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Multiple Antenna Techniques for Wireless Mesh Networks

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1.1 Introduction

Wireless mesh networks (WMNs) is a relatively new and promising key technology for next generation wireless networking that have recently attracted both the academic and industrial interest. Mesh networks are expected gradually to partially substitute the wired network infrastructure functionality by being able to provide a cheap, quick and efficient solution for wireless data networking in urban, suburban and even rural environments. Their popularity comes from the fact that they are self-organized, self-configurable and easily adaptable to different traffic requirements and network changes. Mesh networks are composed of static wireless nodes that have ample energy supply. Each node operates not only as an conventional access point (AP)/gateway to the internet but also as a wireless router (Fig. 1.1) able to relay packets from other nodes without direct access to their destinations [1][2]. The destination can be an internet gateway or a mobile user served by another AP in the same mesh network. Moreover, some nodes may only have the backhauling functionality, meaning that they do not serve any mobile user directly but their purpose is to forward other APs' packets.

For wide area access, the access points (or base stations) are typically located at high towers or at the rooftop of buildings. However, as the capacity demands increase, the AP is moving closer to the user and it could be placed at below-the-rooftop heights. In this way it can provide better signal reception and higher spatial frequency reuse factor. For a cellular network point of view this means that the cell size has to shrink in order to satisfy the increased capacity demands. Therefore, the whole network topology in terms of base station location has to be revised and additional base stations have to be installed by the network operator. In case where fiber is not readily available, the cost of backhauling by using e.g. E3 lines may be prohibitive for the operator. Wireless mesh networks can be proven an appealing alternative backhauling solution in this case since they do not require wired connection, they are easy

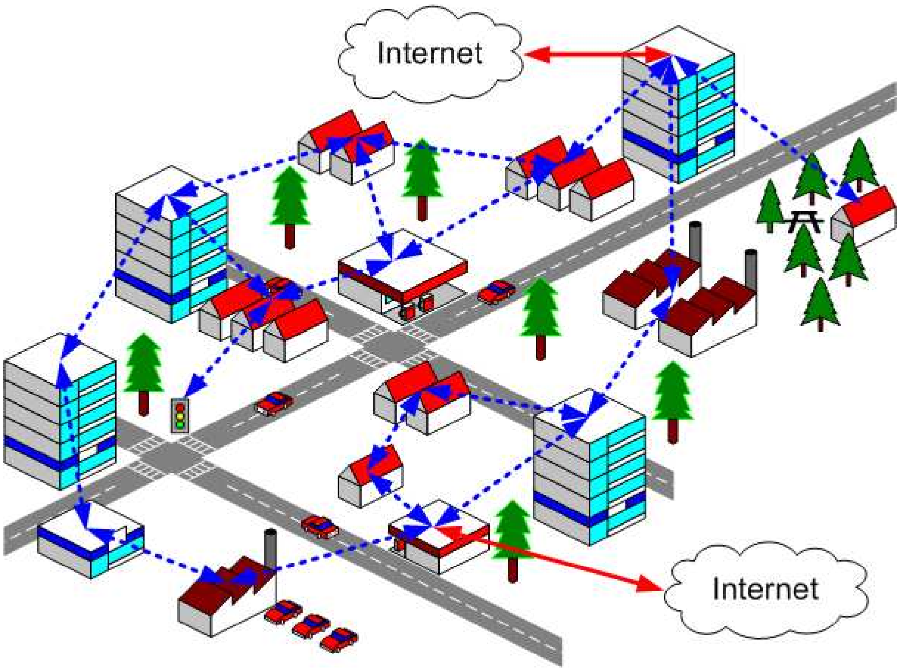

Fig. 1.1. Conceptual illustration of a multi-hop wireless mesh network.

to deploy fast and without extensive network planning requirements since they are self configurable and adaptable to network changes and demands. For instance, Multi-Element Multihop Backhaul Reconfigurable Antenna Network (MEMBRANE) [3] is an IST-funded project that aims to bring an efficient wireless backhaul design as an alternative technology to serve wireless broadband networks in cases where a wired backhaul would be more costly to access and/or would take longer to deploy.

Moreover, wireless mesh network can enhance the presence of broadband in rural and remote zones, thus helping combat the "digital divide" between these areas and the big urban centers, caused mainly by the inadequacy (or even absence) of wired network infrastructure. It is not only doubtful that the required investment for bringing cable and/or fiber will ever pay for itself in such remote zones and communities but, more importantly, such an undertaking will probably take several years. Wireless mesh networks can provide a quick and economically affordable solution in this case.

Technology enablers: Mesh networks must meet a number of technical requirements. First of all, they must meet the high capacity needs of the access nodes which have to forward the accumulated traffic of their underling users. Furthermore, they have to cope with the delay and other strict quality-of-service (QoS) requirements of the end user applications. Finally they must provide a large enough effective communication range to ensure that no APs (or groups of APs) are isolated from the Internet gateways. In order to satisfy the above requirements, a range of novel techniques has to be exploited. Such technology enablers include but not limited to multi-hopping, various multiple antennas techniques and novel medium access control (MAC) and routing algorithms.

Multi-hopping, i.e. the use of multiple relays (or forwarding nodes) between the end user and the Internet gateway, is primarily motivated by the low power and the low heights of the access and relay nodes. Clearly, in low power transmissions, multi-hopping helps increase the range. Moreover, since low height access points are likely to be surrounded by several obstacles (buildings, cars, etc.), their line-of-site (LOS) will be typically obstructed, affecting in this way the one-hop node connectivity to a gateway.

Multiple antenna techniques (also known as smart antennas) constitute another enabling technology that is highly beneficial to the wireless mesh network architectures. These techniques include fixed beam antennas, adaptive antennas and multiple-input multiple-output (MIMO) coding [4][5]. Depending on the used technique, multiple antennas can provide power, diversity and multiplexing gain and therefore increase the transmission range, reduce the transmitting power, mitigate interference, increase channel reliability and increase data throughout. Each of these techniques is more appropriate in different types of propagation scenarios; for example beamforming is well suited to cases with narrow angle spread, such as in high towers; whereas MIMO is more appropriate in cases of rich electromagnetic scattering, such as in low-height links without strong LOS component.

Given the different types of propagation environments that are expected in wireless mesh networks, smart antenna techniques are expected to boost throughput performance and reduce interference and delay, thus improving overall end-to-end performance. However, multiple antenna techniques have been extensively analyzed only for single-link communications. The combination of multi-hopping with multiple smart antennas in a wireless mesh network environment is a field that has not received much research attention. This combination is expected to boost network capacity and achieve the target QoS.

Novel *medium access control and routing algorithms* that are able to exploit the benefits of multiple antenna usage on the wireless mesh access points is another enabling technology of paramount importance. Employment of smart antennas techniques without thorough understanding and consideration of their interaction with layer two and three algorithms can be proven counter productive for the mesh network functionality. Deafness, hidden and exposed terminals and multi-stream interference are some of the problems that have to be addressed by novel MAC and routing schemes since they can highly affect not only the individual links but also the overall network performance.

The main aim of this chapter is to give an insight into both the improvements and various challenges generated by the deployment of multiple antennas in wireless mesh networks and how these can be addressed by layer two and three algorithms. In the rest of this chapter the wireless mesh network and channel characteristics are discussed in section 1.2. A thorough analysis of the various smart antenna techniques and their main advantages and disadvantages follows in section 1.3. In section 1.4, the challenges that smart antenna techniques will impose to medium access control and network layers are introduced together with some possible solutions. Finally, sections 1.5 and 1.6 discus several scheduling and routing schemes respectively with smart antenna considerations.

1.2 Channel characteristics

The wireless channel in a mesh network is expected to be highly dynamic. The dynamic nature of the channel comes both from environmental changes/ movements and from the interference fluctuations from network transmissions. In this chapter, we consider only the access point (AP) to AP communication (rather than the AP to user communication); therefore, we do not expect to have any explicit mobility in terms of transmitter or receiver movement. Nevertheless, the wireless mesh networks are expected to be deployed in urban or suburban environments where the surrounding objects (cars, trains, and people) may be in constant move. Also nodes failure can affect the network connectivity by causing to higher layers similar effects as node mobility.

1.2.1 Propagation scenarios

Unlike legacy cellular networks, where base stations are exclusively mounted on high towers or at the rooftops of tall buildings after extensive network planning, aiming for high LOS coverage, wireless mesh APs can be less neatly deployed. In order to reduce the deployment cost and being closer to the users, the APs and relay nodes are mostly placed at low-to-moderate heights, in order of 3-10m (for example mounted on electrical and telephone poles, traffic lights, building sidewalls and rooftops) where direct LOS is difficult to be guaranteed. Depending on the relative position of the AP we can have different communication scenarios that highly affect the channel propagation statistics [3]:

Rooftop to rooftop: In this scenario both ends of a link are placed above the rooftop level. Pure LoS conditions are met as far as the first Fresnel zone is clear.

Below-rooftop to below-rooftop: This refers to the case where both nodes are deployed below the level of the surrounding buildings and it covers both LoS and NLoS outdoor propagation conditions.

Rooftop to below-rooftop: In this scenario the one end of the link is located above the rooftop level while the other is below that. This case possesses strong similarities with the traditional cellular case. The major difference is the Doppler spectrum shape and that the APs are placed at moderate height. Although LoS conditions are possible, the NLoS case is more probable.

Each scenario has an important impact in various channel properties, such as path-loss, angle and delay spread and highly affect the optimum multiple antenna technique that should be used. For instance, at large scattering angles, MIMO performs better than adaptive beamforming techniques. However, at low-moderate scattering angles adaptive or even some simple switched beam techniques can be more beneficial than MIMO.

1.2.2 Power constrains

Since the mesh network transceivers are usually located on the top or sidewalls of buildings or special contracted poles that have easy access to power through wires, power supply and consumption is not a crucial issue for mesh network unlike sensor and mobile ad hoc networks. Moreover, since they are located close to the users, and for health and safety reasons, the wireless mess transceivers are expected to operate at relatively low powers (on the order of at most a few Watts). Last but no least, total effective radiation power limitations may apply in different countries for directional transmissions in unlicensed bands (where a mesh network can operate) as it will be discussed in a latter section.

1.2.3 Interference characteristics

Inevitably, due to the spatial channel reuse in wireless mesh networks a given node will suffer (co-channel) interference from other nodes making the wireless communication more interference limited rather than noise limited. In multiple-antenna systems it is not only the signal-to-interference-ratio (SINR) that affects the network capacity but also the distribution of the interference power. In a mesh network, the interference is not spatially white but it will rather emanate unequally from different directions (spatial color). Recent results in [6] and [7] shown that MIMO systems for a given SINR perform more efficiently the more spatially colored the interference is (i.e., it is better to have few and high-power interference components rather that many, low-power ones).

Moreover, in urban highways, big buildings in both sides act as natural obstacles that can waveguide the signal and significantly reduce the interference from/towards adjacent streets. The degree that buildings and natural obstacles can affect the signal propagation and reception highly depends on the carrier frequency of the signal. These interference characteristics have to be taken into account for the optimum design of wireless mesh network algorithms.

1.3 Smart antennas techniques

The use of intelligent antennas in ad hoc networks has recently attracted a great amount of attention as a means to optimize power transmission/reception ([8] and references therein). Two basic types of intelligent antennas are considered in this context: directional antennas (fixed beams) and adaptive antenna arrays (also known as smart antennas). A directional antenna generates multiple pre-defined fixed beam patterns and applies one at a time towards the direction of interest. It is the simplest technique, essentially providing sectorisation with the capability of illuminating the selected sector according to, for instance, an SNR-related metric. An adaptive antenna array can formulate the beam structure based on a certain optimization criterion, such as maximizing the array gain towards the signal of interest and suppressing interfering signals. MIMO techniques can be seen as an extension of adaptive antenna arrays. They require multiple antennas at both end of the link and are capable to provide spatial multiplexing or diversity gain. In this section, we a) summarize the different multiple antenna techniques, b) give an insight into the tradeoffs of the various performance gains they can achieve and c) discuss the cases (e.g. channel conditions, network requirements) that their usage would be more appropriate.

1.3.1 Directional antenna techniques

Switched-beam antennas: Switched beam is the simplest technique. A predetermined antenna array pattern or separate directive antennas are used to generate a limited number of beams that point to desired directions. These beams can be used either for transmission or reception and each time a beam-switching algorithm determines which particular beam will be used to maintain the highest quality signal. The predefined beams can be switched in a mechanical or electronic way. This ability to concentrate power in a certain direction provides a directive gain (also called power gain or array gain) that can be used for extending range or reducing power. This type of antenna is easy to be implemented (e.g. using multiple antenna elements, each pointing to different direction, where direction is chosen by choosing the element), but it gives a limited improvement.

Steered-beam antennas (or dynamically phased arrays): Steered beam antennas have also predefined patterns but they can be pointed to any of a near continuous set of directions. This can be achieved by phase shifting and combining the signals emitted from each element of an antenna array. Direction of arrival (DoA) techniques can be used to continuously track the direction of the receiving signal and steer the beam accordingly [4]. This helps to avoid the performance degradation occurred in switched beam antennas due to "scalloping loss" [9] (the degradation due to scalloping loss is more significant in mobile environments rather than in static mesh networks). Although any arrangement of antennas can be used, the most typical would be linear, circular and planar arrays [12].

While directional antenna techniques can provide sufficient gain in terms of signal-to-noise ratio (SNR) in presence of strong line-of-sight component and no interference, their performance deteriorates significantly in multi-path environments where the desirable signal can arrive from multiple directions.

1.3.2 Adaptive antenna techniques

Adaptive antenna arrays, or smart antennas [10], use a combination of an array of multiple antennas and appropriate signal processing to produce desirable antenna patterns. Such patterns have high gain in the direction of desired signals and nulls in the direction of undesired signals.

Adaptive antenna arrays: Adaptive antenna array at the receiver can provide power gain (array gain) by coherent combining the received signal copies from all antenna elements. The effective total received signal power increases linearly with the number of antenna elements. Furthermore, its radiation patterns can be adjusted to null out the interference from other directions [11]. In order to achieve this, intelligent digital signal processing (DSP) algorithms should be used [15] to estimate the DoA (several direction of arrival estimation techniques such as ESPRIT [13] and MUSIC [14] can be used) of all the impinging signals, both signal of interest and interfering signals. Interference suppression is obtained by steering beam pattern nulls in the direction of the interfering signals while maintaining the main lobe in the direction of the desired signal. For an antenna array with N elements and for M interfering nodes ($M < N$), M nulls can be formed to eliminate the receiving power of N separate interference while the remaining $N - M$ antennas can be used to beamform towards the direction of the desired signal. Finally, at the transmitter side the adaptive array can form a narrow beam towards the direction of the desired receiver while optimally suppresses the interference towards any other possible adjacent receivers.

MIMO techniques: MIMO systems can be viewed as an extension of the smart antenna techniques described above. The main characteristic of MIMO techniques is their ability to exploit multi-path propagation rather than mitigate it. They take advantage of random channel fading and multi-path delay spread for multiplying transfer rates (multiplexing gain) or improve the transmission quality/reliability (diversity gain) at no cost of extra spectrum (only hardware and complexity are added). In this way it transforms a traditionally pitfall of wireless channel into a benefit of the communication system.

CSI: There is a large number of transmission and reception schemes over MIMO channels depending on the channel state information (CSI) available at the transmitter and/or receiver side and on the diversity and/or multiplexing gain that has to be achieved. CSI at the receiver end (CSIR) can be obtained fairly easy by sending a pilot symbol for channel estimation. At the transmitter side, channel state information (CSIT) can be obtained by CSIR transmission from the receiver through a feedback channel. Alternatively, CSIT can be estimated in bi-directional systems without feedback by exploiting the reciprocal properties of the channel. The former method introduces a trade-off between feedback channel bandwidth and CSI accuracy while the latter one cannot be applied in communication systems, such as frequency-division duplex (FDD) systems, where the reciprocal property does not hold.

Spatial diversity gain: Antenna diversity (or spatial diversity) can be achieved by placing multiple elements at the receiver and/or the transmitter. These antenna elements need to be placed sufficiently far apart such that the received signal replicas from different antenna elements fade more or less independently. In this case, there is a high probability that at least one or more of these signal components will not be in a deep fade that reduces the variance of the SNR. The required antenna separation depends on the local scattering environment as well as on the carrier frequency. The spatial diversity gain depends on the diversity order, which in turn depends on the degree of which the multi-path fading on the different antenna elements is uncorrelated. For M transmit and N receive antennas a maximum diversity gain of MN can be achieved.

Transmit diversity can be achieved via space-time-coding (STC) schemes. The simplest STC scheme is the Alamouti scheme [16], designed for two transmit and two receive antennas without any feedback from the receiver and is one of the most popular techniques proposed in several third-generation cellular standards for transmit diversity. Space-time block coding (STBC), introduced in [17], generalizes the Alamouti scheme to an arbitrary number of transmit antennas and is able to achieve the full diversity promised by the transmit and receive antennas. At the receiver end linear processing maximum likelihood (ML) decoding is used to decouple the signals transmitted from different antennas and perfect CSIR is assumed.

Spatial Multiplexing gain: In the presence of multi-path or rich scattering, a MIMO system can provide spatial multiplexing gain. This can be achieved by simply sending independent data streams over each of the transmit antenna elements. This technique is known as Vertical Bell Labs Space-Time Architecture (V-BLAST) [18] and it is the first spatial multiplexing technique implemented in real-time in a laboratory. For M transmit and N receive antennas, and under fast fading channel conditions, $\min(M, N)$ independent data stream can be transmitted (often referred to as degrees of freedom (DOFs)). In slow fading channel though, the V-BLAST architecture is strictly suboptimal. Another architecture, i.e., Diagonal Bell Labs Space-Time Architecture (D-BLAST) [19] can provide significant improvements by coding and interleaving the code-words across the antennas. However, the diagonal approach suffers from certain implementation complexities. The receiver must multiplex the signals in order to reconstruct the transmitting symbols. Maximum likelihood (ML) decoding is an optimal solution in the sense that it compares all the possible combinations of the symbols, but its complexity increases with the modulation order. Other popular techniques include zero forcing and minimum mean square error estimation combined with successive interference cancelation (MMSE-SIC) [20]. Diversity and multiplexing gain can be simultaneously obtained for a given multiple-antenna channel, but there is a fundamental tradeoff between how much each coding scheme can get [21].

1.3.3 Space-division multiple access (SDMA)

In a wireless network scenario with several nodes communicating to a common receiver, multiple receive antennas also allow the spatial separation of the signals of different transceivers, thus providing a multiple-access gain. This use of multiple antennas is also called space-division multiple access (SDMA). The fact that a MIMO receiver can isolate and decode $\min(M, N)$ independent data streams (M transmit and N receive antennas), can be extended to the case of single receiver employed with N antennas and M independent transmitters with one antenna element. This can be generalized to the case of several transmitters using overall M antenna elements in any possible combination given that the received streams are independent.

Based on the communication scenario (e.g., LOS or NLOS), the nature of the channel (e.g., fast or slow fading, high or low SNR) and the type of gain (e.g., power, range, diversity, multiplexing) that has to be achieved, the multiple antenna transceivers have to choose the optimum technique for communication [22]. However, in wireless mesh networks, the choice of a multiple antenna technique in a single link can highly influence the respective decisions of the adjusted links and affect in this way the overall network performance. In this point, it is the responsibility of the higher layers to assist and coordinate the individual link decisions based on one-hop and end-to-end characteristics and requirements in order to harmonize the network functionality. Therefore, it is of paramount importance to design novel medium access control and routing schemes that are able to apply these techniques to the dynamic wireless mesh networks. The deployment of multiple antenna techniques gives to this design an additional degree of freedom compared to the traditional omni-directional transceivers and makes it an extremely interesting and challenging task. In the remaining of this chapter we give a description of the several research and implementation challenges that come along with the usage of multiple antennas in wireless mesh networks (Section 1.4) and describe several scheduling (Section 1.5) and routing (Section 1.6) proposed solutions.

1.4 Smart antenna challenges and design criteria for mesh protocols

While antenna arrays can provide numerous advantages to wireless communications as discussed above, their introduction in wireless mesh network communication has to be thoroughly investigated since inappropriate or unde-

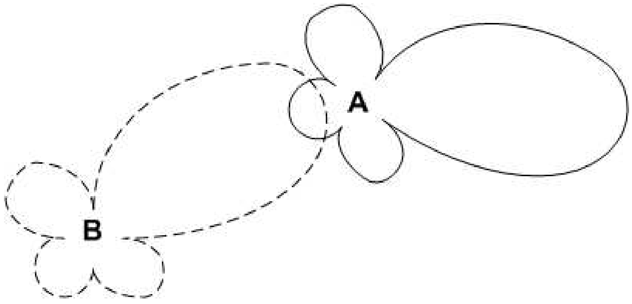

Fig. 1.2. Deafness problem.

sirable interaction with higher layers can lead to overall performance degradation. In the following of this section, we introduce and analyze all these issues and research challenges that have to be taken into account during the design of medium access control and routing protocols that used in conjunction with different antenna array techniques. It will be clear that some of the existing layer two and three traditional protocols cannot be used unmodified since their performance will be much worse compared to the omni-directional transmission.

In order to simplify the representation of different communication scenarios we use the same terminology as in [23] to define the distance between two neighbor nodes:

Omni-Omni (OO) neighbors: Nodes can directionally communicate with each other even if both of them are in omni-directional mode.

Omni-Directional (OD) neighbors: Nodes can directionally communicate with each other even if one of them is in omni-directional mode and the second one in directional mode, pointing the first one.

Directional-Directional (DD) neighbors: Nodes can directionally communicate with each other only if both of the nodes are using directional transmission/reception and pointing each other.

Note here that two OO-nodes can achieve OD and DD communication and an OD pair can perform DD communication but not the other way around.

1.4.1 Deafness

Deafness is a common problem that arises due to the use of directional antenna techniques and it occurs when a transmitter fails to communicate to its intended receiver, because the receiver beamforms towards a direction away from the transmitter [24]. Therefore, a receiver can increase its power gain from the direction of its main beam(s), but at the same time it becomes deaf in all the remaining directions. For example, in Fig. 1.2, node A is unable to hear nodes B transmission since node A's main-lobe is shifted to a different direction. Deafness can give rise to other problems such as the exposed terminal problem and back off fairness. Deafness can be a useful property if proper action is taken into account from higher layers since it can be used for interference mitigation purposes. For instance, a receiver can become deaf to the direction of the impinging interfering signals. In a mesh network, where multiple transmission take place new scheduling algorithms have to be defined such that they mitigate the deafness effect for useful signals reception while at the same time take advantage of its interference suppression properties.

1.4.2 Hidden/exposed terminal problem escalation

The hidden/exposed terminal problem is a well known issue in wireless networks [25]. Hidden is a terminal that is outside the coverage area of the transmitting node but within the coverage area of the receiving node. This has as a result the hidden terminal to be unable to sense the ongoing transmission, therefore it may try to transmit and inevitably create interference (or possible packet collision) to the receiving node. Exposed is a terminal that is located within the coverage area of the transmitting node but outside the coverage area of the receiving node. As a result, the exposed terminal will sense the ongoing transmission and will defer its transmission while it should be able to transmit (to another available receiver) since its transmission will not interfere with the ongoing transmission.

Proposed solutions to the hidden/exposed terminal problem are the transmission of a busy tone from the receiver in a separate channel [25] and the exchange of signaling between transmitter and receiver (request-to-send (RTS) and clear-to-send (CTS)) before the actual transmission takes place [26]. The commercial IEEE 802.11 [27] protocols have adopted the RTS/CTS signaling concept from [26] enhanced with the network allocation vector (NAV). While directional transmission can reduce the interference to adjacent nodes at the same time it can augment the hidden and exposed terminal problem if careful consideration of the impact of the beamforming on the medium access control algorithms design is not taken into account [28]. In the following we analyze all these issues related to the usage of directional antennas in carrier sensing multiple access (CSMA) based MAC protocol.

Initial channel sensing: It is desirable for an idle user to listen the channel omni-directionally (unless there is a special topology or it knows the location of the transmitter a priori) because a potential transmitter can be located in any possible position around. Moreover, a node has to overhear any other ongoing transmission around its area of coverage. The problem in this case though is that direct communication cannot be established if the transmitter is far enough (DD-neighbors) that cannot be sensed even if directional transmission of RTS takes place. Direct DD-communication could be possible if the receiver is sensing the channel directionally towards the direction of RTS transmission. Therefore a special mechanism is needed to inform the receiver for the potential transmitter direction. On the other hand a node that is willing to transmit has to sense the channel in the direction of the receiver

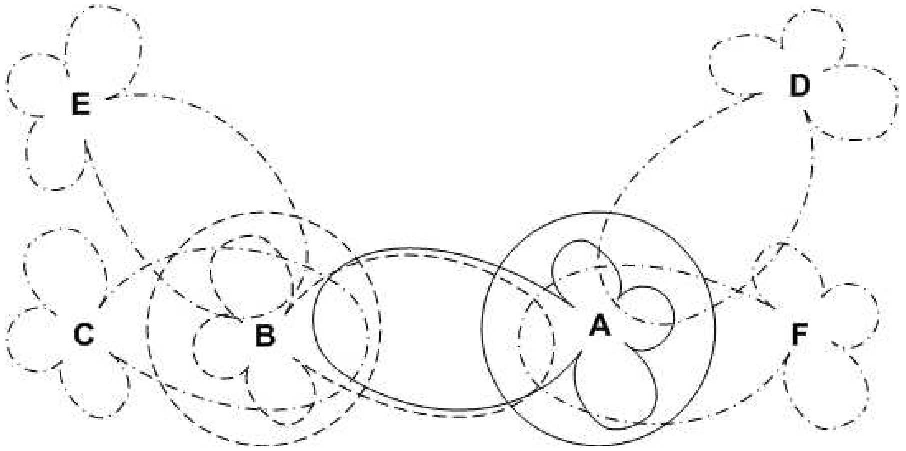

Fig. 1.3. A communication example - hidden terminals.

in order to avoid hidden terminals in that direction. However, for the time the potential transmitter is in a directional sensing mode it is deaf to any transmission in the direction of its side lobes.

RTS transmission: Since the idle nodes sense the channel omni-directionally a directional RTS packet transmission is needed to initiate communication with an OD-neighbor. Otherwise only the OO-neighbors within its omni-directional coverage area will be able to sense the RTS packet. However, this may generate some hidden terminals in the direction of the transmitter's side lobes.

Channel sensing after RTS transmission (transmitter): After sending a directional RTS packet the potential transmitter senses omni-directionally for CTS reply or any other transmission. This has as an effect the escalation of the exposed terminal since it will sense transmissions from directions that will be eventually suppressed from the side lobes. Furthermore, it will be unable to sense possible transmission from the direction of its receiver that are located outside the omni-directional carrier sensing range but inside the directional range.

For example in Fig. 1.3, node A sends a directional RTS to node B and switches to omni-mode to sense the channel. Node A will sense the transmission from node D, it will assume that this will overlap with its own transmission and it will defer its transmission. However, this transmission will be suppressed by its side lobes and will not affect the A to B communication. On the other hand, transmission from C will not be detected if A is in omni-mode, and will create a collision since A and C are DD-neighbors that point to each other.

Consider now the case that after sending a directional RTS packet the potential transmitter continues to sense at the same direction for CTS packet or any other transmission. This solves the hidden and exposed terminal problem

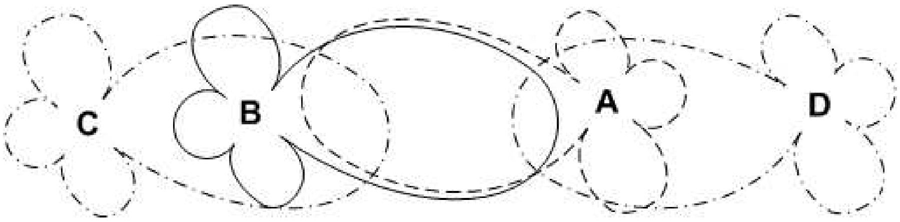

Fig. 1.4. Directional CTS communication.

of the previous case but will not avoid hidden terminals from the direction of its side lobes. For example, the node A becomes deaf to the direction of node F. Node F may create interference to node B since they are DD-neighbors that point to each other.

Channel sensing before CTS transmission (receiver): After a node receives an RTS packet it has to determine its DoA and if a packet is destined for itself or any other node. If the packet is intended for the given receiver it can directionally sense the channel towards the estimated DoA for any other ongoing or new transmissions. In this way it reduces the impact of both the hidden terminals problem in the direction of the main beam and the exposed terminals problem from the direction of the side lobes. Collisions can still occur as it is demonstrated by the following example:

Node B sends an RTS to node A (Fig. 1.3) that successfully receives the packet and continues to sense the channel omni-directionally before it replies with a CTS. Node C is unaware of the RTS transmission and performs directional transmission to the direction of A. Node A, which is unable to sense the transmission from C, will proceed on CTS transmission and collision will occur since A and C are DD-neighbors that point to its other. In a separate case, node D, that is also unaware of the RTS transmission, performs directional transmission to the direction of A. Node A will sense the transmission from D and abort its CTS reply. However, this is a wrong decision since the transmission from D will be suppressed from A's side lobes and will not affect the nodes A and B communication. If directional channel sensing takes place at node A, these two events will be avoided. However node A is unable to sense the transmission from node F that will create interference to node B. This could have been avoided by omni-directional carrier sensing.

CTS transmission: By sending a directional CTS packet the potential receiver will inform the nodes towards its main-beam direction for the forthcoming data transmission. However, this does not solve the future hidden terminal problem from the directions of its side lobes. These terminals will be unable to hear the CTS transmission and the will assume that the channel is idle. For example in Fig. 1.4, node A sends a directional RTS, and node B replies with directional CTS. In this way, node D that is willing to transmit toward the direction of B (and therefore performs directional sensing) will be able to sense the CTS. Note that node D has not sensed the directional RTS from

A. Node C on the other hand will sense the RTS from A but not the CTS from B and it may assume that the RTS was unsuccessful and the channel is free. Omni-directional CTS transmission does not solve the problem either since the adjacent nodes sense omni-directionally the channel and therefore only the OO-neighbor may sense the CTS transmission (OD-neighbors may be able to sense the CTS transmission only if they point towards the direction of the CTS transmitter). For example, node D (in Fig. 1.4) will not be able to sense an omni-directional CTS transmission from B.

Data and acknowledgment transmission: Data transmission and positive or negative acknowledgment from the receiver have to take place in a directional way.

Different antenna beamforming patterns: In a practical mesh network it is possible that not all of the wireless transceiver will be equipped with multiple antennas. Therefore, some of the nodes may be able to perform only omni-directional transmission and reception. Furthermore, the radiation patterns (beam-width and directivity) may be different in each transceiver depending on the available number of antenna elements. All these issues have to be also taken into account in the design of realistic medium access control protocols.

As a conclusion, hidden terminal problem is a highly important and still open research issue for nodes communication in a wireless mesh network that is complicated by the introduction of directional transmissions. Traditional RTS/CTS techniques are proven to be inadequate for directional transmissions. Medium access control schemes may have to allocate considerable amount of their wireless resources to mitigate this problem and exploit the benefits of beamforming. Therefore very careful consideration must be taken into account in the design of higher layer protocols for wireless mesh networks.

1.4.3 Congestion control: hidden terminal vs deafness fairness

From the above discussion it is clear that packet collision and deafness are two different issues that have as a result a node to abort its transmission and increase its back-off period. However, these two events have to be handled in a different way. For instance, the fact that a receiver is deaf towards a specific direction does not imply that the network is highly congested; therefore an unsuccessful transmitter should not increase its back-off period because this will highly decrease its probability to win the channel contention when the channel becomes finally available. On the other hand, a series of unsuccessful transmissions due to collision implies heavy traffic condition that has to be handled by appropriate congestion control.

Therefore, a novel mechanism has to be defined that differentiate these two events and take appropriate action whenever each of them takes place. Moreover most of the existing back-off algorithms have been designed and optimized for an omni-directional network model. Its performance may have to be reconsidered for a directional antenna system.

1.4.4 Directional NAV

Another issue that has to be taken into account when directional transmission is employed in a mesh network is the modification of the *Network Allocation Vector (NAV)*. Sensing a transmission from a specific direction does not necessarily imply that a node has to defer its own transmission and modify its back-off timer (as it happens in the omni-directional case). On the contrary, if a node is able to resolve the angle of arrival and deduce that its transmission does not interfere with the ongoing communication, it should presume that the channel is idle. Therefore, a node needs a table to keep track of the directions and the corresponding durations towards which a node must not initiate a transmission, i.e., *Directional NAV (DNAV)*. The continuous update of this table with the right information in order to keep neighbors silenced towards the right direction during a transmission is important both for dealing with the hidden terminal problem as well as for the spatial reuse.

1.4.5 MIMO related issues

Multiple-input multiple-output (MIMO) links have been seen in the previous section to provide high spectral efficiency in rich multi-path environments through multiple spatial channels without additional bandwidth requirements. This enormous spectral efficiency is obtained for a single link with no external interference. In a wireless mesh environment though, there will be channel reuse and therefore co-channel interference from other APs transmissions. Recent research results have shown that co-channel interference can seriously degrade the overall capacity when MIMO channels are used in a cellular system [29].

Moreover, it has been proven that for flat Rayleigh fading channels, with independent fading coefficients for each path, it is possible to achieve higher capacity by reducing the number of MIMO streams. More specifically, for a system with n receive antennas, m transmit streams and k interfering streams, all the m transmit streams can be isolated and decoded successfully as long as $m+k \leq n$. A group of m antenna elements will be used for data reception while the remaining $n-m$ elements are used to null out the interfering streams. The best performance is achieved when all the degrees of freedom of the MIMO channel are used, i.e., $m = n - k$. On the other hand, if the incoming streams are more than the receiver antenna elements (i.e., $m + k \geq n$), it may not be possible for the receiver to decode any of the desired signal streams if the excess streams degrade the overall SINR below a threshold. It must be noted here that if the interfering (k) streams are far weaker than the desired (m) streams, it may be possible to decode the desired streams (even if $m + k \geq n$) given that the SINR is above the required threshold.

These observations can be directly applied to the design requirements of multiple access schemes for wireless mesh networks with MIMO channels.

Moreover, it has been shown [20] that for multi-user communication, the channel capacity can be achieved by letting all the users simultaneously transmit and jointly decoded by the receiver rather than organize orthogonal channel access. However, the total number of possible simultaneous transmissions that can be decoded is limited by the number of the antenna elements at the receiver end. Given n receiver antennas, a rule of thumb is to have groups of n users transmit simultaneously and schedule different groups in an orthogonal way (e.g., TDMA).

In a wireless mesh network where multiple antennas are deployed at each AP a transmission can occupy multiple streams depending on the number of transmit antenna elements. In this case, it is more appropriate if a transmitter chooses only a subset of the strongest streams and distributes its power (e.g. using different water-filling techniques) over these streams instead of using the maximum number of streams for transmission [9]. The gain (known as stream control gain) is twofold: only the best channel modes (streams) are used for transmission while on the other hand multiple transmissions take place simultaneously which leads closer to capacity achievement as discussed above. The optimal number of simultaneous transmissions depends on the number of antenna elements used in each transceiver subset, the number of antennas at the receiver end and the number of possible interfering streams.

However, this requires perfect channel state estimation at the transmitter end in order to choose the strongest channel modes. At the receiver side, MMSE is the optimal compromise between maximizing the signal strength from the user of interest and suppressing the interference from the other users. Even better performance can be achieved from an MMSE with successive interference cancelation (MMSE-CSI) receiver.

All these make clear the paramount importance for novel medium access control and routing schemes that exploit these new communication opportunities provided by MIMO channels. For instance, the MAC scheduler should be able to allocate appropriate number of streams per transmitter-receiver pair in a way that a receiver is not overwhelmed by extended number of transmissions. This gives a rise to new kind of hidden and exposed terminal issue. Optimal resource allocation between data and feedback channel must be also performed (for instance, this information can be included in RTS and CTS packets [9]) so that always the best channel models are used. Here, a fairness model (e.g. proportional fairness) should be used in conjunction with the medium access control scheme so that weaker links in the mesh network are not starving. Moreover appropriate power control schemes needed so that interference suppression can be performed in the receiver side in conjunction with the stream control. The multiplexing vs diversity trade off must be also taken into account since channel reliability and delay limitations are as much important as high throughput for QoS constrained applications. Finally QoS routing schemes should include these MIMO parameters (degrees of freedom, stream quality, and multi-stream interference) in their utility functions during route discovery and maintenance.

1.4.6 FCC regulations

In this point we would like to briefly discuss another emerging issue regarding the maximum allowed transmitting power for directional transmissions if the wireless mesh network operates in unlicensed frequency bands. For example, U.S. Federal Communications Commission (FCC) regulations extended the total effective radiated power in unlicensed radio bands from 30dBm for single antenna systems, to 36dBm for beamforming systems. Most of the academic works on MAC and routing schemes for mesh networks do not take into account this parameter and they assume much higher directive gain (compared to the omni-directional transmission) in order, for example, to decrease the number of hops in multi-hop transmissions or increase the network connectivity. However this is a realistic and highly important issue that must be considered in the design of practical wireless mesh networks.

To summarize this section, it is of paramount importance the introduction of novel medium access control and routing schemes that exploit the benefits of multiple antenna deployment on the receiver and/or the receiver side of a wireless mesh network. Without careful consideration in the design of higher layers the usage of smart antenna techniques can have negative impact on the overall mesh network performance. This is why recently the design and performance analysis of medium access control and routing schemes with multiple antennas have attracted high research interest and some of them will be presented in the next section. A cross-layer approach must be taken since most of the issues cannot be handled by individual layers.

1.5 Smart antennas for scheduling

In the following we describe a number of proposed medium access control schemes with multiple antenna arrays for wireless mesh networks. These protocols are exploiting the benefits of multiple antenna systems while at the same time are trying to overcome the aforementioned problems and challenges that multiple antenna techniques will impose to higher layers. We initially present some CSMA based MAC schemes extensions of the popular IEEE 802.11 protocol that take into account the directional transmission property of smart antennas, we follow with description of a TDMA based scheme with directional antennas and we conclude this section with a couple of MAC protocols that exploit the diversity and multiplexing gain of MIMO systems.

1.5.1 Directional-MAC (DMAC)

Directional-MAC (DMAC) [30] is a scheme similar to IEEE 802.11 adapted to the use of directional antennas. The popular 4-way handshake CSMA/CA is used for channel reservation, data transmission and acknowledgment (for more information on the 4-way handshake CSMA/CA and IEEE 802.11 protocol see [27]). The RTS and CTS packets are transmitted directionally while the idle transceivers listen to the channel omni-directionally. In this way a potential receiver is able to estimate the DoA of the RTS packet and set the direction of the CTS accordingly. More specifically, the DMAC scheme operates as follows:

RTS transmission: Under the assumption that a transmitter knows the location of the receiver, a source performs directional physical carrier sensing towards the direction of the receiver. If the channel is sensed idle the source checks the back-off counter in the Directional Network Allocation Vector (DNAV) where the virtual carrier sensing status for each DoA is maintained. If the back-off counter counts down to zero, the RTS packet is directionally transmitted.

RTS reception and CTS reply: An idle transceiver is sensing the channel omni-directionally. In this way, the receiver of an RTS packet should be able to determine the DoA of the incoming signal (different DoA estimation techniques such as ESPRIT [13] and MUSIC [14] can be used). If transmission is permitted (both directional physical and virtual carrier sensing) towards the direction of source, the receiver beamforms towards the direction of the source and continues to sense the channel for SIFS time slots. If the channel remains free for the duration of SIFS the receiver replies with a CTS packet, otherwise, if the carrier is sensed busy the CTS transmission is canceled (similar to 802.11 [27]). All the other nodes (except the potential receiver) that are receiving the RTS packet update their respective DNAV tables with the transfer duration specified in the RTS packet. This prevents them from transmission in a certain range towards the reverse direction of the DoA of the receiving RTS.

CTS reception and DATA/ACK reply: The source node continues to beamform to the direction of the receiver, waiting for the CTS packet reply. If the CTS packet is successfully received within the CTS-timeout duration the DATA transmission starts. Both transmitter and receiver have their beam shifted towards the direction of each other. Upon the successful completion of DATA transfer the receiver replies with an ACK. If the CTS packet is not received within the CTS-timeout duration the transmission is canceled and the source reschedules the transmission of RTS according to the updated pack-off counter. All other nodes that overhear the CTS, DATA and ACK packets update their respective DNAV tables with the directions specified in these packets.

DMAC is a simplified approach that manages to exploit (up to certain point) the beamforming capabilities of multiple antenna transmitters in a wireless mesh network. Nevertheless, DMAC has failed to address the deafness problem while hidden terminals still exit as a result of the omni-directional channel sensing. Moreover, DMAC is unable to establish direct communication between DD-neighbors. See [24] for a more thorough discussion on the problems with DMAC.

1.5.2 Multi-hop RTS MAC protocol (MMAC)

Multi-hop RTS MAC (MMAC) protocol [23] is an extension of the basic DMAC protocol described before. MMAC attempts to exploit the extended transmission range property of directional antennas. If both transmitter and receiver are pointing their beams to each other the communication range can be significantly extended. DMAC has failed to address this property since the idle transceivers listens omni-directionally for new transmissions. This is highly important since it can reduce the number of hops between source and destination and reduce the end-to-end delay in multi-hop communications and increase the spatial reuse factor.

Although two DD-neighbors can communicate with each other directly, they need somehow to coordinate their beams to point to each other's direction. This is the main motivation of MMAC protocol that attempts to find an alternative DO-neighbor route for signaling exchange between the two DD-neighbors to coordinate their directions of transmission. To achieve this, an RTS packet has to be forwarded from the DD-source through multiple DO-neighbors to reach the DD-destination while the DD-source is inactively waiting for CTS reply. For instance, in Fig. 1.5, nodes A and B are DD-neighbors that cannot communicate unless they point each other. An RTS packet is sent through the A-C-D-B route to inform B for A's intention. The multi-hop RTS transmission and CTS, DATA and ACK packet exchange mechanism is described in the following:

RTS transmission: MMAC protocol does not provide any neighbor discovery phase. Therefore it is anticipated that each node have knowledge of the position of all its DD and DO-neighbors. Moreover it is assumed that a module running above the MAC layer is capable of deciding the appropriate communication scheme (e.g. sometimes it may be more appropriate to use multi-hop DO-route rather than direct DD-transmission) and finding the optimal DO-route to a DD-neighbor.

The source performs directional physical carrier sensing towards the direction of the potential DD-neighbor receiver. If the channel is sensed idle and also the DNAV allows a transmission to this direction, the source is sending an RTS packet towards the DD-receiver. There is a high probability that this packet may not reach the destination DD-neighbor since this node may be in omni-mode or has shifted its beam to different direction. The aim of such a transmission is to reserve the channel in the region between the DD-neighbors rather than to successfully deliver the RTS packet. Nodes in this region that overhear the RTS transmission will update their DNAV table to defer any transmission towards the directions of both the DD-neighbor nodes for a certain time. This time duration is specified in the RTS packet and is equal to

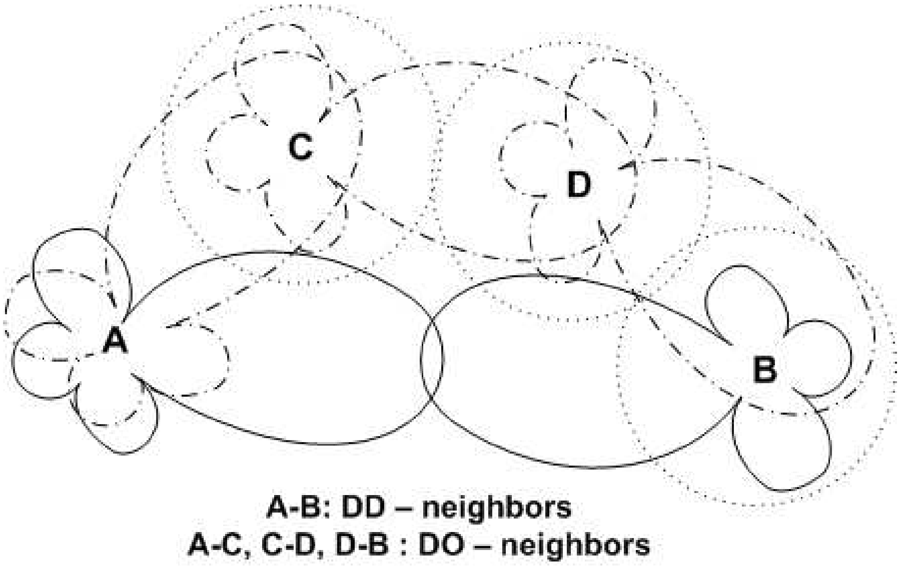

Fig. 1.5. DD-link activation in MMAC protocol.

the time required for the RTS packet to reach the DD-receiver plus the CTS packet transmission time (these time durations are described in the following).

If the DD-receiver happens to be beamformed to the direction of RTS, it may directly reply with a CTS packet and the DD-neighbors can proceed on the DATA/ACK phase. Otherwise, the DD-transmitter constructs a special type of RTS packet (called forwarding RTS) that is delivered to destination over multiple DO-hops. This packet contains the information of the DO-neighbors in the route from source to destination. None of the nodes modify their DNAV tables on receiving or overhearing the forwarding-RTS packet. The forwarding-RTS packet gets highest priority for transmission (it does not involve any back-off) while the nodes in the forwarding route simply drop the RTS if they are busy. This implies that the time required for a successful RTS transmission is a constant, known a priori.

RTS reception and CTS reply: In the DD-receiver side two events may happen. If this receiver happens to be beamformed to the direction of the DD-transmitter it can receiver the direct RTS packet. In this case it can directly reply with a directional CTS packet such that the multiple RTS forwarding procedure will be avoided. (Note that in [23] it is not clear when such an event may happen, since whenever a node is idle and able to receive it will be in omni-mode by default. Nevertheless, this can happen in case the DD-neighbor pair wants to extend their ongoing communication). In the second event, on receiving the forwarding-RTS packet, the DD-receiver proceeds on virtual and physical carrier sensing toward the direction of the DD-transmitter

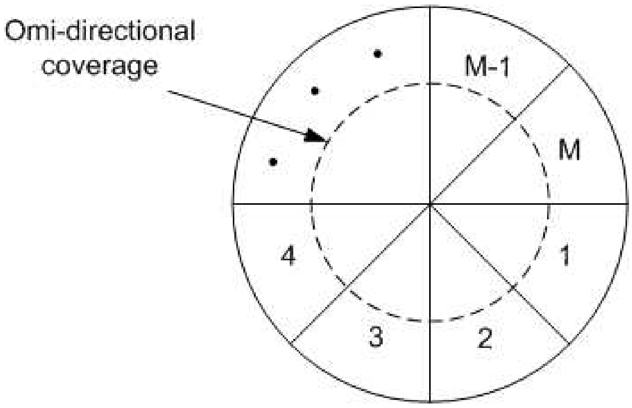

Fig. 1.6. Circular directional RTS transmission.

for SIFS time slots (similar to DMAC) and continues with CTS directional transmission.

CTS reception and DATA/ACK reply: Upon the reception of the CTS packet, the DD-link has been established and the DATA transmission starts. If the DATA transmission finishes successfully, the DD-receiver acknowledges the DD-transmitter with an ACK packet. If no CTS packet received during the CTS-timeout duration the transmission is aborted and the DD-transmitter reschedules the RTS transmission according to its directional back-off timer. Nodes that overhear the CTS and DATA packets update their DNAV with the duration specified in the packets.

MMAC can significantly increase the spatial reuse in a wireless mesh network. Simulation results for random topologies [24] have been shown that MMAC outperforms DMAC and IEEE 802.11 with omni-directional transmissions. The performance of MMAC is expected to be even better in the case of wireless mesh networks where the topology is more structured and static. Nevertheless, the multi-hop forwarding of RTS packet highly increase the probability of packet collision or drop (since back-off is not used) especially when the traffic demand in the network increases. This can offsets the advantages of utilizing DD-links when using MMAC as it increases the average end-to-end delay compare to DMAC.

1.5.3 CRTS and CRCM:

Circular RTS (CRTS) [31] is a simple in implementation protocol based on the concept of the IEEE 802.11 but it uses only directional transmissions. It assumes antenna with predefined number if beams i.e., switched beam antenna, that cover all the area around the transmitter. In this scheme the RTS is transmitted directional consequently, in a circular way, so that it covers

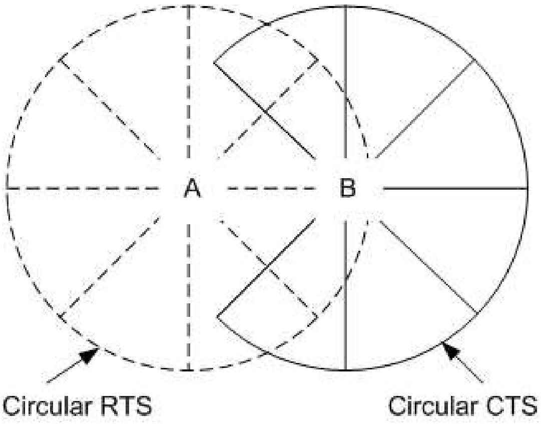

Fig. 1.7. Circular directional RTS and CTS transmission.

the entire azimuthal-angle domain. For instance, in Fig. 1.6, a nodes with M predefined number of beams starts sending its RTS with beam 1. Short afterwards it turns its transmission to beam 2 and transmits the same RTS packet and so on until it covers the whole are by transmitting with beam M. The RTS contains the direction and duration of the intended four way handshake (similar to 802.11).

At the end of the RTS circulation, all the neighbors of the transmitter are informed about the intended transmission and after executing a simple algorithm [31] decide if they will defer their transmission in the direction of transmitter or receiver. On the other hand, the transmitter hears the channel omni-directionally to receive the CTS reply within a predefined period. Note that the receiver has to wait appropriate time until the transmitter finishes the RTS circulation and switches to receiving mode before it proceeds to its CTS reply.

Circular RTS and CTS MAC (CRCM) [32] is an extension of CRTS that further improves the robustness of medium access control by introducing a combination of circular transmission of RTS and CTS messages. In CRTS, not all of the receiver's neighbors are made aware of the pending DATA and ACK transmissions and therefore it does not solve the hidden terminal problem in receiver's neighborhood. In particular, these nodes can initiate transmissions that can cause a collision during the ACK reception at the transmitter.

In order to tackle this problem the CRCM algorithm introduces an efficient mechanism for the directional transmission of CTS. The circular RTS transmission is the same as CRTS, however the receiver after replying with a directional CTS to the transmitter will further transmit directional CTS messages towards the unaware neighboring nodes (i.e., those nodes that are in the coverage range of the receiver but not in that of the transmitter). For example, in Fig. 1.7, node B avoids the transmission of CTS to the directions that have been already covered by the circular RTS message. The receiver's neighbors execute the same algorithm [32] as did the transmitter's neighbors in order to decide on whether or not to postpone their transmission towards the sender-receiver pair.

CRCM algorithm gives a solution to the hidden terminal problem due to asymmetry in gain, arising due to the deployment of directional antennas in wireless ad hoc or mesh networks. While power consumption because of the extensive circular packet transmission is not an important issue in mesh networks, the time spent for these transmissions can be proven crucial for several delay sensitive applications.

1.5.4 ToneDMCA

ToneDMAC [24] is a medium access control scheme that tries to alleviate the impact of deafness problem while retaining the benefits of directional beamforming. Similar to previous directional MAC protocols, ToneMAC has adopted the CSMA/CA principles of IEEE 802.11 and combines it with switched beam antenna transceiver and a tone-based mechanism. The main idea is that both transmitter and receiver, after the completion of their communication, transmit omni-directionally out-of-band tones to differentiate deafness from congestion. In this way, the backlogged nodes can deduce deadness as the cause of their previous failure (and not congestion) and adjust their back-off interval accordingly.

In the beginning, the transmitter and receiver exchange directional RTS and CTS packets without trying to inform their "omni-directional" neighbors of their intended communication. If the initial handshake is successful, data and ACK packets transmission follow in a similar directional way. After the completion of their dialogue, both nodes omni-directionally transmit out-of-band tones to notify their neighbors that it was them that have been engaged in communication over the recent past.

The intended transmitter beamforms in the direction of its intended receiver and performs physical carrier sensing towards that direction. If the channel is sensed idle the transmitter randomly chooses the time it will transmit within the back-off window interval $[0, CW_{min}]$. Then it switches to omni-directional mode and senses the channel while performing the back-off counting. If a signal is sensed, it performs azimuthal beam scan to determine its DoA. If the signal arrives from direction different than the direction of its potential receiver continues with the countdown. Otherwise it stops the counter until the channel is sensed idle again. Note here that since this node is in sensing mode, it may happen to receive a RTS packet that is intended for itself. In this case, it may choose to abort its own transmission and reply with a CTS packet, alleviating the possibility of deafness and deadlock.

In ToneMAC the channel is divided into two sub-channels: a data channel where RTS, CTS, data and ACK packets are transmitted and narrow control channel where the busy tones are sent. The busy tones do not contain any information (e.g. sinusoids with sufficient spectral separation). These tones can only be detected (through energy estimation) but the receivers will not be able to determine the sender of the tones. To solve this issue, ToneMAC proposes a simple hash function that allocates tones of different frequencies and time durations to different nodes according to node's identifier. If a node i can choose a tone of frequency f_i from a set of K frequencies, and an integer time duration t_i from an interval $[t_{min}, T]$, a simple hash function is used to assign a tuple (f_i, t_i) to node i such that:

$$f_i = (i \mod K) + 1 \tag{1.1}$$

$$t_i = (i \mod (T-1)) + 2. \tag{1.2}$$

The transmit power of the tones is increased such that the omni-directed transmission range will be equal to the range of directional transmission. (Please note that even this is what is mentioned in [24], smaller transmission power will be appropriate since the busy-tone has only to be sensed but not decoded [12]). Of course there is a small probability that two or more nodes have the same (f, t) signature or they may have the same frequency and different tone duration but their tones overlap in time. This probability is quite small since these nodes may be located far away from each other or they point in different directions; also their randomized back-off counters further reduce the probability of simultaneous tone transmission (for more information on this issue see [24]).

ToneDMAC comprises a practical solution for CSMA based mesh networks with directional antennas due its ability to reduce channel-idle time and resolve deafness deadlocks. Nevertheless, since tones are transmitted on a narrow bandwidth channel, and the duration of transmission is short, tones may be detected partially, or may not be detected at all. Multi-path effects can also cause a tone to arrive from a different direction than the known direction of a neighbor. Clearly, both these effects can cause a node to misclassify the cause of transmission failure.

1.5.5 Directional Transmission and Reception Algorithm (DTRA)

DTRA [33] is a TDMA-based MAC algorithm for load-dependent slot reservation in a wireless ad hoc network with directional antennas. The main characteristics of DTRA are that (1) it provides fully directional transmission/reception, (2) it is distributed, (3) it provides dynamic on-demand slot allocation and reservation to different links and (4) it includes power control. Its TDMA-based reservation scheme makes it appropriate for quality-of-service (QoS) support in wireless ad hoc and mesh networks. DTRA requires that each node is equipped with one transceiver with a steerable antenna and all nodes are synchronized. Each node can rapidly switch between transmitting and receiving mode (half duplex). In order to communicate, two nodes must point their beams at each other at the same time and be in a complementary transmit-receive mode. The timeline is divided into frames that each of them comprises three sections dedicated to neighbor discovery, data reservation and data transmission.

Neighbor discovery phase: During neighbor discovery phase a node performs a scan by transmitting a sequence of advertisements in each possible direction. A three-way handshake is used, where the receiver node of an advertisement replying with its own advertisement and expecting to receive an acknowledgment in return within a short time interval. During the three-way handshake the nodes can exchange transmit power level information and also redefine their directional information. Moreover, they make an agreement on the future mini-slots that they will listen to each other in the reservation phase (a detailed description of the handshake algorithm and information exchanged is given in [33]). These agreements are valid until the time the two nodes detect each other again. The actual number of scans needed by a node to discover all of its potential neighbors depends on the characteristics of the achievable network graph, its beam-width and the algorithm used in each node for their mode (scanning or listening) decision. A deterministic mode selection algorithm is proposed that two neighbors can be detected by each other in at most $log_2 N$ scans, where N is the maximum number of nodes in the network. A random mode selection algorithm has been also proposed in [34] where a node decides whether to be in scan or listen mode with equal probability independent of the decisions made in previous slots.

Slot contention and reservation phase: In the reservation phase, reassurance of two nodes connection and reservation of data slots will take place. Two nodes will re-detect each other at the predefined mini-slots by pointing in the direction agreed on during neighbor discovery. A three-way handshake will take place similar to the discovery phase where the two nodes negotiate who is going to transmit/receive and agree on the mutual available slots to be reserved for data transmission in the next phase. It is possible that none of the nodes desire to make a reservation or the mutual available slots are not sufficient for their communication (e.g. QoS requirement are not satisfied).

Data transmission and QoS: In order to provide QoS support, three priority queues for each neighbor are defined and the available slots in the data transmission phase are ranked with a priority metric. When making a reservation, if there are not sufficient slot for high-priority traffic, slots allocated to lower priority can be asked to be reallocated. To ensure fairness, a threshold on the maximum number of slots for each priority class should be set.

One of the main advantages of DTRA protocol is that it takes advantage of the fully directional communication (both directional transmission and reception all the time) capability of a multiple antenna system. Moreover its slot reservation scheme makes it appropriate to a mesh network with various QoS constrains and demands. One of the main disadvantages is its delay performance for low traffic (e.g., compared to omni-directional IEEE 802.11) because of the fixed resource allocation phase. Such delays will be accumulated in each hop in a multi-hop scenario. Since it is based on directional transmission, the performance of DTRA will highly degrade in multi-path communication environment without a dominant LOS component.

1.5.6 SD-MAC

SD-MAC [35] is an IEEE 802.11 based medium access control scheme that exploits the spatial diversity gain of MIMO systems, given that the wireless transceiver are employed with multiple antennas. In order to achieve full-order spatial diversity space time coding is used on the transmitter end. CSI knowledge is required at the transmitter while channel gains at the receiver are obtained by using preamble symbols. SD-MAC is based on the RTS/CTS mechanism of the IEEE 802.11 distributed coordination function (DCF). More specifically a source node performs channel virtual carrier sensing similar to 802.11 and physical carrier sensing by using all its antenna elements. If NAV is empty and channel is sensed free the RTS packet is transmitted in a default rate using space-time coding in order to exploit the transmission diversity. The destination node receives the RTS and uses the preamble symbols to perform channel estimation before it decodes the space-time encoded packet. Other nodes that overhear the RTS packet they just decode the transmission duration and update their NAV tables. The destination node replies with a space-time encoded CTS packet that contains the rate control information for the following DATA packet based on the channel estimation. The source node receives the CTS packet, adapts its transmission data rate according to the information passed by the CTS and transmits the multi-rate DATA packet. The destination replies with a default-rate ACK packet to confirm the data reception.

While SD-MAC scheme exploits the spatial diversity of the MIMO system, it fails to exploit multiplexing gain. This could be achievable since the RTS/CTS packets can be used as a feedback channel for CSI information at the transmitter. The diversity can improve significantly the channel reliability and increase the transmission rate indirectly. On the other hand, diversity can also increase the transmission range for the same data rate. This can have a great impact on the routing scheme since it can reduce the number of hops and decrease the corresponding end-to-end delay. However, a higher transmission range will increase the area of coverage which can lead to delays due to contention and packet collisions. The impact of SD-MAC on the routing in terms of the optimal hop distance is analyzed in [35].

1.5.7 Stream Controlled Medium Access (SCMA)

Both a centralized and distributed versions of Stream Controlled Medium Access have been proposed in [9]. Since the main focus of this chapter is on distributed algorithms for mesh networks, only the latter version will be presented here. The main objective of SCMA is to maximize the network utilization subject to a given fairness model. More specifically SCMA tries to leverage the benefits of stream control (transmission on a subset of the strongest streams) and partial interference suppression (use the remaining streams for interference suppression) in a distributed way where all the available degrees of freedom are shared between the mesh network transceivers. The main components of the SCMA algorithm are presented in the following:

Node Coloring: Initially the distributed SCMA protocol performs identification of bottleneck links, i.e., the links that belong to multiple contention regions in the network. These bottleneck links are colored "red" while the remaining nodes of each contention region are colored "white". The red links are scheduled in a non-stream controlled manner (operate on all available steams) while the white links are based on pure stream control. This is due to the fact that the red links are consuming resources from multiple contention regions that otherwise can operate simultaneously on all their available resources. Therefore it is preferable that the red links are scheduled independently (for some examples on how this differentiation will improve the overall resource allocation together with the complete coloring algorithm description see [9]).

Contention and Channel Access: After the nodes have chosen their color, they move to the channel contention phase that depends on their color. This includes four modes (1) $No\_Contend$,(2) *Contend*,(3) *Acquire* and (4) $Sched\_White\_Links$. Every node is initially in the $No\_Contend$ mode. Whenever a node having a packet to transmit it moves to *Contend* mode with probability $P_{new} = P_{old}$ (P_{old} is a network parameter that represents the persistence value; the entire network adaptation progress is based on this value). In Contend mode a node chooses a waiting time (in number of slots) uniformly distributed from the interval $(0, B)$ after which it senses if the channel is busy. The busy state of the channel here corresponds to a lack of available degrees of freedom (streams) in the channel around the transmitter and the receiver. If the channel is sensed busy, the node aborts its transmission and readjust its persistence to $P_{old} = (1 - \beta)P_{old}$. Moreover, if the it is a white node, it further updates its P_{new} value to $P_{new} = (P_{old}K_{old})/K_{new}$. Same readjustment is performed if the node faces or detects a collision.

If the channel is sensed idle the node proceeds to *Acquire* mode where the actual data transmission takes place. Every node in the two-hop range away from the transmitter automatically expends the appropriate number of resources (antenna elements) to suppress the interference from this transmission. At the end of a transmission all the neighbour nodes having a packet to transmit increase their persistence $P_{old} = P_{old} + \alpha$, while the white nodes further update their $P_{new} = (P_{old}K_{old})/K_{new}$. Typical values for α and β are

0.1 and 0.5 respectively [9]. In order to determine the resource availability a node has to estimate each time the amount of remaining streams of every node in its two hop neighbourhood by listening to the control (RTS/CTS) packets transmissions. Therefore the reception range of the control packets has to be extended by a factor of two. This can be achieved by transmitting multiple copies of the control packets on at least four streams (double range can be achieved with 4 antenna elements and a path-loss exponent of 4). Since CSI is not available at the receiver in this stage, space-time block codes can be used to exploit the transmit diversity gain of MIMO for range extension.

Coordinated Scheduling: The first white node in a clique that gains access to the channel, it also coordinates the other white nodes to transmit in the same slot using their own estimated fair share. This is the $Sched\_White\_Links$ mode. This is achieved by the introduction of a flag in the RTS/CTS packets. All the white links that have a packet to transmit schedule themselves in the same slot, irrespective of whether they contend for channel access in that slot or not. However, all the transmitting white links (except the initiator of the coordinating scheduling) will still have to update their persistence to $P_{old} = (1 - \beta)P_{old}$.

SCMA algorithm comprises a novel technique to exploit the propitious characteristics of MIMO links in wireless mesh networks. SCMA can improve the aggregate network throughput and improve the fairness [9] compare to CSMA/CA(k), i.e. conventional CSMA with transmission over all the k-streams. However, as the number the nodes density increases, more independent contention regions will overlap, and as a result more nodes will be colored red and the SCMA network performance will converge to CSMA/CA(k). Moreover, further investigation needed on how the power of adjusted interfering streams does affect the ongoing data stream transmissions.

1.5.8 Conclusions on Scheduling with Multiple Antennas

In this section several distributed medium access control protocols with multiple antennas deployment have been presented and their advantages and drawbacks have been discussed. The majority of these schemes ([30][23][31][32][24]) are extensions of the popular IEEE 802.11 protocol, therefore are based on random channel access that makes them inappropriate for strict QoS constraints. DTRA [33] protocol provides slot reservation that can promise QoS at the price of relatively high delays for low traffic networks as discussed before. All these protocols are based on beamforming techniques. SD-MAC [35] and SCMA [9] on the other hand, are exploiting the diversity and multiplexing gain respectively of the MIMO channel in order to increase channel reliability and data throughput.

The overall mesh network system performance can be further improved if opportunistic transmissions are considered. Recent work on opportunistic scheduling [36] with omnidirectional transmissions has shown that by using appropriate utility functions considerable opportunistic gain can be achieved, while at the same time the generated interference is reasonably temporal-correlated. This is an important property that ensures satisfactory channel prediction for better distributed power control and scheduling performance. Opportunistic scheduling schemes combined with the aforementioned multiple antenna techniques is an unexplored and promising area of high research interest and potentials (e.g., it is part of the research agenda for the MEMBRANE project [3]).

1.6 Smart antennas for routing

While multiple antenna techniques have been widely analyzed from a MAC perspective, their usage and impact on network layer and more specifically their interaction with routing has not received much research attention. Moreover, the research community interest over the last decades regarding wireless routing has been only concentrated on omnidirectional transmissions. In the following we briefly demonstrate and discus a number of proposed routing schemes that take into account multiple antenna techniques (mainly for directional transmission).

The impact of smart antennas on QoS routing for multi-hop wireless networks is evaluated by simulations in [37] as an extension of the Wireless Fixed Relay routing (WiFR) [38] protocol. However, the analysis is based on a mathematical programming model, and no routing algorithm is defined in terms of signaling that has to be exchanged through the route and the required cross layer interaction in order to solve the aforementioned problems related with directional transmissions.

The routing improvement using directional antennas in adhoc networks is demonstrated in [39] where two techniques are proposed to a) bridge permanent network partitions and b) repair routes in use in case of link breakage by using directional transmissions. The design and evaluation is based on the Dynamic Source Routing protocol [40], an on-demand routing protocol for mobile adhoc networks, in which the originator of a packet decides the entire sequence of hops through which the packet is to be forwarded to the final destination. However, this protocol is designed to enhance network connectivity rather than increasing the end-to-end throughput or guarantee quality of service. Therefore, the directionality is used only when two nodes are located far enough for omnidirectional communication (the decision is based on SINR measurements).

Another approach on routing with beamforming is illustrated in [41]. The proposed algorithm is based on the well known Ad-Hoc On-Demand Distance Vector routing protocol (AODV) [42] with directional transmitters and omnidirectional receivers. Nodes are assumed to be equipped with switched beam antennas consisting of K directional non-overlapping beams each of them spanning an angle of $2\pi/K$ radians. For unicasting packets, if the destination nodes are located on the direction of the same beam the transmissions are time multiplexed, while different beams are simultaneously activated if the receivers are located in separate directions. For broadcasting messages, such as Route Request, all the beams are activated. However, this work also fails to address the problem of deafness and the beam synchronization for DD-nodes communication.

While the previous work on routing with multiple antennas is mainly focused on using the directionality to increase connectivity, a wireless mesh network must also provide high data throughput and meet the various QoS requirements of the overlying applications. Smart antennas is definitely a key technology that can highly contribute towards this direction. Therefore, it is of paramount importance to design efficient QoS routing protocols that harmonically coexist with lower layers and exploit the multiple capabilities and benefits that the multiple antenna technologies can provide. For instance, novel routing schemes exploiting the SDMA opportunities of MIMO techniques have to be investigated in conjunction with new utility functions comprising of new interference patterns and increased transmission ranges. Furthermore, algorithms for DD-synchronization and communication through the route have to be designed to reduce end-to-end packet delays.

Conclusions

The impact of multiple antenna array techniques on medium access control schemes for mesh networks has been analyzed in this chapter. Several multiple antenna architectures and methodologies, such as steered-beam antennas, adaptive antennas and MIMO coding, have been demonstrated. It has been clear that while these techniques can significantly improve the performance of single-link communications, from a wireless mesh network perspective they can also considerably degrade the overall performance of wireless mesh networks if careful consideration of their interaction with higher layers is not taken into account. Deferent design challenges, such as deafness, hidden and exposed terminals and MIMO related issues have been discussed. Several proposed MAC protocols for wireless ad hoc and mesh networks with directional antennas and MIMO techniques have been presented and their advantages and weaknesses have been discussed. Finally, we briefly discussed the lack of efficient routing algorithms for nodes with multiple antennas and the need of routing schemes that exploit the smart antenna's capabilities.

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References

1. I. F. Akyldiz, X. Wang, “A Survey on Wireless Mesh Networks,” *IEEE Communications Magazine*, pp. 23-30, vol. 43, issue 9, Sept. 2005.
2. I. F. Akyldiz, X. Wang, W. Wang, “Wireless Mesh Networks: a survey,” *ELSEVIER Computer Networks*, pp. 445-487, vol. 47, no. 4, March 2005.
3. IST-MEMBRANE: Multi-Element Multihop Backhaul Reconfigurable Antenna Network (www.ist-membrane.org).
4. P. H. Lehne and M. Pettersen, “An Overview of Smart Antenna Technology for Mobile Communication Systems,” *IEEE Communications Surveys*, pp. 2-13, Vol. 2, No. 4, Fourth Quarter 1999.
5. A. Alexiou, M. Haardt, “Smart Antenna Technologies for Future Wireless Systems: Trends and Challenges,” *IEEE Communications Magazine*, pp. 90-97, Sept. 2004.
6. M. Webb, M. Beach, A. Nix, “Capacity Limits of MIMO Channels with Co-Channel Interference,” *in Proc. of VTC 2004-Spring*, 17-19 May 2004.
7. Y. Song and S. D. Blostein, “MIMO Channel Capacity in Co-Channel Interference,” *in Proc. of 21st Biennial Symposium on Communicatios*, pp. 220 - 224, June 2002.
8. S. Bandyopadhyay, S. Roy, T. Ueda, *Enhancing the Performance of Ad Hoc Wireless Networks with Smart Antennas*, Auerbach Publications, 2006.
9. K. Sundaresan, R. Sivakumar, M.A. Ingram, T.-Y. Chang, “Medium Access Control in Ad Hoc Networks with MIMO Links: Optimization Considerations and Algorithms,” *IEEE Trans. on Mobile Computing*, pp. 350-365, vol. 3, no. 4, Oct.-Dec. 2004.
10. J. H. Winters, “Smart Antennas for Wireless Systems,” *IEEE Personal Communications*, pp. 23-27, vol. 5, no. 1, Feb. 1998.
11. J. H. Winters, “Smart Antenna Techniques and Their Application to Wireless Ad Hoc Networks,” *IEEE Wireless Communications*, pp. 77-83, vol. 13, no. 4, Aug. 2006.
12. J. A. Stine, “Exploiting Smart Antennas in Wireless Mesh Network Using Contention Access,” *IEEE Wireless Communications*, pp. 38-49, vol. 13, no. 2, April 2006.
13. R. H. Roy, T. Kailath, “ESPRIT - Estimation of Signal Parameters via Rotational Invariance Techniques,” *IEEE Trans. on Acoustics, Speech, and Signal Processing*, pp. 984 - 995, vol. 37, no. 7, July 1989.
14. R. O. Schmidt, “Multiple emitter location and signal parameter estimation,” *IEEE Trans. on Antennas Propagation*, pp. 276-280, vol. 34, no. 3, March 1986.
15. S. Bellofiore, J. Foutz, R. Govindaradjula, I. Bahceci, C.A. Balanis, A.S. Spanias, J.M. Capone, T.M. Duman, “Smart antenna system analysis, integration and performance for mobile ad hoc networks (MANETs),” *IEEE Trans. on Antennas and Propagation*, pp. 571-581, vol. 50, no. 5, May 2002.
16. S.M. Alamouti, “A simple transmit diversity technique for wireless communications,” *IEEE Journal on Selected Areas in Communications (JSAC)*, pp. 1451-1458, vol. 16, no. 8, Oct. 1998.
17. V. Tarokh, H. Jafarkhani, and A. R. Calderbank, “Space-time block codes from orthogonal designs,” *IEEE Trans. on Information Theory*, pp. 1456-1467, vol. 45, no. 5, July 1999.

18. P. W. Wolniansky, G. J. Foschini, G. D. Golden, R. A. Valenzuela, “V-BLAST: an architecture for realizing very high data rates over the rich-scattering wireless channel,” *in Proc. of URSI International Symposium on Signals, Systems, and Electronics*, Sept.-Oct. 1998.
19. G. J. Foschini, “Layered Space-Time Architecture for Wireless Communication in a Fading Environment when Using Multi-Element Antennas,” *Bell Labs Technical Journal*, pp. 41-59, vol. 1, no. 2, Fall 1996.
20. D. Tse and P. Viswanath, *Fundamentals of Wireless Communications*, Cambridge University Press 2005.
21. L. Zheng and D. Tse, “Diversity and Multiplexing: A Fundamental Tradeoff in Multiple-Antenna Channels,” *IEEE Trans. on Information Theory*, pp. 1073-1096, vol. 49, no. 5, May 2003.
22. K. Sundaresan, S. Lakshmanam, R. Sivakumar, “On the Use of Smart Antennas in Multi-Hop Wireless Networks,” *in Proc. of BROADNETS*, Oct. 2006.
23. R. R. Choudhury, X. Yang, R. Ramanathan, N. H. Vaidya, ”Using Directional Antennas for Medium Access Control in Ad Hoc Networks,” *in Proc. of ACM MOBICOM’02*, Sept. 2002.
24. R. R. Choudhury and N. H. Vaidya, “Deafness: A MAC Problem in Ad Hoc Networks when using Directional Antennas,” *in Proc. of the 12th IEEE International Conference on Network Protocols (ICNP’04)*, Oct. 2004.
25. F. A. Tobagi and L. Kleinrock, “Packet switching in radio channels: Part II - the hidden terminal problem in carrier sense multiple-access modes and the busy-tone solution,” *IEEE Trans. in Communications*, pp. 1417-1433, vol. COM-23, no. 12, Dec. 1975.
26. P. Karn, “MACA - A New Channel Access Method for Radio Packet Radio,” *in Proc. of the 9th ARRL Computer Networking Conference*, 1990.
27. ANSI/IEEE Std 802.11, “Wireless LAN Medium Access Control (MAC) and Physical Layers (PHY) Specifications,” 1999.
28. G. Li, L. L. Yang, W. S. Conner, B. Sadeghi, “Opportunities and Challenges for Mesh Networks Using Directional Antennas,” *in Proc. of IEEE WiMesh*, Sept. 2005.
29. M. F. Damirkol, M. A. Ingram, “Stream Control in Networks with Interfering MIMO Links,” *in Proc. of Wireless Communications and Networking WCNC*, March 2003.
30. Y. B. Ko, V. Shankarkumar and N. H. Vaidya, “Medium Access Control Protocols Using Directional Antennas in Ad Hoc Networks,” *in Proc. of IEEE INFOCOM*, March 2000.
31. T. Korakis, G. Jakllari, L. Tassiulas, “A MAC Protocol for Full Exploitation of Directional Antennas in Ad-Hoc Wireless Networks,” *in Proc. of ACM MobiHoc*, June 2003.
32. G. Jakllari, I. Broustis, T. Korakis, S. V. Krishnamurthy, L. Tassiulas, “Handling Asymmetry in Gain in Directional Antenna Equipped Ad Hoc Networks,” *in Proc. of IEEE PIMRC*, Sept. 2005.
33. Z. Zhang, “DTRA: Directional Transmission and Reception Algorithms in WLANs with Directional Antennas for QoS Support,” *IEEE Network*, pp. 27-32, vol. 19, no. 3, May-June 2005.
34. M. E. Steenstrup, “Neighbor Discovery Among Mobile Nodes Equipped with Smart Antennas,” *in Proc. of ADHOC’03*, May 2003.

35. M. Hu and J. Zhang, “MIMO Ad Hoc Networks: Medium Access Control, Saturation Throughput and Optimal Hop Distance,” *Special Issue on Mobile Ad Hoc Networks, Journal of Communications and Networks*, pp. 317-330, Dec. 2004.
36. Yun Hou and Kin K. Leung, “A Novel Distributed Scheduling Algorithm for Wireless Mesh Networks,” *in Proc. of IEEE Globecom 2007*, Nov. 2007.
37. L. Coletti, D. Ciglioni, A. Capone, M. Zambardi, “Impact of Smart Antennas on QoS Routing for Muli-hop Wireless Networks,” *in Proc. of the 14th IST Mobile and Wireless Communications Summit*, June 2005.
38. A. Capone, L. Coletti, M. Zambardi, “QoS Routing in Multihop Wireless Networks: New Model and Algorithm,” *in Proc. of QoS-IP 2005*, Feb. 2005.
39. A. K. Saha, D. B. Johnson, “Routing Improvement Using Directional Antennas in Mobile Ad Hoc Netwroks,” *in Proc. of IEEE Globecom 2004*, Nov. 2004.
40. D. B. Johnson, D. A. Maltz, “Dynamic Source Routing in Ad Hoc Wireless Networks,” *Mobile Computing*, ch. 5, pp. 153-181, Kluwer Academic Publishers, 1996.
41. N. Nie, C. Comaniciu, “Energy Efficient AODV Routing in CDMA Ad Hoc Newtorks Using Beamforming,” *in Proc. of IEEE Vehicular Technology Conference (VTC)*, May-June 2005.
42. C. E. Perkins, “Ad hoc On-Demand Distance Vector (AODV) Routing,” RFC 3561, IETF Network Working Group, July 1998.