Location-Aware Power-Efficient Directional MAC in Ad Hoc Networks using Directional Antenna

ABSTRACT

Usually, in ad hoc networks, all nodes are equipped with omni-directional antenna. However, ad hoc networks with omni-directional antenna uses RTS/CTS based floor reservation scheme that wastes a large portion of the network capacity by reserving the wireless media over a large area. To alleviate this problem, researchers have proposed to use directional (fixed or adaptive) antennas that direct the transmitting and receiving beams toward the receiver and transmitter node only. This would largely reduce radio interference, thereby improving the utilization of wireless medium and consequently the network throughput. However, in order to implement effective MAC and routing protocol in this context, a node should know how to set its transmission direction to transmit a packet to its neighbors and to avoid transmission in other directions where data communications are already in progress. So, it becomes imperative to have a mechanism at each node to track the locations of its neighbors and to know the communication status of neighboring nodes. However, this location tracking mechanism in the context of wireless ad hoc networks with directional antenna is a serious problem, since it incurs a lot of control overhead. In this paper, we are proposing a receiver-centric approach for location tracking and MAC protocol. In order to track the location of its neighbor, each node n periodically *collects* its neighborhood information and forms an Angle- Signal Table (AST). Based on AST, a node n knows the direction of node m and controls the *medium access* during transmission-reception. The performance evaluation on QualNet network simulator [12] indicates that our protocol is highly efficient with increasing number of communications and with increase in data rate.

1. Introduction

The recent progress in wireless communication and personal computing leads to the research of ad hoc wireless networks, which are envisioned as rapidly deployable, infrastructure-less networks with each node acting as a mobile router, equipped with a wireless transceiver. Usually, in ad hoc networks, all nodes are equipped with omni-directional antenna. However, ad hoc networks with omni-directional antenna uses RTS/CTS based floor reservation scheme that wastes a large portion of the network capacity by reserving the wireless media over a large area. Consequently, lot of nodes in the neighborhood of transmitter and receiver has to sit idle, waiting for the data communication between transmitter and receiver to finish. To alleviate this problem, researchers have proposed to use directional (fixed or adaptive) antennas that direct the transmitting and receiving beams toward the receiver and transmitter node only. This would largely reduce radio interference, thereby improving the utilization of wireless medium and consequently the network throughput [1-11]. As shown in figure 1, while node n is communicating with node m using omni-directional antenna, node p and r have to sit idle. However, with directional beam forming, while node n is communicating with node m, both node p and r can communicate with node q and s respectively, improving the medium utilization or the SDMA (space division multiple access) efficiency drastically.

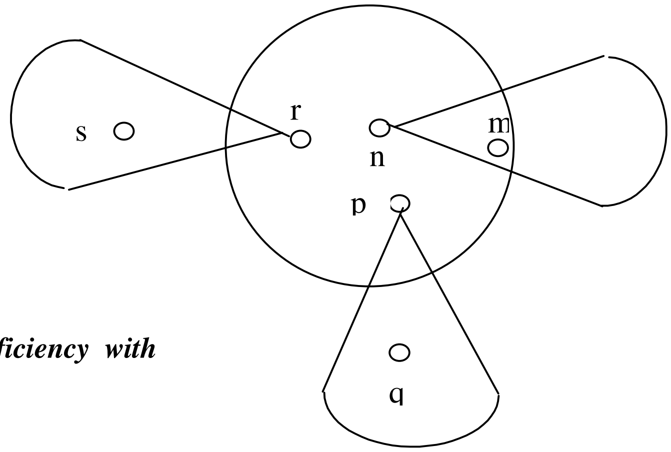


Figure 1: Improving SDMA efficiency with Directional Antenna

In order to fully exploit the capability of directional antenna, it is necessary for each node to know the information of the neighboring nodes (such as node-ID, direction, link quality, etc) beforehand. Node p can initiate a communication with q only if the direction from p to q is not in the same as direction of p to m or p to n. Thus, whenever a source and a destination node are engaged in a communication, all the neighbors of source and destination nodes should know the direction of communication so that they can initiate new communication in other directions, thus preventing interference with on-going data communication between source and destination. In other words, in order to implement effective MAC and routing protocol in this context, a node should know how to set its transmission direction to transmit a packet to its neighbors. So, it becomes imperative to have a mechanism at each node to track the locations of its neighbors. However, this location tracking mechanism in the context of wireless ad hoc networks with directional antenna is a serious problem, since it incurs a lot of control overhead. In this paper, we are proposing a receiver-centric approach for location tracking and MAC protocol. In order to track the location of its neighbor, each node n periodically *collects* its neighborhood information and forms an Angle- Signal Table (AST). Based on AST, a node n knows the direction of node m and controls the *medium access* during transmission-reception. The performance evaluation on QualNet network simulator [12] indicates that our protocol is highly efficient with increasing number of communications and with increase in data rate. The one-hop MAC throughput of our protocol is 1.8 times as compared to that of IEEE 802.11.

2. Related Work

In spite of the advantages of directional antennas, work on developing efficient MAC protocol using directional antennas in the context of ad hoc networks is limited because of the inherent difficulty to cope up with mobility and de-centralized control in ad hoc networks. Some researchers in the past have tried to address this challenge in several ways. Zander [1] have proposed the use of directional antennas in packet radio networks. MAC protocols using directional antenna has also been proposed in [2], where each station is assigned a tone that is unique to its neighbors. When a station receives a packet, it broadcasts its tone immediately for a period of time so that its neighbor can identify its presence and avoid transmitting to its direction. In recent years, several MAC protocols that rely on RTS-CTS type handshaking as in IEEE 802.11 have been suggested with directional antennas [3-11]. In [3], a set of D-MAC (Directional MAC) schemes has been proposed where combination of directional/ omni-directional RTS / CTS are used to block nodes from transmitting in directions that would interfere with existing data transmission while allowing them to transmit on other directions. In [4], a MAC protocol to achieve multihop efficiency has been proposed with multihop-RTS-singlehop-CTS using directional antenna. In this mechanism, using larger range of directional beam, a destination is reachable in less number of hops as compared to that using omni directional antenna. In both the schemes [3-4], the mobile nodes are assumed to know the physical locations of themselves and their neighbors using GPS. Due to directional RTS and directional CTS scheme, several issues like a *new hidden terminal problem* due to asymmetry in gain & due to unheard RTS/CTS, *deafness* and *higher directional interference,* as depicted in [4], remains unsolved. In [5], the proposed MAC protocol need not know the location information; the source and destination nodes identify each other's direction during omni-directional RTS-CTS exchange in an on-demand basis. It is assumed that all the neighbors of s and d, who hear this RTS-CTS dialog, will use this information to prevent interfering with the ongoing data transmission. However, because of omnidirectional transmission of RTS and CTS packets, this protocol provides no benefits in the spatial reuse of the wireless channel. However, it still improves the throughput over a MAC using omnidirectional antennas due to the reduced amount of interference caused by the directional data transmission [11]. In [6], Ramanathan studied the performance of ad hoc networks using beamforming antennas with changing antenna patterns and beam control, channel access mechanisms, link power control and neighbor discovery. The authors assume prior knowledge of location information In [7], concept of Directional NAV (the network allocation vector) has been used , one for each sector, allowing immediate transmission of control packets on those sectors which are clear instead of having to defer the transmission until it is safe to transmit on all sectors at the same time. In [8] also, Takai et al. proposed a directional NAV with a direction and a width, which is set depending on the signal strength in that direction. Also, with a smarter antenna, multiple Angle of Arrivals for a single signal due to its multipath components can be identified and utilized to block multiple DNAVs with different widths and angle.

Developing a suitable MAC protocol in ad hoc network to exploit the advantages of directional antenna for overall performance improvement requires proper location tracking and neighborhood knowledge. Each node has to know the direction in which it can communicate with a neighbor directionally. With this information, it is able to choose the angle or the beam formation to ensure effective communication. At the same time, each node has to know about the current communications in the shared neighborhood so that it can initiate communication in other direction without disturbing the existing communication. Moreover, propagation of this neighborhood information including directional access information of each node to each of its neighbors would also be helpful in designing an efficient proactive routing protocol [10], since it helps the network to maintain approximate network status information.

Location tracking has been done in [2] by using set of tones and maintaining extensive network status information at each node in the network. However, this is unrealistic in a dynamic scenario. In [5], the source and destination nodes identify each other's direction during omni-directional RTS-CTS exchange. However, in this mechanism, a node is not aware of its complete neighborhood information. In [3-4], the use of GPS is proposed to track the location of each node but the exact mechanism of information exchange and the consequent overhead has not been discussed. In our earlier work, we have developed a MAC protocol [9], where each node keeps certain neighborhood information dynamically through the maintenance of an Angle-SINR Table. In this method, in order to form AST, each node periodically sends a directional beacon in the form of a directional broadcast, sequentially in all direction at 30 degree interval, covering the entire 360 degree space. The nodes, which receive these signals at different angles, determine the best received signal strength and transmit the information back to the source node as data packet with RTS/CTS handshake. However, the overhead due to control packets is very high in this method [9].

In this paper, we will illustrate a receiver-oriented location tracking mechanism to reduce the control overhead and a simple MAC protocol for efficient medium utilization. We have done extensive performance evaluation using QualNet to demonstrate its effectiveness. This MAC protocol is based on omni-directional exchange of RTS and CTS. However, the objective of RTS/CTS here is *not to inhibit* the neighbors of transmitter and receiver from transmitting or receiving (as is the case with omni-directional antenna) *but to inform* them about this communication. It also specifies the approx. duration of communication. All the neighboring nodes of transmitter and receiver keep track of the communication, whose direction is known to the each of them from the respective AST and set directional NAV for virtual carrier sense to inhibit communication in that direction only.

3. System Description

3.1 Antenna Model

There are basically two types of smart antennas used in the context of wireless networks: switched-beam or fixed beam antennas and steerable adaptive array antennas [12,13,14]. A switched-beam antenna generates multiple pre-defined fixed directional beam-patterns and applies one at a time when receiving a signal. It is the simplest technique, and comprises only a basic switching function between separate directive antennas or predefined beams of an array of N antenna elements which are deployed into non-overlapping fixed sectors each spanning an angle of $360/N$ degrees. Signals will be sensed in all sectors and the antenna is capable of recognizing the sector with the maximum gain. When receiving, exactly one sector, which usually is the one chosen by the sensing process, will collect the signals.

In a steerable adaptive array antenna which is more advanced than a switched beam antenna, the beam structure adapts to Radio Frequency (RF) signal environment and directs beams towards the signal of interest to maximize the antenna gain, simultaneously depressing the antenna pattern (by setting nulls) in the direction of the interferers [14]. In adaptive array antennas, an algorithm is needed to control the output, i.e. to maximize the Signal to Interference and Noise Ratio (SINR). The difference between both kinds of smart antennas can be resumed as follows: fixed beam antennas focus their smartness in the strongest strength signal beam detection and adaptive array antennas benefit from all the received information within all antenna elements to optimize the output SINR through a weight vector adjustment.

We have developed a wireless ad hoc network testbed using smart antenna[15] where each user terminal uses a small, low-cost smart antenna, known as ESPAR (Electronically Steerable Passive Array Radiator) antenna [16,17,18]. The adaptive array antennas are normally digital beamforming antennas. On the other hand, ESPAR antenna relies on RF beamforming which drastically reduces the circuit complexity. Since ESPAR antenna requires only one receiver chain, it is possible to provide drastic improvement in both dc power dissipation and fabrication costs, by eliminating the need for frequency converters and analog-digital converters by the number of array branches [16]. The ESPAR antenna consists of one center element connected to the source (the main radiator) and several surrounded parasitic elements (typically four to six passive radiators) in a circle (Fig. 2). Each parasitic element (the passive radiators) will be reactively terminated to ground. By adjusting the value of the reactance that terminates the parasitic elements forms the antenna array radiation pattern into different shapes. The features of ESPAR are: controlling beam direction, multiple beams (with same frequency) formation, steerable beam (360 degree sweeping) and controlling null steering. For receiver application, the null should be steered in the direction from which an interfering signal is coming. An adaptive null-steering algorithm at the receiver can also be used [17] to automatically suppress the interfering signal coming from other direction. It has been observed that 360 degree continuous beam / null steering is possible with seven-element ESPAR antenna, with a simultaneous 8dBi beam gain and –30 dBi null [17]. It has also been observed that simultaneous formation of *multiple directed beams and multiple nulls are possible* with seven-element ESPAR antennas.

Developing suitable MAC protocols with adaptive antenna in ad hoc networks is a challenging task. That is why, most of the works in the context of ad hoc networks assume to use simpler switched beam antenna. In this work also, we are using smart ESPAR antenna as a switched beam antenna. ESPAR antenna can also be used as a generalized switched beam antenna or quasi-switched beam antenna, by selecting the value of reactance for one specific directional beam among multiple directional beam patterns, without using multiple receiver chains (frequency converters and analog-digital converters). By including some mechanism to detect *direction of arrival* (DoA) for the signal received from the user (as will be illustrated shortly), continuous tracking can be achieved and it can be viewed as a generalization of the switched beam concept [14]. In this case also, the received power is maximized. The advantage of using ESPAR antenna as generalized switched beam antenna is that, with only one receiver chain, continuous tracking is possible and we can have variable number of beam-pattern. In other words, the directional beams that are formed with ESPAR antenna when used in switched-beam mode need not be restricted to non-overlapping fixed sectors, each spanning an angle of 360/*N* degrees, as in the case of conventional switched beam antenna with N elements. Since ESPAR antenna would be a low-cost, low-power, small-sized antenna, it would help to reduce the power consumption of the user terminals in Wireless Ad Hoc Networks and would be able to deliver all the advantages of switched beam antenna.

The antenna pattern of ESPAR antenna with 60 degree beam width is shown in figure 3(a) and 3(b). Figure 3(a) shows pattern at 0 degree: a beam pattern formed at each antenna element at an interval 0 to 60 degree, 60 to 120 degree and so on, thus forming 6 beams. Figure 3 (b) shows pattern at 30 degree : a beam pattern formed at each in-between antenna elements at an interval 30 degree to 90 degree, 90 degree to 150 degree and so on, thus forming 6 more pattern. Together they constitute 12 overlapping pattern at 30 degree intervals. Figure 3(c) shows the QualNet Default Antenna pattern with 45 degree beam width and figure 3(d) shows an ideal directional antenna with 45 degree beam-width with insignificant side-lobes. As will be demonstrated in performance evaluation, the performance of ideal directional antenna is the best (as expected); at the same time, ESPAR performance is much better than the default antenna pattern of QualNet. The reason is, the pattern of ESAPR has less coverage area with less-pronounced sides lobes, as compared to that with default antenna pattern in QualNet.

3.2 Detecting *direction of arrival* (DoA) and A Location Tracking Mechanism

In this study, each node waits in omni-directional-receive-mode while idle. Whenever it senses some signal above a threshold, it enters into *rotational-sector-receive-mode*. In rotational-sector-receive mode, node n rotates its directional antenna sequentially in all direction at 30 degree interval, covering the entire 360 degree space in the form of the sequential directional receiving in each direction and senses the received signal at each direction. After one full rotation, it decides the best possible direction of receiving the signal with maximum received signal strength. Then it sets its beam to that direction and receives the signal.

However, in order to enable the receiver decoding the received signal, each control packet is transmitted with a preceding tone with a duration such that the time to rotate a receiver's rotational receive beam through 360 degree is less than the duration of the tone. The purpose of this transmitted tone before any control packet is to enable the receiver to track the best possible direction of receiving the signal. Once it sets its beam to that direction, the purpose of tone signal is over and subsequently the control packet is transmitted.

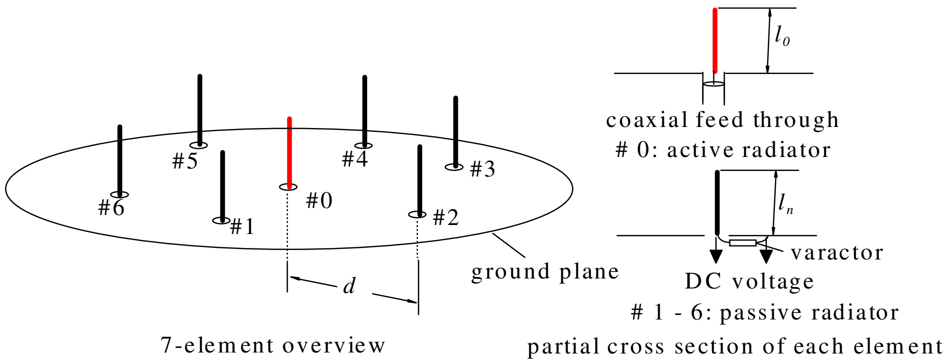
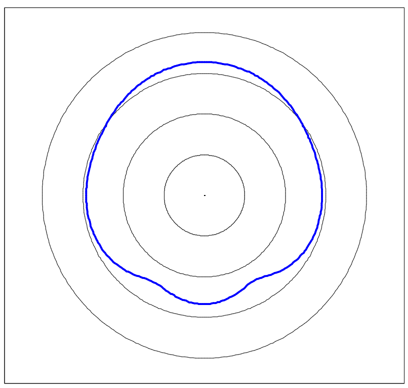
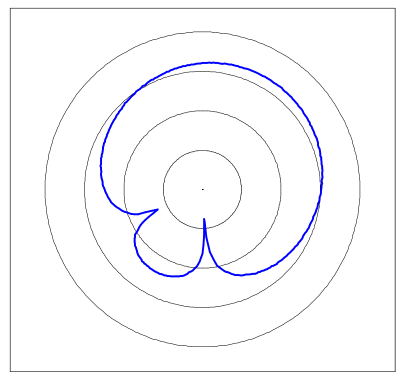


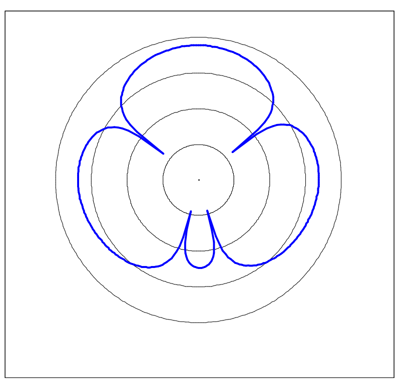
Figure 2: Configuration of ESPAR antenna



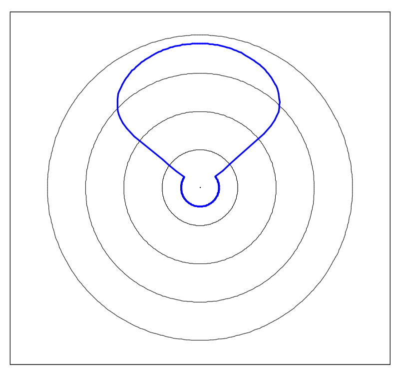
(a) ESAPR pattern at 0 degree



(b) ESAPR pattern at 30 degree



(c) DEFAULT Switched beam antenna pattern in QualNet



(d) IDEAL Directional Antenna

Figure 3. Different Directional Antenna Pattern Used in our Simulation

In this proposed framework, we have used three types of control packets: beacon or "hello" packet used to track the location of neighboring nodes), RTS (Request to send) and CTS (clear to send) for medium access control. Beacon is a periodic signal, transmitted from each node at a pre-defined interval. At each periodic interval, each node, say, m, sends an omni-directional beacon to its neighbors, if the medium is free. As indicated earlier, each beacon is transmitted with a preceding tone signal that helps the receivers to detect the best possible direction of receiving the beacon. Then each receiver sets its beam to that direction and receives and decodes the beacon. Thus, the node n which is, say, a neighbor of m forms the Angle-Signal information for node m, and similarly, for other neighbors. An entry in AST of node n for its neighbor m is $SIGNAL^{á}_{n,m}(t)$, which is the maximum strength of received signal at node n from node m at an angle á with respect to n and as perceived by n at any point of time t. Based on AST, a node n knows the direction of node m and controls the medium access during transmission-reception.

Since RTS is a broadcast packet and contains source address, nodes can decode that RTS also to form the Angle-Signal Table. So, we have used RTS as beacon. If an RTS is sent, beacon timer is reset. The use of RTS as beacon is advantageous at high traffic where overhead due to beacon is minimized. This is because, the transmitting nodes don' t have to send an additional beacon to inform its neighbors of its presence.

3.3 Medium Access Control Protocol to Support Directional Communications

In IEEE 802.11 MAC protocol standard, RTS-CTS-DATA-ACK exchange mechanism is used to ensure reliable data communication. In our scheme, initially, when node n wants to communicate with m, it senses the medium and if it is free, sends *omni-directional RTS*. The back-off mechanism is same as in IEEE 802.11. The purpose of RTS is to inform all the neighbors of n, including m, that a communication from n to m has been requested. It also specifies the approximate duration of communication. All the neighboring nodes of n keep track of this request from node n, whose direction is known to the each of them from the received RTS signal. The mechanism for receiving RTS is same as that for beacon.

The target node m sends an *omni-directional CTS* to grant the request and to inform the neighbors of m that m is receiving data from n. It also specifies the approx. duration of communication. All the neighboring nodes of m keep track of the receiving node m, whose direction is known to the each of them from the received CTS signal. Once again, the mechanism for receiving CTS is same as that for beacon. It is to be noted that the objective of RTS/CTS here is not to inhibit the neighbors of n and m from transmitting or receiving (as is the case with omni-directional antenna) but to inform the neighbors of n and m that m is receiving data from n.

After transmission of omni-directional CTS, the receiving node waits in directional receive mode until Data is transmitted or timeouts and returns to omni-directional receive mode. Also, once the CTS is received, the transmitter transmits Data directionally and waits for Acknowledgement directionally until Acknowledgement is received or timeouts and returns to omni-directional receive mode. The directional reception mode ensures proper reception of signal from the required direction and minimization of interference from other direction.

Other nodes in the neighborhood of n and m, who overheard the RTS/CTS exchange, set their Directional Network Allocation Vector (DNAV) in the direction which they detected as the direction of arrival of the RTS or CTS respectively. Now, if they have a packet to send to a node, whose direction (as known from AST) is not in the direction of blocked DNAV, then they can issue both RTS and CTS omni-directionally *without disturbing the communication between n and m*. If the direction of receiving node is blocked by DNAV and RTS is issued, it is most probable that CTS will not be issued or their may be RTS collision. As a result, the node will increase its contention window and enter into backoff. This may happen repeatedly and as a result, the node will get less chance to transmit. So, we do not allow transmission of RTS in this case. Here, the node waits for DNAV time and then tries to start communication, which is similar to waiting for NAV as explained in standard IEEE 802.11.

Figure 4 illustrates the mechanism of two simultaneous communications in the same region. Let us assume that nodes S and D are communicating. The directional beam from S covering D is shown in the figure. Now, another pair of nodes X and Y, both in the omni-directional neighborhood of S and D, desires to communicate (fig. 4). Both of them have already received RTS/CTS from S-D. From their respective ASTs, X knows the angular position of S and D with respect to X and Y also knows the angular position of S and D with respect to Y. Both X and Y will set the DNAV towards S and D. If the directional beam from X to Y captures S or D, then the node X has to sit idle until time-out mentioned in DNAV and thus defer its desire. Otherwise, node X can issue a RTS. In other words, a node can issue RTS only if this communication does not intrude into the area of existing communications. Figure 5 shows the State Transition Diagram of the proposed scheme.

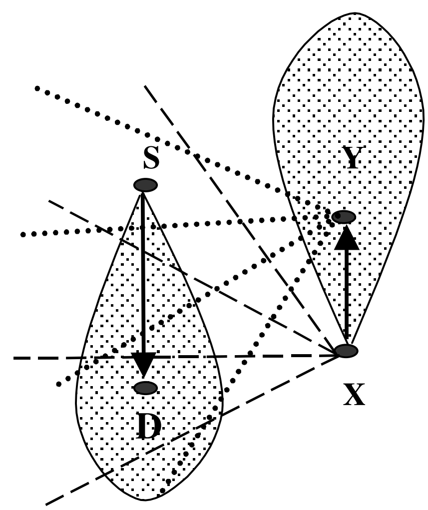
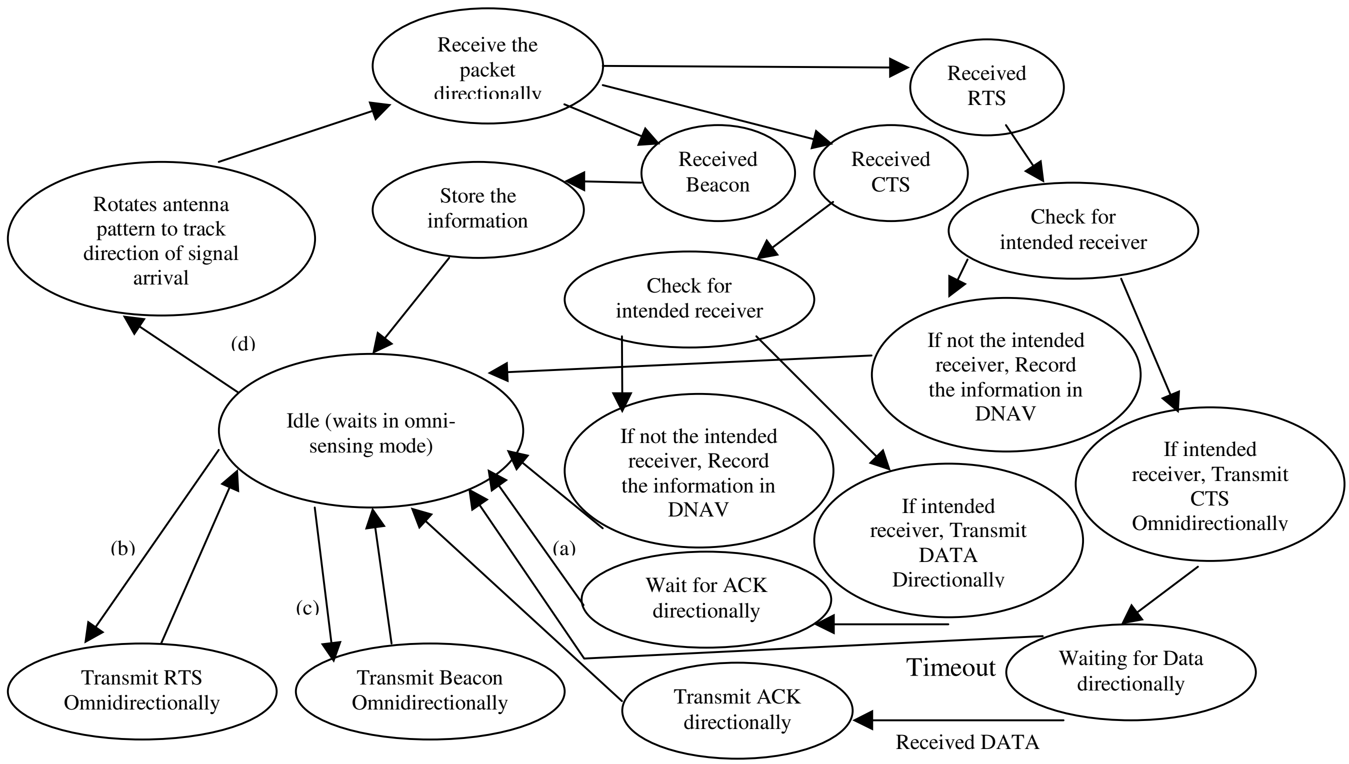


Figure 4: Multiple Simultaneous Communication



(a) Received ACK or timeout
(b) Data to send and DNAV in the direction of the receiver is not blocked
(c) Timeout Beacon Timer
(d) Signal Level above Sensing Threshold

Figure 5: State Transition Diagram of the Proposed Scheme

3.4 A Few Assumptions and the Rationales

- When the antenna of a node operating in omni-directional mode, it is capable of transmitting and receiving signal from all directions with a gain, say, G^{omni}. While idle, a node operates in omni-directional receive mode.
- When the antenna of a node operating in directional mode, a node can point its beam (main lobe) towards a specified direction with beam width *w* and with a gain, say G^{dir} ($G^{dir} >> G^{omni}$). Beam width is around 60 degree in our simulation.
- Consequently, for a given amount of input power, the transmission range R^{dir} with directional antenna will be much larger than that with corresponding omni-directional antenna (R^{omni}).
- We define neighbors of a node n as a set of nodes within the omni-directional transmission range of n. they are assumed to be one-hop away from n. It implies that, a node outside the

omni-directional transmission range of n will not be considered as neighbor of n, even if it is reachable by n in one-hop using directional beam from n formed towards that node. From the perspective of directional data communication, it implies that a neighbor, say, m of a node, say, n is always a *strong* neighbor. As shown in figure 1, when a node n forms a directional beam towards its neighbor m, m is well-within the transmission zone so formed (as shown). Hence, the received signal strength at m from n is always high to ensure proper capture even in presence of other interferences. Thus, the chance of m getting disconnected or weakly connected during a data packet transfer from n due to an outward mobility of either m or n is far less.

- This will alleviate the problem of hidden terminal in this context as indicated in [4]. Let us consider figure 6 where node n is communicating with node m with directional beam. Node p now wants to communicate with node q . If node p is within the neighborhood of n, this communication will not be initiated, since p is not allowed to form directional beam towards n and/or m. However, if node p is outside the neighborhood of n, node p forms a directional beam towards node q and starts communication. This may interfere with node m's reception. However, since the distance p and m is larger than n and m by at least R^{omni} (the omni-directional range), the received signal at m from n will predominate and chance of data packets being lost due to this interference will be insignificant.
- However, as a consequence of this assumption, we are sacrificing multihop efficiency which could have been achieved using directional antenna, since using larger range of directional beam, a destination is reachable in fewer number of hops as compared to that using omni directional antenna. However, what we are gaining is SDMA efficiency, as will be demonstrated in the performance evaluation.

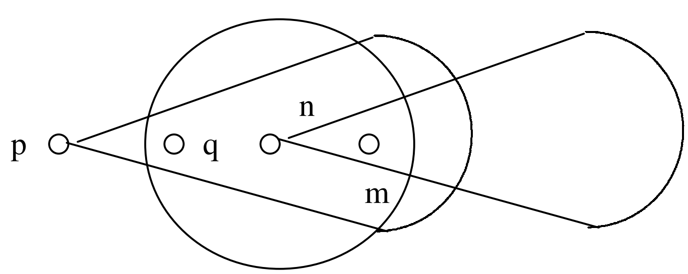


Figure 6: The capture of receiver m by transmitter n is strong enough to tolerate interference from another transmitter p.

4. Performance Evaluation

4.1 Simulation Environment

The simulations are conducted using QualNet 3.1 [12]. We have simulated ESPAR antenna in the form of a *quasi-switched beam antenna*, which is steered discretely at an angle of 30 degree, covering a span of 360 degree. We have simulated our MAC protocol with (i) Simulated ESPAR Antenna Pattern (ESPAR), (ii) QualNet' s default directional antenna pattern (DEFAULT) and (iii) an Ideal directional antenna pattern without sidelobes (IDEAL) as described in Section 3.1. We have done the necessary changes in QualNet simulator to implement Directional Virtual Carrier Sensing in MAC Layer and directional transmission in Physical Layer of QualNet simulator. In our simulation, we have chosen the duration of preceding tone in control packets to be 200 microseconds, based on the hardware performance of ESPAR antenna.

We have used simple one-hop randomly chosen communication in order to avoid the effects of routing protocols to clearly illustrate the difference between 802.11 and our proposed MAC. Also, we have used static routes to stop all the packets generated by any routing protocol, whether it is proactive or reactive. In our simulation, we studied the performance of the proposed MAC protocol in comparison with the existing omnidirectional 802.11 MAC protocol by varying the Data Rate and number of simultaneous communications. In studying our MAC protocol, we have used different antenna patterns as described above to ensure the robustness of our proposed MAC protocol. In doing this, we have used ESPAR antenna as one of the antenna patterns, to evaluate the performance of the ESPAR antenna as well.

40 nodes are randomly placed over 1000 x 1000 meter area. The simulation has been conducted in 2 steps. Firstly, keeping the number of simultaneous communication constant at 10, the data rate is gradually increased from 81.92Kbps (512 bytes of Data Packets injected at an interval of 50ms) to 2.048 Mbps (512 bytes of Data Packets injected at an interval of 2ms). Secondly, keeping the data rate constant at 409.6Kbps (512 bytes of Data Packets injected at an interval of 10ms), number of simultaneous communication is increased from 4 to 12. In both the steps, we evaluated Average Throughput and One Hop Average End-to-End Delay.

The set of parameters used is listed in Table I.

Table I. Parameters used in Simulation

Parameters	Value
Area	1000 x 1000 m
Number of nodes	40
Transmission Power	15 dBm
Receiving Threshold	-81.0 dBm
Sensing Threshold	-91.0 dBm
Data Rate	2Mbps
Packet Size	512 bytes
Duration of Preceding Tone in RTS/CTS/Beacon	200 microseconds
CBR Packet Arrival Interval	2 ms to 50 ms
Number of simultaneous communication	4 to 12
Simulation Time	5 minutes

4.2 Results and Discussions

We have used the existing IEEE 802.11 MAC, which we caption as "802.11", as a benchmark to compare and evaluate the performance of our proposed MAC protocol with ESPAR antenna (ESPAR), QualNet' s default antenna(DEFAULT) and an ideal antenna (IDEAL) respectively. Our evaluation is based on two criteria: ***Average Throughput,*** and ***One Hop Average End-to-End Delay.***

The results are shown in Figure 7 and Figure 8 respectively. Each result reported is an average of ten executions with different seeds. So, to complete our results, we had to simulate over 400 scenarios, each of which was executed in the simulator for 5 minutes to get an overall average result.

In Figure 7(a), it is seen that with increasing data rate, average throughput of our proposed MAC protocol (E-MAC) with any directional antenna pattern is much better than that of IEEE 802.11 with omni-directional antenna. It is also seen in Figure 7(b), that One Hop Average End-to-End Delay performance of E-MAC with any directional antenna is much better than that obtained with IEEE 802.11 protocol.

In omnidirectional 802.11, nodes have to enter in a backoff state more often as they find the medium busy. With increasing data rate, contention in MAC increases. But, with the use of directional antenna, and the implementation of Directional Virtual Carrier Sensing, E-MAC creates an environment of lower contention which "802.11" cannot create with an omnidirectional antenna. Hence, with increasing data rate, Average Throughput increases sharply in E-MAC as shown in Figure 7(a). In E-MAC, once RTS/CTS handshaking is done, a node transmits and receives Data and Acknowledgement directionally with high gain. So, the chance of missing the Data at the receiver end or the Acknowledgement at the transmitter end is minimised. But, in 802.11, the chance of missing Data is even more than that of RTS/CTS. This is due to two reasons: (a) Data is sent with same gain as in RTS/CTS omnidirectionally and received omnidirectionally, and (b) Data is a large packet compared to RTS/CTS and proper reception requires SINR level to remain high for a longer period of time. These reasons also account for higher Average Throughput and lower end-to-end delay in E-MAC as compared to 802.11.

MAC Performance depends much on directional antenna pattern also. So, we have simulated for 3 different types of directional antenna patterns. QualNet default is a standard antenna pattern. Ideal antenna is an ideal directional antenna pattern with no sidelobes. This is already illustrated in section 3.1. Average throughput with ESPAR Antenna is better than the QualNet default antenna, and the gain in throughput obtained with ESPAR is nearly 1.8 times than that of IEEE 802.11.

In Figure 8(a), it is observed that with increasing number of simultaneous communication, average throughput decreases in both E-MAC and 802.11, but E-MAC shows significant gain in Average Throughput. This is because E-MAC does not inhibit neighboring nodes to transmit, but just informs neighbors of the ongoing communication and its direction, so that they can start communication in other directions. But 802.11 with omnidirectional antenna, keeps all neighboring nodes silent by issuing RTS/CTS.

Also, with increasing number of simultaneous communication, Average End-to-End Delay (one-hop) increases in both IEEE 802.11 and E-MAC, as shown in Figure 8(b), but the increase is much prominent in "802.11" than in E-MAC, irrespective of the directional antenna pattern used. With increasing number of simultaneous communication, interference to each communication increases due to interference of added number of simultaneous communication. But, E-MAC not only informs other nodes in its vicinity of the on-going communication, but also transmits and receives directionally with larger capture, which minimizes interference from other directions also. Thus E-MAC exploits SDMA efficiency for which more number of simultaneous communication is possible which leads to lesser queuing delay and lesser one hop average end-to-end delay as observed in Figure 8(b).

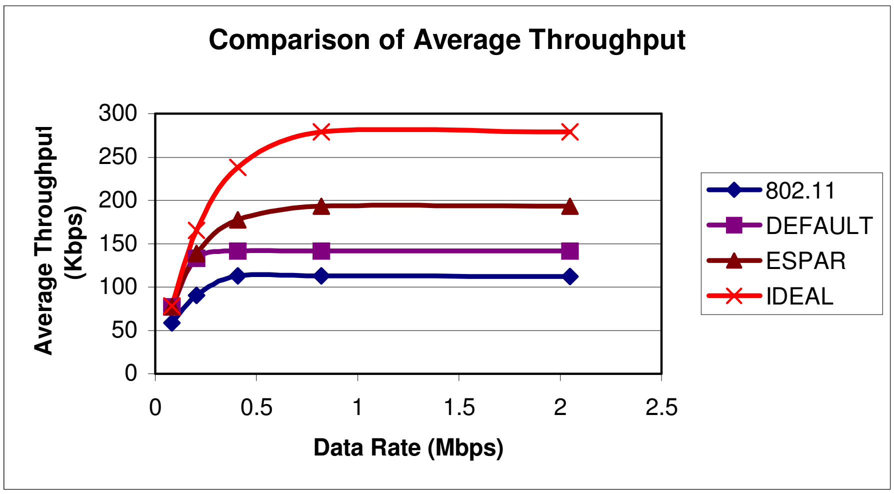


Figure 7(a): Comparison of Average Throughput of IEEE 802.11 and E-MAC with Espar Antenna, QualNet Default Antenna and an Ideal Antenna with increasing Data Rate at 10 simultaneous communications

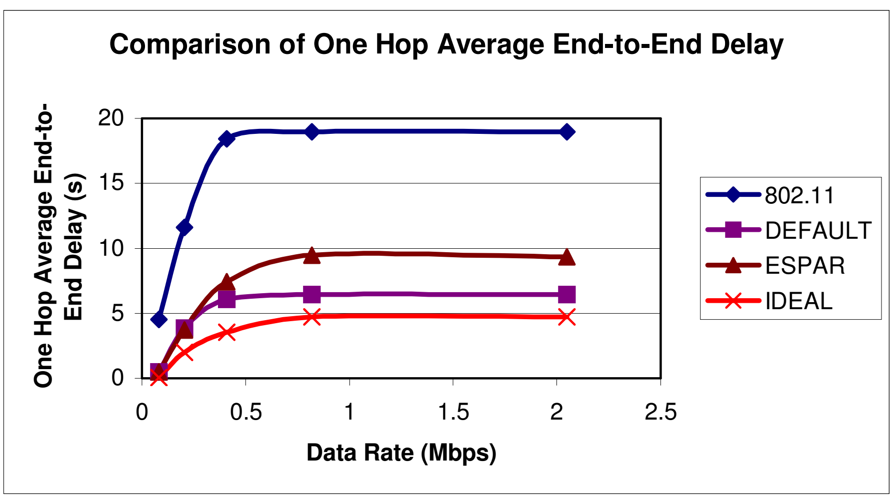


Figure 7(b): Comparison of One Hop Average End-to-End Delay of IEEE 802.11 and E-MAC with Espar Antenna, QualNet Default Antenna and an Ideal Antenna with increasing Data Rate at 10 simultaneous communications

Figure 7: Performance Evaluation of the proposed MAC protocol with directional antenna with increasing data rate

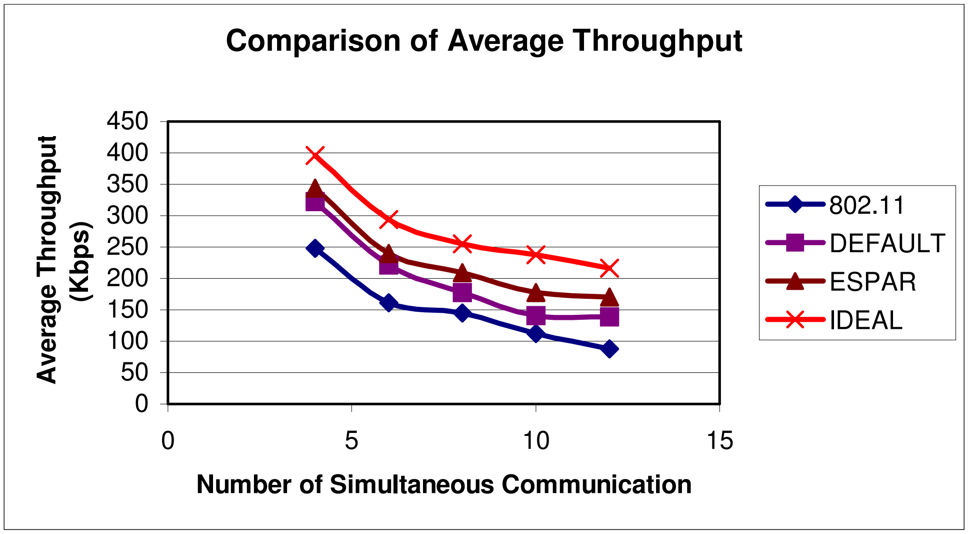


Figure 8(a): Comparison of Average Throughput of IEEE 802.11 and E-MAC with Espar Antenna, QualNet Default Antenna and an Ideal Antenna with increasing number of simultaneous communications at a constant data rate of 100 packets per sec. where each packet is of 512 bytes

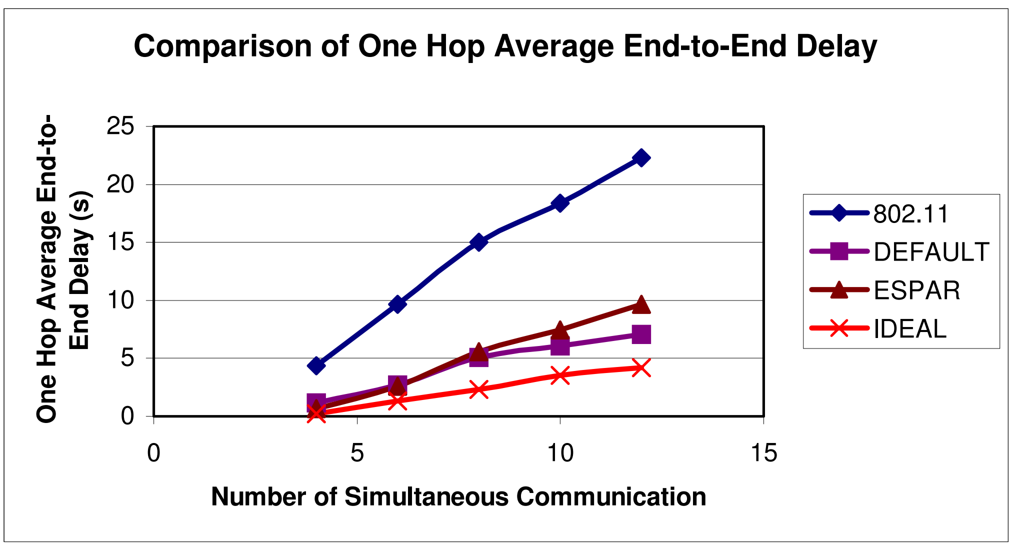


Figure 8(b): Comparison of One Hop Average End-to-End Delay of IEEE 802.11 and E-MAC with Espar Antenna, QualNet Default Antenna and an Ideal Antenna with increasing number of simultaneous communications at a data rate of 100 packets per sec. where each packet is of 512 bytes

Figure 8: Performance Evaluation of the proposed MAC protocol with directional antenna with increasing number of simultaneous communication

5. Conclusion

Use of directional antenna in ad hoc wireless network can drastically improve system performance, if proper MAC protocol can be designed. With directional setting of Virtual Carrier Sensing, medium can be utilized to its maximum with directional antenna. With a minimum overhead of location tracking, gain obtained in MAC is really significant. Also, the success of the MAC protocol highly depends on the directional antenna pattern. Average throughput with ESPAR Antenna is better than the QualNet default antenna, and the gain in throughput obtained with ESPAR is nearly 1.8 times than that of IEEE 802.11.

The location tracking mechanism as done in our proposed MAC protocol can be utilized in designing efficient Routing protocol also as done in [19]. Presently, we are working on efficient controlling of transmission power to improve the proposed MAC performance.

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