Performance of Directional MAC Protocols in Ad-Hoc Networks over Fading Channels

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Abstract— **The application of directional antennas in mobile ad-hoc networks (MANETs) has proved to offer large throughput gains relative to single-antenna systems. Recent works on directional Medium-Access-Control (MAC) protocols have been *only* focused on their performance over additive white-Gaussian noise (AWGN) channels. In this paper, we evaluate the performance of directional MAC protocols when the channel is modeled as a slow-fading one. In this case, directional antennas are used for the transmission of data frames while control frames are sent using an omnidirectional antenna. Considering a slow-fading channel, our results show large throughput improvements when using directional MAC protocols relative to the IEEE 802.11 standard. Furthermore we show that the throughput loss on the fading channels relative to the AWGN channel, can be well compensated using antenna arrays. All our results show that the use of directional antennas at the mobile station can improve the channel efficiency in an ad-hoc network.**

Index terms— Ad-hoc networks, directional antennas, fading, system throughput.

I. INTRODUCTION

A mobile ad-hoc network (MANET) consists of a collection of possibly mobile devices or nodes that establish communications with each other without any pre-existing infrastructure where network control is distributed among the mobile nodes [1],[2]. In that sense, it is a self-organizing and self-configuring multihop wireless network. In a MANET, each node functions not only as a host but also as a router which maintains a routing path and relays data packets to other nodes in the network that may not be within the direct wireless transmission range. Given the diverse advantages of ad-hoc networks, it has been widely deployed in many applications.

Directional antennas have been proposed as a means to enhance performance of mobile ad-hoc networks [3],[4]. It can improve the overall network capacity by increasing the range of communications while reducing the susceptibility to detection errors, interception and jamming. With antenna beamforming, one can also conserve more transmission power and reduce collisions. From the network throughput point of view, the most important feature of a smart antenna system is its capability to cancel co-channel interference (i.e., collisions). While traditional mobile nodes were only equipped with omnidirectional antennas, recent development of efficient algorithms and low power hardware implementations will make it possible to implement adaptive antenna arrays on low power mobile nodes [5].

In ad hoc networks, the transmission and reception of users' signals are based on omnidirectional antennas. The distributed coordination function (DCF) of the MAC layer protocol defined in the IEEE 802.11 standard is usually used in ad hoc networks [1],[2]. Using Carrier sense multiple access with collision avoidance (CSMA/CA), all nodes in an ad hoc network contend for a single channel access. Therefore, when the number of nodes increases, the performance of the system will dramatically degrade due to the large number of collisions. This, in turn, results in an overall low system throughput. Recent works on improving the throughput of ad hoc networks have focused on Frequency Division Multiple Access (FDMA) techniques as in [6]-[9]. In this case, the throughput improvement is achieved through multiple frequency channels and based on a single-antenna transmission/reception. As an alternative to using multiple frequency channels, it has been shown that the use of directional antennas can bring the overall system throughput to higher levels (e.g., [10]-[15]). In these multiple antenna systems, every ad hoc node is assumed to be equipped with multiple antennas to improve the spatial use of the channels between different users in the network. Recently, many works have focused on the potential gains achieved using directional antennas in ad hoc networks. In [10], Ku *et. al* proposed two MAC schemes using directional antennas. The first scheme makes use of directional request-to-send (DRTS) while in the second scheme both DRTS and omnidirectional RTS (ORTS) are employed. Following the same lines, the Choudhury *et. al* [13] proposed two MAC protocols: (i) a Directional MAC (DMAC) protocol (ii) Multi-Hop RTS MAC (MMAC) protocol. Based on the performance results presented in [13], the authors showed that both DMAC and MMAC perform better than the IEEE 802.11 (although the performance is dependent on some conditions in the network [13]). Furthermore, in [15], a two-channel MAC layer protocol that avoids the hidden-terminal problem has been introduced and examined over AWGN channels. The proposed protocol in [15] includes a new frame called *Request for address*. This frame is used to exchange the position information among

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active stations which is then used to update the antenna array weights.

Since users in an ad hoc network are free to move, the transmitted signals from the source to the destination node will suffer from multipath fading. In this paper, we evaluate the effect of signal fading on the throughput performance of mobile ad hoc networks when equipped with directional antennas. Considering a slow-fading channel, our results show large throughput improvements when using directional MAC protocols relative to the IEEE 802.11 standard. Furthermore we show that the throughput loss on the fading channels relative to the AWGN channel, can be well compensated using antenna arrays.

The rest of the paper is organized as follows. In Section II, we give an overview of the directional MAC protocol used in our study. The simulation model is presented in Section III. Simulation results and performance comparisons are given in Section IV. Finally, conclusions are provided in Section V.

II. PROTOCOL REVIEW

In this section, we give an overview of the directional MAC protocol proposed in [15]. Later, we consider this MAC protocol, as one of the existing protocols, to evaluate the performance of the ad hoc network on a slow-fading channel. In [15], each mobile ad-hoc station is equipped with a global positioning system (GPS) to obtain its position information. Different from other directional MAC protocols, in [15], the RTS and CTS frames can carry position and antenna weight information. The protocol in [15] introduces a new frame referred to as request-for-address (RFA), used to exchange position information among active stations.

To describe the operation of the two-channel MAC protocol, we show a simple 4-station scenario as Fig. 1. As shown, station A transmits to station B and station C transmits to station D. Assuming that station A initiates the transmission, it sends an RFA frame using its omnidirectional mode on the control channel. Once station A's RFA is received by station B, it replies back with its own position information in an Request-for-address acknowledgement (RFA-ACK) packet. Upon receiving this information, station A writes the position information of A and B into its RTS frame, combined with other information, and sends it back to station B using the omni mode and on the control channel. Once receiving the RTS, station B also writes the position information of A and B into its CTS frame, and sends it back to station A when the channel is free. After receiving the CTS (i.e., now station A knows the position of station B as well), station A starts its data transmission to station B using its directional mode on the data channel. Note that one key feature of this directional MAC protocol, is that the antenna beamforming process takes into consideration the direction of interfering stations. This, in turn, improves the overall network throughput since more simultaneous transmissions within the network range can take place with minimum interference/collisions.

Going back to the scenario in Fig. 1, now stations A and B finish the handshake period in the control channel. When station C's NAV decreases to zero and if station C has data to send to station D, it then sends an RFA to D on the control channel. Station D then replies back with an RFA-ACK. Note that, now, station C acquires the position information of the stations within it neighborhood (i.e., received from A's RTS and in D's RFA-ACK). Given this information, station C can perform a virtual carrier sense. Based on a Pre-set bit-error-rate (BER) threshold, station C can decide whether to use the data channel to send messages by using the directional mode on the data channel or not. Note that if the virtual carrier sense shows that the data frame transmitted from C may cause failures to ongoing transmissions (or station D could not receive data in a satisfied bit error rate) station C will keep silent until the ongoing transmission finishes. On the other hand if the virtual carrier sense shows that the use of data channel by station C and D will not interfere with any ongoing transmissions, station C will keep the weights of C and A in its memory.

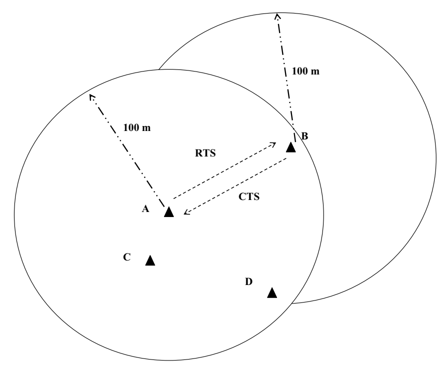

Fig. 1. 4-station scenario.

III. SIMULATION MODEL

To examine the performance of directional MAC protocols, we consider a simple ad hoc network comprised of 10 nodes in a square area 200 meter by 200 meter (see Fig. 2). Each station randomly moves in this network resulting in a different (random) network topology at different simulation times. To realize the new protocol, all stations are equipped with directional antennas, which can be operated in both omni and directional modes of operation. The link between the transmitting station and the receiving one is modeled as a flat slow-fading channel where the fading coefficient is fixed within a frame period and change independently from one frame to another.

For practical considerations, and since power requirements are stringent in ad hoc networks, we assume that the radio range for both the omni and the directional modes of operation are the same and equal 100 meters. Also, in order to study the out-of-range problem, we assume that the radio range of each station be 100 meters. Similar to previous works [10]-[14], we assume that each ad hoc station be equipped with a GPS to determine its position. It is to be mentioned that in recent works, other location techniques like Ad Hoc location sensing (AHLoS) can be used to replace the GPS in some cases. In general, there are two other possible techniques that can be more suitable than the GPS in indoor applications: (i) Infrared (IR) location based systems such as the Active Badge system where nodes are equipped with IR devices that offer very high precision in determining the location of nodes [16],[17].

Two FDMA channels are used; one channel is dedicated to control signals between the transmitting and receiving stations, referred to as the control channel. This channel is mainly used for the transmission of RTS, CTS, and ACK frames. The second channel, referred to be as the data channel, is used for data transmissions between mobile stations.

IV. Throughput Performance over Fading Channels

Throughout our simulation, we consider two network populations: (i) The fixed topology of ten users discussed earlier, where users 1 to 5 act as the transmitting stations and users 6 to 10 as the receiving ones. (ii) a 30-user network where users 1 to 15 act as the transmitting stations and users 16 to 30 as the receiving ones. For this 30-user network, we evaluate the average throughput over 50 randomly generated topologies. In both scenarios, Without loss of generality, we consider a transmission scenario as follows: $1 \rightarrow 6/16$, $2 \rightarrow 7/17$, $3 \rightarrow 8/18$, and so on, where $x \rightarrow y$ signifies a transmission from station x to station y. The total throughput is defined as the average number of successfully received frames per second (control frames are not included). Similar to [15], the directional MAC protocol employs a one-hop routing protocol to solve the out of range problem (only one station acts as router in the transmission path from the source to destination station). All the simulation results were obtained using Matlab. The remaining simulation parameters are assumed as follows:

- The length of the RTS and CTS are fixed to 20 bytes and 14 bytes respectively, as defined by the IEEE 802.11 standard. Since both the RTS and CTS messages in our protocol carry positions information, one would expect the length of these messages to grow with the number of users.
- The simulation time is 1 second, and the channel rate for each station is set to 1 Mbps with a data frame length of 8,000 bits.
- Since the main focus of our work is to evaluate the throughput performance over fading channels, we assume that the data frames from upper layers are available at the source station and ready to transmit.

In Fig. 3, we compare the total throughput achieved as a function of the signal-to-noise ratio (SNR) over both the slow-fading and AWGN channels. Also to see the advantage of using antenna arrays as opposed to omni-directional antennas, we include the results for the single-antenna IEEE 802.11 over both channel models. For the case of directional MAC, the number of antennas is set to five elements. As shown from these results, the total system throughput is dramatically affected by the fading channel impairments relative to the AWGN channel. This performance degradation compared to the AWGN channel is mainly due to the large probability of errors at low SNRs, which is translated into low system throughput. Note that, the BER threshold for successful transmission of a data frame is set to 10^{-5}. That is to say if the BER of the received data frame is greater than 10^{-5}, we consider the received packet to be in error and a retransmission is requested. This is clear from the throughput performance over the fading channel, where at large SNRs (>35 dB) the throughput performance of both channels is almost the same. Later, we show that one can achieve a throughput close to the AWGN channel at moderate SNRs by increasing the number of antennas. This throughput versus antenna tradeoff will be discussed when we examine the effect of the number of antennas on the throughput performance. One final remark on the results in Fig. 3, is that the maximum achieved throughput

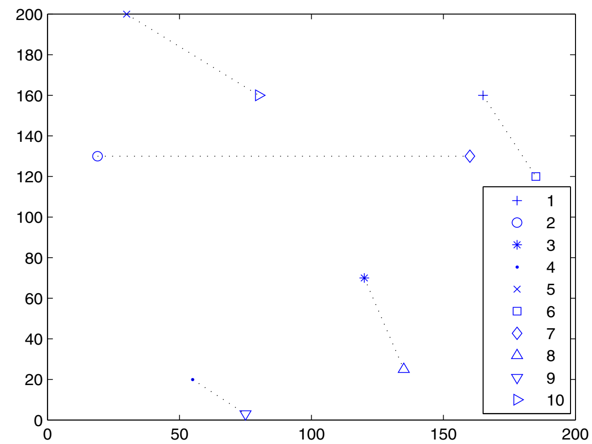

Fig. 2. 10-station scenario with random configuration.

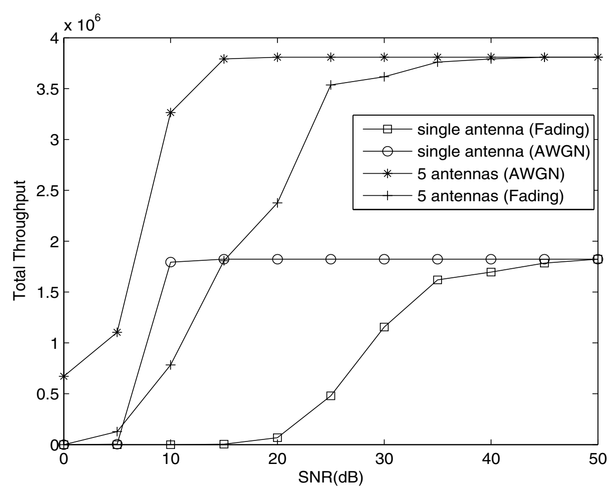

Fig. 3. *Total throughput* of the two-channel directional MAC protocol for fading and AWGN channels with 5-antenna elements and a load of 1 Mbps per station.

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(for both the AWGN and fading channels) is around 3.8 Mbps. A close look at the topology in Fig. 2, this throughput can be easily justified with four stations simultaneously being able to transmit at the full rate of 1 Mbps using the 5-element antenna array (all stations can transmit to their destination stations, except station 2→7). One should note that for the case of single-antenna element, only two pairs of stations can simultaneously communicate and hence the throughput upper bound in this case is limited to 2 Mbps (i.e., only 2 pairs of stations are out of range).

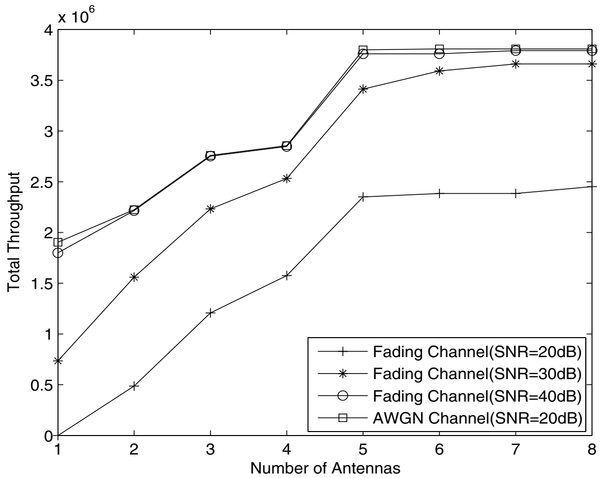

Fig. 4. Effect of number of antennas on the *total throughput* with load per station=1Mbps.

In Fig. 4, we examine the effect of antenna array elements on the throughput performance as a function of the SNR. Without loss of generality and for the purpose of getting an insight of the operation of the directional MAC protocol, we consider the snapshot topology in Fig. 1. Later we present simulation results for the more general case of randomly generated topologies. Several remarks can be drawn from these results. For the case of single-antenna element, the maximum number of transmitting stations is limited to two regardless of the channel model. Confirming our previous conjunctures, the throughput in this case is upper bounded by 2 Mbps. For the AWGN channel, and since the BER performance at the prescribed SNR is low (lower than the threshold BER), a performance very close to this throughput upper bound is achieved. Similar arguments can be applied to the results of the fading channel. At fixed SNR the throughput performance (on both channels) is shown to increase as the number of antennas gets larger, demonstrating the ability of adaptive antennas in canceling interference and hence allowing for more simultaneous transmissions. This advantage diminishes when the number of antennas reaches a point where all neighboring stations can simultaneously communicate (4 pairs of stations for the topology of Fig. 2). Note that the difference in the maximum achieved throughput at different SNRs, relative to the AWGN channel, is simply due to the unsuccessful transmissions caused by the channel errors.

Fig. 5 shows the throughput performance on the slow-fading channel at different fixed loads per station for the topology in Fig. 2 and using 3-antenna elements. Also for reference, we include the throughput results for the AWGN channel. In this case, using three antennas can allow three stations (neighboring) to transmit simultaneously resulting in a maximum throughput close to 3 Mbs as depicted from these results.

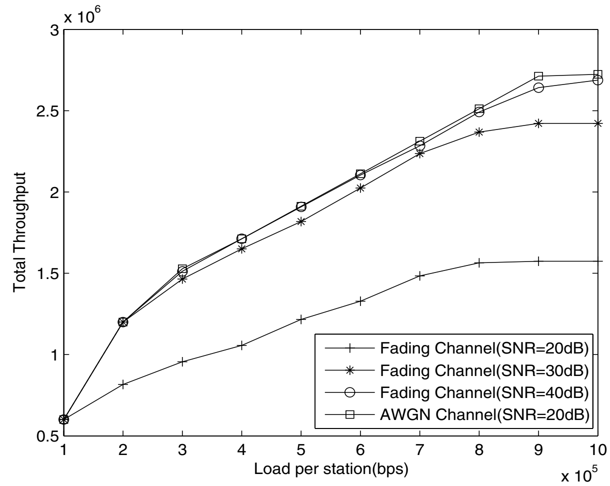

Fig. 5. *Total throughput* for fading and AWGN channels at different loads and 3-antenna elements per station.

In the following simulation results, we consider the performance of the two-channel directional MAC protocol in the highly condensed network comprising of 30 stations over the area of 200 meter by 200 meter. The total throughput is averaged over 50 randomly generated topologies. In Fig. 6 the average system throughput is obtained as a function of the number antenna elements, for a fixed rate of 1 Mbps per station. One interesting remark on these results, compared to the 10-user topology discussed earlier, is that here throughput grows almost linearly with the number of antennas. Also when compared to the 10-user topology, we noted as the network becomes highly populated, large number of antennas are required to reach the maximum throughput (i.e., 5 antennas for the 10-user topology, and 12 antennas for the 30-user topology). This clearly shows the advantage of using directional antennas in highly condensed networks where interefrnce/collision is high.

In Fig. 7, for the 30-station network, the average throughput of the 50 random topologies is shown for different loads per station. In these results, the number of antennas is fixed to three. Both the AWGN and slow-fading channel are considered. As shown from Fig. 7, when the system load is light, the average throughput is the same for both the AWGN and fading channels. This is simply due to the fact that when the load is light (< 0.2 Mbps per station), all transmitting stations can finish their transmission during the simulation period. The results in Fig. 7 suggest that the use of directional antennas, in general, will improve the overall network throughput over fading channels. Also one should note that, the throughput is

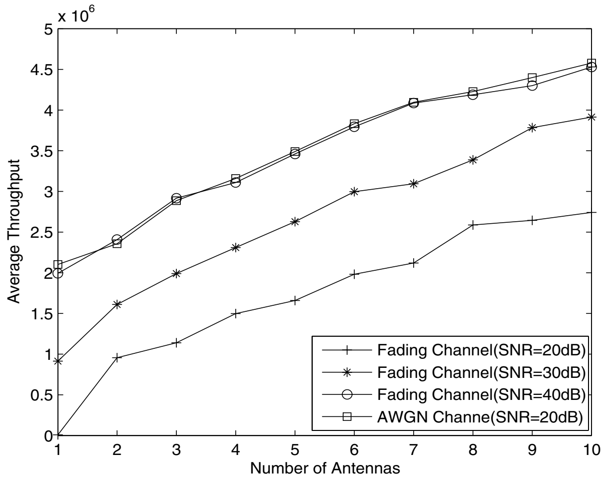

Fig. 6. *Average throughput* for fading and AWGN channels using different number of antennas and load per station=1Mbps (50 random topologies).

dependent not only on the number of antennas and transmitted signal power, but also on the network topology and the number of active stations within this topology. This is clear from Fig. 5 (10 stations) and 7 (30 stations) where almost the same throughput is achieved.

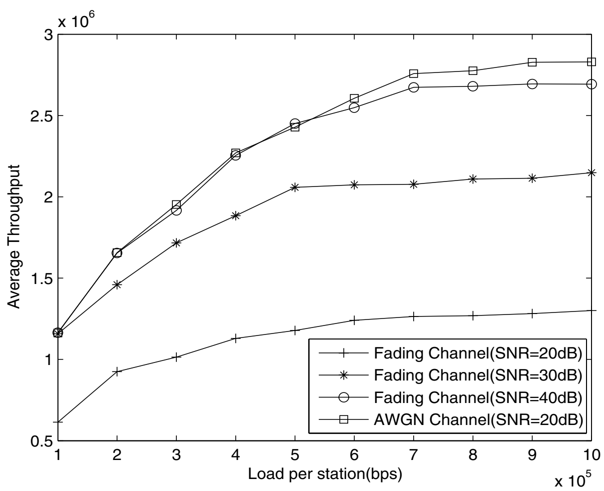

Fig. 7. *Average throughput* for fading and AWGN channels with different loads per station, 3-antenna elements per station (50 random topologies).

V. CONCLUSIONS

The performance of directional MAC in ad hoc networks was evaluated on slow-fading channels. The use of adaptive antennas at the mobile ad hoc stations is shown to significantly improve the overall network throughput relative to the case of single omni-directional antennas. This large throughput gain is achieved by allowing more simultaneous transmissions relative to the single-antenna case where interference limits the overall network throughput. Furthermore, it was shown that the throughput performance is highly dependent on both the network topology and the number of active users.

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