SMART ANTENNA TECHNIQUES AND THEIR APPLICATION TO WIRELESS AD HOC NETWORKS

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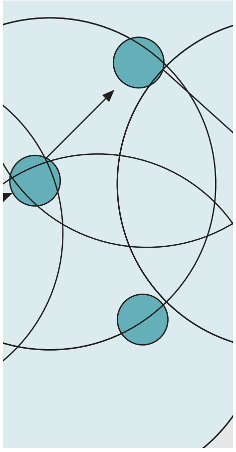

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ABSTRACT

In this article the use of smart antennas in mobile ad hoc and mesh networks is discussed. We first give a brief overview of smart antenna techniques and describe the issues that arise when applying these techniques in ad hoc networks. We consider ad hoc/mesh networks with directional antennas, beamforming/adaptive antennas, and/or multiple-input-multiple-output (MIMO) techniques. We then show how the MAC/routing techniques can be modified to get the maximum benefit with smart antennas, while also showing examples of degradation in system performance, rather than improvement, when smart antenna techniques are added to networks with standard MAC/routing techniques.

INTRODUCTION

Wireless local area networks (WLANs) are becoming ubiquitous with rapid growth in both the home and enterprise markets. However, users are often not satisfied with the coverage and performance of these networks for several reasons. First, the quality of service (QoS) for each user may not be consistent. For example, the user may be too far away from an access point (AP), behind a wall, in a "dead" spot, or suffering from low data rate due to range and/or interference problems. Furthermore, the user may be working with a laptop or handset with a battery where the power drain of the WLAN may be unacceptably high, or may simply find that one AP cannot cover their house.

Two key techniques that can be used to overcome these problems are smart antennas [1] and ad hoc networking [2]. Although smart antennas are a physical-layer technique and ad hoc networking is a media access control (MAC) layer technique, one should not assume that the two techniques can be implemented independently. That is, just adding a smart antenna technique that increases the capacity of a link *M*-fold does not necessarily mean that the capacity of the ad hoc network will also be increased *M*-fold. Indeed, as we show in this article, adding smart antennas to an ad hoc network can, in some instances, actually decrease the network capacity. However, when added properly, that is, using cross layer optimization techniques, smart antennas can provide gains that are in excess of *M*-fold.

In this article, we first briefly describe smart antennas and discuss their properties that are useful in ad hoc networks. This includes the two basic types of smart antennas: directional (or multibeam) and adaptive arrays. We then briefly describe ad hoc networks, their implementation issues, and how smart antennas can be used to overcome these issues. Finally, we discuss how smart antennas can be easily added to ad hoc networks to gain most of their benefits.

SMART ANTENNAS

A smart antenna [1] is a multi-element antenna where the signals received at each antenna element are intelligently combined to improve the performance of the wireless system. The reverse is performed on transmit. These antennas can increase signal range, suppress interfering signals, combat signal fading, and increase the capacity of wireless systems.

There are two basic types of smart antennas, as shown in Fig. 1. The first type is the directional antenna, which forms a narrow beam in the desired direction. This can be implemented by a switched multibeam antenna (Fig. 1a) in which one of several beams (or antenna elements) is selected for reception and transmission. Generally, this is the beam with the strongest signal. Another implementation method is a linear array of half-wavelength-spaced antenna elements where the received signals are phase shifted (in linear steps across the array) and combined to form a beam in a given direction, based on direction-of-arrival beamforming techniques. The second type is defined here as an adaptive array (Fig. 1b) in which the signals from several antenna elements (not necessarily a linear array), each with similar antenna patterns, are weighted (both in amplitude and phase) and combined to maximize the performance of the output signal. Note that the adaptive array will form a narrow beam in a line-of-sight environment without multipath, but can also optimally suppress interference and provide fading mitigation and gain in a multipath environment. The switched multibeam antenna is less complex because it uses simple beam tracking. That is, the beam-selection technique needs only look at

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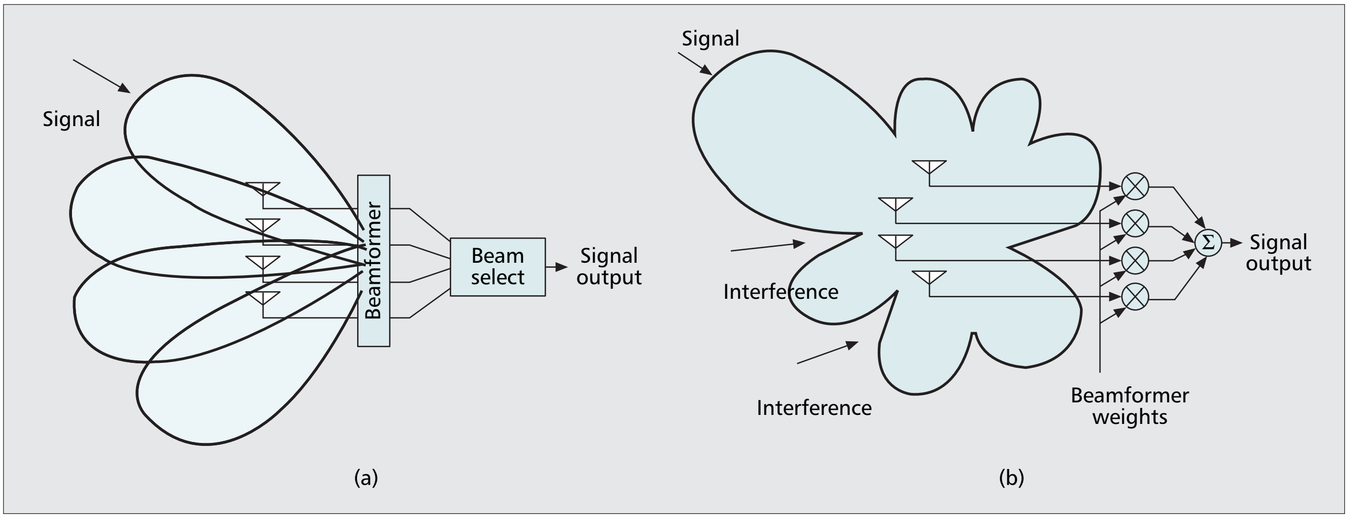


Figure 1. *Two basic types of smart antennas: a) switched multibeam antenna; b) adaptive array.*

the signal level in each beam every few seconds to determine which beam to use. Similarly, in the linear array implementation of the directional antenna, the phase shifts only need to be slowly adjusted to track the change in angle-of-arrival of the received signal. On the other hand, the beamformer weights in the adaptive array need to track the fading of the desired signal. For example, at 2 GHz with 100 km/hr vehicle speeds, the Doppler is about 200 Hz and the complex weights need to be calculated at least 100 times faster for accurate tracking (i.e., the complex weights need to be calculated at a 20 kHz rate). However, although the adaptive-array processing is much more computationally complex, the requirement is well within the capability of current signal processing ICs.

Also, for transmission, the directional antenna can use the same beam for transmission as used for reception, while for the adaptive array the issue is more complicated. In time-division duplex (TDD) systems the same frequency is used for transmit and receive, but at different times, and adaptive arrays can use the receive weights for transmission — although antenna calibration may be required to obtain the needed accuracy. In frequency-division duplex (FDD) systems different frequencies are used for transmission and reception, and it may not be possible to determine the adaptive array transmit weights from the receive weights in a multipath environment, since the fading can be different at the two frequencies.

The adaptive array has significant advantages in performance over the directional antenna (note that the adaptive array may also be able to form a directional beam if that would provide the best performance). Although both types of smart antennas can provide an array gain, that is, increase in receive output signal-to-noise ratio (SNR) averaged over any fading, of M with M beams or antenna elements, with the directional antenna this gain only occurs in line-of-sight or limited-scattering environments. In multipath environments, the signals can arrive from multiple directions into multiple beams, and a single beam does not contain all the signal energy, particularly when the angular spread of the environment (the range in angle-of-arrival for a received signal from a single transmitter) is greater than the beamwidth of a single beam. Furthermore, the directional antenna only reduces interference if it is outside the main beam, and it also has limited diversity gain (defined as the reduction in the variation of receive output SNR in a fading environment) against multipath fading. The adaptive array, however:

- Provides an antenna array gain of M, independent of the environment, as long as the antenna elements are spaced at least a half-wavelength apart (or, more specifically, when the antennas are placed such that mutual coupling among antennas is not a significant impairment)
- Can suppress $M - 1$ interferers [1, 3, 4]

In a multipath environment, this interference suppression is independent of the interferer location, and an M-fold diversity gain can also be achieved (as long as the signals have independent fading at the antennas — also noting that interference suppression reduces the array and diversity gain, e.g., the array and diversity gain is $M - N$ with nulling of N interferers). In addition, the ability to suppress $M - 1$ interferers means that MIMO with spatial multiplexing can be used [3, 4], whereby an M-fold increase in capacity can be achieved without any increase in signal bandwidth or total transmit power through appropriate signal processing if both the transmitter and receiver have at least M antennas. Because of their ability to provide gains in both line-of-sight and multipath environments, as well as the ability to provide substantial capacity increase in nearly all indoor and outdoor environments, the adaptive array is the main focus for smart antennas in wireless systems, including the developing standard IEEE802.11n.

The adaptive array can be used to improve the performance of most wireless systems, including WiFi, WiMax, cellular, RFID, UltraWideBand, GPS, and satellite video and radio systems. In WiFi systems (which are currently the major commercial application for ad hoc networks), adaptive arrays can provide:

- A higher antenna gain for extended battery life, extended range, and higher throughput
- Multipath diversity gain for improved reliability, including more robust operation of services that require high QoS, such as VoIP
- Interference suppression (this is particularly important in the unlicensed bands where there is less control of the interference)
- Reduced interference into other systems on transmission
- Higher link capacity through the use of MIMO with spatial multiplexing

Since WiFi systems are TDD systems, the received weights can be used for transmission to obtain the same gains in both directions with the use of smart antennas on one side (client or AP) only. As examples, a four-antenna array can provide up to a 13 dB SNR gain (6 dB array gain plus a 7 dB diversity gain), or the possibility of data rates as high as 500 Mb/s (as considered for IEEE802.11n). Similar gains can be achieved in WiMax systems (particularly those using TDD), and gains on the order of 6 to 11 dB [5] can be achieved in cellular systems which have FDD operation. Note also that the five gains listed above cannot all be obtained simultaneously (e.g., suppression of $M - 1$ interferers and a diversity gain of M are mutually exclusive); however, each adaptive array in a system can optimize its performance in different combinations of the items listed above depending on its situation [6].

AD HOC NETWORKS

Wireless ad hoc networks are networks of hosts that may be mobile, with no preexisting infrastructure (if the infrastructure is fixed and regular, then this network can be considered a mesh network — similar results to those discussed here also apply), as shown in Fig. 2. Multiple hops are used for routing, and the neighbors and routing change with time (with user mobility and changes in the environment). The advantages of ad hoc networks are that they:

- Can require less transmit power (for longer battery life)
- Are easy and fast to deploy
- Have performance that is not critically dependent on the infrastructure
- Can have higher frequency reuse for higher capacity

Applications include home networking, meetings and conventions, and military and emergency networks. Note that for WiMAX an optional mesh mode is in IEEE 802.16™-2004 (with further standardization under consideration); for WLANs a standard under development for mesh networks of access points is IEEE802.11s. A major commercial application today is mesh networks for large area/municipal WiFi. For example, Philadelphia and San Francisco, along with a growing number of communities, are currently building mesh networks to provide ubiquitous WiFi coverage over an entire city.

However, there are several issues that are of concern in a wireless ad hoc network, including limited range between nodes, fading, packet loss, changes in routing and neighbors due to movement, and power limitations. The MAC and routing techniques need to be adjusted to accommodate these issues, with this process further complicated by the possible mixture of different types of users, equipment, symmetric and asymmetric links, and so forth. Furthermore, the broadcast nature of the environment adds additional problems which include frequency reuse limits due to interference and the hidden node problem [7], as described below.

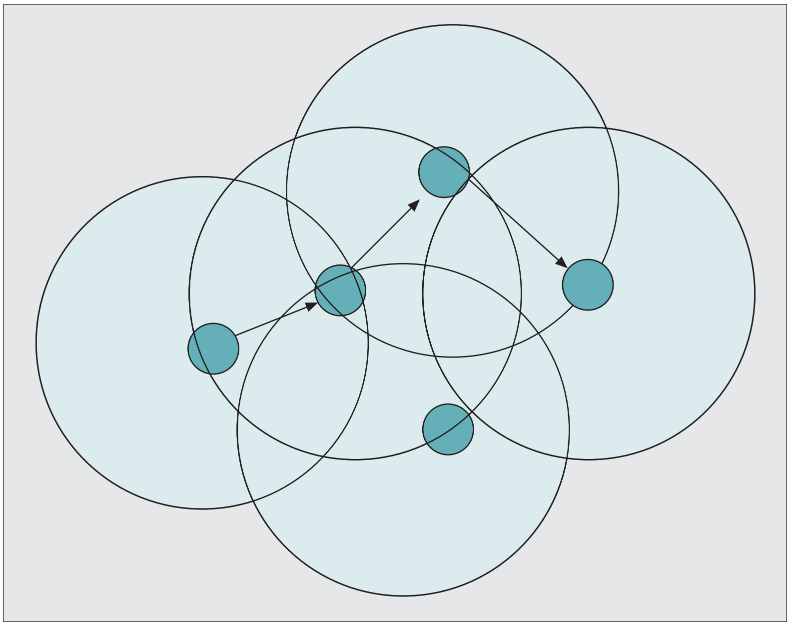
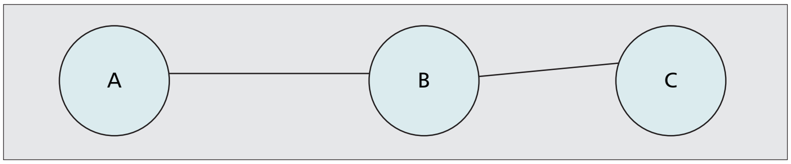


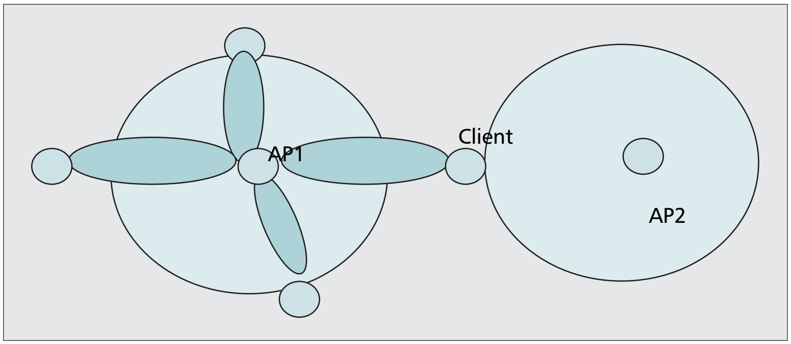
Figure 2. *An ad hoc network.*

The hidden-node problem is shown in Fig. 3. In a wireless environment, consider the case where nodes A and B, as well as nodes B and C, are close enough to communicate, but nodes A and C are too far apart to hear each other. Thus, if node A is transmitting to node B, node C may not hear the transmission and, thinking that the channel is clear, may transmit to node B, with the result that the packets from node A and C collide at B, with both packets lost. One method to avoid this problem is the use of a request to send (RTS) packet, as in the standard IEEE802.11: if node A has a packet to send to node B, it sends an RTS to node B, node B responds with a clear to send (CTS), node A sends the data, and node B sends an Acknowledgment. However, if node C is transmitting to another node, for example, node D (not shown in this figure), its transmission could still collide with packets from node A at node B, since it could be unaware that node A was transmitting.

Another issue is the use of TDD versus FDD (where different frequencies are used for transmitting and receiving from each node), as used in cellular systems. Note that FDD requires designation of uplink and downlink (to determine the frequency band), which is fine for cellular systems with base stations, but becomes difficult in ad hoc networks where all nodes may be treated equally and complicates the MAC. TDD also allows for unequal allocation of the transmit and receive capacity, which can improve overall network efficiency. Furthermore, TDD systems can use the receive antenna pattern for transmission



■ **Figure 3.** *Illustration of the hidden node problem.*



■ **Figure 4.** *A mixed mode network with association problems.*

(although antenna calibration may be required), while FDD systems generally cannot in multipath environments, particularly with adaptive arrays. Therefore, TDD is the preferred method for ad hoc networks.

IMPACT OF SMART ANTENNAS IN AD HOC NETWORKS

Most systems today only consider the use of omnidirectional antennas for ad hoc networks. However, this reserves the spectrum over a large area, wasting network resources. Smart antennas not only can mitigate this problem, but also can provide the other advantages listed above. The main type of smart antenna that has been considered in the literature on ad hoc networks is the directional antenna. The reasons given for the emphasis on directional antennas over adaptive arrays in the literature are typically that they are considered easier and less costly to implement, as well as easier to study and analyze. However, this is not necessarily always true, as discussed below.

Since smart antennas are a physical-layer technique, existing approaches for MAC/routing in ad hoc networks can be used with smart antennas, but these MAC/routing techniques need to be modified to achieve the full benefits of smart antennas (in some cases the use of smart antennas can actually degrade performance if they are added without changing the MAC/routing techniques, as shown below). Indeed a variety of modified MAC/routing techniques have been developed for directional antennas [8–11], and we consider some of these below.

DIRECTIONAL ANTENNAS IN AD HOC NETWORKS

Directional antennas provide a higher gain (up to M-fold with M beams), and permit greater frequency reuse and topological control as well as increased connectivity [8–11]. For example, greater frequency reuse can be achieved through the use of a directional MAC. If the transmitter (node A) knows the location of the intended receiver (node B), then the RTS can be sent with a directional beam, although it would be received with an omnidirectional beam at node B, since node B would not know that the RTS was sent. Node B would then send the CTS with a directional beam (as would be done with the data and Acknowledgment packets as well). This increases range and reduces the required transmit power (so as to reduce interference levels and increase battery life), as well as increases frequency reuse and network connectivity. However, there is still a hidden-node problem, which is worsened by the asymmetry in the gain for transmit and receive at node B, and a loss of receive gain for the RTS packet (e.g., an access point does not know which beam to use when the client transmits first).

There are also association problems with mixed mode access points. For example, consider the case shown in Fig. 4 where access point AP1 uses directional beams, whereas AP2 only uses an omnidirectional antenna. Since the beacons for association are transmitted omnidirectionally from both AP1 and AP2 (as they are intended for all clients), then a client may associate with the closer access point, AP2, even though it should associate with AP1 since it will provide the stronger signal with a directional beam. Furthermore, if a client associates with an access point with a directional beam, it may continue to associate with that access point (since the signal may remain strong) even after it moves beyond other access points. Thus, with movement, after a period of time many of the clients could be associated with the wrong access points, leading to a large reduction in overall network capacity.

However, the main issue with directional antennas is that they do not work well in multipath environments, which are typical of most wireless systems. Note that the multipath environment may even be richer (with greater angular spread) in ad hoc networks since transmission may be between mobiles/clients, which are lower to the ground than base stations. In this case, the degradation due to multipath fading can dominate over the propagation loss, the direction-of-arrival of the received signal may not be a good indicator of user location, the signal from each interferer can be received by many, if not all, beams, and the array gain can be lost.

ADAPTIVE ARRAYS IN AD HOC NETWORKS

Adaptive arrays do work well in multipath environments, though [12–17]. They provide multipath mitigation as well as the full array gain, do not use directional-of-arrival information in generating the weights, can suppress up to $M - 1$ interferers with M antenna elements, and provide up to an M-fold capacity gain with spatial multiplexing. Furthermore, the adaptive array can be adjusted to optimally trade-off these gains (which cannot all be achieved simultaneously) to maximize link and/or network performance. In addition, unlike multibeam antennas, the adaptive array can listen omnidirectionally, but beamform when the packet is received, thus obtaining the adaptive array gains even when a packet arrives from an unknown location. This increases the range for the RTS packet even when the location of the transmitting node is unknown a priori, unlike directional beam systems. Although the hidden-node problem still exists, the ability to suppress up to $M - 1$ interferers means that effect of the interference is at most only the loss of the interfering packet. Indeed, up to M users can transmit to an adaptive-array node and all packers can still be correctly received. Even the association problem is reduced somewhat, since beamforming on receiving the beacon provides multipath mitigation that is not present in a directional beam system.

Concerning cost and implementation complexity, we note that adaptive antennas are the main smart-antenna technique being currently implemented in WLANs, and they are being introduced cost effectively, including in single-chip solutions. Furthermore, on the handset/client side, the use of directional beams is problematic, since the device-form factor and interaction with nearby objects (such as the head and hand) make generating beams difficult. Adaptive arrays, on the other hand, can be readily implemented even in very small form factors and adjust to the interactions in the environment.

The final issue is how to effectively add adaptive arrays to ad hoc networks. Since adaptive arrays are being introduced in WLAN clients and access points today, it is increasingly likely that future ad hoc networks will have smart antennas in them. As discussed above, one can just add smart antennas to an ad hoc network without changing the MAC/routing algorithms. But this may not always have the desired effect (see, e.g., [9] for a discussion of degradations when using directional antennas in WLANs). For example, consider the case of using MIMO with spatial multiplexing. With M transmit and M receive antennas, this technique can increase the link capacity M-fold, but this does not necessarily mean that the network capacity is also increased M-fold.

For example, consider the WLAN network shown in Fig. 5, which is assumed to operate in the unlicensed ISM band at 2.4 GHz, as with IEEE802.11b/g. There are three nonoverlapping channels available in this band, which we refer to as C1, C2, and C3. As shown in Fig. 5, the network of four nodes can be fully connected with these three channels. Now, consider adding MIMO with spatial multiplexing to nodes A and B, as considered for IEEE802.11n, to double the data rate of this link. However, because of a variety of factors, including the increased signal processing needed for spatial multiplexing and the fact that spatial multiplexing makes the signal transmitted from a single interfering node appear as multiple interfering signals, the tolerable level of adjacent channel interference may be lower for IEEE802.11n than for IEEE802.11b/g. Thus, if MIMO with spatial multiplexing is used for the link from node A to node B, the links between nodes B and D and nodes B and C may not be able to use channels C2 and C3 without creating too much adjacent-channel interference into the link from node A to B. That is, the link from node A to node B may only be able to operate when channels C2 and C3 are not in use (or the link from node A to node B may have to operate with a much lower data rate when either C2 or C3 is being used). Thus, the link from node A to B would need to time-share transmissions with the link from node B to D and the link from B to C (similar to what would happen with a single channel), resulting in an overall decrease in network capacity if all the links have similar traffic. Only if the smart antennas at nodes A and B were used for increased gain without spatial multiplexing could the network capacity potentially be increased in this case.

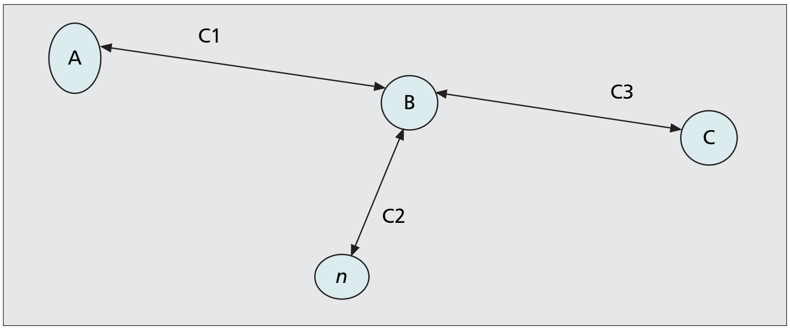


Figure 5. *Network of four nodes to illustrate the effect of smart antennas on network capacity.*

CROSS-LAYER OPTIMIZATION

MAC extension to support the use of smart antennas has been seen as likely requiring high complexity. The MAC/routing algorithms are already seen as being complex, particularly since mobility and wireless links greatly increase the complexity of these algorithms over those for fixed networks. Smart antennas add an additional level of complexity, particularly if all the features of the smart antenna are to be considered. Indeed, the algorithms previously considered for directional antennas require knowledge of such features as the beamwidth, number of beams, pointing directions of the beams, and backlobe strength, which can vary for each node, as well as the direction of each node and, of course, the scattering environment [8–11]. Even with adaptive arrays, information such as knowledge of the number of antennas, type of beamforming, maximum number of spatially multiplexed streams, measurement of the level of interference between each user, and so forth is needed to obtain the full benefit of these antennas (e.g., [12, 16, 17] discuss and propose techniques for cross-layer optimization for MAC/routing techniques with MIMO in ad-hoc networks). Such measurements may not even be currently available in standards-based systems (although such types of measurements are being proposed for the IEEE802.11k standard, among others).

However, for adaptive arrays, many of their advantages can be obtained using a limited set of parameters that may not significantly increase the complexity of existing MAC/routing algorithms, and do not require additional measurements. The main features of adaptive arrays are the ability to suppress up to $M - 1$ interferers with M antennas, allowing for spatial reuse in

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the adjacent cell, and spatial multiplexing (as proposed for IEEE802.11n) with MIMO that permits multiple channels in the same frequency band.

Thus, MIMO with spatial multiplexing can increase the number of channels (combination of frequency and spatial channels) by a factor of *M*. This can permit higher throughput on heavily used links, which is of particular importance to those links near gateway nodes, where traffic is aggregated as it approaches a gateway to the Internet. The additional channels also provide better statistical multiplexing so that the average throughput gain can be greater than *M*-fold. Spatial multiplexing also can be used to decrease the transmission time for a given number of bits, either data or control-channel information. For example, modification of the protocol for *M*-fold spatial multiplexing would reduce the control channel frame length by a factor of *M*, thereby increasing control channel capacity by the same amount. As discussed above, MIMO provides the ability to trade-off spatial streams, interference suppression, and diversity and array gain for each link to optimize overall network performance (see, e.g., [6]).

Another key issue is transmit beamforming. In general, the transmit beamforming weights for each link for a given node would be stored at that node. The routing table would utilize the quality (SNR and data throughput capability) for each link, which would be updated each time a packet (data or control information) was received at a node for the link. Note that the beamforming weights and link quality are time-sensitive information whose temporal usefulness depends on the expected dynamics of the system, (i.e., whether the system was fixed or used by pedestrians or in vehicles). Specifically, after a period of time or for neighbor discovery, transmit beamforming could not be used. In this case, the signal would need to be transmitted omnidirectionally, although transmit diversity (such as with space-time coding) could be used (as in [12]), which provides a diversity gain, but not an array gain. Note that spatial multiplexing could still be used, but with equal power signals from each antenna rather than higher-throughput techniques for transmit beamforming, such as singular value decomposition (SVD). However, when a response is received at a node, the transmit beamforming weights and link quality can be determined. For example, in IEEE802.11 the RTS may sometimes need to be transmitted without transmit beamforming, but the CTS and subsequent data packets and Acknowledgments could always use transmit beamforming.

Although in a TDD system the adaptive-array receive weights could be used for the transmit weights, this may not be the best technique in an interference environment, since that environment can be different on transmit and receive. In this case, using the receive weights for transmit can reduce the interference into other nodes, but at the expense of a reduction in array and diversity gain. Using transmit weights calculated from the receive weights based only the desired signal may offer better performance, depending on the predicted interference environment. This is an additional level of complexity that could be utilized by the MAC/routing algorithms for better performance.

These techniques can increase the link capacity by a factor of *M* (or more due to factors such as statistical multiplexing, e.g., 2, 4, or even 8 times the capacity of networks without smart antennas — with two or four antennas at the AP). These gains can dwarf the variation of performance of various routing techniques/protocols, but these gains can be lost if the MAC/routing techniques do not accommodate smart antenna capabilities. With these advantages, the MAC/routing algorithms for ad hoc networks with smart antennas may even be able to have lower complexity than the algorithms without smart antennas and still have improved performance.

Note that the major recent and developing wireless physical-layer communication standards (such as WiFi, WiMAX, and cellular) already use training sequences and/or pilot tones that can be used for adaptive array training. Although MAC-layer coordination of training-sequence transmission from multiple nodes could lead to even better network performance, this would increase MAC complexity and is not necessary to achieve the large gains of smart antennas in ad hoc networks. This is because the adaptive-array weights to suppress interference and provide spatial multiplexing and diversity and array gain can be determined on a packet-by-packet basis without knowledge of the prior interference environment. But certain basic modifications are needed.

Specifically, hooks are needed for frequency-assignment techniques to include reusing a frequency (up to $M - 1$ times) if APs have *M* antennas. That is, with a contention-based protocol, allow the frequency reuse of a channel by an adjacent AP. Also, hooks are needed for the inclusion of multiple radio capabilities to include multiple radios in the same channel, as with spatial multiplexing. This includes the ability to limit adjacent channel interference, that is, forbid the reuse of a channel by the adjacent AP, if spatial multiplexing is used. The only additional information required is then the number of antennas at, interferers that can be suppressed by, and spatially multiplexed channels that can be supported by each node. This information only needs to be available when a node enters the network. With this information, the main advantages of smart antennas can be incorporated into ad hoc networks without significant changes in the MAC/routing algorithms.

CONCLUSIONS

In this article the use of smart antennas in mobile ad hoc and mesh networks has been discussed. Although smart antennas can greatly increase the performance of these networks, providing gains greater than the sum of the gains of each technique, MAC/routing algorithms need to be modified in order to avoid problems with implementation. We have discussed how smart antennas implemented as adaptive arrays, rather than directional antennas, can greatly enhance the performance in typical wireless environments with multipath, and then have described how the MAC/routing algorithms can be modified to get most of the benefits of these smart antennas, without significantly increasing their complexity. Further research is needed (particularly on standards development), but the potential improvement is substantial.

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BIOGRAPHY

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