Angular MAC Protocol with Location Based Scheduling for Wireless Ad Hoc Networks

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Abstract - Smart antenna systems not only enable users to have high quality links but also increase network throughput by allowing spatial reuse of wireless channels by the use of directional transmission. The performance of smart antenna systems is limited because of the increased hidden terminal problem and deafness of nodes. We have proposed Angular MAC (ANMAC) protocol that avoids both problems through medium access tables in the nodes that keep track of the locations of the destination nodes as well as all communicating neighbors. With this feature, angular CSMA and Space Division Multiple Access (SDMA) are achieved. In this paper, we present detailed performance analysis of ANMAC considering different topologies and traffic scenarios, and we show that SDMA cannot be fully exploited without a smart scheduler. We propose ANMAC with Location based Scheduling (ANMAC-LS) and compare its performance with other smart antenna approaches and omni 802.11 MAC. We prove the efficiency of location based scheduling in wireless networks with smart antennas, and we also show the effects of antenna orientation on throughput, using realistic antenna patterns and ANMAC protocol.

Keywords - smart antenna, directional, scheduling, 802.11, Wireless LANs

I. INTRODUCTION

Using smart antennas in wireless communications enable high quality links because of the directivity of the antennas [1]. Enhancements quantified for the physical layer may not be efficiently utilized, unless the Media Access Control (MAC) layer is designed accordingly. Moreover, directional transmission introduces new problems such as hidden terminals and deafness of the nodes.

Previously, in the literature, application of directional antennas in wireless networks has been investigated. In [2], Vaidya et al proposed a MAC protocol where network capacity is increased by the use of directional antennas together with Global Positioning System (GPS) to determine the direction to communicate with a given destination. However, directional transmission causes the deafness problem, where a node attempts to transmit to another node that is already busy. The transmission of a busy station cannot be detected by an attempting station. This causes successive collisions and retries, and consequently, the throughput gained from directional transmission is reduced. In [3], a solution to deafness is proposed by using simple tones to inform other stations. In [4] and [5] Directional CSMA/CA is proposed for 2, 4 and 8 sectored antennas with the lack of deafness solution. We have developed Angular MAC (ANMAC) protocol to solve both hidden terminal and deafness issues. ANMAC avoids hidden terminal problem by using angular RTS/CTS messages and prevents deafness by informing surrounding nodes about by sending dummy bits on other sectors for the remaining part of the data packet [6].

One key advantage of using directional antennas is the ability to achieve Spatial Division Multiple Access (SDMA) [7] [8]. In SDMA, stations are separated by their locations, and by the use of proper MAC, simultaneous transmissions can occur at the same time and frequency. The existing algorithms proposed for SDMA, e.g., [9], [10], assume contention free, reservation based medium access. In both schemes, synchronization and initialization are important issues to be addressed in realistic scenarios. On the other hand, SDMA with random access is challenging in realistic scenarios, especially when packet destinations are not known. Since the medium is shared, the stations have to determine which stations and which sectors are idle in order to avoid collisions and retries. Queuing delays can grow unboundedly if a packet at the head of the sender’s queue is destined to a busy node or towards a busy sector, also resulting in low throughput.

In this paper, we extend the ANMAC framework with a location-based scheduler to support SDMA with random access. The new protocol is named as ANMAC with Location Scheduling (ANMAC-LS). ANMAC-LS fully exploits the advantage of directional transmission in spatially divided channels, while still avoiding the hidden terminal problem and deafness, and guaranteeing range extension by using only directional antennas. The location-based scheduler utilizes the location information, which is already available through the medium access table of ANMAC protocol.

Through detailed simulations, the performance gains of ANMAC protocol and ANMAC-LS are quantified against omni 802.11 transmission and other MAC protocols that use directional carrier sensing. We show the advantage of location-based scheduling in all systems with smart antennas, and show that ANMAC-LS has the best performance, in various network topologies.

The rest of the paper is arranged as follows. Section 2 provides the summary of Angular MAC (ANMAC) including station properties, basic protocol operation, SDMA support, deafness problem and the location based scheduler. Section 3 presents our performance evaluation, including antenna and
network models and simulation results. Finally section 4 includes our conclusions.

II. ANGULAR MAC (ANMAC) PROTOCOL

A. Station Properties

In ANMAC, every station has beams of 90° beamwidth that covers 360° by four antennas. Stations can monitor the signal level on all beams, and choose the best one. The best beam is defined as the beam over which a station gets a signal with maximum Signal-to-Noise Ratio (SNR). Each station keeps a medium access table (Figure 1), where it stores its best beam number to communicate with a neighbor and the neighbor’s best beam number to communicate with itself. The blocking condition for every beam indicates whether that beam is busy or not, so as to avoid deafness and collisions. ANMAC uses modified RTS/CTS [11] messages, namely Angular RTS/CTS to signal the information about the locations of communicating nodes to other stations in the medium, which are used in updating medium access tables in the stations. The packet format of Angular RTS (AN-RTS) and Angular CTS (AN-CTS) are shown in Figure 2, and Figure 3, respectively.

![Fig.1. The medium access table](image1)

<table>
<thead>
<tr>
<th>My Address</th>
<th>Neighbor’s Address</th>
<th>Beam 0</th>
<th>Blocking</th>
</tr>
</thead>
<tbody>
<tr>
<td>My Beam</td>
<td>Neighbor’s Beam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Fig.2. AN-RTS Frame Format](image2)

<table>
<thead>
<tr>
<th>Framecontrol</th>
<th>Duration</th>
<th>Receiving Address</th>
<th>Transmitting Address</th>
<th>Transmitter Beam Number</th>
<th>FCS</th>
</tr>
</thead>
</table>

![Fig.3. AN-CTS Frame format](image3)

<table>
<thead>
<tr>
<th>Framecontrol</th>
<th>Duration</th>
<th>Receiving Address</th>
<th>Transmitting Address</th>
<th>Receiver’s Best Beam Number</th>
<th>Transmitter Beam Number</th>
<th>Transmitter’s Best Beam Number</th>
<th>FCS</th>
</tr>
</thead>
</table>

![Fig.4. Example scenario](image4)

B. Basic Protocol Operation

Consider the scenario in Figure 4. If node A wants to send a data packet to node B, it sends an AN-RTS packet in each direction, i.e., over all beams. The “Transmitter Beam Number” field in the AN-RTS packet indicates the index number of the beam over which the packet is sent. Upon receiving the AN-RTS message, all surrounding nodes learn about not only the upcoming packet exchange, but also about their own location with respect to the transmitting node, that is they mark the index number of their receivers’ best beam which would be used during communication with the transmitter node. At the destination node, the beam over which the signal with maximum power is received, is marked, (in this example, beam #1 is marked at Node B) and all other beams are blocked. All other nodes block their beams in the direction of data (the best beam over which AN-RTS message is received) so as not to interfere with the data packet. By the way, these beams are blocked according to the duration field of the received AN-RTS packet. This is called as Directional Network Allocation Vector (D-NAV) in [3], which is similar to the NAV of 802.11, only set for a specific direction.

The receiver, node B, sends an AN-CTS packet in response to AN-RTS. AN-CTS frame is also sent in all directions to prevent the hidden terminal problem. As node A gets the AN-CTS packet, it finds out that the medium is available for communication, and also selects the best beam, beam with highest signal level, as beam #3. In the AN-CTS packet (Figure 3), the beam number in “transmitter’s best beam number” field indicates that this beam was chosen and will be used during data exchange by source node and the beam number in “receiver’s best beam number” field indicates that this beam was chosen and will be used during data exchange by destination node. After angular AN-RTS/AN-CTS handshake, node A sends the data over its best beam and node B gets the data packet by its best beam. The directional transmission will reduce the interference and establish a reliable and high quality channel between communicating nodes. During the operation, we need orientation of the nodes. Using a compass can make it possible as suggested by Nasipuri in [12].

By the way stations do not attempt to transmit any signal over their beam (block the beam) if it is in the direction of the best beam of source, node A or destination, node B, otherwise packets will collide. During the communication between these two nodes, other nodes can transmit a signal only over idle beams. In this manner, idle beams of node C are beam #0 and #2. All the beams of node D are idle during the communication because neither of the beams is facing to the best beam of node A nor node B.

C. SDMA and Deafness

In the example scenario in Figure 4, suppose that node D wants to send a packet to node C, while node A is communicating with node B. Nodes C and D have both blocked and non-blocked antennas. Therefore if the antennas and sector are available, simultaneous communication may be

1 This operation requires four individual RF transmitters and a single MAC chip in a node.
possible between these two nodes without interfering with the ongoing transmission, which is named as Space Division Multiple Access (SDMA).

Stations contend for the other diagonal (sector) after waiting for AN-RTS/AN-CTS handshake of communicating nodes. This period is named as SHORT_NAV in [13].

Node D sends AN-RTS packet over all its non-blocked beams. In this scenario, node D has no blocked antenna. Node C hears the AN-RTS packet and will respond with AN-CTS. However the first and third beams of node C are blocked until node A and node B complete communication. Hence, node C sends an AN-CTS packet from zeroth and second beams. Node C selects beam #0 as best beam, blocks the beam #2, and updates the D-NAV of the previously blocked beams #1 and #3 by the duration of the new exchange, obtained from the AN-RTS packet. When node D gets the AN-CTS packet, it selects its second beam as the best beam, and it blocks beams #0, #1 and #3. After the handshake, node D sends the data packet over its second beam and waits for the ACK from node C. The network throughput is doubled since two data exchanges simultaneously take place in the same basic service set of nodes. Therefore, spatial reuse, i.e., SDMA is achieved.

However, due to the deafness problem, existing MAC protocols designed to work with directional antennas are limited to some cases. If a node is not detected the transmission of another station that is already busy, it can assume it as idle and may attempt to transmit a packet to this node. However, the busy station can not get signal from the attempting station and this causes successive collisions and retries, and consequently, the throughput gained from directional transmission is reduced.

ANMAC protocol solves the deafness problem as follows. Consider the scenario in Figure 4: Node C may want to send a data packet to node D during communication of node A and node B. Since node A and node B have previously started communication over their best beams and blocked their other beams, both nodes will be unaware of the packet transmission attempt, i.e. AN-RTS packet, of node C, which is called the deafness problem. If node C is aware of A to B communication, it can calculate the required time to complete data exchange. By comparing the remaining time of D-NAV duration for A to B communication with the required total time to transmit the new data frame to D, it can decide to complete its data exchange in this remaining time or to wait until A to B communication is finished. In the former case, node C completes its exchange before A to B communication without causing or being subject to any interference. In the latter case, node C may wait for the completion of the A to B communication and then all nodes contend for the channel. In this case, the expected network capacity increase with the use of directional antennas will not be achieved, and the same performance of omni directional system of current WLANs will be obtained.

On the other hand, node C may compare the remaining time of D-NAV duration and required total time for ANRTS/ANCTS handshake. If it is enough to complete the handshaking in the remaining time, node C will send an AN-RTS packet over unblocked antennas and start data exchange before the completion of A to B communication. Node C may inform A and B by the method that we proposed in ANMAC protocol to avoid deafness [6]. The method works as follows; after the completion of A to B communication, D-NAV of blocked beams in node C expire and at this time node C opens all blocked antennas and send RF power from those previously blocked antennas, too. Only sending the remaining part of the data packet over all antennas via RF switches can easily do this. Such RF switches are used to switch between beams in [14]. SENDING the packet in its mid-point cannot give any information which is actually recognized as dummy bits but this will make them to defer their transmissions because of carrier sensing mechanisms. By this way, the surrounding nodes will be aware of the ongoing transmission. At the end of carrier sensing, node A and node B wait for ACK_DURATION + SIFS time to protect ACK of node D and keep them silent and do not attempt to transmit any signal till the end of communication between C and D. After the completion of C to D communication, all nodes will back-off and re-contend for the channel.

D. Location Based Scheduler

In ad hoc networks, every station may want to communicate with any of the others. In omni-directional WLAN systems, a station creates a packet and contends for the channel to send it. Because of using omni-directional antenna, single user can capture the channel to communicate and others wait for them to finish and avoid collisions. In case of directional transmission systems, spatial reuse of the channel is possible. This allows simultaneous transmissions between nodes without interfering each other. However, nodes have to determine idle stations and idle sectors to achieve spatial reuse. If two nodes are communicating, another node must not attempt to send a packet to any of these over idle sectors. If a node has a packet at the head of its queue to any of these two communicating nodes, it has to skip this packet and get the second one and check whether the packet is destined to an idle station or a busy one. If the packet is destined to any of stations other than these two communicating nodes, the node can try to send the packet to a new destination and leave the first packet in the queue. After completing the transmission, the node removes this unsent packet from the head of the queue and contends for the channel to send this unsent packet.

The scheduler also provides self-learning of the neighbor nodes’ locations. To determine whether the node can send a data packet to another node or wait, the node needs to check the medium access table. If the destination is not in the list, the node will send AN-RTS packet over all unblocked beams because the node is unaware of the location of destination node. Surely the node looks for the destination node in the medium. But if the station has recorded the destination node in the table before, it can make a decision for sending a packet. With these enhancements unsuccessful, consecutive retries will be avoided and unnecessary queue waiting times will be avoided and the capacity increase obtained with SDMA will be maximized.

III. Performance Analysis

A. Antenna and Network Models

The performance of our protocol is examined by Optimum Network Engineering Tool (OPNET) [15]. In addition to
modeling the ANMAC protocol, we have modified the physical layer model to make the nodes work with four separate antennas. We have used predefined and fixed beams defined in the pattern editor of OPNET and we created an antenna pointer model that switches between the beams as dictated by ANMAC. It is worthwhile to note that there must be some difference between power levels of two simultaneously arriving packets in order to capture the more powerful packet from one beam and to avoid collisions. This rejection threshold typically ranges from 1 to 20 dB, and we used 10 dB in our model.

The four antennas in the antenna model cover four different directions: North-East, North-West, South-East, and South-West. The first antenna pattern we considered has 10 dBi of directional gain with 90° beamwidth and 40 dB of front to back ratio. These patterns are assumed to have ideal shape with full reception in the desired beam and rejection in others as depicted in Fig.5a. Despite being ideal, four perfect antennas can create overlap regions of total 2° at the beam edges (Fig.5a). These overlap regions are blind angles where packet reception, i.e. capture, is not possible. We have simulated packet capture events with our ideal antenna model and ANMAC, and by keeping one of the nodes fixed and rotating the other node around the fixed node we measured the effective aperture of the ideal antenna pattern. Fig. 6 shows the packet capture of ideal pattern as a function of angle of arrival ranging between 0 and 180 degrees. This experiment proved that the effective aperture of the ideal antenna pattern is 88°. In other words, if two nodes are within up to 88° with respect to each other, they can communicate with ANMAC; otherwise the packets will be lost.

In practice, it is not possible to have a perfect beam shape antenna. Next, we consider a more realistic pattern with 40° half-power beamwidth and overlapping regions between beams as shown in Fig.5b. For modeling this antenna, we used real patterns of commercially available antennas. Again, the darken zones in Fig.5b indicate the blind regions. The packet capture experiment is repeated for this realistic pattern. Fig.7 shows the packet capture with respect to angle of arrival. For the realistic antenna the effective aperture per beam is measured as 70°.

These experiments show that the orientation and positioning of nodes with respect to each other is important for successful packet capturing with directional antennas. In this manner, in our topologies for our simulations, we assumed that the nodes are deployed in such a way that they face each other from non-blind angles. The nodes are fixed so that their positioning does not change.

B. Simulation Results

In this work, we modified the existing 802.11 MAC model in OPNET to implement our new MAC protocol, ANMAC, and location based packet scheduler. In our simulations we have used characteristics of the IEEE 802.11b standard.

In our simulation experiments, we examined network throughput versus traffic load and medium access delay versus network throughput. The simulated topologies are shown in Figure 8. It is assumed that all nodes are within the coverage area of each other. The simulated protocols are:

- ANMAC
- ANMAC with Location based Scheduler (ANMAC-LS)
- Directional CSMA (D-CSMA) proposed in [4]
- D-CSMA with Location based Scheduler (D-CSMA-LS)
- IEEE 802.11 Omni

In the omni system, the stations use omni directional antenna and initiate communication one by one. D-CSMA is based on simultaneous sensing of carriers in different sectors. However, D-CSMA is incapable of avoiding deafness. ANMAC performs directional carrier sensing, as D-CSMA, but also prevents the deafness problem by modified RTS/CTS messages, medium access tables and dummy bits. ANMAC-LS and D-CSMA-LS are enhanced versions of the two algorithms that involve a smart packet scheduler.

Fig.8. Topologies examined in computer simulations
The first simulation scenario we consider is the example scenario referred in section 2 (shown as topology 1 in Fig.8). The four nodes in the network choose their destinations randomly. Figure 9 shows the throughput values measured for different traffic load. Both D-CSMA and ANMAC have performances close to (even lower than) the omni directional system, because of choosing random destinations. A node can wait for a long period of time, inefficiently, due to the activity in the destination node or sector. Therefore, the advantage of spatial re-use cannot be exploited. D-CSMA has the worst performance due to the deafness problem introduced. The effect of location-based scheduler can be easily deferred from the performance of ANMAC-LS that outperforms the throughput of omni 802.11 by 55%.

The performance of D-CSMA is also enhanced by the scheduler; however, its throughput is still below omni 802.11 because of deafness. Figure 10 shows the medium access delay with respect to measured throughput. ANMAC-LS has the best delay performance with maximum throughput.

Secondly, we examine the topology 2 shown in Fig.8. There are 9 nodes deployed on a 3x3 grid. Figure 11 shows the throughput values for varying traffic load. ANMAC and D-CSMA, where there is no scheduler, have lower performance than omni directional system because of crowded network topology, which causes too many collisions and long delays. ANMAC-LS outperforms omni 802.11 by 40%, and D-CSMA-LS by 10%. However, D-CSMA-LS this...
time has closer performance to ANMAC-LS because of using the location-based scheduler in the grid topology. Location based scheduler prevents stations from sending packets through busy sectors, and this avoids deafness in some cases. Figure 12 shows the medium access delay vs. throughput performance of topology 2. We can easily find out that the performance of delay in ANMAC-LS is better than all other schemes.

Topology 3 in Figure 8 is examined next. There are 6 nodes that are deployed randomly in the network. D-CSMA, ANMAC, omni 802.11 and D-CSMA-LS schemes have lower performances than ANMAC-LS. We can see the effect of deafness again because of the network topology. D-CSMA and ANMAC have closer performances to the omni system similar to topology 1. In this topology, although D-CSMA-LS has a scheduler, the deafness conditions occurred more frequently and decreased the performance of D-CSMA-LS. However ANMAC-LS has 35% better performance than the omni system, and 48% better performance than D-CSMA-LS.

IV. CONCLUSIONS

In this paper, we have enhanced the Angular MAC protocol with a Location based Scheduler (ANMAC-LS). ANMAC enables users to keep locations of other stations by the use of medium access tables. The stations use the location information of others to determine the busy destinations and busy sectors to avoid collisions and congestions in the network. As shown in our simulations, the advantage of SDMA can be obtained with ANMAC-LS while still avoiding deafness and hidden terminals.

We evaluated the performance of ANMAC-LS against omni 802.11 and directional CSMA via simulations. In addition to modeling the MAC layer, we modeled antenna characteristics, location based scheduler and the wireless channel in detail to reflect interference scenarios accurately. Our results promise significant enhancements over omni 802.11, with throughput gains 35-55%. The extent of the performance improvement depends on the network topology. We envision that the AN-MAC-LS protocol will be most appropriate for wireless bridges interconnecting networks of buildings, since extra antenna deployment and multiple transceivers would be affordable. We intend to extend our performance analysis to include more different topologies and scenarios with increased number of antennas per node.

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