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A. Capone, F. Martignon, L. Fratta

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Directional MAC and Routing Schemes for Power Controlled Wireless Mesh Networks with Adaptive Antennas

A. Capone[*], F. Martignon[†], L. Fratta[*]

Abstract

Wireless Mesh Networks (WMNs) have emerged recently as a technology for next-generation wireless networking. Several approaches that exploit directional and adaptive antennas have been proposed in the literature to increase the performance of WMNs. However, while adaptive antennas can improve the wireless medium utilization by reducing radio interference and the impact of the exposed nodes problem, they can also exacerbate the hidden nodes problem. Therefore, efficient MAC protocols are needed to fully exploit the features offered by adaptive antennas. Furthermore, routing protocols that were designed for omnidirectional communications can be redesigned to exploit directional transmissions and the cross-layer interaction between the MAC and the network layer.

In this paper we first propose a novel Power-Controlled Directional MAC protocol (PCD-MAC) for adaptive antennas. PCD-MAC uses the standard RTS-CTS-DATA-ACK exchange procedure. The novel difference is the transmission of the RTS and CTS packets in all directions with a tunable power while the DATA and ACK are transmitted directionally at the minimal required power.

We then propose the Directional Deflection Routing (DDR), a routing algorithm that exploits multiple paths towards the destination based on the MAC layer indication on channel availability in different directions.

We measure the performance of PCD-MAC and DDR by simulation of several realistic network scenarios, and we compare them with other approaches proposed in the literature. The results show that our schemes increase considerably both the total traffic accepted by the network and the fairness among competing connections.

Index Terms: - Wireless Mesh Networks, Adaptive Antennas, Medium Access Control, Power Control, Deflection Routing, Cross-Layer Design.

1   Introduction

Wireless Mesh Networks (WMNs) have emerged recently as a technology for next-generation wireless networking [1, 2]. WMNs are the ideal solution to provide both indoor and out-

[*]A. Capone and L. Fratta are with the Department of Electronics and Information of Politecnico di Milano, P.zza Leonardo da Vinci 32, 20133 Milan, Italy. E-mail: {capone, fratta}@elet.polimi.it

[†]F. Martignon is with the Department of Information Technology and Mathematical Methods, University of Bergamo, Dalmine (BG) 24044, Italy. E-mail: fabio.martignon@unibg.it

door broadband wireless connectivity in several environments without the need for costly wired network infrastructures.

The network nodes in WMNs, named mesh routers, provide access to mobile users, like access points in Wireless Local Area Networks, and they relay information hop by hop, like routers, using the wireless medium. Mesh routers are usually fixed and do not have energy constraints. WMNs, like wired networks, are characterized by infrequent topology changes and rare node failures.

In recent years, adaptive antenna technology has been studied in 802.11-based networks [3]. Since the IEEE 802.11 standard Medium Access Control (MAC) [4] has been optimized for omnidirectional antennas, new efficient MAC protocols are needed to exploit the advantages of this technology.

The use of routing schemes that exploit MAC layer information and the spatial reuse made available by adaptive antennas can further improve the network performance.

The problem of designing efficient MAC protocols with adaptive antennas has been deeply investigated for ad hoc network scenarios [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. Some solutions [13, 14, 15] envisage the utilization of power control techniques to further enhance spatial reuse and to achieve higher wireless medium utilization. Several routing protocols have been also proposed for ad-hoc networks [11, 13, 16] and WMNs [17, 18, 19].

Differently from existing MAC protocols, that will be revised in Section 2, in Section 3 we propose a Power-Controlled Directional MAC (PCD-MAC), a novel MAC protocol designed for Wireless Mesh Networks where nodes use adaptive antennas and power control. Its key innovative feature is that nodes spread the wireless medium reservation information to the maximum possible extent without interfering with the connections already established in the network. This is achieved by sending RTS/CTS frames in each antenna sector using the maximum power that does not cause interference with ongoing transmissions. Then the DATA/ACK exchange takes place only directionally and at the minimum needed power.

The performance of routing protocols in WMNs can be improved by using the Directional Deflection Routing (DDR) presented in Section 4. DDR is a routing algorithm for WMNs based on a cross-layer approach that is inspired by a routing protocol first proposed for optical networks [20, 21]. Each node maintains a sorted list of next-hop nodes per destination according to paths lengths, and it forwards packets to the first available node in the list. Node availability is obtained by the MAC layer indication on channel status in different directions.

In Section 5 we evaluate PCD-MAC and DDR through extensive simulation, comparing their performance with other solutions proposed in the literature. Numerical results measured in several realistic network scenarios show that PCD-MAC and DDR outperform existing schemes both in terms of total traffic accepted in the network and fairness among competing connections. Finally, Section 6 concludes the paper.

2   Directional Antennas: MAC and Routing issues

In this Section we review some MAC and routing protocols proposed in the literature for ad hoc and Wireless Mesh Networks which are related to the scenario and the approach considered in this paper. The main advantage of using directional antennas with 802.11-based wireless multi-hop networks is the reduced interference and the possibility of having

parallel transmissions among neighbors with a consequent increase of spatial reuse of radio resources [3].

However, directional antennas have a deep impact on the operation of the MAC layer originally devised for omnidirectional antennas. The presently used 802.11 MAC relies on two main mechanisms: the physical carrier sense (PCS), based on the received signal strength, and the virtual carrier sense (VCS), based on MAC layer signaling frames RTS/CTS.

The use of directional antennas affects the basic operation of PCS and VCS since neighbor nodes may be no longer informed on all the ongoing transmissions. Therefore, the hidden terminal problem that causes collisions becomes more critical. In other cases, unsuccessful RTS transmissions can cause useless retransmissions and prevent other nodes from possible transmissions (deafness problem).

To alleviate the effects of hidden terminal and deafness problems, the existing directional MAC protocols exploit directional and omnidirectional transmissions in different ways.

2.1 MAC protocols

Several solutions have been proposed in the literature for enhanced 802.11-like MAC protocols able to exploit the features of directional and adaptive antennas in ad hoc networks. The common goal of all proposals is to increase the spatial reuse of radio resources and consequently the network utilization. Some solutions use power control techniques to limit the interference on already established connections and to save nodes' energy.

The Network Allocation Vector (NAV) definition is extended in [7, 8] using a direction field, indicating that the NAV applies only for the specified direction. The NAV is set only in the direction of each received transmission. Obviously, multipath phenomena and nodes mobility may affect the accuracy of this information in ad hoc networks, while in Wireless Mesh Networks, being nodes positions fixed, direction information can be exploited more easily.

In both [7, 8] all frames are transmitted directionally. In [8], directional transmissions have a larger range than omnidirectional ones, and this feature is exploited using multi-hop RTSs to establish links between distant nodes, while CTS, DATA and ACK are transmitted over a single hop. Both these schemes present some drawbacks due to the deafness problem [3, 22]: whenever a node is occupied to transmit or receive a frame directionally, it may not hear RTS/CTS exchanges regarding newly established transmissions. As a consequence, it can interfere with them once its transmission is completed.

In [5] the authors assume that each node knows its own position and that of neighbor nodes, and that directional and omnidirectional transmissions have the same range. Two different schemes are proposed: in the first one, Directional RTS MAC (DRTS-MAC), the RTS frame is transmitted only directionally, while in the second scheme, Omnidirectional RTS MAC (ORTS-MAC), the NAV is checked and the RTS is sent omnidirectionally if all directions are free, otherwise it is sent directionally as in the first scheme. In both schemes the DATA/ACK exchange takes place directionally, while the CTS is transmitted omnidirectionally if it does not interfere with ongoing transmissions in any direction, otherwise it is dropped. Since DRTS-MAC performs better than ORTS-MAC, as shown in [5], we will consider only DRTS-MAC for comparison purposes.

The algorithm proposed in [10] assumes that each sector has associated a directional antenna, and transmits every frame (RTS, CTS, DATA or ACK) in all sectors that are free according to the D-NAV information. Even if this approach reduces the collision probability spreading the channel utilization information in all available directions, it may also reduce the reuse efficiency.

In the *circular directional RTS* scheme, proposed in [6], the RTS frame is transmitted directionally and consecutively, in a circular way, scanning all the area around the transmitter. The CTS and the DATA/ACK frames are transmitted directionally. After transmitting the RTS frame, the node waits for the reception of the corresponding CTS listening omnidirectionally. Similarly to the previous scheme, this procedure increases the number of nodes that receive the RTS and set the directional NAV correctly, but it pays the price of an increased collision probability of RTS messages.

In [11] the authors propose several solutions to limit the impact of the hidden terminal problem caused by directional antennas; three novel directional NAV indicators are introduced to indicate ongoing communications to a hidden terminal. However, though effective, these solutions require significant changes to the standard MAC protocol.

The schemes proposed in [12, 13] combine the utilization of adaptive antennas and power control techniques. In [12] various power control techniques to exploit spatial reuse are proposed. However, the power control is adopted only for the transmission of DATA frames. The solution proposed in [13] is characterized by the use of a sophisticated backoff procedure for contention resolution following a collision, and the utilization of a simple power control technique where the transmission power for RTS frames is increased upon each RTS retry. Since all frames are transmitted directionally, the deafness problem is worsened [3, 22].

Differently from the above schemes, our PCD-MAC is based on the idea of transmitting control messages (RTS/CTS) in all directions with a tunable power per direction that is adjusted to avoid interference with ongoing transmissions. This informs the maximum number of neighbors of the new transmission limiting the deafness problem. In addition, the data exchange (DATA/ACK) is performed only directionally using the minimum power to reach the intended receiver.

2.2   Routing protocols

Since WMNs share common features with ad hoc networks, the routing protocols developed for ad hoc networks can be applied to WMNs [1]. Existing routing protocols for ad hoc networks include: proactive routing protocols, like Optimized Link State Routing Protocol (OLSR) [23] and Destination-Sequenced Distance Vector (DSDV) [24], and reactive routing protocols, like Dynamic Source Routing Protocol (DSR) [25] and Ad hoc On-Demand Distance Vector Routing (AODV) [26]. Hybrid protocols, like for example Zone Routing Protocol (ZRP) [27], combining the features of proactive and reactive routing algorithms have also been proposed.

While the above routing algorithms are designed for omnidirectional antennas, other ad hoc networks routing protocols that exploit directional antennas have been proposed in [11, 13, 16]. A routing protocol that selects maximally zone disjoint routes to minimize the effect of mutual interference of routes is presented in [16]. The Orthogonal Routing Protocol proposed in [11] is a DSR-based on-demand routing protocol that aims to increase network utilization by preventing adjacent links along a path to be aligned and thus

interfering. Finally in [13] a complete multi-hop wireless system exploiting directional antennas is presented; however, the routing protocol does not take into account direction information of available routes.

The routing protocols proposed in [17, 18, 19] are specifically designed for WMNs with omnidirectional transmissions. The Link Quality Source Routing (LQSR) [17] is based on DSR and aims at selecting routing paths according to link quality metrics. Three quality metrics are proposed: the expected transmission count, the per-hop RTT, and the per-hop packet pair, based respectively on the link loss rate, delay and jitter. Two novel quality-aware routing metrics are introduced in [28] to take into account time-varying channel conditions. A routing protocol for multi-radio WMNs is proposed in [19] together with a new routing metric that takes into account both link quality and minimum hop-count.

The Directional Deflection Routing (DDR) scheme we propose in this paper is based on a strict interaction with the directional MAC scheme. The basic idea is that of using a list of routes towards the destination with different next-hop nodes sorted according to the considered routing metric. Based on the information of the MAC layer, packets are forwarded to the first next-hop node in the list corresponding to a transmission direction not blocked by other transmissions.

This is the concept of deflection routing, originally introduced in the context of optical mesh networks [20, 21]. The DDR scheme can be used in combination with any routing metric, including link quality metrics.

3 Power-Controlled Directional MAC

In this Section we present the Power-Controlled Directional MAC protocol (PCD-MAC), designed for WMNs where nodes use adaptive antennas.

3.1 Assumptions

To specify the WMN scenario we are dealing with, the following definitions and assumptions are needed.

- **Directive antenna**: The radiation pattern of a directive antenna is divided into N non-overlapping sectors, each of width equal to $\frac{360}{N}$ degrees. Within each sector there are M transmission ranges according to the selected transmission power level [14]. To account for the side lobes, we adopt in this paper the sector model shown in Fig. 1 where the circle represents the omnidirectional coverage around the station due to side lobes and the triangle, graded in M parts, represents the main radiation lobe. If g_m is the maximum radiation gain, the gain of the side lobes can be assumed 10 dB lower [29, 30].

  We assume that the antenna with N sectors covers the entire circle around itself and that the power level in each sector can be set independently from the others. This is however a simplified model, since practical implementations will obtain more irregular radiation patterns. More sophisticated is the antenna implementation, more realistic becomes this model.

  Possible practical implementations can be obtained by multiple sectored antennas [10, 31, 32], or by adaptive array antennas, synthesized as proposed for example
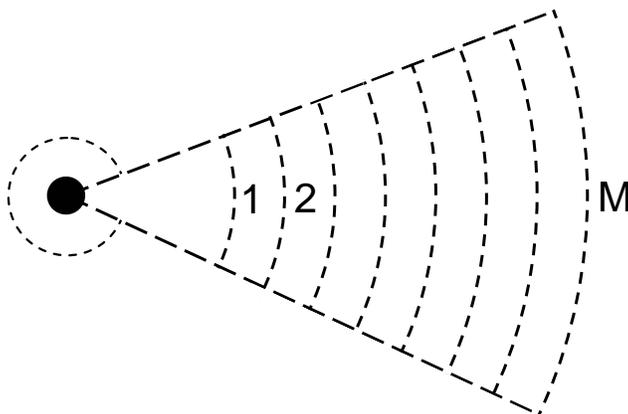
Figure 1: Sector model: M transmission ranges are available, and the circle represents the omnidirectional coverage around the station due to side lobes.

in [33].

- **Mesh routers**: WMN nodes are fixed and are assumed to know their own and their neighbors location. More generally we assume that mesh routers know the radio channel propagation gain towards all their neighbors. For sake of simplicity, when presenting the protocol, we further assume isotropic propagation in all directions.

  To account for links gain variation due to fading each node periodically broadcasts a control frame at a fixed, known power, so that all neighbors can estimate the link gain based on the received power. If such a mechanism is implemented, the assumption on propagation gain becomes more realistic since we need to assume stationary propagation behavior only for the duration of the control interval [14, 34].

  This procedure introduces some protocol overhead due to the periodic transmission and processing of control messages. In our simulations we have not implemented such a procedure since we assume stationary propagation conditions for the whole duration of the simulation. This allows to evaluate a bound of the performance of the proposed MAC protocol obtained in ideal conditions. In realistic conditions the propagation behavior changes but it is expected that in wireless mesh networks a quite long control interval is sufficient to capture these changes (quasi-stationary behavior). As a consequence, the link gain update procedure implemented in a mesh backbone should have a little degradation on the performance.

- **D-NAV information**: The D-NAV for each sector has an entry specifying: the minimum power gain to reach an active node, and for how long such node will be engaged in the current transmission. According to this D-NAV information a node knows the maximum power it can transmit in each sector without interfering with transmissions in progress. The D-NAV information is updated at the reception of packets (RTS, CTS, DATA) from any neighbor.

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3.2 Power-Controlled Directional MAC

The PCD-MAC protocol is a novel variant of the CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) approach. Several protocols proposed in the literature are representatives of this approach, including the IEEE 802.11 Distributed Coordination Function standard for wireless LANs [4].

The basic idea is that a station desiring to transmit senses the medium. If the medium is busy (i.e. some other station is transmitting) the station defers its transmission to a later time. If the medium is sensed free for a specified time (called Distributed Inter Frame Space in the standard [4]) the station is allowed to transmit. The sender sends a Request-To-Send (RTS) and the receiver responds with a Clear-To-Send (CTS) as a prelude to data packet transmission. Nodes hearing this exchange defer for the subsequent DATA-ACK(nowledgment) exchange. The reader is referred to [4] for details.

The receiving station checks the correctness of the received DATA packet and sends an ACK packet. If the sender does not receive the ACK, it retransmits the packet until it gets acknowledged or discarded after a given number of retransmissions.

The stations perform the standard exponential backoff algorithm as in the IEEE 802.11 standard MAC in the following situations:

- when the station senses the medium busy before the first transmission of a packet,

- after each retransmission,

- after a successful transmission.

In the following we describe in details the two procedures implemented in PCD-MAC which differ from the standard IEEE 802.11 MAC: D-NAV information updating and Packet transmission.

D-NAV information updating

Node i, upon reception of:

- RTS or DATA frames, updates:

  - the D-NAV entry of the sector of the sending node (s);
  - the D-NAV entry of the sector of the destination node (d), if d is a neighbor of i. Otherwise, no update is performed.

- CTS frames, updates:

  - the D-NAV entry of the sector of the destination node (d), if d is a neighbor of i. Otherwise, no update is performed.

Packet transmission

Node i, upon request to transmit:

- an RTS frame to node j:

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- checks the sector availability to reach node j through the D-NAV information;

- if j is available, then i transmits the RTS frame in all sectors at the power level indicated by the corresponding entries in the D-NAV. Otherwise, i performs the standard backoff procedure.

- a CTS frame to node j:

  - checks the sector availability to reach node j through the D-NAV information;

  - if j is available, then i transmits the CTS frame in all sectors at the power level indicated by the corresponding entries in the D-NAV. Otherwise, no action is performed.

- a DATA or ACK frame to node j:

  - transmits the DATA or ACK frame in the sector of j at the minimum power required to reach j.

Comments

According to mesh routers assumptions a node knows the location of s, d and j if they are neighbors, and the corresponding link gain. The update of the D-NAV is straightforward. Note that the adaptive antenna settings corresponding to any possible D-NAV value can be pre-set due to the reasonable almost stationary propagation conditions in WMN scenarios. The reception of a CTS updates the D-NAV of the destination node d only, since in the IEEE 802.11 standard the CTS frame does not specify the source node s.

Transmissions of RTS and CTS frames are spread over all available sectors in order to inform as many neighbor nodes as possible of the new wireless medium reservation request. This is meant to reduce the undesired hidden terminal and deafness effects. On the contrary, the transmissions of DATA and ACK frames are performed to reach the destination using one sector only and the minimum required power. This is meant to reduce interference and increase channel reuse.

The reception of CTS, DATA and ACK frames takes place directionally, i.e. with the receiving node having its antenna steered in the sector that contains the node transmitting such frames.

As an example of PCD-MAC operation, let us consider the network scenario shown in Figures 2 and 3, where two connections are active between nodes 3-4 and 5-6. The adaptive antenna has 8 sectors and 8 different transmission power levels. The D-NAV information at nodes 1 and 2 regarding the coverage is graphically represented by the gray area in Figures 2(a) and 2(b), respectively.

If node 1 wants to transmit a packet to node 2, it transmits an RTS using the adaptive antenna transmission range represented by the gray area in Fig. 2(a). Similarly, Fig. 2(b), node 2 transmits the corresponding CTS. The ensuing DATA/ACK exchange then takes place directionally and at the minimum necessary power, as illustrated in Figures 3(a) and 3(b).

In this example, the power control feature of PCD-MAC allows to establish the connection between nodes 1 and 2, even if the D-NAV of node 1 indicates that there is an ongoing transmission (between nodes 3 and 4) in the sector that contains node 2.
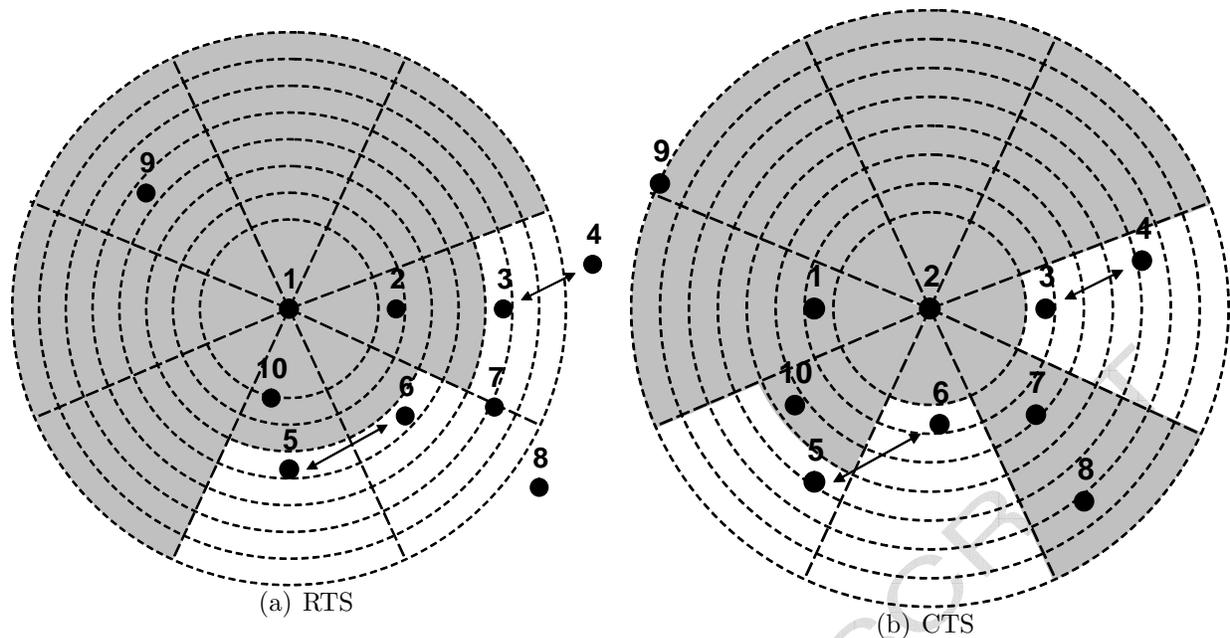
Figure 2: PCD-MAC: antenna pattern (a) used by node 1 to send the RTS frame (b) used by node 2 to send the CTS frame; two connections are already established, between nodes 3-4 and 5-6.

The main features of PCD-MAC rely on sectored transmissions and power control. The latter enables the stations to effectively change the transmission range according to the needs in order to improve the overall performance. Power control tuning, however, may be somehow critical when the assumed channel stationary propagation conditions are compromised.

To evaluate the actual improvement produced by power control, in our numerical results (Section 5) we have considered a protocol version, Directional MAC (D-MAC), where the power control is inhibited. In an available sector the transmission always occurs at the maximum power level, P. Hence, RTS and CTS frames are transmitted at power level P in all sectors specified as "free" (no active nodes) by the D-NAV. DATA and ACK frames are also transmitted at power level P but in one sector only. We expect that this simplified version of PCD-MAC performs worse, but it is the only actually implementable when propagation conditions vary fast as in mobile ad hoc networks. Its performance represents a lower bound to that of PCD-MAC endowed with any more sophisticated estimate which captures link fading/shadowing effects that exist in real scenarios.

4   Directional Deflection Routing

The existing MAC protocols and PCD-MAC, presented in the previous Section, are used for transmissions between two adjacent nodes. To exploit their capabilities in the implementation of a Wireless Mesh Network, a routing algorithm is needed.

In the following we present a novel routing algorithm, Directional Deflection Routing (DDR), that is based on the deflection routing approach originally proposed for optical mesh networks [20, 21]. Note that DDR can be used with any directional MAC.

Let us represent a WMN by a graph $G = (V, E)$ where the nodes belonging to set V represent the wireless routers and the arcs $(i, j) \in E$ represent connections between routers

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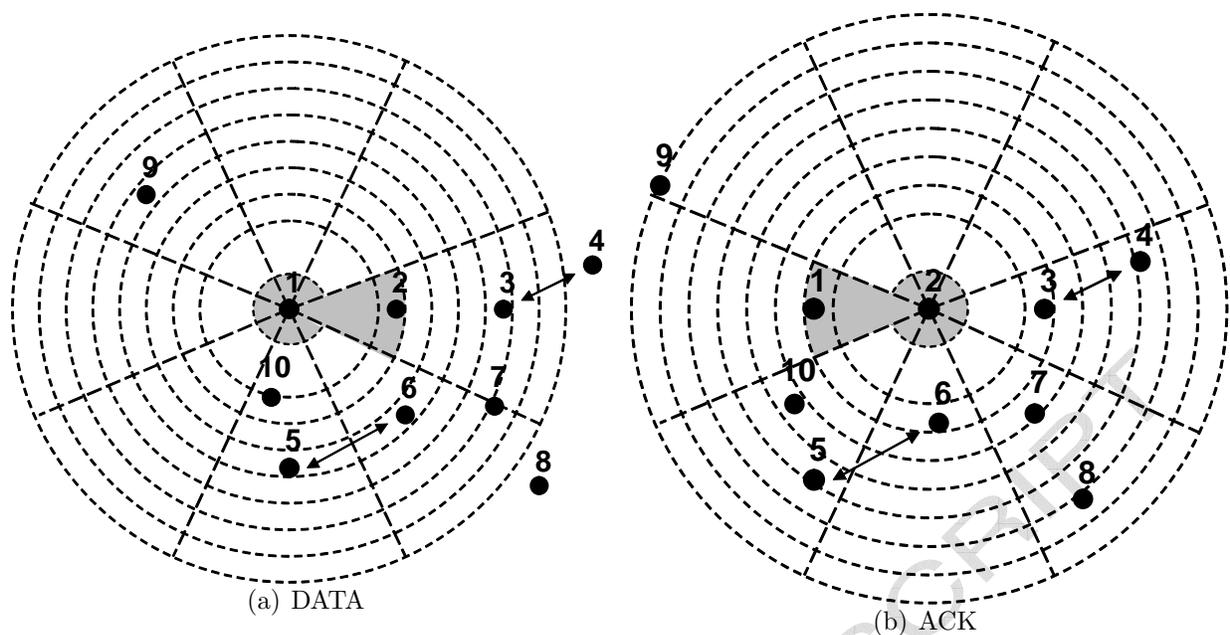
Figure 3: PCD-MAC: antenna pattern (a) used by node 1 to send the DATA frame (b) used by node 2 to send the ACK frame; two connections are already established, between nodes 3-4 and 5-6.

within transmission range. A weight is associated to each arc.

Each node n caches routing tables specifying for any destination a set of shortest paths, one per each adjacent node. For each destination, all shortest paths are sorted according to increasing length. The metric used in this paper is the number of hops in a path, but other metrics as those applied in [17, 18, 28] could be used. Since nodes are fixed, the update of routing tables is needed only when topology changes occur. Routing tables update is out of the scope of DDR; however, we observe that it can be easily done using for example any link-state routing protocol like for example OLSR [23].

In our simulations we consider only static topologies, so that multiple path choices can be statically pre-set in each node. This allows us to evaluate exclusively the performance gain achieved by DDR without considering the link-state protocol overhead. Evidently, in real network scenarios, the choice of the link-state routing protocol impacts on the overhead necessary to maintain the link-state database updated. However, DDR does not add any further overhead regardless to the link-state routing protocol used, since as long as each node has its link-state database updated, it has all the information needed to compute multiple paths towards the destinations with only a slight increase in computational effort with respect to computing a single path.

DDR Algorithm

Upon request to transmit a packet addressed to node m, the list of shortest paths to m is scanned and the shortest path with the first hop available is selected. The hop availability is obtained by the D-NAV at node n. If no hop is available, the packet forwarding is delayed until a next hop becomes available. If destination node m is adjacent to n and the link (n, m) is busy, no deflection is performed. Packet transmission is delayed until link (n, m) becomes free. A packet is never forwarded to the node from which it was received.

To illustrate the operation of Directional Deflection Routing, let us consider the Wireless Mesh Network in Fig. 4, where lines represent wireless links. Nodes 2-6 are currently involved in a frame exchange, represented with arrows, and node 1 wants to send a packet to node 3.
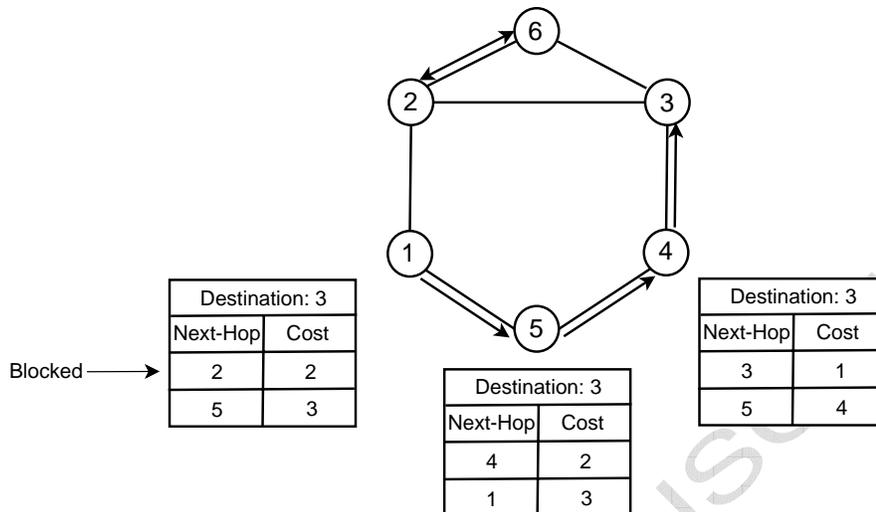
Figure 4: Example scenario that illustrates the operation of Directional Deflection Routing: node 1 wants to transmit a packet to node 3, while nodes 2-6 are currently involved in a frame exchange. The routing tables at nodes 1, 5 and 4 for packets with destination node 3 are also reported.

The routing tables at nodes 1, 5 and 4 for packets with destination node 3 are shown in Fig. 4. Upon request to transmit a packet to node 3, node 1, according to DDR, scans the list of shortest paths. The first path, with next hop node 2, is not available as signaled by the D-NAV. The next one is available and the packet is forwarded to node 5. Same procedure at node 5 which forwards the packet to node 4. Node 4 is adjacent to packet destination, node 3, and has no option to deflect.

The DDR procedure, applied on a per-packet basis, guarantees the selection of the best available path to the destination with a consequent expected improvement of the end-to-end throughput [35, 36]. However, selecting the path on a single packet basis can result in out-of-sequence packet delivery which can affect TCP performance. The whole system has been simulated to obtain the numerical results presented in Section 5. To investigate closer the effect of out-of-sequence packet delivery we have also considered a modified version of DDR, the Stabilized-DDR (SDDR), where the shortest path selection is no longer applied packet by packet, and once a path has been selected it remains unchanged for a given holding time.

5   Numerical Results

In this Section we evaluate the performance of PCD-MAC and Directional Deflection Routing, and compare it with that of other schemes proposed in the literature by extensive simulations performed using the Network Simulator *ns* ver.2 [37].

The performance is measured by the network goodput and the fairness among competing connections. The network goodput is defined as the total traffic accepted in the

network and correctly delivered. Packet retransmissions within the network are not considered. The fairness is measured by the fairness index introduced by Jain [38], and defined as follows:

$$Jain's\ Fairness\ Index = \frac{(\sum_{i=1}^{n} x_i)^2}{n \cdot \sum_{i=1}^{n} x_i^2}$$

where n is the number of connections offered to the network.

If x_i is the goodput of the $i - th$ connection, as assumed in this paper, the above definition measures the fairness among all connections, i.e. the fairness as perceived by the users, which is an important parameter to evaluate the goodness of MAC and routing protocols for Wireless Mesh Networks [39, 40].

We further considered the Min-Max fairness index (proposed in [41]), defined as $\frac{\min\{x_i\}}{\max\{x_i\}}$, which, differently from the Jain's index, tracks more efficiently connections that obtain very low goodput.

Both fairness indices values are in the [0,1] range. Value 1 is achieved when all connections obtain exactly the same goodput (perfect fairness).

Note that the fairness indices still apply when the connections can be routed over multiple paths, since x_i represents the total goodput achieved by the $i - th$ connection.

In our simulator we have assumed a radio transmission rate of 11 Mbit/s and a maximum transmission range of 215 m. The antenna model used is that described in Section 3 (with $N = 8$ sectors and $M = 8$ power levels) so that transmission patterns as those shown in Figures 2 and 3 are implemented in the simulator.

As for the traffic offered to the network, we consider both UDP and TCP traffics. UDP traffic is modeled using Poisson packet arrivals at each sender, at a rate sufficiently high to saturate the capacity of the wireless link. Packet size is equal to 1000 bytes. We consider also bulk FTP transfers performed by using the standard TCP NewReno protocol, with full-sized segments of 1500 bytes.

All numerical results have been calculated over long-lived data exchanges, achieving very narrow (less than 5%) 95% confidence intervals.

5.1 PCD-MAC performance

We evaluate the performance of PCD-MAC and compare it with that of the standard IEEE 802.11 MAC [4], and the DRTS-MAC proposed in [5] which is based on a similar approach. To investigate the power control effect on the PCD-MAC performance we have also simulated the D-MAC described in Section 3.

Several scenarios have been simulated. Some, very simple, have been considered to verify preliminarily the main features of PCD-MAC. Then, more realistic grid and random topology scenarios with a large number of connections are used to investigate the performance.

Fully connected network

In such a network all nodes are neighbors of each other. We have simulated the 4 nodes network shown in Fig. 5 where two connections are established: C1 between nodes 1 and 4 and C2 between nodes 2 and 3.
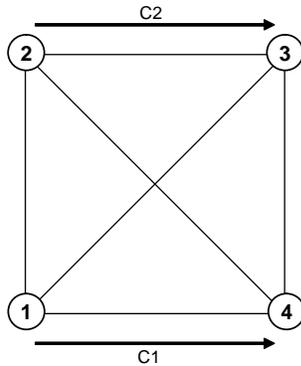
Figure 5: Fully connected square topology scenario with two connections; lines represent wireless links and arrows represent connections.

In this scenario, with the IEEE 802.11 MAC and omnidirectional antennas one connection only can be active at a time. The use of PCD-MAC with directional transmissions activates simultaneously both connections.

Table 1 shows the goodput and the fairness indices with UDP and TCP traffic for the four protocols considered.

Table 1: Simulation results in the network scenario of Fig. 5: average goodput [Mbit/s], Jain's and Min-Max fairness indices for different MAC and traffic types.

	Poisson Traffic			FTP Traffic		
MAC	Goodput	Jain	Min-Max	Goodput	Jain	Min-Max
IEEE 802.11 MAC	4.35	1.00	1.00	4.33	0.99	0.99
DRTS-MAC	5.44	1.00	0.99	4.69	0.99	0.89
D-MAC	8.00	1.00	1.00	8.13	1.00	1.00
PCD-MAC	**8.00**	**1.00**	**1.00**	**8.15**	**1.00**	**1.00**

DRTS-MAC performs slightly better than the standard 802.11 omnidirectional MAC, but the omnidirectional transmission of CTS frames greatly limits its performance.

Note that PCD-MAC achieves significant goodput improvements still maintaining perfect fairness between the two competing flows. We observe that in this scenario the two fairness indices have almost the same value for all the considered MAC schemes.

D-MAC and PCD-MAC perform the same since power control has no effect in this topology.

T-topology network

In the 6 nodes scenario illustrated in Fig. 6, 3 connections are active: C1 between nodes 1 and 2, C2 between nodes 5 and 4 and C3 between nodes 6 and 3.

In this network layout, for the node distances and transmission range specified in Fig. 6, the IEEE 802.11 MAC activates at most one connection at a time. Directional MAC schemes with no power control like the DRTS-MAC and D-MAC allow connections C1 and C2 to be active simultaneously, while C3 is still inhibited as node 3 is exposed
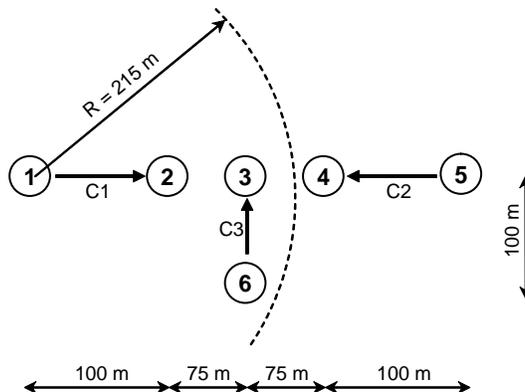
Figure 6: Network Scenario with 3 connections established. The transmission range R of a sample node is reported for clarity.

to the directional transmissions of RTS and DATA from nodes 1 and 5. Alternatively, if C3 is active, C1 and C2 are inhibited. PCD-MAC, having power control on all frames transmissions, allows up to three connections to be active at the same time.

From the numerical results shown in Table 2, for both UDP and TCP traffic, we observe that PCD-MAC not only improves the goodput but also achieves a fair sharing of network resources among competing connections. Higher unfairness has been measured with DRTS-MAC and D-MAC due to the asymmetry between C1, C2 and C3. This is more evident if we consider the Min-Max fairness index, which shows very low values for DRTS-MAC and D-MAC with both types of traffic since one connection achieves almost zero goodput being the channel almost always occupied by the transmissions of the other two connections.

Table 2: Simulation results in the network scenario of Fig. 6: average goodput [Mbit/s], Jain's and Min-Max fairness indices for different MAC and traffic types.

MAC	Poisson Traffic			FTP Traffic		
	Goodput	Jain	Min-Max	Goodput	Jain	Min-Max
IEEE 802.11 MAC	4.30	0.95	0.63	4.31	0.85	0.32
DRTS-MAC	6.02	0.71	0.06	7.31	0.67	0.00
D-MAC	6.84	0.71	0.07	7.80	0.67	0.00
PCD-MAC	**8.65**	**0.98**	**0.76**	**9.64**	**0.99**	**0.83**

Grid networks

The network nodes are allocated on a regular grid of size $L \times L$. K couples of source/destination nodes are randomly selected and the traffic is routed on a shortest path randomly chosen. Note that on a grid several shortest paths may exist between two nodes.

We have simulated a grid with $L = 5$ and elementary link size equal to 70 and 140 meters. In the first case each node has several neighbors (transmission range $R = 215 \gg 70$), while in the second one a node has no more than 8 neighbors. Five random selections of $K = 10$ source/destination couples have been considered and the results shown in

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Tables 3 and 4 represent the average over the five scenarios. Table 3 refers to Poisson traffic and Table 4 to TCP traffic.

In all cases PCD-MAC obtains the largest goodput. The difference between D-MAC and PCD-MAC is greater in dense grid scenarios since in this case the power control allows more connections to be active simultaneously. Also for the fairness indices, PCD-MAC shows a better performance; however, the Min-Max index values are very low for all schemes since at least one connection gets a low goodput in all scenarios. Since in any case we observed that the Min-Max and the Jain's fairness indices exhibit similar trends, but the Jain's one provides a better indication of global fairness among all connections, in the following we report only the results of this last one for sake of simplicity.

Table 3: Average goodput [Mbit/s], Jain's and Min-Max fairness indices for various MAC versions in the 5×5 grid network scenarios with inter-node spacing of 70 and 140 m; 10 connections offer to the network a Poisson traffic.

	Grid 70 m			Grid 140 m		
MAC	Goodput	Jain	Min-Max	Goodput	Jain	Min-Max
IEEE 802.11 MAC	5.67	0.62	0.05	6.13	0.35	0.00
DRTS-MAC	8.98	0.69	0.08	12.47	0.57	0.04
D-MAC	9.27	0.71	0.07	15.23	0.66	0.04
PCD-MAC	**10.27**	**0.76**	**0.13**	**15.55**	**0.67**	**0.05**

Table 4: Average goodput [Mbit/s], Jain's and Min-Max fairness indices for various MAC versions in the 5×5 grid network scenarios with inter-node spacing of 70 and 140 m; 10 connections offer to the network FTP traffic.

	Grid 70 m			Grid 140 m		
MAC	Goodput	Jain	Min-Max	Goodput	Jain	Min-Max
IEEE 802.11 MAC	6.17	0.42	0.00	8.83	0.31	0.00
DRTS-MAC	9.22	0.38	0.00	14.09	0.46	0.00
D-MAC	11.28	0.46	0.00	16.65	0.62	0.00
PCD-MAC	**12.72**	**0.58**	**0.01**	**16.80**	**0.63**	**0.02**

Random networks

To generate a random network with I nodes we randomly select I nodes uniformly distributed on a given square area. Links exist between any two nodes located within the transmission range R. If the resulting topology is connected, a feasible random network is generated. Fig. 7 shows an example of such a network generated selecting $I = 30$ nodes on a 1 km square area and with $R = 215$ m.

Given a feasible network, five random selections of $K = 10$ source/destination couples are considered. The traffic from source to destination is routed on the shortest path. The results shown in Table 5 are averaged on 5 source/destination random selections, and also on 5 random feasible topologies.

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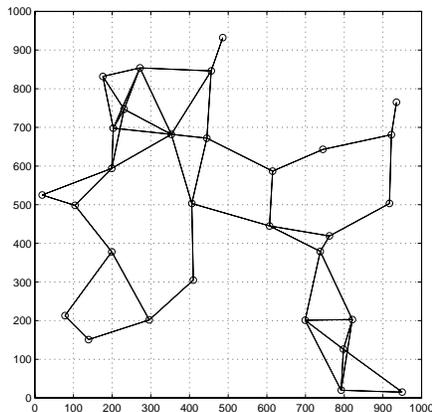
Figure 7: Instance of a generated random topology with $I = 30$ nodes uniformly distributed on a 1 km square area.

Also in this quite practical wireless mesh network scenario PCD-MAC performs best increasing the goodput of about 65% over IEEE 802.11 MAC. Fairness is also improved.

Table 5: Average total goodput [Mbit/s] and Jain's fairness index achieved by the various MAC schemes in the random network scenarios illustrated in Fig. 7 with 30 nodes and 10 connections.

MAC	Poisson Traffic		FTP Traffic	
	Goodput	Jain	Goodput	Jain
IEEE 802.11 MAC	10.18	0.46	12.40	0.44
DRTS-MAC	14.55	0.58	15.84	0.48
D-MAC	15.92	0.67	16.09	0.55
PCD-MAC	**17.02**	**0.68**	**17.84**	**0.59**

As a final scenario, derived from a random network, we consider a wireless mesh network used to interconnect users to the Internet through C concentrators. To generate such a scenario we start from a feasible random network and randomly select C nodes as concentrators. The traffic generated by all nodes is addressed to the closest concentrator. Fig. 8 shows an example of this scenario obtained from the random topology of Fig. 7.

The $C = 4$ concentrators, marked by squares in Fig. 8, have been selected as the most centrally located nodes, one per each of the four 500×500 m square sectors. The corresponding numerical results in Table 6 show once more the superiority of PCD-MAC. The smaller improvement observed in this case is due to the traffic configuration. In fact, being the traffic directed to few concentrators, the opportunities of spatial reuse, the main feature of PCD-MAC, are reduced. Even the power control has a negligible impact on the performance in this scenario.

5.2 Directional Deflection Routing

In this Section we consider the shortest-path routing, the Directional Deflection Routing and the Stabilized-DDR in different network scenarios. In all simulated networks we

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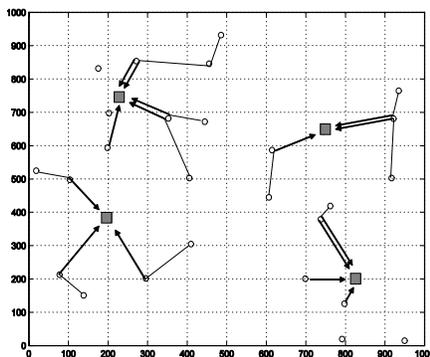
Figure 8: Random topology with 4 concentrators. Connections' paths are indicated with arrows.

Table 6: Average total goodput [Mbit/s] and Jain's fairness index achieved by the various MAC schemes in the random network scenarios illustrated in Fig. 8 with 30 nodes, 4 concentrators and 10 connections.

	Poisson Traffic		FTP Traffic	
MAC	Goodput	Jain	Goodput	Jain
IEEE 802.11 MAC	10.25	0.40	12.99	0.40
DRTS-MAC	12.49	0.65	15.75	0.36
D-MAC	13.83	0.61	15.66	0.43
PCD-MAC	**13.81**	**0.63**	**15.59**	**0.44**

assume that routing protocols operate over the PCD-MAC. The traffic offered to the network is either UDP or TCP as specified later. SDDR is considered only with TCP traffic since its performance provides a bound to the effect caused by out-of-sequence packets generated by DDR.

For sake of simplicity but without loss of generality we measure the length of a path by the number of hops. However, DDR can be used with any routing metric including QoS parameters.

5.2.1 UDP Traffic

In all the networks considered in the following a random Poisson traffic is assumed in each connection.

Polygon topology

This simple topology, the pentagon shown in Fig. 9, provides the performance of routing in topologies where two alternate paths exist to establish a connection. In the example of Fig. 9, we have simulated two active connections: C1 between nodes 2-3 and C2 between nodes 1-3. If shortest-path routing is implemented, the two connections overlap and compete to use link (2,3). DDR, on the contrary, avoids such an undesired situation since the alternate path (1-5-4-3) can be used. In fact, we observed that DDR routes more than 90% of C2's packets on such alternate path. The expected increase of goodput has been

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confirmed by the numerical results shown in Table 7. The fairness provided by DDR is also higher.
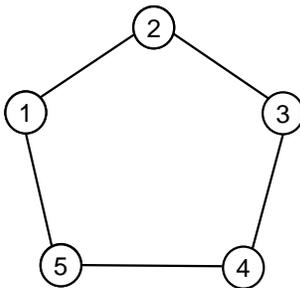
Figure 9: 5 nodes topology: two connections are established, one between nodes 2-3 (C1) and the other between nodes 1-3 (C2).

Table 7: Goodput [Mbit/s] and Jain's fairness index in the network scenario of Fig. 9 where connection C1 is established between nodes 2-3 and connection C2 between 1-3.

Routing Algorithm	C1 Goodput	C2 Goodput	Total Goodput	Jain
Shortest-Path	2.11	0.35	2.46	0.63
DDR	2.11	0.91	3.02	0.86

To show the performance of DDR when link quality metrics are used, we further consider a variation of this network scenario, where node 2 has a radio transmission rate equal to 5.5 Mbit/s, while all the other nodes have a rate equal to 11 Mbit/s. We use as link quality metric the inverse of the transmission rate. Therefore the cost of links (1,2) and (2,3) is twice that of the other links. We consider the same two connections, C1 and C2, considered above. The performance is reported in Table 8 for shortest-path routing and DDR. Shortest-path routing routes packets on disjoint paths, i.e. (2-3) for C1 and (1-5-4-3) for C2. DDR achieves a slight improvement over shortest-path routing since it routes some of C2's packets on the higher-cost path (1-2-3), when node 2 is available.

Table 8: Goodput [Mbit/s] and Jain's fairness index in the network scenario of Fig. 9 where node 2 has a radio transmission rate of 5.5 Mbit/s while all other nodes have a rate equal to 11 Mbit/s. The cost of each link is equal to the inverse of the transmission rate. Two connections are established: connection C1 between nodes 2-3 and connection C2 between 1-3.

Routing Algorithm	C1 Goodput	C2 Goodput	Total Goodput	Jain
Shortest-Path	1.80	0.22	2.02	0.62
DDR	1.67	0.45	2.12	0.75

Grid topology

Similarly to Section 5.1 we consider a grid (6 × 6) with elementary size equal to 140 m, shown in Fig. 10(a). We first consider connections originated at node 13 and destined

to 14, 15, 16, 17 and 18, respectively. Only one connection is active at a time and we measure its goodput achieved by either shortest-path routing and DDR.

For a single-hop connection, both routing algorithms are the same. On a two-hop connection the goodput drastically reduces since both hops (13-14 and 14-15) cannot transmit at the same time. DDR shows an improvement over shortest-path routing since alternate hops, for example 13-20 or 13-8, can be used at the same time as 14-15. This beneficial effect of DDR increases as the number of hops increases as shown in Fig. 10(b).

In our simulations we have observed that the percentage of packets routed on deflected routes increases with the connection length. More specifically, the percentage of deflected packets is approximately 10% for 2 and 3 hop connections, and 20% for 4 and 5 hop connections.

On the same grid topology we have considered two further scenarios with 5 and 10 connections. The connections are randomly selected and their goodputs have been measured and averaged over five different connections selections.

The numerical results of Table 9, averaged over all connections and all selections, show a higher goodput and better fairness achieved by DDR. However, one can observe a smaller improvement as the number of connections increases. This behavior is explained by the reduced number of deflection opportunities when the number of connections increases: fewer nodes are free to forward packets.

When evaluating the performance according to connections length, it turns out that DDR achieves the highest improvement for longer connections. We observed that with shortest-path routing long connections are penalized versus shorter ones, while all the long connections achieve high goodput with DDR by exploiting alternate routes.

We further consider a variation of the 6×6 grid network scenario, with elementary link size equal to 200 m. In this case each node has at most 4 neighbors. We consider the same set of 5 and 10 randomly extracted connections considered above. Table 10 shows the results obtained with shortest-path routing and DDR. The performance of both routing algorithms decreases with respect to the 140 m grid scenario, since the number of hops of each connection is sometimes increased. Furthermore, the performance gain achieved

(a)

(b)
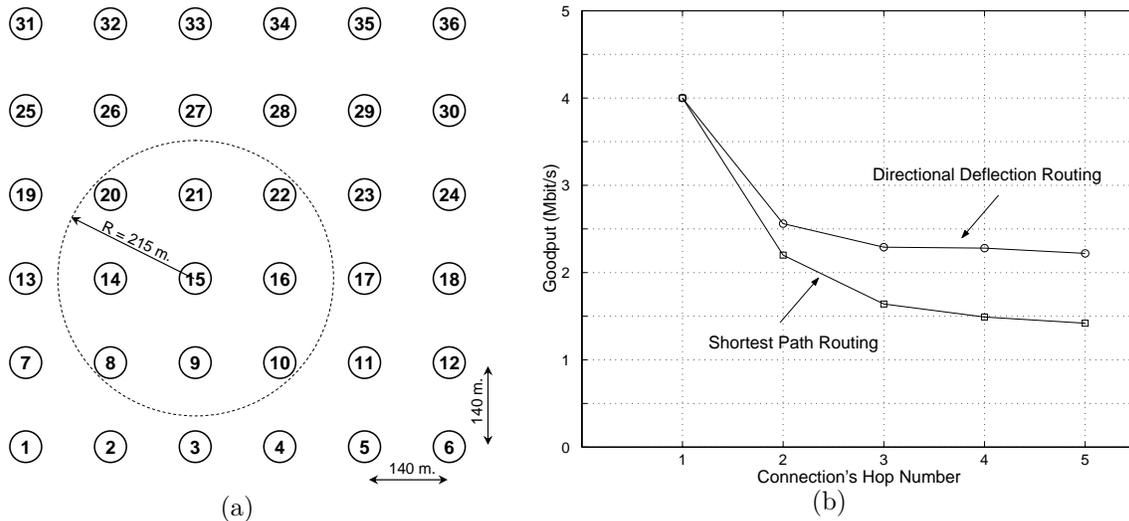
Figure 10: (a) Single multi-hop connection established in a grid scenario with 36 nodes. (b) Goodput achieved by a single multi-hop connection as a function of the number of hops.

Table 9: Simulation results in the grid network scenario of Fig. 10(a), with 5 and 10 established connections: average goodput [Mbit/s] and Jain's fairness index for shortest-path and Directional Deflection Routing.

	5 connections		10 connections	
Routing Algorithm	Goodput	Jain	Goodput	Jain
Shortest-Path	2.64	0.58	6.92	0.43
DDR	3.61	0.87	7.90	0.62

by DDR is smaller than in the 140 m grid since less alternate paths are available for deflecting packets.

Table 10: Simulation results in a 6×6 grid network scenario with elementary link size equal to 200 m, with 5 and 10 established connections: average goodput [Mbit/s] and Jain's fairness index for shortest-path and Directional Deflection Routing.

	5 connections		10 connections	
Routing Algorithm	Goodput	Jain	Goodput	Jain
Shortest-Path	1.57	0.53	4.45	0.42
DDR	2.23	0.83	5.37	0.59

Random topology

According to the procedure used in Section 5.1 we have generated feasible mesh networks with 40 nodes randomly distributed on a 1 km square area.

As in the previous grid topology, we have considered two scenarios with 5 and 10 random connections. The results are shown in Table 11 and confirm that DDR increases both the total goodput and fairness among competing connections.

Table 11: Simulation results in the mesh network scenario with 5 and 10 established connections: average goodput [Mbit/s] and Jain's fairness index for shortest-path and Directional Deflection Routing.

	5 connections		10 connections	
Routing Algorithm	Goodput	Jain	Goodput	Jain
Shortest-Path	4.79	0.63	11.33	0.58
DDR	5.96	0.83	11.93	0.71

5.2.2 TCP Traffic

The TCP traffic scenario has been considered to investigate the effect on the overall network performance of the out-of-sequence packet delivery introduced by DDR. To this aim we have simulated in this scenario also SDDR for comparison reasons.

In more details, the scenario we have simulated consists of the grid topology shown in Fig. 11(a), where a border node (AP) acts as access point to the Internet. Such a node is connected to a TCP server (W) via a wired link with capacity 100 Mbit/s and a propagation delay of 50 ms.
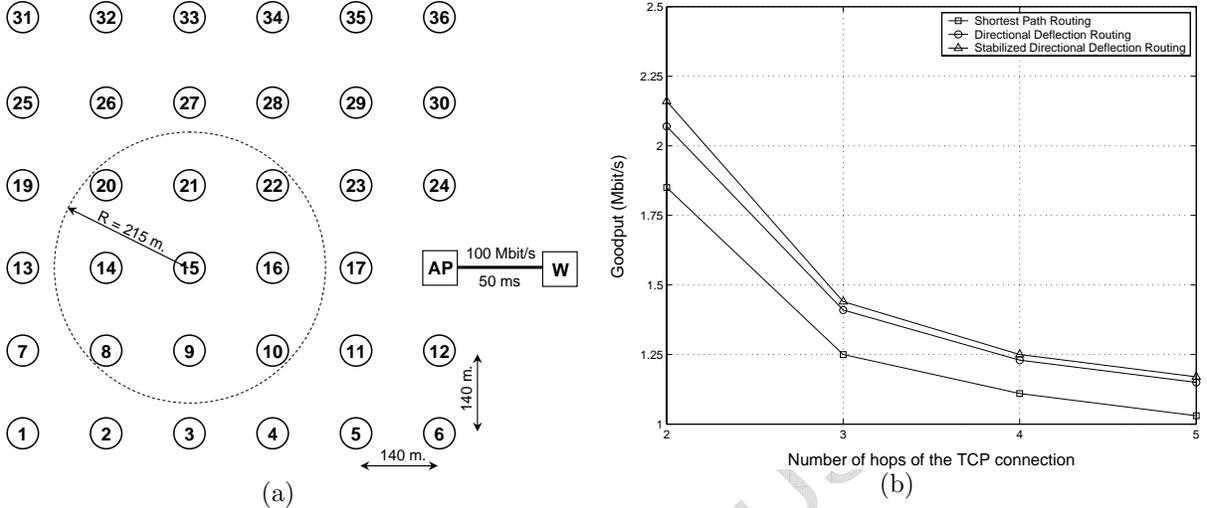
Figure 11: (a) Grid topology with 36 wireless nodes; node AP acts like gateway towards the Internet and it is connected via a wired link to the TCP server W. (b) Performance comparison of a single TCP connection established between the TCP server and a wireless node in the grid topology with an increasing number of hops.

We consider, one at a time, four TCP connections originated at the TCP server, W, and destined to the TCP client at node 16, 15, 14 and 13, respectively.

To implement SDDR one has to set the minimum route holding time. If this time is very small, SDDR behaves as DDR; if it is very long, it behaves as shortest-path routing. In our simulation we have selected this holding time equal to 2500 Extended InterFrame Space (EIFS) periods, corresponding to approximately 0.9 s, since this value provides the best performance in the considered network scenario.

The goodputs as function of TCP connection lengths for the three considered routing algorithms are shown in Fig. 11(b).

SDDR performs best, but the degradation due to frequent out-of-sequence in DDR is almost negligible. The percentage of out-of-sequence packets measured in our simulation increases from 0.02% to 4.12% in 2-hop TCP connections and from 1.4% to 12.53% in 5-hop TCP connections when DDR is used instead of SDDR. Both these routing protocols steadily outperform shortest-path routing. Because of its much simpler implementation we believe that DDR is the best alternative to choose.

6   Conclusion

In this paper we proposed PCD-MAC, a novel power-controlled MAC for adaptive antennas scenarios, and Directional Deflection Routing (DDR), a multiple paths routing algorithm based on the MAC layer indication on channel availability.

PCD-MAC improves spatial reuse limiting the deafness problem by spreading the information about wireless medium reservation to the maximum possible extent without

interfering with the connections already established in the network. DDR exploits the cross-layer interaction with the MAC level to improve network performance: each node maintains a sorted list of next-hop nodes per destination based on shortest paths, and forwards packets to the first available node in the list according to the MAC layer indication on channel status in different directions.

The results show that the use of PCD-MAC and DDR increases remarkably both the total traffic accepted by the network and the fairness among competing connections, thus representing an effective solution for wireless mesh networking.

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