2	SP	60	-12					
3	SP	30	-12					
4	SP	10	-12					
5	SP	60	-20					
6	SP	30	-20					
7	SP	10	-20					
8	SP	60	-30					
9	SP	30	-30					
10	SP	10	-30					
11	EAR	60	-12	6	1	3	100	-12
12	EAR	60	-12	6	1	3	100	-20
13	EAR	30	-12	6	1	3	100	-12
14	EAR	30	-12	6	1	3	100	-20
15	EAR	10	-12	6	1	3	100	-12
16	EAR	10	-12	6	1	3	100	-20
17	EAR	60	-12	3	1	1	100	-12
18	EAR	60	-12	3	1	1	100	-20
19	EAR	30	-12	3	1	1	100	-12
20	EAR	30	-12	3	1	1	100	-20
21	EAR	10	-12	3	1	1	100	-12
22	EAR	10	-12	3	1	1	100	-20

2a through 10a use adaptive pointing with the same directivity and selectivity and with SIR_c = 6 dB, t_s = 1 µs, SIR_f = 3 dB, t_f = 100 µs.
11a through 22a use the EART technique

Table 4: Experiment Settings

Figure 11 compares the MAC throughput when using simple pointing. Initially, the selectivity rather than the directivity had the greater effect on capacity but once the MSLL was below –20 dB, selectivity became more important. We validated this observation by executing additional simulations holding the load constant and varying BWFN and MSLL. The results are shown in Figure 12. MSLL rapidly increases throughput down to -15 dB where it starts to level off. BWFN has a linear effect on throughput. These results indicate that selectivity should take precedence in antenna design until most sidelobes are 15 dB below the mainbeam gain.

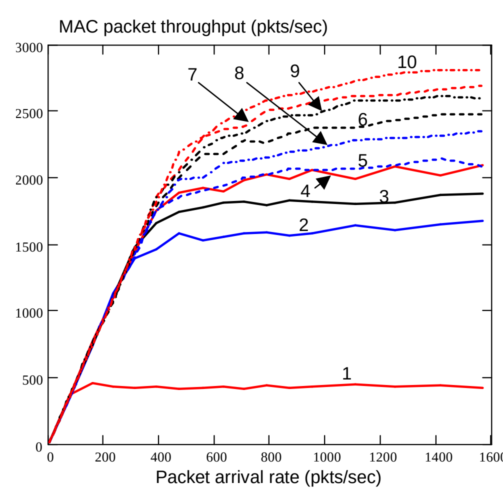
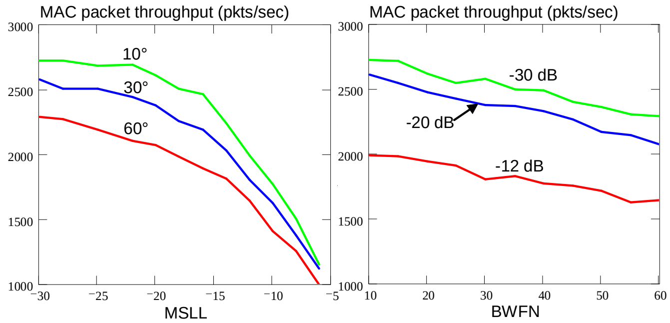


Figure 11: Evaluation of Simple Pointing Performance



a. Holding beamwidth constant b. Holding MSLL constant

Figure 12: Evaluation of the Effect of Directivity and Selectivity on Capacity (Simulations use a common network traffic load of 1100 pkts/sec.)

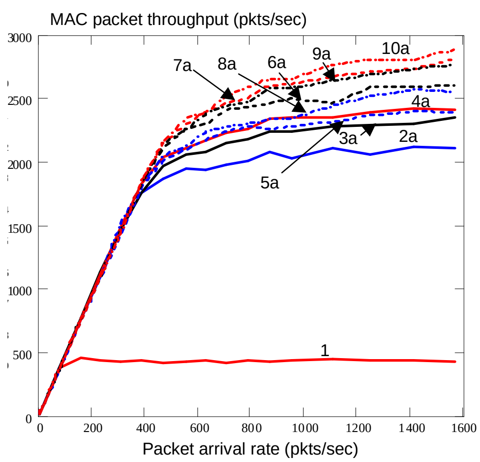


Figure 13: Evaluation of Adaptive Pointing Performance

Figure 13 compares the MAC throughput when using adaptive pointing. There is an improvement over simple pointing. This improvement is due to the adaptation that occurs before receiving the first packet, since the network is stationary all subsequent pointing is the same. We would expect a greater difference in performance if this were a mobile net since the simple pointing techniques are less effective at knowing where to point.

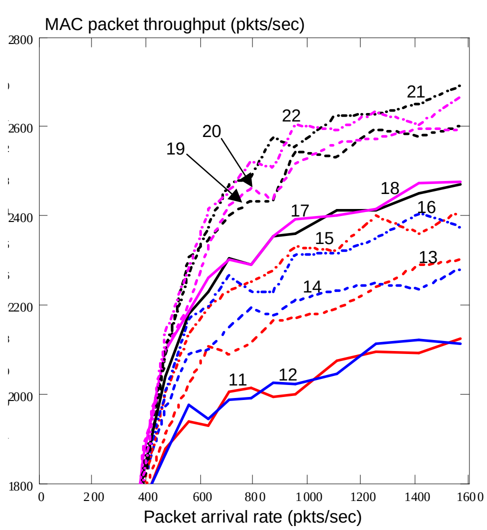


Figure 14: Network Performance Using Environmental Adaptive Reception

Figure 14 illustrates the performance of using EAR. There is little difference between when the EAR gain is –12 dB and –20 dB indicating that a large gain envisioned in pointing nulls is not necessary. Adaptation effectiveness is most dependent on the robustness of the adaptation (i.e. adaptation can occur in a lot of interference.) Performance also improved with the selectivity of the initial antenna pointing. This may be an unrealistic result as highly directional transmissions can reduce the multipath that enables some EAR techniques to work. The take away observation remains that anything that enables the initial adaptation is good.

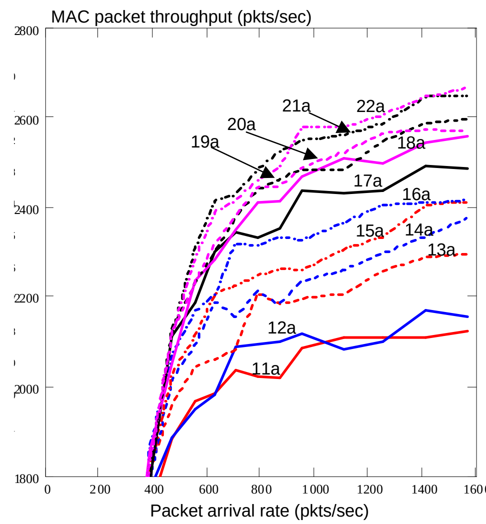


Figure 15: Network Performance Using Both Environmental Adaptive Reception and Transmission

Figure 15 illustrates the performance of using EART. There is little improvement. This further indicates the significance of acquiring the first RTS. There is no difference in the conditions for the success of this first packet between EAR and EART. Environmental adaptive transmission does not kick-in until the CTS and subsequent transmission.

All of our antenna simulations were performed without any processing gain. As we described earlier, one of the techniques that allows a receiver to capture a specific signal among interferers is to use unique training sequences for each receiver. One type of sequence is a the spreading code that is used with Direct Sequence Spread Spectrum.. SCR supports the use of codes in ad hoc environments because it solves the two hard problems of knowing which channel receivers should listen and preventing the near-far effect. Details are in [6]. We conducted further experiments to determine if the smart antennas would provide a benefit if processing gain were used. We repeated all of the experiments described above with a 15 dB processing gain and found that with this large of a processing gain, smart antennas provided little benefit.

Related Work

Two other papers have proposed methods to model smart antennas in OPNET. Singh and Singh [7] also use smart antennas with a synchronous access protocol. The scheme calls for each receiver to use DOA algorithms to identify the directions to all transmitters and then to adapt and listen to the receiver with the strongest signal. The paper does not provide details how and in which processes and pipeline stage the antennas are modeled in OPNET. It does not identify if any criteria is checked for congestion or coincidence. Their simulation, however, use a square tessellation for the placement of nodes which prevents node congestion and coincident transmissions from being an issue. Katz et al [8] combine two external models, one to model the electromagnetic environment, EMEinject and one to model the antennas, Planar and Linear Phased Array Model (PALPAM). In their approach they combine the calculations of the receiver pipeline stages for all the stages except the power and background noise stages and perform them in the error correction stage. The EMEinject model acquires which nodes are interferers during a transmission in the transmitter pipeline stages and then at the error correction stage the cumulative signals that arrive at a receiver are used as input to derive an antenna power pattern. It is not clear whether EMEinject is just tracking the direction and power of arriving signals or if it creates some complex signal for each antenna element of an array that is input into PALPAM. The power pattern after adaptation is applied to determine an SINR for the packets duration and the standard bit error and error correction calculations are made to determine if packet reception was successful. There is no mention of what criteria is used to determine whether adaptation is possible and if any interfering signals are not included in the adaptation.

Conclusion and Future Work

In this paper we provided a brief overview of smart antenna technologies and the challenges in modeling them. We explained that modeling can be abstracted if the access mechanisms can assure a certain order in time and space. We provide a detailed description of our modeling approach and list the requirements of the access protocols to make these models valid. We provided a brief description of the Synchronous Collision Resolution MAC protocol and explain how it not only meets the conditions for our models to be valid but also creates the critical conditions necessary for smart antennas to be employed. We conducted multiple experiments using our models and demonstrated that smart antennas did improve the performance of our network but when comparing technologies, the best improvement comes from technologies that enhance the first reception of an exchange.

In this work we demonstrated the use of smart antenna models in ad hoc networks. In the future, we plan to use these models in the development of a modem using Multiple Input Multiple Output (MIMO) technology. In the long term we hope to create the protocol stack that will allow us to multiplex the transmission and reception of packets as illustrated in Figure 8. We will upgrade these models as necessary for this use.

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