ADAPT: A MEDIA ACCESS CONTROL PROTOCOL FOR MOBILE AD HOC NETWORKS USING ADAPTIVE ARRAY ANTENNAS

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Abstract - Adaptive array antennas have the ability to automatically respond to an unknown interference environment, in real time, by steering nulls and reducing side lobe levels in the direction of interference, while retaining some desired signal beam characteristics. In this paper, we present a protocol (ADAPT) that enables nodes in an ad-hoc network to efficiently utilize adaptive array antennas to communicate. We compare our adaptive antenna configuration {ADAPT, adaptive array antennas} to both an omni-directional setting {802.11,omni-directional antennas} and a directional one {DMAC protocol [6][7], directional antennas} in terms of network throughput and end-to-end delay. Our protocol achieves up to a 60% throughput and 2-3x delay improvement over the omni-directional case and up to a 40% throughput and 55% delay improvement over the directional one, in most scenarios considered.

Keywords - ad-hoc network, adaptive array, smart antenna.

I. INTRODUCTION

Wireless ad-hoc networks are multi-hop networks where all nodes cooperatively maintain network connectivity without the need of any wired infrastructure (e.g. base stations, routers, etc.) It has commonly been assumed that nodes in ad-hoc networks are equipped with omni-directional antennas. However, this trend has changed during the past few years. It is now recognized that the use of directional or smart antennas could be very beneficial in the context of ad-hoc networks [11]. Such antennas have the ability to concentrate the radiated power towards the intended direction of transmission. As a result of this, they can help improve the performance of ad-hoc networks in terms of energy dissipation [2] [12], capacity [9] [16], throughput and end-to-end delay [3] [5] [6] [7] [8] [10] [15].

In order to take advantage of the high potential of directional or smart antennas, it is necessary to design appropriate communication protocols. The majority of such protocols, found in the literature [5] [6] [7] [8] [10] [15], are usually designed for phased-array antennas or switched beam antennas. The former can change their radiation pattern only in so far as to be able to steer the main beam towards different directions, while the latter provide the terminal with a number of fixed beams. We shall call all such antennas simply as *directional*, hereafter. Despite the improvement demonstrated by the use of directional antennas, it has been shown [9] that cumulative interference restricts the maximum number of simultaneous transmissions.

Fully adaptive array antennas (often referred to as *smart antennas*) have the ability to automatically respond to an unknown interference environment, in real time, by steering nulls and reducing side lobe levels in the direction of the interference, while retaining some desired signal beam characteristics. This process is often called *beamforming*. These systems usually consist of an array of weighted antenna elements, whose individual weights are controlled, in real time, in order to produce the desired radiation pattern. A digital processing unit is usually responsible for controlling the element weights towards some optimization of output SINR, in accordance with a control algorithm [1] [17]. Additionally, adaptive antennas can be used to estimate the Direction-Of-Arrival (DOA) of one or more incoming signals [1]. Their use has so far been limited to military applications and in base stations for cellular systems, due to the high cost, complexity and power consumption of digital implementation. However, low cost, low power, analog adaptive array designs have recently been proposed and prototyped, specifically targeting the market of ad-hoc networks [4].

In this paper, we present a protocol called ADAPT that enables ad-hoc nodes to efficiently utilize adaptive array antennas to communicate. It is a based on a mechanism called *smart virtual carrier sensing (SVCS)*. SVCS is an extension of the basic virtual carrier sensing mechanism of 802.11 [14] and allows a node to perform beamforming (desired signal tracking and interference cancellation), on a per packet basis, using only MAC layer information. We complement this mechanism with a real-time adaptive beamforming algorithm, to cope with situations where node mobility is too high. We have used the ns-2 simulator [13] to compare our protocol to typical omni-directional and directional settings. We show that our protocol achieves superior performance, in terms of network throughput and end-to-end delay, in most scenarios considered.

In the next section, we present the antenna models we have used. In section 3, we describe the workings of the ADAPT protocol, in detail. Simulation results are given in section 4. Finally, we conclude our paper in section 5.

II. ANTENNA MODELS

Omni-directional antennas are characterized by uniform gain in the azimuth plane. Let $G_X(\varphi)$ denote the gain of antenna X as a function of the azimuth angle φ. Then we assume that an omni-directional antenna is characterized by

$$G_{omni}(\varphi) = 1 \quad \forall \varphi \in [0, 2\pi) \tag{1}$$

Directional antennas are capable of concentrating the radiated power towards a specific direction. In this work, we adopt the *flat-topped antenna* model, an ideal model, commonly used in literature [6]. Its gain function is given by

$$G_{FT}(\varphi) = \begin{Bmatrix} 1 & |\varphi - \varphi_0| \le \theta/2 \\ G_s & |\varphi - \varphi_0| > \theta/2 \end{Bmatrix} \tag{2}$$

φ_0 denotes the direction the antenna is pointing (boresight), θ the antenna beamwidth and $G_s \in [0,1]$ is the constant antenna gain outside the main beam. We have normalized the gain function to one, in order to obtain the same transmission range as an omni-directional antenna. Finally we assume that the antenna pattern is electronically steerable towards any direction φ_0 in $[0, 2\pi)$.

Our adaptive antenna model consists of a linear array of M elements, each of which is independently weighted at the output. Specifically, at every time instant t the complex signal $s_i(t)$ from an element i is multiplied by a complex weight $w_i(t)$ and then all s_i are added together to give $z(t) = \sum_i w_i(t)s_i(t)$ at the output. There exist a large number of algorithms and techniques for adapting the antenna weights w_i, in order to achieve the desired radiation pattern, some of which can automatically respond to an unknown interference environment, in real time, with almost no information about the desired signal. However, the complexity of some of the algorithms as well as that of the digital hardware required may render their use for resource-constrained wireless terminals prohibitive. It is out of the scope of this paper to describe all existing algorithms or discuss the appropriateness of each one of them in the context of ad-hoc networks. A good presentation can be found in [1] [17]. In this work, we use two relatively simple methods for adjusting the antenna weights, in order to keep the implementation complexity low and our assumptions realistic.

***Semi-static downlink and uplink beam-forming*:** We assume there exists a desired signal S(t) that needs to be received correctly and whose direction-of-arrival (DOA) φ_s is known. Furthermore, there exist up to M interfering signals $I_i(t)$ whose direction-of-arrival φ_i is also assumed to be known. Let Δx denote the element spacing and $\beta = 2\pi/\lambda$ (λ is the carrier's wavelength). The algorithm consists of solving the following (M+1)x(M+1) system of equations on a per packet basis (instead of real-time – thus, the semi-static characterization):

$$\begin{aligned} &\sum_{k=1}^{M+1} w_k e^{-j\beta(k-1)\Delta x \cos\varphi_s} = 1 \\ &\sum_{k=1}^{M+1} w_k e^{-j\beta(k-1)\Delta x \cos\varphi_j} = 0 \quad \forall \mathrm{i} \end{aligned} \tag{3}$$

This method takes advantage of direction-of-arrival (DOA) information about the desired signal and sources of interference, already available at the terminal, and due to the reciprocity theorem it can be used for both transmitting and receiving beams. It is significantly simpler than any real time adaptive algorithm and combines naturally, as we shall see later, with the virtual carrier sensing mechanism of 802.11 type MAC protocols.

Real-time adaptive beamforming: Here we assume that only the direction φ_s of the desired signal is known. The interference environment is unknown. Let superscript H denote the complex conjugate transpose of a vector, $\underline{w} = [w_1, w_2, ..., w_M]$ denote the vector of antenna weights, $R = E[\underline{s} \cdot \underline{s}^H]$ the adaptive array correlation matrix for signal $\underline{s} = [s_1, s_2, ..., s_M]$, and $\underline{sv_s} = [1, e^{j\beta\Delta x \cos\varphi_s}, ..., e^{jM\beta\Delta x \cos\varphi_s}]$ the steering vector associated with the direction of the desired signal. The beamforming algorithm solves the following optimization problem:

$$\underset{\underline{w}}{\text{minimize}} \quad \underline{w}^H R \underline{w}, \qquad \text{subject to } \underline{w}^H \underline{sv}_s = 1 \tag{4}$$

This algorithm seeks to minimize the mean output power of the array, while maintaining unity response towards φ_s. Minimizing the total output noise (including interferences) and keeping a constant response for φ_s is equivalent to maximizing the output SINR. We are not concerned here with the specific algorithm to be used to estimate matrix R *online* in order to calculate the optimal weights [1] [17].

III. ADAPT PROTOCOL

A. Downlink semi-static beamforming using SVCS

The basic component of the ADAPT protocol is the *smart virtual carrier sensing* (*SVCS*) mechanism, which allows nodes to take advantage of the increased adaptive antenna capabilities. As in the case of 802.11 and DMAC [6] [7], nodes utilize overheard information regarding communication intentions of nearby nodes. However, unlike 802.11 and DMAC that use such information to decide whether to initiate or defer a new transmission, here nodes use such information in order to adapt their antenna pattern to the interference environment. Specifically, nodes use information regarding ongoing or incipient transmissions to create *nulls* towards the direction of such transmissions. Information regarding the duration of a transmission is used to decide how long any signal from or to that direction will be suppressed, allowing this way future communication with nodes that may currently be considered as interferers. Each node maintains two tables in order to implement SVCS, namely the DOA and SVCS tables.

Direction-of-arrival (DOA) Table: The DOA table consists of entries of the form {node ID, angle}. It is a cache of the most recently encountered nodes paired with the direction at which the nodes are expected to be found, in respect to the node in question. At initiation of a packet exchange, a node wishing to send a packet to some node d acquires φ_d from the DOA table and uses it along with information about ongoing transmissions (found in the SVCS table), in order to calculate the antenna weights according to Eq.3. This way a downlink semi-static beam, which minimizes interference towards *known* ongoing communications, is formed towards d and used to send the RTS packet. Note that, like every other cache the DOA table is there only to improve performance. A miss may occur during the DOA table lookup, in which case an omni-directional RTS is sent instead.

SVCS table: This table consists of M entries. Each packet transmitted (i.e. RTS, CTS, DATA, ACK) carries a value indicating the remaining communication duration. An entry $\{\varphi, t\}$ in the table indicates that the node has overheard a packet from angular direction φ signalling an upcoming communication until time t. This implies that until t, first, interference from φ may be experienced and, second, any radiation from the node in question to that direction may harm the ongoing communication. To avoid the latter, the node sets a null towards φ until t, when transmitting a packet. The replacement policy followed is that of *shortest-time-to-completion:* let S denote the set of all entries in the SVCS table, and I be the set of ongoing transmissions in the vicinity of the node of which the node is aware of, where $\|I\| > M$. At any time the policy ensures that $\forall\{\varphi_i,t_i\} \in S$, there is no j, such that $\forall\{\varphi_j,t_j\} \in I - S$ and $t_j > t_i$. The policy is intuitively efficient, because there is a higher probability to interfere with an ongoing communication that has a longer remaining time.

Obtaining DOA Information: A question that naturally arises is how can necessary DOA information be obtained. In the simplest case, a node could include its coordinates (e.g. available through GPS) in every packet it sends. Alternatively, as we have noted earlier, adaptive antennas have the ability to automatically estimate the angle-of-arrival of an incoming signal using appropriate signal processing algorithms [1]. Nevertheless, it is out of the scope of this paper to survey possible alternatives for obtaining DOA information. Therefore, we will assume here that such information becomes available to the node whenever it receives a packet.

In Figure 1 we depict a flowchart of ADAPT for the case of a node having a packet to transmit. In order to clarify the functionality related to the adaptive array antenna, we do not depict the detailed FSM of the protocol. Most other protocol mechanisms (e.g. backoff, defer, etc,) remain more or less unchanged from the basic 802.11 implementation. It is an advantage of ADAPT that it retains the general semantics of 802.11 and requires only a few changes to be implemented.

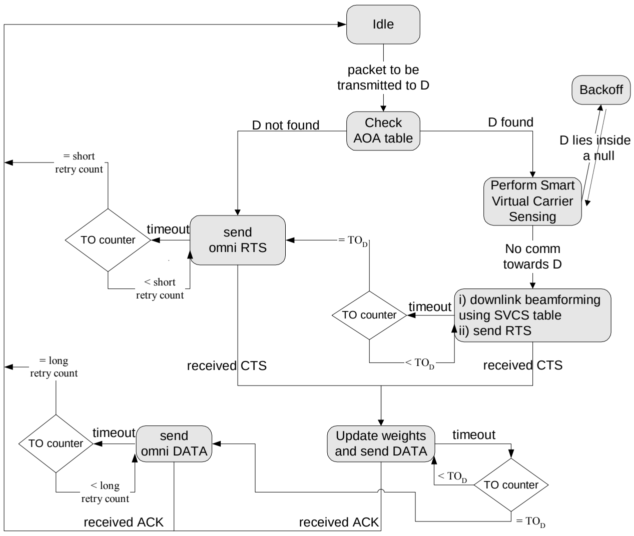

Figure 1: ADAPT flowchart of a transmitting node

B. Uplink semi-static beamforming to mitigate the exposed terminal problem

The exposed terminal problem has been a well-known problem in the context of packet radio networks using omni-directional antennas. In the adaptive antenna case the problem becomes even more pronounced and can be describes as follows: A node A needs to transmit a packet to node B. B is overhearing a number of ongoing transmissions in its vicinity. If B knew of A's direction and A's intention of sending A a packet, it could adapt its antenna weights to create a semi-static receiving beam aimed at A and cancel interference from other nodes. However, B does not know of any such info about A, and cannot ever find out since any RTS packet from A will get garbled at B by interfering signals. This situation can significantly restrict the number of concurrent transmissions in the network and, thus, reduce the maximum network throughput achievable using adaptive antennas.

Having each node perform *semi-static uplink beamforming* when idle can reduce the occurrences of the exposed terminal problem. If S denotes again the set of all entries in the SVCS table, then a node in idle mode updates its antenna weights, on a per packet basis, so that nulls are formed in its receiving beam towards all ongoing transmissions in its vicinity. This ensures that the idle node will be able to receive an RTS destined to it by some other node. Furthermore, since suppressed transmissions are unrelated they can safely be ignored until their completion (an RTS or CTS packet indicates DATA and ACK packets to follow that can be ignored). Finally, when a transmission completes a null will be removed from the respective direction to allow the node to engage itself in future communication.

C. Extending ADAPT to cope with mobility and deafness

Semi-static uplink and downlink beamforming suffices for situations where node mobility is low and traffic is moderate. However, the effect of high mobility and increased *node deafness*, can reduce to a large extent the effectiveness of semi-static beamforming. Due to lack of space, we will not present here the analysis of the effect of these two factors, but only provide some intuition. The detailed analysis can be found in an extended version of this paper [15].

The effect of mobility: As we mentioned earlier, semi-static beamforming is performed on a per packet basis. The DOAs used in Eq.3 to calculate the optimal antenna weights, are taken from the DOA and SVCS tables, and are outdated in the sense that they correspond to the respective angles at some time in the past. If node mobility is low, then these values can serve as good estimates. However, consider the following scenario: At time t_1 node A records in its SVCS table another node B at distance d, as currently receiving some packet until time T. At a later time $t_2 < T$ node A starts transmitting a packet of its own. In order to avoid causing any interference at node B, A creates a null (of angle θ_{null}) in its antenna pattern towards B. Assume further that nodes A and B are each moving independently with some speed v, and towards arbitrary direction. If T is long enough [15] node B will have moved outside the sector of the null formed by node A, and B's reception will be ruined by A's transmission. Consequently, if nodes move with high speeds, many DOA and SVCS table entries will go stale quickly, before they can be used for beamforming.

Node Deafness: Node deafness occurs when an ongoing transmission in the vicinity of some node A does not get recorded in the SCVS table. Since node A performs beamforming only based on information recorded in the SVCS table it may potentially interfere with such a transmission, if it decides to engage itself in communication. An example of how deafness can occur can be seen in the following sequence of events. We use the notation pkt(T) to denote a packet of type "pkt" containing a remaining duration of time T in its header.

- At t_1: node B overhears RTS(T_1) from A. B forms a null towards A, to last until $t_1 + T_1$.
- At $t_2 \in (t_1, t_1 + T_1)$: B sends some CTS(T_2). $t_2 + T_2 > t_1 + T_1$. A is busy transmitting and cannot receive B's CTS.
- At $t_1 + T_1$: B removes the null formed towards A.
- At $t_3 \in (t_1 + T_1, t_2 + T_2)$: A transmits a new packet. A is not aware of B's ongoing communication and does not form a null in its downlink beam towards B. Thus, B's reception gets garbled due to A's transmission.

In order to combat both the effect of high mobility and node deafness, ADAPT includes a real-time adaptive beamforming algorithm as explained in section 2. It is important to note that this scheme does not require training sequences or sophisticated blind beamforming algorithms. Further, since the width of the antenna main beam is, in general, much larger than that of a null, the required accuracy on the desired signal's AOA is much less than that needed to form a null in the semi-static case. Finally, the overhead of real-time adaptive beamforming is only necessary in scenarios of increased mobility and/or high traffic loads. In most cases it might not need to be implemented.

IV. SIMULATION RESULTS

A. Simulation Environment

We have used the ns-2 network simulator, with the CMU wireless extensions, for all our simulations. We compare the following three configurations denoted as {MAC protocol, antenna}: *adaptive* = {ADAPT, adaptive array}, *directional* = {DMAC, flat-topped}, *omni-directional* = {802.11, omni antenna}. We assume the same width for the main beam of the flat-topped and the adaptive antenna. We have implemented the following modules in ns-2: flat-topped antenna and adaptive linear array modules, an accurate interference model, DMAC as described in[6], and ADAPT.

B. Multi-hop Network of Mobile Nodes

We will consider two scenarios, A and B. Scenario A (low mobility) consists of 30 nodes randomly distributed on a plane of size 1000x1000. Nodes are constantly moving with an average speed of 1.5 m/s, according to the ns-2 random waypoint mobility model (i.e. *pause time* is zero). This is a relatively low speed, better modeling walking speeds. Scenario B (high mobility) is the same as scenario A, with the difference that all nodes are highly mobile moving with average speeds of 10m/s. This scenario could model vehicles moving with moderate speed (e.g. cars in city traffic, or heavy military vehicles).

We ran simulations for an increasing number of TCP connections, randomly assigned between all nodes. The attainable network throughput, for each of the three configurations, for both scenarios is depicted in Figure 2. Each simulation point in the plot corresponds to an average over 10 different random scenarios. When mobility is low, it is evident that the adaptive antenna configuration attains superior performance than the other two configurations. This becomes especially pronounced when the network is heavily loaded. However, when mobility is high, we can see the detrimental effect on the performance of semi-static beamforming. Nevertheless, ADAPT using only semi-static beamforming still provides the best performance in the majority of cases. Furthermore, when real-time adaptive uplink beamforming is also implemented the adaptive antenna configuration retains again a clear performance advantage.

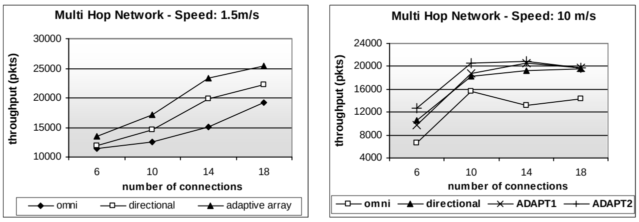

Figure 2: Network Throughput for Scenario A (left) and Scenario B (right). In Scenario B, ADAPT1 only implements semi-static beamforming, while ADAPT2 implements real-time adaptive beamforming, as well.

We further evaluate the 3 configurations in terms of average packet end-to-end delay. To do so, we have used 10 CBR connections, each of rate 100 packets/sec, randomly assigned among all nodes. Results are given in Table 1. It is evident from that table, that the adaptive antenna configuration provides a clear advantage over the other two

TABLE I. END-TO-END DELAY FOR SCENARIO A

Antenna Type	***Omni***	***Directional***	***Adaptive Array***
End-to-end Delay (sec)	0.5761	0.4453	0.2878

V. CONCLUSIONS

In this paper we have developed a protocol (ADAPT) that allows ad-hoc network nodes to take advantage of the capabilities of adaptive array antennas. We have used simulation to compare the performance of an ad-hoc network configurations using fully adaptive array antennas combined with our protocol, to that of typical omni-directional and directional configurations. We conclude that our protocol exhibits a clear performance advantage, in terms of network throughput and end-to-end delay, in the vast majority of scenarios. This fact combined with the gradual advent of small, cheap, and energy efficient, analog adaptive array designs, as well as the ease of implementation of ADAPT, leaves great hope for the future of wireless ad-hoc networks.

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