

# A “Smart” MAC-Routing Protocol for WLAN Mesh Networks

Daniela Maniezzo, Gianluca Villa, Mario Gerla  
Computer Science Department,  
University of California, Los Angeles, CA 90095-1596, U.S.A.  
{maniezzo, gerla}@cs.ucla.edu; gvilla@elet.polimi.it

UCLA-CSD Technical Report Number 040032

October 28, 2004

## Abstract

A new topology of wireless LANs, the Mesh networks, is gaining the attention of the international scientific community and has led the IEEE to the creation of a special working group, IEEE 802.11s. A WLAN mesh network is a IEEE 802.11 WLAN infrastructured network in which the communication within the Access Points in the same Extended Service Set (ESS) is hop-by-hop in a router-like fashion.

The IEEE 802.11s working group has centered the target of focusing on the MAC layer protocol, understanding how the current MAC procedures are insufficient to sustain a WLAN Mesh network and how functions typical of higher layers must be part of the MAC itself to grant good levels of efficiency and bandwidth utilization. The general idea is that of a fusion of different aspects and components within the MAC, designing a cross-layer network optimization which goes beyond the common barriers between the layers in the OSI stack.

In this technical report we propose a routing protocol embedded in the MAC which takes advantage from directional antennas at the physical layer in the communication between the APs of a WLAN Mesh network.

# 1 Introduction

A new topology of wireless LANs, the Mesh networks, is gaining the attention of the international scientific community and has led the IEEE to the creation of a special working group (IEEE 802.11s) which is in charge of studying the issues deriving from what will be a completely wireless distribution system used to interconnect different BSSs (Basic Service Sets) through secure and performing links.

The Mesh networks eliminate the necessity of a wired system between a pair of stations: a data frame, originating in a specific BSS, is passed from the source node to its AP, then the AP, on the basis of a revised MAC layer protocol, becomes responsible for its delivery to the final recipient passing through a multi-hop transmission which involves the intermediate nodes (MESH APs) along the path to the destination.

The Mesh network traffic flows basically in the same way the data packets travel across multiple points in an ad hoc network, the main difference being that in case of a Mesh you have to assure the coexistence of intra-BSS and inter-BSS communications, with all the QoS constraints that this requires.

In its most complex form, a WLAN Mesh network may work like a peer-to-peer network, where APs both send their own data and forward packets for other client stations. In an environment like this the more devices in a network, the better the network works, especially if you derive a mechanism to control the admission of new flows in the Mesh.

The IEEE 802.11s working group has centered the target of focusing on the MAC layer protocol, understanding how the current MAC procedures are insufficient to sustain a Mesh network and how functions typical of higher layers must be part of the MAC itself to grant good levels of efficiency and bandwidth utilization. The general idea is that of a fusion of different aspects and components within the MAC, designing a cross-layer network optimization which goes beyond the common barriers between the layers into the OSI stack.

One of the improvements which promises to give the best performances is the creation of a new forwarding-routing mechanism directly in the MAC protocol. The bottleneck of a Mesh, in fact, lies in the procedures followed by the nodes to access the shared channel: a routing algorithm embedded in the MAC protocol can efficiently exploit the MAC layer information on the medium occupancy to choose the best next hop toward the destination of a packet.

A MAC layer routing protocol, moreover, can gain the greatest benefits from PHY layer evolutions like the use of directional antennas: the WLAN Mesh networks will be characterized by a low mobility of the nodes (the MeshAPs) and in these conditions the spatial diversity given by antennas arrays can greatly increase the channel capacity. But for these systems to work you need a smarter MAC layer able to determine how to access the medium and that cooperates with the routing algorithm in spotting the best next hop for each packet in its transmission queue.

In this technical report we propose a routing protocol embedded in the MAC which takes advantage from directional antennas at the physical layer in the communication between the APs of a WLAN Mesh network.

The use of directional antennas in the context of wireless ad hoc network has been explored recently. General overviews and surveys on smart antennas can be found in [1], [2], [3], [4], [5]. Only in few cases, however, there has been a serious attempt to study their impact on real systems like the IEEE 802.11 WLANs. One of these is certainly the work in [8], where the authors try to derive a joint MAC and routing protocol with a PHY layer equipped with the same kind of antennas we will assume to have. Their system is based on a series of routing tables used to check the feasibility of a new multi-hop path in the network given the spatial resolution of the arrays and the flows currently active in the Mesh. We will describe in further details the drawbacks of their approach and its limits, however their scheme requires an high level of overhead above the MAC (not shown in their paper because of the particular situations in which they assume to work), as these tables must contain a fresh information through continuous updating messages that waste the small bandwidth available. Their mechanism, moreover, totally fails in the same critical cases for which our protocol was derived.

The remainder of the report is organized as follows. In the next section an introduction of WLAN Mesh networks is given. Section 3 analyzes the proposed MAC-routing protocol. Finally section 4 concludes the report and outlines our future research.

## 2 WLAN Mesh Network

A WLAN Mesh is an IEEE 802.11-based Wireless Distribution System (WDS) which is part of a Distribution System, consisting of a set of two or more Mesh Access Point interconnected via IEEE 802.11 wireless links and communicating via the WLAN Mesh Services.

The WLAN Mesh is functionally equivalent to a wired IEEE 802.11 with respect to the stations relationship with the BSS and ESS. The novelty is that if the destination station is not associated to the same AP of the source station, the AP does not forward the packet to all the APs in the ESS but the packet is sent along the APs path to reach the destination station. It is a multi-hop ad-hoc network between the APs in the same ESS.

The WDS will use an extension of the IEEE 802.11 MAC/PHY to provide a protocol for auto-configuring the paths between the APs in a multi-hop topology, supporting broadcast, multicast and unicast traffic.

One of the possible applications of WLAN Mesh networks is the digital home. In this case the primary purposes for the mesh network are to create a low-cost, easily deployable, high performance wireless coverage throughout the home. The mesh network should help to eliminate RF dead-spots. Mesh APs may need to be configured as bridges to other LANs within the home,

including legacy Ethernet LANs. Stations are a combination of PCs, laptops, and PDAs, digital cameras, MP3 players, DVD players, and home automation devices such as control panels.

Wireless mesh networks are particularly useful in an office scenario, in areas where Ethernet cabling does not exist or its installation is economically prohibitive. With wireless mesh networks, enterprises can reduce capital costs associated with cable installation and reduce time required for its deployment. Enterprises may benefit from an increase in employee productivity through expanded connectivity to key data network resources. Examples include small and large offices, manufacturing plants, university campus, government buildings, and health care/hospitals.

Mesh networking technology provides numerous and unique capabilities that can facilitate the deployment of public access wireless networks, as it enables higher reliability Internet access services by providing a fault tolerant infrastructure and redundant (with respect to traditional wired methods) access links. Moreover WLAN Mesh networks enable advanced applications/services through ubiquitous access and reliable connectivity.

The kind of Mesh networks addressed in this report may be any environment characterized by a not too high scattering, where it's still possible for the PHY layer to exploit beamforming techniques and steer the radiation pattern in the direction of the desired signal. This situation, if typical of outdoor settings, may be found also in big structures as airports, large offices or openspaces, where the possibility of installing a completely wireless network may be seen as a fast and reliable solution to assure an always-on connection to the Internet or intranet, eventually through a transparent multihop packet forwarding mechanism.

### **3 Routing at the MAC layer with smart antennas**

As underlined in the previous section, we have to focus on small WLAN Mesh networks characterized by up to 32 nodes with low mobility. In this scenario the topology can be considered as slowly varying with time and this feature, if we imagine that the Mesh APs are equipped with directive antennas arrays, can be exploited at the MAC layer to derive a new distributed routing mechanism. The proposal we present in this paragraph wants to show how, with slight modifications to the IEEE 802.11 '99 standard and with the aid of smart antennas at the physical (PHY) layer, it is possible to increase the global network capacity.

Let us start from the basics. IEEE 802.11 standard is based on the carrier sense mechanism, which requires a station (STA) to listen to the wireless medium before transmitting a frame to the next hop towards the final destination of a traffic stream. We also know how the four-way-handshake can be helpful in controlling the hidden terminal problem, giving the possibility to every wireless STA in the range of both the transmitter and the receiver to properly set their Network Allocation Vectors (NAVs) on the basis of the Request To Send (RTS) or the Clear To Send (CTS) message (or both). Even if the effectiveness of this mechanism is easily demonstrable, the network sensing technique reveals all its drawbacks as soon as we focus

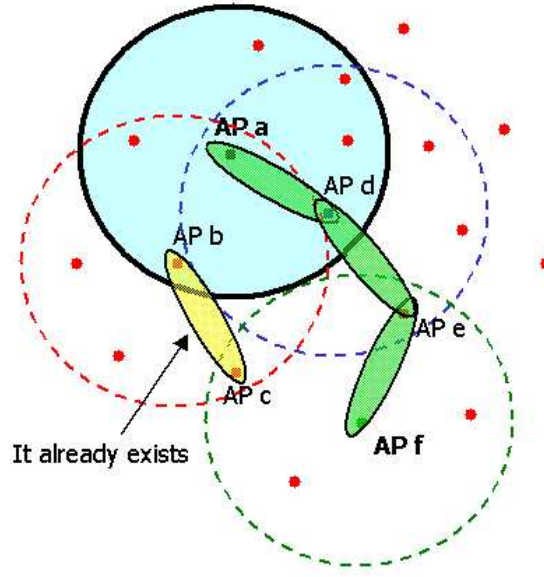


Figure 1: Routing at the MAC layer with directional antenna

on multihop networks with smart antennas at the PHY layer and we try to exploit the path diversity towards the same destination. This is just the case of the WLAN Mesh networks, which are intended to be a WDS used to manage the communications between different BSSs thanks to low mobility Mesh APs.

In these scenarios the carrier sense mechanism prevents the networks from being fully exploited, as every time a STA senses a busy channel it starts the backoff procedure and waits for a random time before trying to access the wireless medium again. The IEEE 802.11 standard was intended to work with omnidirectional antennas and the backoff algorithm was an effective way to prevent mutual interference between two or more stations transmitting on the same PHY channel. Moreover, until now, the routing has always been seen as laying above the MAC protocol and in this perspective there was no way for a STA to exploit PHY layer improvements like MIMO systems if not in the direction of space-time coding techniques or the spatial multiplexing of different data streams between the same pair of nodes. With a low varying topology and proper beamforming algorithms, we can move a step further in the development of a high capacity network with full backward compatibility with the pre-existing IEEE 802.11 standard but able to recur to the carrier sense mechanism (so the backoff procedure) only when strictly needed and to derive multiple parallel flows every time you have enough information about the current state of the network and which are the current transmission on the shared medium. Thanks to the low mobility which will characterize the future WLAN Mesh networks this is possible

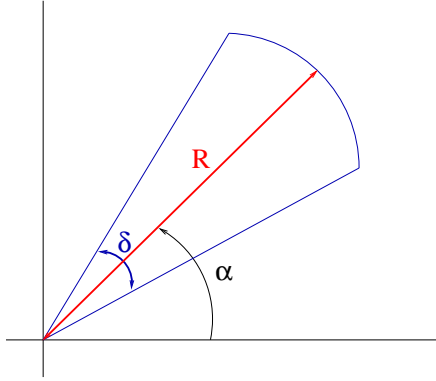


Figure 2: Antenna Radiation Diagram

without an excessive flooding of routing packets and in a fully distributed way. Figure [?] is an example of the joint MAC-routing protocol. Let us suppose that APa has a packet for APf and the primary routing path involve APb and APc. Let suppose that there is an on-going transmission between APb and APf. If APa has an alternate path to reach APf, it can transmit through that path (in Figure [?] APa reaches APf through Apd and APe.

### 3.1 General assumptions and route discovery algorithm

In this section we show the antenna model used throughout in the report and how to derive a PHY layer information like the direction of arrival of the signals received by an antennas array. We also introduce an efficient and effective route discovery algorithm, which will be the basis for our joint MAC and routing proposal with directional antennas.

#### 3.1.1 Smart antennas: a simplified radiation model

We consider a Flat-top radiation pattern. This is a simplified model used in the ad-hoc networking community that corresponds to an idealized angular response with a constant gain within the beamwidth and no side-lobes [7]. The antenna radiation diagram is shown in Figure 2 where  $\delta$  is the beamwidth (determined by the array length),  $R$  is the transmission range and  $\alpha$  the angular direction along which the array is steered. Obviously, if  $\delta = 2\pi$  we have an omnidirectional transmission. We imagine that all the arrays in the WLAN Mesh have the same beamwidth  $\delta$ .

In the following we will suppose to have an ideal power control mechanism that decreases the transmission power while transmitting in directional mode to have the same transmission range  $R$  of the omnidirectional mode.

Considering the Flat-top radiation pattern, the gain of the antenna is  $G = \frac{2\pi}{\delta}$ . Therefore to

have the same transmission range  $R$  the transmission power must be decreased of a factor  $1/G$ . Notice that this approach assures longer battery lives, a fundamental characteristic in wireless networks.

### 3.1.2 DoAs: Direction of Arrival of the First-Hop Signals

A mechanism to flood the network topology information is required if we want a distributed routing algorithm which is able to derive a feasible path from a specific source to the intended destination of the traffic stream. Thanks to the low mobility of the Mesh APs, the frequency with which we have to update the topology information is low and the overhead can be maintained at acceptable values.

As shown in the following subsections, however, the topology awareness must be enriched with a PHY layer information like the Direction of Arrival (DoA) of the signals transmitted by the first hop peers. If we suppose that every Mesh AP is equipped with an antenna array, the DoAs can be obtained through the difference in the phases of the signals received by each element of the array on the basis of the PHY layer preambles.

In our scheme, nevertheless, a node does not need a complete DoAs table for every AP in the WLAN Mesh network: a two-hop information is enough, i.e. the DoAs of the signals from its first hop peers and those of the signals received by the first hop peers themselves (basically the two hop neighbors).

## 3.2 The Embedded Algorithm: How to Build the Routing Tables

We will suppose that each node in the network has three different tables:

- One-hop Neighbors Table,
- Two-hop Neighbors Table,
- Topology Table.

### 3.2.1 One-hop Neighbors Table

This table contains an entry for all the one-hop neighbors of the target node, together with the DoA under which each them is seen.

### 3.2.2 Two hops neighbors Table

This table contains an entry for each first hop peer: given a peer  $i$ , the corresponding entry will contain both the list of all the one-hop neighbors of  $i$  and their DoAs as estimated by  $i$  itself.

These two table are built using an HELLO packet exchange. An HELLO is a packet broadcasted periodically within two-hops which carries information about a node's direct neighbors and their relative DoAs. This, as will be shown in the next sections, is absolutely necessary to permit different and parallel transmissions to coexist in the network, thanks to the spatial diversity given by the smart antennas adopted at the PHY layer.

### 3.2.3 Routing Table

Every node maintains a Routing Table with an entry for each other node in the network. For each node  $i$  in the network the table contains all the possible one-hop neighbors through which it's possible to reach  $i$  on a specific path, along with the weight of this path.

Periodically the nodes communicate their Routing Table information to all the other nodes in the network. Using these refresh messages, each node can update its own Routing Table using a Link State based protocol that maintains multiple next-hop node addresses to reach a destination.

Each node memorizes the packet identification number before forwarding it, in order to avoid the Count-to-Infinity problem.

When an AP has to send a packet to a destination AP  $d$ , it queries  $d$  entry in the Routing Table and chooses the next-hop associated with the minimum path weight to reach  $d$ . As describe later, according with the information received from the MAC about the ongoing transmissions, the chosen next-hop is busy, the AP will pick on the alternative next-hop to reach  $d$ .

Notice how in our scheme an intermediate node just decides the next-hop node along the path to the final destination and neither the source node determines the entire path before sending a packet. This strategy allows a good level of flexibility while re-routing a packet because of a busy next-hop node, as it happens if it is currently involved in another transmission on the channel. In other words, a complete knowledge of network status is not necessary, i.e. each node does not have to maintain a complex table where to memorize which are the flows active in the WLAN Mesh at the moment.

This approach, as underlined in the introduction, is completely different from the one adopted in [8]. In this work there is a continuous refreshing process of what is called "the active directional neighbors table", where for every transmission zone (i.e. the area covered by an antenna array steered in a specific direction) the authors explicitly notify which are the nodes currently involved in a transmission. This information, periodically updated, is required by



their scheme to determine the feasibility of a new flow, through the concept of the "correlation factor", with other flows (paths) in the network. The actual path choose to reach a specific destination highly depends on these checks.

The effectiveness of this kind of mechanism, however, is granted as long as the information stored in these heavy tables reflects the real status of the WLAN Mesh, thus leading to a huge increase in the MAC layer overhead in case of variable inter-BSSs communications inside the network, an aspect which is not shown in their ad hoc simulation results.

Our scheme, on the contrary, requires only a topology refresh, while the outgoing link on the path to the intended recipient of a packet is derived on the basis of a fully MAC layer knowledge built through improved RTS-CTS and backoff procedures, as it will be show in the next section.

### 3.3 Our Scheme: Changes in the IEEE 802.11 '99 Standard

One of the emerging characteristics of the high capacity wireless LAN (as seen in IEEE 802.11n, which will be the basis also for the future WLAN Mesh networks) is the necessity of aggregating as many frames as you can at the MAC layer creating large packets which must be protected by the RTS-CTS exchange. By now every time a node receives an RTS or a CTS it has to set its NAV accordingly in order to prevent itself from interfering with the ongoing transmission.

Suppose that node  $i$  wins a Transmission Opportunity (TXOP) and wants to transmit a burst of frames to a final destination for which the first hop is node  $j$ . Let us say that node  $i$  hears an RTS transmitted by node  $k$  to start a TXOP with node  $l$ . With the IEEE 802.11 standard,  $i$  can do anything else but deferring the packets transmission towards  $j$ . Obviously this is not necessary if we introduce smart antennas at the physical layer and we suppose that two peers can communicate using narrow beams and thus being protected from other parallel transmission in the WLAN Mesh.

In our scheme we propose to use omnidirectional RTS and CTS messages and to steer the beams only after this initial handshake has been completed. This goes in the direction of creating a network status awareness at each node which could avoid the interference between new and already established peer-to-peer communications within narrow beams.

#### 3.3.1 Network Allocation Table

As we want to exploit the spatial diversity permitted by smart antennas at the PHY layer, we cannot consider the usual NAV setting procedure where a single network allocation vector is updated every time a frame is received. While this remains the only solution in case of legacy stations with omnidirectional radiation patterns, a station should in general have a NAV for each outgoing link. Every time a frame is detected, a station has to modify its Allocation Table accordingly. If  $i$  receives the RTS sent by  $s$  to  $t$ , for example, it has to adjust the information

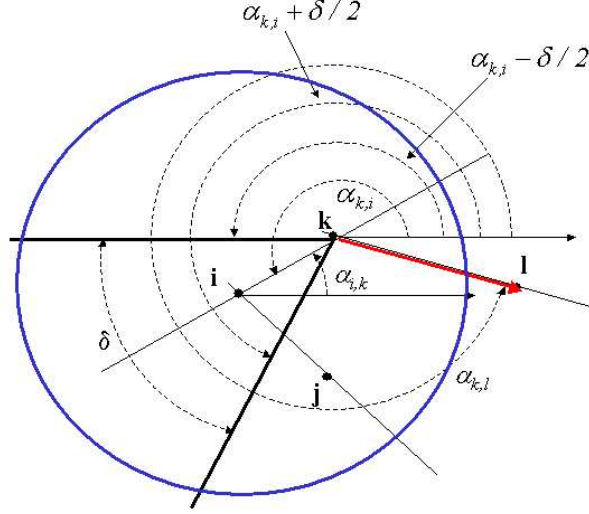


Figure 3: RTS-CTS: procedures at node  $i$

stored in its Allocation Table specifying that  $s$  is involved in a transmission towards  $t$  for the time interval indicated in the duration field of the RTS. The same has to be done hearing a CTS. With these slight modifications to the IEEE 802.11 '99 standard, every node knows which is the status of the network in one hops, and this permits the smart RTS-CTS exchange presented below.

### 3.3.2 A smart RTS-CTS handshake

Suppose that every node has a common reference direction and every angle is measured anti-clockwise with respect to it: with  $\alpha_{x,y}$  we will indicate the angle under which  $x$  can see  $y$ . Let's call  $\delta$  the width of each directive beam.

Consider the situation in Figure 3, where  $k$  and  $j$  are within the omnidirectional range of  $i$ . Now imagine that  $i$  is aware of the ongoing transmission between  $k$  and  $l$  and it wants to transmit a packet to  $j$ . Suppose, moreover, that both  $i$  and  $j$  have a complete and fresh information about which other transmissions are present within their respective radio ranges at the moment: we will show in the following as this, in the general case, is only an optimistic assumption and how to react if  $i$  or  $j$  or both are not aware of all the flows currently active within their respective transmission ranges.

Thanks to the information collected during the topology discovery phase and stored in the Two-hop Neighbors Table,  $i$  knows the angles  $\alpha_{i,j}$  and  $\alpha_{i,k}$ , moreover it knows the angle  $\alpha_{k,l}$  as  $k$  is one of its first hop peers. Here are the steps which must be followed by  $i$  and  $j$  before

starting their communication.

## PROCEDURES AT NODE $i$

STEP ONE: checks on the direct flow  $(i, j)$

Before sending the RTS,  $i$  has to verify if the new transmission could interfere with the ongoing transmissions in its transmission range; in the example with the reception at node  $k$ . To do that it will follow the following procedure for each valid entry in the Allocation Table. Supposing to have just the entry corresponding to  $k$  in the Table,

- if  $\alpha_{k,l} \notin [(\alpha_{k,i} - \delta/2); (\alpha_{k,i} + \delta/2)]$ ,  $i$  is outside the reception beam of  $k$ : it doesn't matter which is the angle  $\alpha_{i,j}$  used by  $i$  for the transmission to  $j$ ,  $i$  cannot interfere with the ongoing data exchange between  $k$  and  $l$ . Go to step two.
- if  $\alpha_{k,l} \in [(\alpha_{k,i} - \delta/2); (\alpha_{k,i} + \delta/2)]$ ,  $i$  is seen by the reception beam of  $k$ . In this case  $i$  has to check if the directional beam it will use for the transmission towards  $j$  covers node  $k$ , id est if  $\alpha_{i,j} \in [(\alpha_{i,k} - \delta/2); (\alpha_{i,k} + \delta/2)]$ . If this condition is verified  $i$ , communicating with  $j$ , will interfere with the reception at node  $k$ : the two flows  $(k, l)$  and  $(i, j)$  are not compatible, so  $i$  cannot send the RTS to  $j$ . If so go to step four, otherwise go to step two.

STEP TWO: checks on the reverse flow  $(j, i)$

After the previous step is completed,  $i$  could send the RTS to  $j$  being sure that its transmission will not interfere with the reception at node  $k$ . But what happens when node  $j$  replies? Obviously there is the possibility of an interference with even both of  $k$  and  $l$ , depending on the angular distance between these nodes and the direction  $\alpha_{j,i}$  used by  $j$  for the transmission towards  $i$  and depending on the orientation of the main beams steered by  $k$  and  $l$ . We would like to foresee this situation before sending the RTS, but notice that this is possible thanks to the first hop information collected by  $i$  in its Two-hop Neighbors Table:  $i$  knows exactly if  $k$  and  $l$  are within the range of  $j$ ,  $i$  it also knows all the angles  $\alpha_{j,k}$ ,  $\alpha_{j,l}$  and  $\alpha_{j,i}$  (so also  $\alpha_{k,j}$  and  $\alpha_{l,j}$ ). Similarly to what has been done in the first step, consider node  $k$  (see figure 4):

- if  $\alpha_{k,l} \notin [(\alpha_{k,j} - \delta/2); (\alpha_{k,j} + \delta/2)]$  or
- if  $\alpha_{k,l} \in [(\alpha_{k,j} - \delta/2); (\alpha_{k,j} + \delta/2)]$  and  $\alpha_{j,i} \notin [(\alpha_{j,k} - \delta/2); (\alpha_{j,k} + \delta/2)]$

the transmission of node  $j$  does not interfere with node  $k$ . In the same way  $i$  has to check the compatibility between  $j$  and  $l$ , if  $l$  is within the range of  $j$ . In case a possible interference,  $i$  cannot send the RTS and goes to step four. Otherwise it enters step three.

STEP THREE: choice of the radiation pattern for the RTS

At this point  $i$  is sure, according to its routing table, that a flow  $(i, j)$  would not interfere with the ongoing data exchange between  $k$  and  $l$ . Now  $i$  has to decide how to transmit

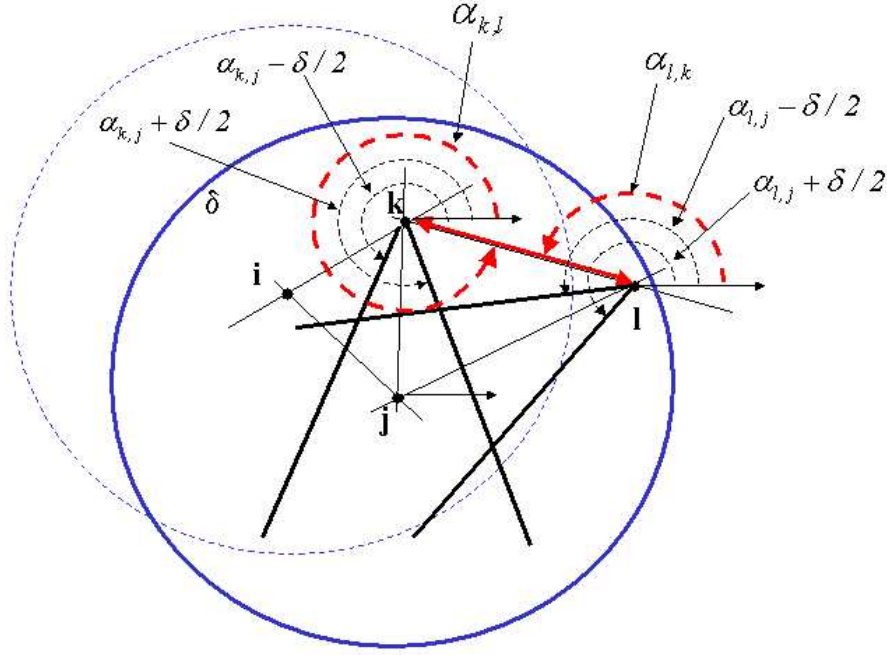


Figure 4: RTS-CTS: procedures at node  $i$

the RTS. If at the first step it has realized to be inside the main beam used by  $k$ , the RTS cannot be sent omnidirectionally otherwise it could interfere with the reception at node  $k$ . In this case the array must be set so as to have a notch in the radiation pattern in the direction  $\alpha_{i,k}$  (and  $\alpha_{i,l}$  too, if  $l$  is within the range of  $i$  and the same conditions stand): this is possible via non tricky PHY layer beamforming in the same way it's possible to steer the array in a specific direction. If  $i$  is outside the main beam of  $k$  (and  $l$  if the case), the RTS can be transmitted omnidirectionally.

Remind that the purpose of this step is to assure that as many peers as possible can intercept the RTS-CTS handshake and accordingly modify their routing tables to memorize that a new transmission is going on on the wireless medium and inside the first hop range.

STEP FOUR (if needed): check if another transmission is possible

If node  $i$  has realized that the communication with  $j$  would interfere with the present flow  $(k,l)$  and if node  $j$  is a relay of a multihop path,  $i$  query the Routing Table checking for an alternative next hop to reach the final destination. This is the novelty of the protocol. Thanks to the available routing information, the MAC protocol will not defer a transmission. The packet will be go thought a path that not interfere the on-going communications.

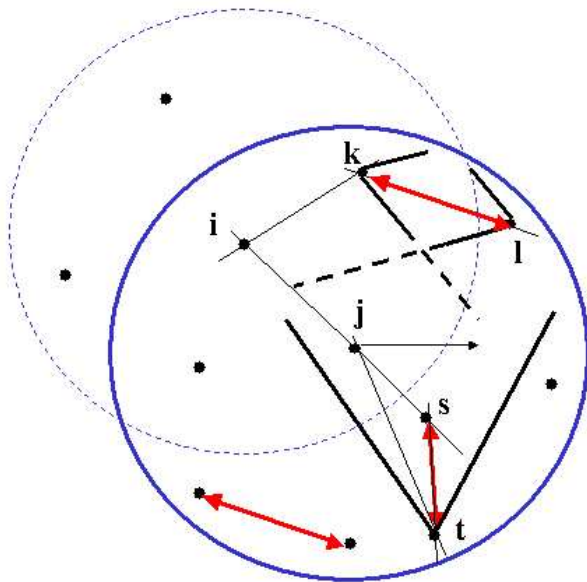


Figure 5: RTS-CTS: procedures at node  $j$

Thanks to the procedures carried out at node  $i$  (who has requested to communication through the RTS)  $j$  should be sure that its transmission will not interfere with  $k$  and  $l$ . We could think that new checks at node  $j$  would be useless or redundant, but this is not the case. It may happen, in fact, that the transmission of  $j$  interferes with flows of which only  $j$  is aware of, because they are going on within its coverage area and between nodes who are not direct peers of  $i$  (see figure 5). This can happen both during the post-CTS directive transmission and during the transmission of the CTS itself. It may also happen that the topology information stored by  $j$  about its angular distances with respect to  $k$  and  $l$  is more recent than the one at node  $i$ . All these situation must be considered before  $j$  replies to the RTS sent by  $i$ .

Let us start showing as, with a proper constraint on the width  $\delta$  of the narrow beams, the directional transmission of  $j$  cannot interfere with possible communications carried on in the coverage range of  $j$  only (these checks were not done by  $i$  because the endpoints were outside its range). Consider the situation in Figure 6: if the condition  $\delta < 120^\circ$  stands, by geometry every node inside the range of  $j$ , but outside the one of  $i$ , cannot be disturbed by the beam pointed by  $j$  to transmit towards  $i$ . Notice that this condition is not so restrictive, as recent works in the beamforming field suggest that beams with a width around  $15^\circ$  are perfectly feasible at the PHY layer.

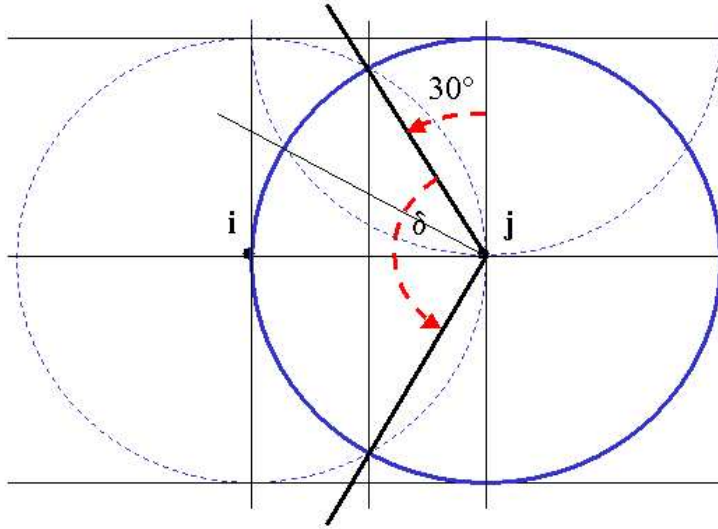


Figure 6: RTS-CTS: an acceptable constraint on the beam width

With the above condition, as soon as  $j$  receives the RTS it only has to follow the following two steps.

STEP ONE (if needed): re-check the eventuality of an interference with  $(k, l)$  This may be useful in case  $j$  has fresher information than  $i$ . In case  $j$  decides there could be a collision with the flow  $(k, l)$  the easiest solution is not to transmit the CTS. We can assume (see the next section) that  $i$  can react to a lost CTS without entering a backoff procedure, thus verifying if there are other feasible candidates for a transmission on the channel (as in the step four of the RTS-CTS procedure at the transmitter side shown above).

STEP TWO: choice of the radiation pattern for the CTS As in the case of the transmission of the RTS, with the CTS we would like to use an omnidirectional radiation pattern any time this is possible. The checks that  $j$  must conduct have to include any node in its action range which is currently involved in a communication: coming back to figure 5, a notch is needed in the direction  $\alpha_{j,t}$ .

### 3.3.3 A few critical cases: RTS-CTS and backoff procedures

In the previous treatment we have assumed that both  $i$  and  $j$  have a perfect (complete) knowledge of what is going on in their respective action ranges. That was an initial hypothesis just to introduce the idea of how to realize multiple parallel communications using the available topology information and listening to every RTS and/or CTS exchanged by the first hop neighbors. Unfortunately this is not the general case, because when two nodes have steered their beams to communicate with each other they may ignore other flows which are beginning in the network.

Let us start from a couple of simple cases.

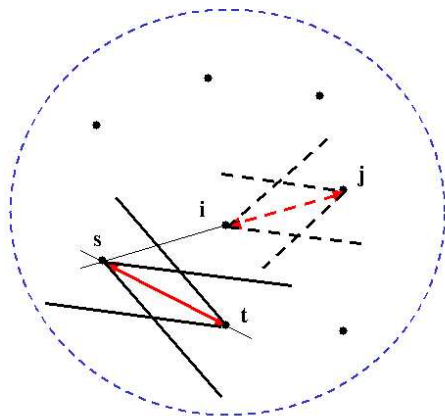


Figure 7: Critical cases

In figure 7  $s$  and  $t$  are within the range of  $i$  and are involved in a direct communication through narrow beams. Suppose that node  $i$  did not hear the RTS-CTS exchange between  $s$  and  $t$  because its array was steered in the direction of  $j$  while that handshake took place: the direct consequence is that  $i$  has only a partial information about the status of its peers and completely ignores the ongoing transmission. Suppose that  $i$  picks a packet from its queue for which the next hop is  $s$ : as  $i$  is outside the main beams of both  $s$  and  $t$ , the carrier sensing mechanism has no way to detect a medium occupancy and  $i$  can only assume that the channel is free. Now, if  $i$  sends the RTS to  $s$ , no CTS would be sent in reply as  $s$  does not hear it.

The IEEE 802.11 '99 standard requires that after a lost CTS a node shall start the backoff procedure, waiting a random time before attempting a new transmission on the channel.

As our system is equipped with antenna arrays, however, we can decide not to start the backoff but to choose a different next hop node in an alternative path to reach the final destination. This means, in our example, that  $i$  could send the current packet to another peer on the way of its destination (if the routing scheme gives second choice routes) or that it could decide to

pick another packet from its queue with a different outgoing link. Only if this is not possible  $i$  must use the usual backoff mechanism.

Obviously it could also happen that  $i$  does not receive the CTS from  $s$  not because of the situation in figure 7 but simply as an error may occur due to fast fading effects: our solution is effective as well, as it acts on top of the normal IEEE 802.11 '99 standard.

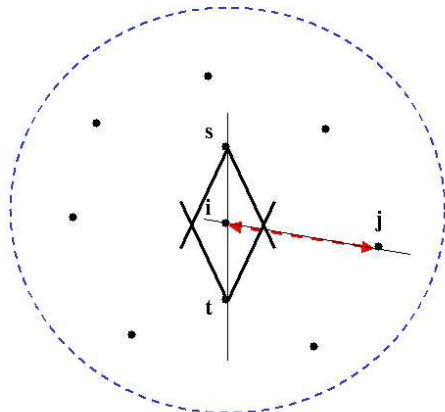


Figure 8: Critical cases

In figure 8 we show a luckier situation in which  $i$  is inside the coverage area of both  $s$  and  $t$ . In this case even if  $i$  did not hear the RTC-CTS handshake between  $s$  and  $t$ , the basic carrier sense mechanism is able to detect the ongoing transmission and  $i$  can easily realize that both  $s$  and  $t$  are unavailable for a communication, setting the NAVs for these outgoing links accordingly to the duration field of the first frame detected.

Let us analyze a more complex situation, the one depicted in figure 9. In this case suppose that  $i$  wants to communicate with  $j$  and that  $s$  and  $t$  are involved in a data flow with narrow beams. Imagine that  $i$  has an out-of-date information about its peers (among which  $s$ ) while  $j$  is perfectly aware of the ongoing transmission between  $s$  and  $t$ . In this case, as  $i$  is outside the main beam used by  $s$ , even an omnidirectional RTS wouldn't interfere with the reception at node  $s$ , but as  $j$  is inside the coverage area of  $s$  and  $\alpha_{j,s} \in [(\alpha_{j,i} - \delta/2); (\alpha_{j,i} + \delta/2)]$ , from its point of view a transmission towards  $i$  would create an interference situation. In this case the reaction should be the same underlined in the previous subsection,  $j$  cannot send the CTS in reply to the RTS of  $i$  and this node instead of starting a backoff procedure will look for other feasible transmissions if any.

The last case we would like to present is definitely the most critical for our scheme, but it can easily be observed that it's likely not to be so common in practice. Consider the situation in Figure 10, where as usual  $i$  wants to start a communication with  $j$ . As you can see  $s$  and  $t$  are



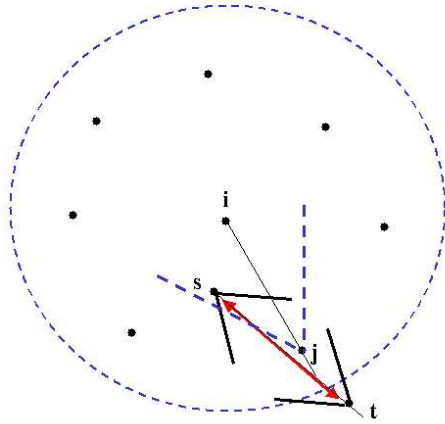


Figure 9: Critical cases

transmitting to each other and even if  $i$  is outside the coverage of the beam steered by  $s$ , it is right inside the one pointed by  $t$  in the direction of  $s$ . If, in this case,  $i$  doesn't know that  $s$  and  $t$  are communicating, it may decide to send the RTS to  $j$  just while  $t$  is in its receive status, so that the carrier sense mechanism has no way to detect the frame exchange between  $s$  and  $t$ . If this happens a collision at node  $t$  would occur and this cannot be avoided with our scheme. In cases like this it may be useful a concept like the transmission opportunity (TXOP) of IEEE 802.11e: if we imagine that the whole TXOP is protected by a RTS-CTS exchange and the interference between  $i$  and  $t$  happens only during the RTS transmission by  $i$ , in fact,  $t$  will loose only one of the frames sent by  $s$  before the TXOP expires. If  $\alpha_{i,t} \in [(\alpha_{i,j} - \delta/2); (\alpha_{i,j} + \delta/2)]$ , instead, even with the IEEE 802.11e functionalities there could be a sort of coupling between the two flows  $(s, t)$  and  $(i, j)$  leading to a situation of complete interference.

Notice, however, that the case shown in picture 10 shouldn't be too common, especially if we suppose to use beams with a width less than 15. Moreover such a situation happens only if the carrier sensing mechanism is unable to detect the ongoing transmission and this further on reduces the probability of having a collision.

Notice, finally, that these critical cases are not cited in [8], even if they depend on the nature of the directional transmissions itself and not on the particular approach followed to find out a route in the WLAN Mesh. Our scheme faces these aspects and reacts (when possible) with improved backoff and RTS-CTS procedures and with nullforming techniques in case an omnidirectional transmission is not feasible.

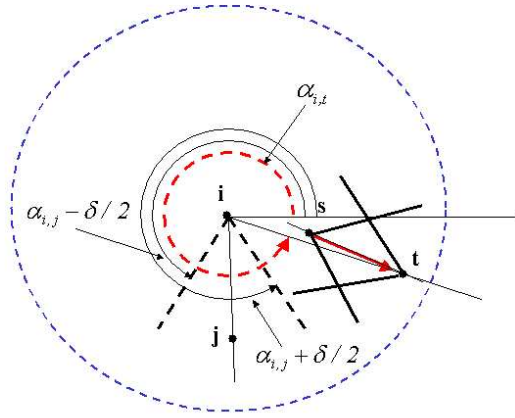


Figure 10: Critical cases

### 3.3.4 Backward compatibility with legacy APs and stations

Notice that every improvement we have proposed in this report acts on top of the current IEEE 802.11 standard, which was studied for use with omnidirectional antennas. In case you have STAs not equipped with antennas arrays at the PHY layer, our scheme assures a complete backward compatibility as it doesn't change the current standard but only adds new functionalities within the RTS-CTS and backoff procedures. However an AP able to identify the proper route toward a destination is still required, as it's not possible to count on an external distribution system.

### 3.3.5 Routing at the MAC layer and network load balancing

Only a rapid hint at a possible integration of our scheme with load balancing techniques.

One of the best ways to differentiate the transmissions on the wireless channel is that of exploiting the spatial diversity: thanks to the smart antennas at the PHY layer and to the information collected in the routing tables about the DoAs of the first hop neighbors, it's easy to derive a forwarding mechanism which also takes into account the necessity of balancing the traffic in the WLAN Mesh and chooses the best next hop in the direction of the destination node, in order to assure an equal amount of load in the network. This could be carried out on the basis of a set of load status metrics obtained through the CTS-RTS handshake, memorizing the status of each peer at the time of the last direct communication.

## 4 Conclusions and work in progress

We developed a totally new joint MAC and routing protocol for Mesh networks of the future generation, exploiting an efficient PHY layer equipped with smart antennas and deriving new RTS-CTS and backoff mechanisms. Our scheme is supposed to provide a great level of channel utilization, permitting multiple and parallel streams inside the Mesh through the spatial diversity assured by the antennas arrays and their beamforming and nullforming capabilities.

The next step will be the integration of our procedures in the NS2.26 simulator environment (where the IEEE 802.11 '99 protocol is already available), starting a final phase of validation and performances analysis and thus showing the benefits of our scheme over the current IEEE 802.11 '99 standard.

Our final target would be to submit our proposal to the IEEE WGs, i.e. before the call for proposal deadline which will be hold with every probability in July 2005.

## References

- [1] P. H. Lehne and M. Pettersen, *An overview of smart antenna technology for mobile communications systems*, IEEE Communications Surveys, vol. 2, no. 4, pp. 213, 1999.
- [2] S. Bellofiore, J. Foutz, C. A. Balanis, and A. S. Spanias, *Smart-antenna system for mobile communication networks .2. beamforming and network throughput*, IEEE Antennas and Propagation Magazine, vol. 44, no. 4, pp. 10614, 2002.
- [3] L. C. Godara, *Applications of antenna arrays to mobile communications. i. performance improvement, feasibility, and system considerations*, Proc. the IEEE, vol. 85, no. 7, pp. 103160, 1997.
- [4] R. Ramanathan, *On the performance of ad hoc networks with beamforming antennas*, in Proc. ACM MOBIHOC 2001, Long Beach, CA, 2001, pp. 95105.
- [5] J. H. Winters, *Smart antennas for wireless systems*, IEEE Personal Communications, vol. 5, no. 1, pp. 237, 1998.
- [6] Y. B. Ko, V. Shankarkumar, and N. H. Vaidya, *Medium access control protocols using directional antennas in ad hoc networks*, in Proc. IEEE INFOCOM 2000, vol. 1, 2000, pp. 1321.
- [7] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides, *Energylimited wireless networking with directional antennas: the case of session-based multicasting*, in Proc. IEEE INFOCOM02, vol. 1, New York, NY, 2002, pp. 1909.
- [8] S. Roy, D. Saha, S. Bandyopadhyay, T. Ueda and S. Tanaka, *A network-aware MAC and routing protocol for effective load balancing in ad hoc wireless networks with directional antennas*, Mobihoc'03, Annapolis, Maryland (USA), June 2003.

- [9] IEEE Standard 802.11, *Wireless LAN media access control (MAC) and physical layer (PHY) specifications*, 1999.
- [10] <http://grouper.ieee.org/groups/802/11/>