# Multi-Channel Power-Controlled Directional MAC for Wireless Mesh Networks

Fabio Martignon*

**Abstract**

Wireless Mesh Networks (WMNs) have emerged recently as a technology for providing high-speed last mile connectivity in next-generation wireless networks. Several MAC protocols that exploit multiple channels and directional antennas have been proposed in the literature to increase the performance of WMNs. However, while these techniques 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 need to be carefully designed to fully exploit the features offered by multiple channels and directional antennas.

In this paper we propose a novel Multi-Channel Power-Controlled Directional MAC protocol (MPCD-MAC) for nodes equipped with multiple network interfaces and directional antennas. MPCD-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 on a separate control channel, while the DATA and ACK packets are transmitted only directionally on an available data channel at the minimum required power, taking into account the interference generated on already active connections.

This solution spreads the information on wireless medium reservation (RTS/CTS) to the largest set of neighbors, while data transfers take place directionally on separate channels to increase spatial reuse. Furthermore, power control is used to limit the interference produced over active nodes.

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

*Index Terms*: - Wireless Mesh Networks, Medium Access Control, Multiple Channels, Directional Antennas, Power Control.

## 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 outdoor 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 limited node failures.

Supporting high throughput is an important challenge in Wireless Mesh Networks, since the IEEE 802.11 standard Medium Access Control (MAC) [3] can lead to poor performance for such networks, due to its unfriendliness with multi-hop operation [4, 5]. It is therefore important to devise efficient MAC schemes which make it possible to operate WMN nodes in multi-hop mode without excessive performance degradation. On the other hand, the IEEE 802.11 standard is so established by now that any completely new MAC will find it very hard to succeed commercially. Our approach in this paper is therefore to consider small variations to the current standard in order to solve the main performance problems without requiring major hardware modifications.

The solution we propose leverages on the fact that multiple channels are available in the industrial, scientific, and medical (ISM) band used for wireless LANs, so that the handshake used for contention and

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

channel allocation can be separated from the actual user traffic. This makes it possible to increase the performance of WMNs using multiple antennas tuned on non overlapping channels and running multiple channels in parallel.

Furthermore, in recent years, directional antenna technology has been studied in 802.11-based networks. The increased spatial reuse with the combination of extended transmission range is especially attractive for 802.11-based mesh networks [6, 7]. Regrettably, directional transmissions can also cause serious problems in a WMN environment, increasing the number of instances of the hidden terminal problem [8]. Therefore, efficient MAC protocols need to be designed, since the IEEE 802.11 standard MAC has been optimized for omnidirectional antennas.

The problems of designing efficient multi-channel MAC protocols [4, 5, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18] and single-channel MAC schemes with directional antennas [19, 20, 21, 8, 22, 23, 24] have been deeply investigated in the research area of ad hoc networks. Some solutions envisage the use of power control techniques to further enhance spatial reuse and wireless medium utilization in single-channel networks [7, 25, 26, 27].

In this paper we propose the Multi-Channel Power-Controlled Directional MAC (MPCD-MAC), a novel MAC protocol designed for Wireless Mesh Networks where nodes use multiple channels, directional antennas and power control. Its key innovative feature is that the transmission of the RTS and CTS packets takes place in all directions at the maximum transmission power on a separate control channel, while the DATA and ACK packets are transmitted only directionally on an available data channel at the minimum required power. Furthermore, a novel connection is established between two nodes only if the interference produced over already active connections is sufficiently low to permit concurrent transmissions to take place.

This solution spreads the information on wireless medium reservation (RTS/CTS) to the largest set of neighbors, while data transfers take place only directionally on a separate channel to increase spatial reuse and minimize interference.

We evaluate extensively MPCD-MAC through simulation, comparing its performance with other solutions proposed in the literature. Numerical results measured in several realistic network scenarios show that MPCD-MAC outperforms existing schemes both in terms of total traffic accepted in the network and fairness between competing connections, even when a very small number of orthogonal channels is available.

This paper is organized as follows: Section 2 discusses technical challenges of using multiple channels, directional antennas and related work. Section 3 describes the Multi-Channel Power-Controlled Directional MAC. Section 4 analyzes and discusses the performance of MPCD-MAC, comparing it with other MAC protocols proposed in the literature. Finally, Section 5 concludes the paper.

# 2 Related work

In this Section, we review some MAC protocols proposed in the literature for ad hoc and Wireless Mesh Networks which are related to the approach considered in this paper.

We first consider *multi-channel* MAC protocols, which allow concurrent connections to transmit contemporarily exploiting orthogonal channels, thus reducing collisions and increasing the network throughput.

Then we review *single-channel* MAC protocols that exploit directional transmissions and power control. 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 [6].

## 2.1 Multi-channel MAC Protocols

To increase the performance of Wireless Mesh Networks, each node can use multiple channels to reduce the number of collisions and increase the spatial reuse.

In the following, we review the most notable MAC protocols proposed in the literature for multi-channel WMNs. Following the classification in [1], a multi-channel MAC may belong to one of the following categories:

- **Multi-channel single-transceiver MAC.** In each node, only one transceiver is available and therefore only one channel is active at a time. However, different nodes may operate on different channels simultaneously to improve system capacity. To coordinate transmissions between network nodes under this situation, protocols such as those proposed in [10, 11, 12, 13] are needed.

- **Multi-channel multi-transceiver MAC.** In this scenario, a radio includes multiple parallel RF front-end chips and baseband processing modules to support several simultaneous channels. On top of the physical layer, there is only one MAC layer (like those proposed in [5, 14, 15, 16, 17, 28, 29]) that coordinates the functions of multiple channels.
- **Multi-radio MAC.** All network nodes have multiple radios, each with its own MAC and physical layer. Communications in these radios are totally independent. Thus, a virtual MAC protocol, such as the Multi-radio Unification Protocol [18] or the Hybrid Multi-Channel Protocol [4], is required on top of the MAC layer to coordinate communications in all channels.

### 2.1.1 Multi-channel single-transceiver MAC protocols

This class of MAC protocols uses a single channel interface that can be tuned dynamically on different channels. However, the utilization of multiple channels can produce a new kind of hidden terminal problem, known as *multi-channel hidden terminal problem*. Let us suppose that $N$ orthogonal channels are available; one channel is dedicated to the transmission of signaling frames, the others to data transmissions. When a node is not involved in a frame transmission or reception, it listens to the signaling channel; however, if a node is transmitting or receiving DATA/ACK frames on a data channel, it may not hear the RTS/CTS frames sent by other nodes that intend to transmit, thus eventually using the same data channel causing a collision.

The *Multichannel MAC protocol* (MMAC) has been proposed in [10] for ad hoc wireless networks that utilize multiple channels dynamically. The protocol requires only one transceiver per host, and tries to solve the multi-channel hidden terminal problem using temporal synchronization.

Briefly, MMAC operates as follows: nodes periodically switch to a common control channel, negotiate their channel selections, and then switch to the negotiated channel, where they contend as in IEEE 802.11.

However, several problems have not been solved in the MMAC protocol. First of all, global synchronization is difficult to achieve in a wireless network with a large number of hops and nodes. Second, the channel selection criterion used in MMAC is not very efficient and can lead to poor performance, as pointed out in [1]. Third, packet delays in MMAC can be as large as hundreds of milliseconds, even for a single hop. Finally, MMAC eliminates multi-channel hidden nodes, but it also generates many exposed nodes.

The *Hop Reservation Multiple Access MAC* [11] is a multi-channel protocol for networks that use slow frequency hopping spread spectrum. Network nodes hop among channels according to a predefined hopping pattern. When two nodes agree to start a communication, they stay tuned on the same frequency, while the other nodes continue hopping so that multiple communications can occur contemporarily on different channels. However, such scheme can be applied only to frequency hopping networks, and cannot be used in systems using other mechanisms such as direct sequence spread spectrum.

SSCH [12] is a single-interface virtual MAC that operates on top of the IEEE 802.11 standard MAC. SSCH uses a pseudorandom sequence to decide which channel to switch the interface to every time slot. The pseudorandom sequence used by any two nodes is guaranteed to overlap periodically, thereby ensuring that any two nodes within communication range can communicate with each other. While a single interface is sufficient for SSCH operation, it may introduce significant delay with multi-hop communication, as packets may be delayed at each hop if the subsequent hop node is on a different channel.

The *Load Based Concurrent Access Protocol* (LCAP) has been proposed in [13] for MANETs with directional antennas. LCAPs novelty lies in using an elaborate packet-based power control strategy that is aimed at increasing the channels spatial reuse by allowing interference-limited, concurrent directional transmissions to take place in the same vicinity. LCAP employs a separate control channel and accounts for minor-lobe interference.

In LCAP, RTS messages are sent omnidirectionally, while CTS/DATA/ACK frames are sent directionally. The choice to send CTS messages directionally, however, can decrease the number of nodes which are informed of the current transmission, thus exacerbating the hidden terminal problem. Furthermore, in LCAP only one Network Interface Card (NIC) is used, and the node switches between the control channel (used to transmit RTS and CTS frames) and the data channel (used to transmit DATA/ACK frames).

When a node is tuned on the data channel, however, it cannot hear the signaling frames transmitted on the control channel, thus leading to the multi-channel hidden terminal problem.

#### 2.1.2 Multi-channel multi-transceiver MAC protocols

This class of protocols uses several interfaces on top of which a single MAC layer coordinates all operations.

The *Multichannel CSMA protocol* proposed in [15] uses one control channel and $N$ data channels. The source exchanges control packets to decide on the best channel to send the data packet on. Such protocol, however, requires the utilization of a large number of NICs (one for each channel), and therefore it represents quite an expensive solution.

The *Control Channel based MAC Protocol* ($C^2M$) [16] permits simultaneous channel contention and data transmission by incorporating advance reservation on the control channel, and data aggregation on the data channel. However, $C^2M$ uses omnidirectional transmissions on both the control and data channels; furthermore, it does not consider the interference that is produced over already active connections.

A two-channel MAC protocol is proposed in [28] for ad hoc networks that are equipped with directional antennas. One channel is used for control information, which is transmitted omnidirectionally, while the second is used for user-data transmissions, which are performed directionally using antenna arrays.

The authors of [29] propose a multi-channel directional MAC protocol for dense vehicular ad hoc networks. Directional antennas are shown to enable higher spatial reuse, increasing the performance in a vehicular environment.

The *Dynamic Channel Assignment with Power Control* MAC protocol (DCA-PC) [17] is a multi-channel MAC that uses power control to reduce the interference generated on the data channel. Each node is equipped with 2 NICs: one is dedicated to the control channel, while the other can be tuned on different channels and is used for data transmissions.

The data channel is chosen based on a Free Channel List (FCL), which is included in the RTS message, while the receiver chooses the data channel (if at least one channel in the FCL is available). A further RES message is used to reserve the data channel.

The DCA-PC scheme, however, performs only omnidirectional transmissions on both the control and data channels, and therefore it does not exploit the spatial reuse made possible by the utilization of directional antennas.

Finally, the MAC protocols proposed in [5, 14] are similar to DCA-PC.

Note that the proposed Multi-Channel Power-Controlled Directional MAC belongs to this class of protocols.

#### 2.1.3 Multi-radio MAC protocols

Multi-radio MAC protocols are characterized by multiple wireless network interface cards on each node, each with its own MAC and physical layer.

The *Multi-radio Unification Protocol* (MUP) [18] exploits multiple NICs, tuned on orthogonal and fixed channels; therefore, for full utilization of available channels, an interface is necessary for each channel. Hence, this proposal is expensive to implement when several channels are available. Furthermore, the hidden node problem is not effectively solved in MUP, and packet reordering can occur, thus causing low end-to-end throughput in multi-hop networks like WMNs.

The *Hybrid Multi-Channel Protocol* (HMCP) [4] assumes that each node has at least two interfaces. One interface is tuned to a specified fixed channel, and the other interface can switch between the remaining channels. HMCP tries to ensure that the number of nodes using each fixed channel is balanced. Each node advertises its fixed channel using broadcast *hello* packets. When a node A wants to send a packet to some node B, then it has to first switch its second interface to the fixed channel of B (if B and A use different fixed channels).

### 2.2 Single-channel Directional 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 Network Allocation Vector (NAV) definition is extended in [7, 21, 8, 30] using a direction field, indicating that the NAV applies only for the specified direction. The NAV is set only in the estimated direction of arrival of each received transmission.

In [21, 8] all frames are transmitted directionally.

Both these schemes present some drawbacks due to the *deafness* problem [6, 31]: whenever a node is engaged in transmitting a frame directionally, it may not hear RTS/CTS exchanges between newly established transmissions, and consequently it can interfere with them once its transmission is completed.

The MAC protocols proposed in [32, 33] exploit directional antennas enabling high spatial reuse in WMNs.

The algorithm proposed in [22] assumes that each sector has associated a directional antenna; the 802.11 CSMA/CA protocol is replicated for each antenna, implementing a Directional CSMA/CA: each node transmits every frame in all sectors that are free according to the Directional NAV (D-NAV) information. Even if this approach reduces the collision probability spreading the information on channel utilization in all available directions, it may also reduce the reuse efficiency.

In [23] the authors propose several solutions to limit the impact of the hidden terminal problem caused by directional antennas. However, though effective, these solutions require consistent changes to the standard MAC protocol.

A power controlled MAC protocol is proposed in [34] to reduce energy consumption and increase network throughput and lifetime.

The schemes proposed in [7, 24, 25] combine the utilization of adaptive antennas to power control techniques, whose benefits are studied analytically in [35]. An optimal power control scheme is studied in [36] for RTS/CTS based MAC protocols.

Various power control techniques are proposed in [24]; however, in all these schemes, power control is adopted only for the transmission of DATA frames.

The solution proposed in [25] introduces two novelties: the first is the adoption of a sophisticated backoff procedure for contention resolution following a collision; the second is the use of a simple power control technique where the transmission power for RTS frames is increased upon each RTS retry. All frames are transmitted directionally. As we noted before, this choice can worsen the deafness problem and lead to unfairness and performance degradation [6, 31].

Differently from the above cited schemes, the PCD-MAC protocol we proposed in [7] 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 a large number of neighbors of the new transmission, limiting the deafness problem. On the contrary, the data exchange (DATA/ACK) is performed only directionally limiting the power to that necessary for reaching the intended receiver.

However, recent experimental works [37] pointed out that the antenna patterns used in PCD-MAC are difficult to achieve in practice, for several physical problems. More specifically, multi-sector activations reduce the signal strength of a link compared to single-sector activations due to antenna design constraints. Hence, contrary to the assumptions made in [7] as well as in several MAC and topology control algorithms, the performance of a link can be radically different under single-sector and multi-sector activations due to antenna design constraints such as the antenna array factor [38].

Therefore, in the proposed MPCD-MAC protocol we only consider single-sector antenna patterns, in addition to omnidirectional transmissions, which can both be easily realized using current antenna technologies. Furthermore, the utilization of multiple orthogonal channels enables high performance improvements with respect to PCD-MAC, as we will show in Section 4. Finally, we underline that MPCD-MAC is less exposed to the directional hidden terminal problem than PCD-MAC since the former transmits RTS/CTS messages omnidirectionally at the maximum transmission power, like in the standard IEEE 802.11 MAC, thus informing the maximum number of users of the new transmission.

# 3 Multi-Channel Power-Controlled Directional MAC

We now present the Multi-Channel Power-Controlled Directional MAC protocol (MPCD-MAC), designed for WMNs where nodes use multiple channels, directional antennas and power control.

## 3.1 Assumptions

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

- **Channel Model**:

  In designing our protocol, we make the following assumptions, in line with [26]: (1) the channel gain is stationary for the duration of the control and the subsequent data frame transmission periods; (2) the gain between two nodes is the same in both directions; (3) data and control frames between a pair of nodes observe similar channel gains; (4) a two-ray propagation model is assumed.

- **Directive Antenna and Power Control**: 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 [26]. To account for the side lobes, we adopt in this paper the sector model shown in Figure 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 [39, 40].

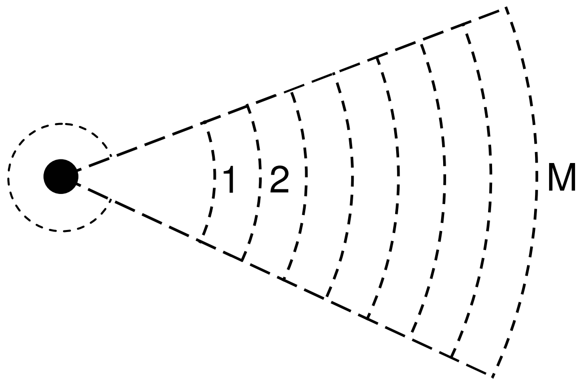



Figure 1: Sector model: $M$ transmission ranges are available, and the circle represents the omnidirectional coverage around the station due to side lobes.

  Possible practical implementations can be obtained by multiple sectored antennas [22, 41, 42], or by adaptive array antennas, synthesized as proposed for example in [43]. Furthermore, small-size sectored antennas have been studied extensively in [37], where the authors demonstrated their practical utilization in real WMN implementations.

- **Orthogonal channels**: Let $N_C$ be the total number of orthogonal channels that are available. One channel is used as signaling channel, to transmit RTS and CTS messages, while the other $N_D = N_C - 1$ channels are used for data exchange, including the acknowledgment packets.

  For example, the IEEE 802.11a standard provisions for 12 non-overlapping channels in the US. However, measurements conducted in [4] suggest that a smaller number of channels (5-6) are orthogonal when using off-the-shelf hardware. In the same way, the work in [44] points out that cross-channel interference is present also in current IEEE 802.11b/g technology, thus limiting the number of non-overlapping channels available in practice.

  Therefore, in this paper we consider a maximum of $N_C = 5$ orthogonal channels; furthermore, we will show that the proposed MPCD-MAC protocol achieves a high performance gain in several network scenarios even if only two orthogonal channels are available.

- **Mesh routers**: We assume that each node has two Network Interface Cards (NICs), and that it is able to hop among channels in a timely fashion. One NIC is equipped with an omnidirectional antenna, which is always tuned on the signaling channel, while the other NIC is endowed with a directional antenna that can be tuned on different data channels. The Carrier Sense Threshold is set equal to the Receive Threshold, in order to maximize spatial reuse. This setting is adopted in several widespread wireless cards, like those based on the Intersil chipsets [45].

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 [26, 46]. 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.

- **NAV information**: Each node maintains two Network Allocation Vectors (NAV): one for the signaling channel, called $\text{NAV}_S$, which specifies for how long such channel will be occupied by an RTS-CTS exchange. The other, called *Directional NAV* (D-NAV), which has an entry for each data channel $C$ and for each sector $s$ specifying: (1) the minimum power gain that can produce interference with an already active node, and (2) 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 for each data channel, and in each sector, without interfering with transmissions in progress. Let us indicate with D-NAV$[C][s]$ the D-NAV entry related to data channel $C$ and sector $s$. The D-NAV information is updated at the reception of packets (RTS, CTS, DATA) from any neighbor.

## 3.2 Multi-Channel Power-Controlled Directional MAC

The MPCD-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 [3].

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 [3]) 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 [3] 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.

To implement the MPCD-MAC protocol, the standard RTS and CTS packet formats are extended including:

- A novel field in the RTS message that indicates the data channel chosen by the sender ($C_S$).
- Three novel fields in the CTS message. One field includes the *id* of the source node, in line with what is already standardized for the RTS message; the second field reports the data channel chosen by the sender, $C_S$, and finally the last field indicates if $C_S$ is available also at the receiver. These

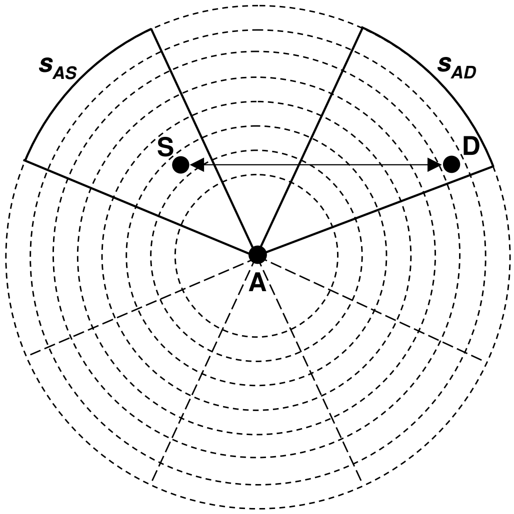



Figure 2: Example network scenario: node $S$ wants to send a packet to node $D$, and $A$ listens to the message exchanges between $S$ and $D$. The sectors of the sending node ($s_{AS}$) and of the receiving node ($s_{AD}$) are also illustrated in bold.

fields allow the neighbors of the destination node to individuate the CTS frame sender, and to update their D-NAV information accordingly.

In the following we describe in detail the three procedures implemented in MPCD-MAC which differ from the standard IEEE 802.11 MAC: $\text{NAV}_S$ and D-NAV information updating, and Packet transmission.

For this purpose, let us consider the network scenario illustrated in Figure 2, where a source node $S$ wants to send a packet to destination node $D$, and $A$ is a neighbor node that listens to the message exchanges between $S$ and $D$.

#### 3.2.1 $\text{NAV}_S$ information updating

Node $A$, upon reception of the RTS frame sent by $S$, updates the $\text{NAV}_S$ entry, indicating that the signaling channel will be occupied for the interval indicated in the *duration* field of the RTS message. Note that such duration includes only the RTS-CTS exchange, since DATA-ACK transmissions occur on a separate channel.

#### 3.2.2 D-NAV information updating

When $A$ receives an RTS or a CTS message which specifies that data channel $C_S$ will be used for the transmission of DATA and ACK packets, it updates the D-NAV information performing the following operations:

1. it computes the sector of the sending node (referred to as $s_{AS}$) and the sector of the receiving node ($s_{AD}$), which are both shown in Figure 2;
2. it updates the D-NAV variables D-NAV$[C_S][s_{AS}]$ and D-NAV$[C_S][s_{AD}]$.

The D-NAV setting in sectors $s_{AS}$ and $s_{AD}$ is performed by node $A$ taking into account that, during the DATA-ACK exchange, $S$ keeps its antenna steered in the direction of $D$, and vice versa, using the directional antenna pattern shown in Figure 1; as a consequence, $A$ can compute for these sectors the maximum transmission power that can be used on channel $C_S$ without interfering with the $S-D$ transmission.

The D-NAV information updating procedure can therefore be formalized as follows.

Node $i$, upon reception of an RTS or a CTS frame (on the signaling channel) that indicate the intention to use data channel $C_S$, or a DATA frame on channel $C_S$, updates:

- the D-NAV entry of the sector of the sending node ($n$), D-NAV$[C_S][s_{in}]$;

- the D-NAV entry of the sector of the destination node ($t$), D-NAV[$C_S$][$s_{it}$], if $t$ is a neighbor of $i$. Otherwise, no update is performed.

We observe that the computation of the sending and receiving nodes' sectors can be performed either exploiting the knowledge that each node has of the position of its neighbors (according to the Mesh routers' assumptions, Section 3.1), or by using sector selection mechanisms like those proposed in [37], which rely on measurements in different sectors, and perform well both in dense indoor and outdoor wireless deployments.

### 3.2.3 Packet transmission

When node $S$ wants to transmit to destination $D$, it randomly selects a data channel ($C_S$) from the set of available data channels (such information can be easily obtained from the D-NAV). If no data channel is available, $S$ defers its transmission until the first data channel becomes available.

Then $S$ transmits the RTS frame omnidirectionally on the signaling channel at the maximum available power. The RTS frame indicates the data channel chosen by the sender, $C_S$, to transmit the DATA packet.

After the reception of the RTS frame, $D$ transmits the CTS frame omnidirectionally on the signaling channel at the maximum power level with (a) a flag indicating that the receiver agrees on using $C_S$, if such channel is available also at $D$ or (b) a flag indicating that $C_S$ cannot be used, if such channel is not available at the receiver. In this latter case, the sender node $S$ retries after backoff, choosing another available data channel (if any), or deferring its transmission if no channel is available.

The DATA-ACK exchange between $S$ and $D$ then takes place directionally on channel $C_S$ at the minimum power necessary to reach the intended destination.

The packet transmission procedure is therefore formalized as follows.

Node $i$, upon request to transmit:

- an RTS frame to node $j$:
  - checks the signaling channel availability to reach node $j$ through the $\text{NAV}_S$ information;
  - if $j$ is not available, then $i$ performs the standard backoff procedure;
  - otherwise, if $j$ is available, $i$ transmits the RTS frame omnidirectionally on the signaling channel at the maximum power level available. The RTS frame indicates the data channel chosen by the sender ($C_S$) to transmit the DATA packet. $C_S$ is selected randomly among the set of available data channels.
- a CTS frame to node $j$:
  - checks the signaling channel availability to reach node $j$ through the $\text{NAV}_S$ information;
  - if $j$ is not available, then no action is performed;
  - otherwise, if $j$ is available, two situations can occur: (1) if the data channel chosen by the sender of the RTS frame ($C_S$) is available, then $i$ transmits the CTS frame omnidirectionally on the signaling channel at the maximum power level with a flag indicating that the receiver agrees on the use of $C_S$. (2) Otherwise, if $C_S$ is not available, $i$ transmits the CTS frame omnidirectionally on the signaling channel at the maximum power level, with a flag indicating that $C_S$ is not available and therefore it cannot be used.
- a DATA or ACK frame to node $j$:
  - transmits the DATA or ACK frame on the $C_S$ channel in the sector of $j$ at the minimum power required to reach $j$.

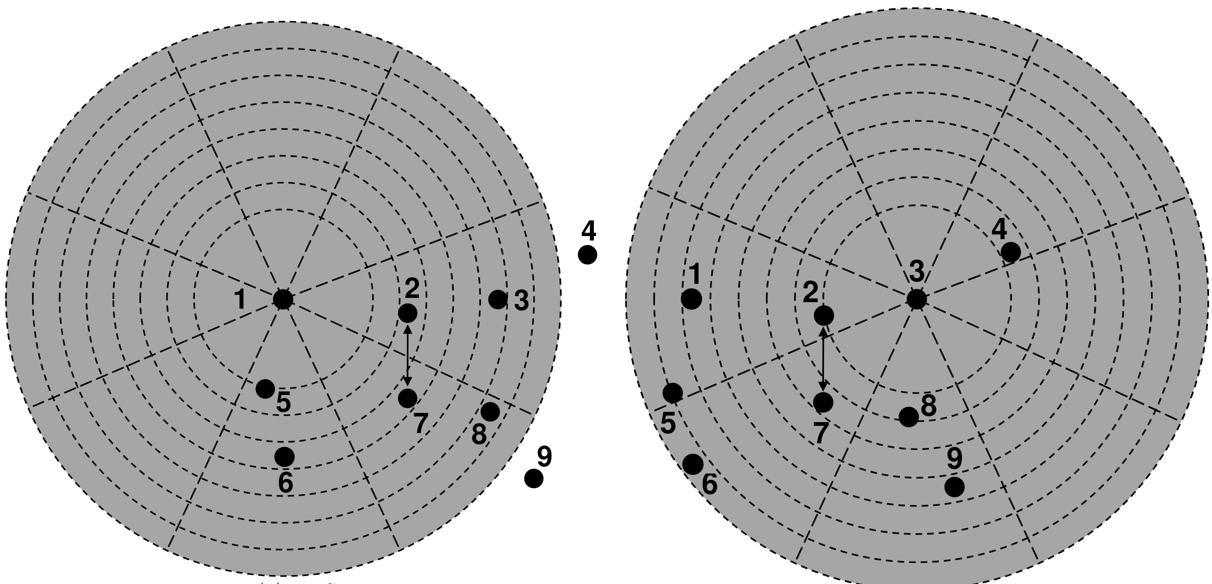
### 3.2.4 Comments

According to mesh routers assumptions, a node knows the location of all its neighbors, and the corresponding link gain. The update of $NAV_S$ and D-NAV is straightforward. Note that the directional antenna settings corresponding to any possible D-NAV value can be pre-set due to the reasonable almost stationary propagation conditions in WMN scenarios.

Transmissions of RTS and CTS frames are spread omnidirectionally on the signaling channel at the maximum transmission power 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. More specifically, MPCD-MAC is not affected by the directional hidden-terminal problem individuated in [8], which is caused by directional RTS/CTS transmissions that may not be heard by neighbor nodes that are currently involved in a data exchange, thus increasing the number of frame collisions. On the contrary, the transmissions of DATA and ACK frames are performed to reach the destination using a separate channel, one sector only and the minimum required power. The goal is to reduce interference and increase channel reuse. Note that the minimum power required to reach the destination is computed taking into account the position of this latter; the sending node selects the minimum transmission range (among the $M$ available, see Figure 1) that allows the transmitted signal to be correctly decoded by the receiver.

The reception of 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.

To illustrate the operation of MPCD-MAC let us first refer to the example network of Figures 3 and 4, where one connection is active between nodes 2-7, and node 2 is currently sending a data frame to node 7 with a directional transmission on channel $C_1$. Node 1 wants to transmit a packet to node 3, and we assume that these two nodes received the RTS/CTS exchange of connection 2-7, so that the information contained in their $NAV_S$ and D-NAV reflects correctly the current situation. We further assume that the positions of the four nodes allow both connections to transmit contemporarily provided power control and directional transmissions are used. In fact, the antenna gain of node 2 (illustrated in Figure 4) is sufficiently low in all sectors excluding that containing node 7, so that the frames sent by nodes 1 and 3 do not produce significant interference at node 2.




(a) RTS (b) CTS

Figure 3: MPCD-MAC: omnidirectional antenna pattern (a) used by node 1 to send the RTS frame (b) used by node 3 to send the CTS frame. Both transmissions occur on the signaling channel. One connection is already established, between nodes 2-7, and is currently exchanging DATA/ACK frames on data channel $C_1$.

After the time indicated in $NAV_S$, node 1 can use the signaling channel to send an RTS frame to node 3. Therefore, node 1 selects randomly a transmission channel, $C_S$, over which the DATA and ACK frames will be transmitted (including in this case also $C_1$, as we will explain in the following),

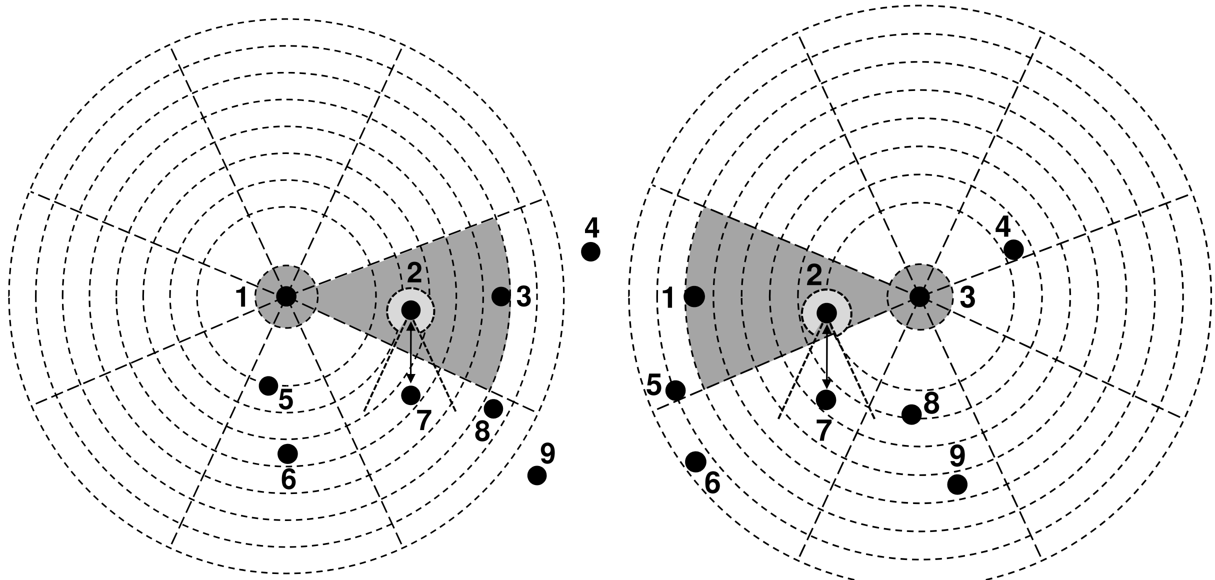



Figure 4: MPCD-MAC: power-controlled directional antenna pattern (a) used by node 1 to send the DATA frame (b) used by node 3 to send the ACK frame. Both transmissions occur on a data channel $C_S$ randomly chosen by the sender, which can coincide in this case with $C_1$. One connection is already established, between nodes 2-7, and is currently exchanging DATA/ACK frames on data channel $C_1$. The directional antenna pattern of node 2 is also reported.

and it includes such information in the RTS frame. In this example, node 3 agrees with node 1 on the utilization of such channel, and it sends a CTS frame confirming such choice. Both the RTS and CTS frames are transmitted on the signaling channel omnidirectionally and at the maximum transmission power, as illustrated in Figure 3.

Then, the data communication occurs on channel $C_S$ only directionally and at the minimum power necessary to reach the other node, as illustrated in the antenna patterns shown in Figure 4. This minimizes the interference produced by the DATA/ACK exchange over ongoing transmissions between nodes 2 and 7.

We recall that during the DATA/ACK exchange of connection 2-7, node 2 keeps its antenna steered in the sector that contains the transmitting node 7 (as illustrated in Figure 4), and therefore the level of interference generated by connection 1-3 is sufficiently low to allow the two data transfers to occur on the same data channel $C_1$.

Figure 5 illustrates another example scenario with two overlapping connections. Connection 2-3 is already active, and uses data channel $C_1$, while node 1 wants to communicate with node 4. In this case, if at least two data channels are available, node 1 will choose a different channel ($C_2 \neq C_1$), since otherwise the transmissions of nodes 1 and 2 would interfere at the receiving node 3, and in the same way the transmissions of nodes 3 and 4 would interfere at node 2.

These examples point out that MPCD-MAC can exploit directional transmissions, power control and multi-channel operation to permit simultaneous transmissions.

We observe that the proposed MPCD-MAC protocol can be easily coupled with traffic differentiating mechanisms like the enhanced distributed channel access scheme (EDCA), currently part of the IEEE 802.11 standard [47], which enables traffic differentiation through varying the amount of time a station would take to sense a channel as idle and the length of the contention window during backoff.

Finally, note that it is easy to extend MPCD-MAC including in the RTS frame the list of data channels available at the sender side, leaving to the receiver the choice of which channel to use in the data transmission. A similar technique has been proposed in [5, 17] but we did not implement it in MPCD-MAC since it requires a larger overhead in the signaling frames and the introduction of a further message (from the sender to the receiver) that confirms the utilization of the chosen data channel.

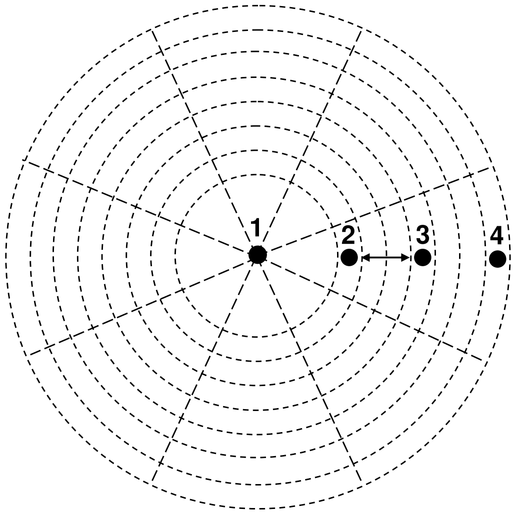



Figure 5: Example network scenario with 2 overlapping connections. Connection 2-3 is already active and transmitting data on channel $C_1$ when node 1 starts transmitting to node 4. In this case, MPCD-MAC uses a separate data channel $C_2 \neq C_1$ to allow the two connections to transmit contemporarily.

### 3.3 MPCD-MAC Variations

To gauge the performance gain achieved by directional transmissions, power control and interference awareness in MPCD-MAC, we further consider the following variations:

- Multi-channel Omnidirectional MAC (MO-MAC);
- Multi-channel Power-Controlled MAC (MPC-MAC);
- Interference-Unaware MPCD-MAC (IU-MPCD-MAC).

MO-MAC uses omnidirectional transmissions both on the signaling and data channels, without power control: all frames are transmitted omnidirectionally at the maximum transmission power. Therefore, concurrent connections that are spatially superposed can transmit contemporarily only if different data channels are used.

MPC-MAC further implements power control on the DATA channel with respect to MO-MAC, while transmitting all frames omnidirectionally.

Finally, IU-MPCD-MAC implements both power control and directional transmissions on the data channel. However, unlike MPCD-MAC, IU-MPCD-MAC does not exploit the knowledge of how much interference is produced over already active connections. More specifically, the D-NAV information updating is performed as follows: if $S$ transmits to $D$ using data channel $C$, and node $A$ listens to the RTS/CTS frames exchanged between the two nodes, then $A$ sets D-NAV[$C$][$s_{AS}$] and D-NAV[$C$][$s_{AD}$] to the minimum power gain necessary to *reach* such nodes.

As a consequence, in the example network of Figures 3 and 4, IU-MPCD-MAC does not allow the two connections 2-7 and 1-3 to transmit at the same time using the same data channel, since the D-NAV in node 1 will be set to the power gain necessary to reach node 2, and therefore node 1 will not be able to reach node 3. In such scenario, IU-MPCD-MAC must necessarily use two separate data channels to permit contemporary transmissions.

We observe that in this scenario also MO-MAC and MPC-MAC must use two separate data channels to permit parallel transmissions, since the antenna patterns used by such protocols are always omnidirectional for both frame transmissions and receptions.

Hereafter we provide a brief comparative analysis of all the protocols introduced in our paper, focusing on their features and complexities, which are summarized in Table 1. We observe that MO-MAC only requires the utilization of multiple channels, since it uses neither directional transmissions nor power-control. Therefore, its implementation can be realized quite straightforwardly. MPC-MAC only introduces power-control with respect to MO-MAC, and therefore it relies on correct computations of radio channel gains;

hence, it is exposed to all problems related to link gain variations and fading, as discussed in Section 3.1. Finally, IU-MPCD-MAC utilizes all the features of MPCD-MAC, but it implements only a slightly more conservative approach which limits the spatial reuse. However, its computation complexity and easiness of implementation are comparable to those of MPCD-MAC.

Table 1: Comparison of the features and complexity of the proposed MAC protocols.

| MAC | Multiple Channels | Power Control | Directional Antennas | Interference Awareness |
|---|---|---|---|---|
| MO-MAC | Yes | No | No | No |
| MPC-MAC | Yes | Yes | No | No |
| IU-MPCD-MAC | Yes | Yes | Yes | No |
| MPCD-MAC | Yes | Yes | Yes | Yes |

# 4 Numerical Results

In this Section, we evaluate the performance of MPCD-MAC, and compare it with both single-channel and multi-channel MAC schemes by performing extensive simulations with the Network Simulator, *ns* ver.2 [48]. Single-channel MAC protocols include the standard IEEE 802.11 MAC [3], and the PCD-MAC protocol proposed in [7], which exploits power control and directional transmissions. We have also considered the multi-channel schemes MO-MAC, MPC-MAC and IU-MPCD-MAC, described in Section 3.3, to investigate the effect of power control, directional antennas and interference awareness. Finally, we also compared the proposed protocols with the LCAP scheme [13] in random network scenarios.

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

It is an undisputed fact that fairness is an important element of a well-designed MAC protocol for Wireless Mesh Networks [50, 51]. However, most popular MAC protocols fail to obtain an acceptable level of fairness in media access, while we will show that MPCD-MAC performs consistently better in all the scenarios we considered.

The parameters used in our simulations are listed in Table 2.

In our simulator we have assumed a radio transmission rate of 11 Mbit/s to permit a comparison with existing MAC schemes; however, MPCD-MAC can be applied to any wireless technology. With the settings of Table 2, the maximum transmission range is equal to 215 m. The antenna model used is that described in Section 3, with $N = 8$ sectors and $M = 8$ power levels, which correspond to the following transmission ranges: 66, 86, 107, 128, 149, 170, 191 and 215 m. One channel is used as signaling channel, while $N_D$ channels are used as data channels.

In our simulations, the carrier sense threshold was set equal to the reception threshold, in order to maximize spatial reuse. Note that this is also the standard setting used in several widespread wireless cards, like those based on the Intersil chipset [45].

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.

Table 2: Parameters used in the simulations.

| | |
|---|---|
| Beamwidth | 45° |
| Power levels ($M$) | 8 |
| UDP Packet size | 1000 bytes |
| TCP Packet size | 1500 bytes |
| Data channel rate | 11 Mbit/s |
| Reception Threshold | -67 dBm |
| Carrier Sense Threshold | -67 dBm |
| Capture Threshold | 10 dB |
| Maximum Transmission Power | 90 mW |

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

Several scenarios have been simulated. Some, very simple, have been considered to verify preliminarily the main features of MPCD-MAC using only UDP traffic. Then, more realistic grid and random topology scenarios with a large number of connections are used to investigate the performance in the presence of both UDP and TCP traffic.

## T-topology network

In the 4 nodes scenario illustrated in Figure 6, two connections are active: C1 between nodes 1 and 2 and C2 between nodes 3 and 4. We first assume that the number of available data channels ($N_D$) is equal to 1.

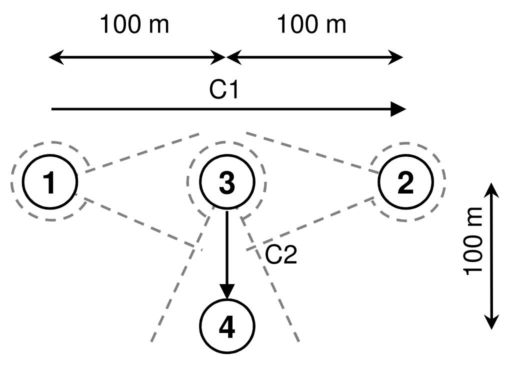



Figure 6: Network scenario with 2 connections. The antenna sectors used for directional transmissions of DATA/ACK frames are also illustrated, together with nodes' minor lobes.

In this network layout, for the node distances specified in Figure 6, MPCD-MAC allows the two connections to be active at the same time, since it uses directional data transmissions and power control to limit the mutual interference between C1 and C2. In fact, the receiving antenna gain of node 3 exhibited towards the sending sectors of nodes 1 and 2 is sufficiently low, so that DATA/ACK transmissions between nodes 1 and 2 do not disturb the reception of ACK frames at node 3. On the other hand, all the other MAC protocols activate at most one connection at a time.

Table 3 shows the numerical results obtained in this scenario, i.e. the total goodput achieved by the two connections, the percentage improvement with respect to the IEEE 802.11 standard MAC and the fairness index. We observe that MPCD-MAC not only improves consistently the goodput (up to 83 %) but also achieves a perfect fair sharing of network resources among competing connections.

This is essentially due to the increased spatial reuse made possible by the utilization of multiple channels, directional antennas and power control, as well as by the utilization of a separate signaling channel that informs all network nodes of new data transmissions, thus enabling multiple parallel transmissions to take place.

Table 3: T-Topology network: average goodput [Mbit/s], percentage gain with respect to the IEEE 802.11 standard MAC and Jain's fairness index for all the considered MAC protocols. Two connections offer to the network a Poisson traffic. A single channel is available for transmitting data ($N_D = 1$).

| **MAC** | Goodput | Gain (%) | Fairness Index |
|---|---|---|---|
| IEEE 802.11 MAC | 4.35 | —— | 0.99 |
| PCD-MAC | 4.35 | 0 | 0.99 |
| MO-MAC | 4.35 | 0 | 0.99 |
| MPC-MAC | 4.35 | 0 | 0.99 |
| IU-MPCD-MAC | 4.99 | 14.71 | 0.79 |
| **MPCD-MAC** | **7.99** | **83.68** | **1.00** |

Table 4: T-Topology network: average goodput [Mbit/s], percentage gain with respect to the MO-MAC protocol and Jain's fairness index for all the considered multi-channel MAC protocols. Two connections offer to the network a Poisson traffic. Two channels are available for transmitting data ($N_D = 2$).

| **MAC** | Goodput | Gain (%) | Fairness Index |
|---|---|---|---|
| MO-MAC | 7.99 | —— | 1.00 |
| MPC-MAC | 7.99 | 0 | 1.00 |
| IU-MPCD-MAC | 7.99 | 0 | 1.00 |
| **MPCD-MAC** | **7.99** | **0** | **1.00** |

We then consider a variation of this network scenario where the number of available data channels is equal to 2; the corresponding numerical results are shown in Table 4 for all the considered multi-channel MAC schemes. In this case, all the protocols achieve the maximum performance, both in terms of transmission rate and fairness index. Obviously, the same behavior is observed for $N_D > 2$, since only two connections are active in this scenario.

Note that all other multi-channel protocols achieve the same performance of MPCD-MAC only using 2 separate data channels. On the other hand, MPCD-MAC achieves the best performance even when a single data channel is available, due to its characteristic features that increase spatial reuse by limiting the mutual interference among competing connections.

## 8-node scenario

We then consider the network scenario illustrated in Figure 7, where 4 connections are active: C1 between nodes 1 and 4, C2 between nodes 5 and 8, C3 between nodes 6 and 2, and finally C4 between nodes 7 and 3.

Table 5 illustrates the numerical results obtained with all the considered MAC protocols, assuming

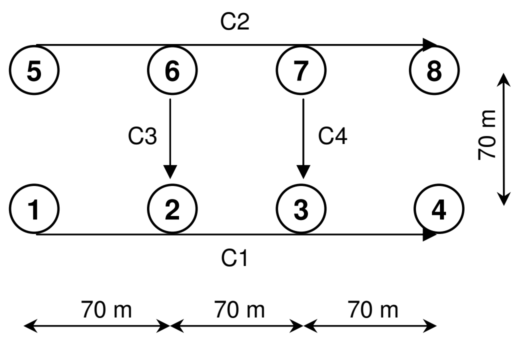



Figure 7: Eight-node scenario with 4 active connections.

Table 5: 8-node scenario: average goodput [Mbit/s], percentage gain with respect to the IEEE 802.11 standard MAC and Jain's fairness index for all the considered MAC protocols. Four connections offer to the network a Poisson traffic. A single channel is available for transmitting data ($N_D = 1$).

| **MAC** | Goodput | Gain (%) | Fairness Index |
|---|---|---|---|
| IEEE 802.11 MAC | 4.42 | —— | 0.99 |
| PCD-MAC | 6.87 | 55.43 | 0.64 |
| MO-MAC | 4.42 | 0 | 0.99 |
| MPC-MAC | 4.42 | 0 | 0.99 |
| IU-MPCD-MAC | 8.00 | 81.00 | 0.50 |
| **MPCD-MAC** | **12.32** | **178.73** | **0.99** |

Table 6: 8-node scenario: average goodput [Mbit/s], percentage gain with respect to the MO-MAC protocol and Jain's fairness index for all the considered multi-channel MAC protocols. Four connections offer to the network a Poisson traffic. Two channels are available for transmitting data ($N_D = 2$).

| **MAC** | Goodput | Gain (%) | Fairness Index |
|---|---|---|---|
| MO-MAC | 8.76 | —— | 1.00 |
| MPC-MAC | 8.77 | 0.11 | 1.00 |
| IU-MPCD-MAC | 12.32 | 40.64 | 1.00 |
| **MPCD-MAC** | **12.32** | **40.64** | **1.00** |

that each node has only one data channel available ($N_D = 1$). In this scenario, only MPCD-MAC allows connections C1 and C2 to transmit at the same time as C3 and C4 on the same data channel, since it performs power control and takes into account that, during the DATA-ACK exchange, nodes 6-2 and 7-3 keep their antenna steered in the direction of the partner node, thus limiting the interference caused by C1 and C2. This is reflected in the higher goodput and fairness index values obtained by MPCD-MAC, which strikes a good balance between these two performance figures, since it delivers a consistently high level of fairness regardless of network topology and traffic type, maintaining at the same time high goodput.

On the other hand, the IU-MPCD-MAC protocol obtains a goodput and a fairness level which are consistently lower than MPCD-MAC; more specifically, the lower fairness index value is due to the fact that connections C3 and C4 tend to transmit more than C1 and C2.

When two data channels are available, also IU-MPCD-MAC can activate all four connections contemporarily, and this is reflected in the numerical results shown in Table 6. MO-MAC and MPC-MAC achieve a higher performance with respect to the single data channel case, but the gap with respect to MPCD-MAC is still evident.

## 10-node scenario

Figure 8 illustrates a network scenario that stresses all the features of MPCD-MAC, viz. multi-channel operation, power control, directional transmissions and interference awareness. Five connections are established, as shown in the Figure; four connections are spatially superposed, namely connection 1-5 with 2-4 and connection 6-10 with 7-9.

Table 7 shows the numerical results obtained with $N_D = 1$. The protocols that do not use directional transmissions (namely, the IEEE 802.11 MAC, MO-MAC and MPC-MAC) tend to distribute network resources equally among the 5 connections, as indicated by the high fairness index values. The total goodput achieved by such protocols, however, is quite low since only one connection at a time can transmit. IU-MPCD-MAC achieves a higher performance, but it does not allow the vertical connection 8-3 to transmit in parallel with the horizontal connections. Also in this scenario, MPCD-MAC outperforms all the other protocols, even when a single data channel is used.

The numerical results obtained using $N_D = 2$ data channels are shown in Table 8. In this case, MO-MAC and MPC-MAC almost double their goodput with respect to the $N_D = 1$ scenario, while IU-

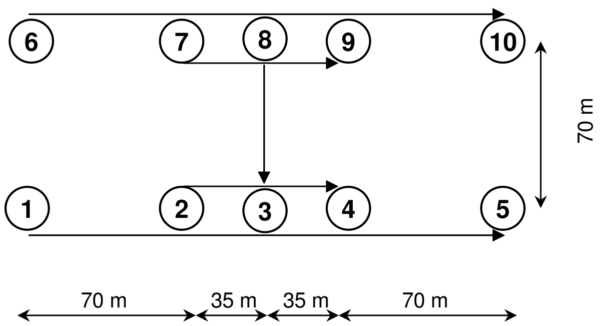



Figure 8: 10-node network scenario. 5 connection are established.

Table 7: 10-node scenario: average goodput [Mbit/s], percentage gain with respect to the IEEE 802.11 standard MAC and Jain's fairness index for all the considered MAC protocols. Five connections offer to the network a Poisson traffic. A single channel is available for transmitting data ($N_D = 1$).

| **MAC** | Goodput | Gain (%) | Fairness Index |
|---|---|---|---|
| IEEE 802.11 MAC | 4.41 | —— | 0.99 |
| PCD-MAC | 6.16 | 39.68 | 0.75 |
| MO-MAC | 4.41 | 0 | 0.99 |
| MPC-MAC | 4.41 | 0 | 0.99 |
| IU-MPCD-MAC | 8.87 | 101.13 | 0.56 |
| **MPCD-MAC** | **10.71** | **142.86** | **0.83** |

MPCD-MAC and MPCD-MAC further increase their performance, both in terms of achieved goodput and fairness.

Finally, in the same network topology we further gauge the sensitivity of the goodput achieved by all the considered multi-channel MAC protocols to the number of available data channels, $N_D$. Figure 9 illustrates the corresponding numerical results, with $N_D$ ranging from 1 to 4.

The curves corresponding to MO-MAC and MPC-MAC practically overlap for every $N_D$ value, while IU-MPCD-MAC achieves a higher performance, especially for $N_D = 1$ and $N_D = 2$.

MPCD-MAC performs the best for all $N_D$ values. Obviously, when the number of available data channels increases it is possible to parallelize all connections, so that all multi-channel MAC protocols perform the same. In this limiting case, the utilization of simpler schemes like MPC-MAC or MO-MAC could be advisable, since they are simpler, more robust to implement (as discussed in Section 3.3), and do not require any complex setting, like sectored antennas, power control and channel gain estimation schemes.

However, we observe that MPCD-MAC achieves a very high goodput even if only one data channel is available. We could observe such behavior in all the considered network scenarios, which confirms the effectiveness of the proposed MAC scheme. Therefore, when few orthogonal channels are available, as it may happen in practice, MPCD-MAC represents a better choice to increase the network performance.

Table 8: 10-node scenario: average goodput [Mbit/s], percentage gain with respect to the MO-MAC protocol and Jain's fairness index for all the considered multi-channel MAC protocols. Five connections offer to the network a Poisson traffic. Two channels are available for transmitting data ($N_D = 2$).

| **MAC** | Goodput | Gain (%) | Fairness Index |
|---|---|---|---|
| MO-MAC | 8.85 | —— | 0.99 |
| MPC-MAC | 8.86 | 0.11 | 0.99 |
| IU-MPCD-MAC | 12.71 | 43.62 | 0.99 |
| **MPCD-MAC** | **12.93** | **46.10** | **1.00** |

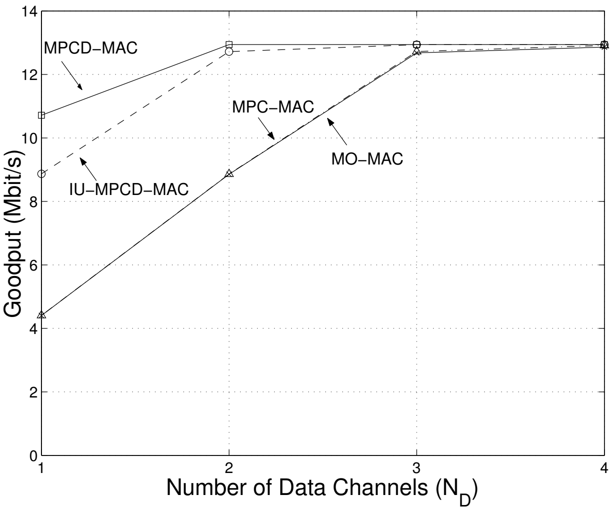



Figure 9: 10-node scenario: goodput achieved by the considered multi-channel MAC protocols as a function of the number of available data channels ($N_D$).

## Grid networks

In this scenario, the network nodes are allocated on a regular square grid. $K$ couples of source/destination nodes are randomly selected and the traffic is routed on a shortest path randomly chosen.

We have simulated a $5 \times 5$ grid with elementary link size $L$ equal to 70, 90 and 140 meters, as shown in Figure 10. In the first two cases each node has several neighbors (transmission range $R = 215 \gg 70$ and 90), while in the third one a node has no more than 8 neighbors. For the sake of clarity, Figure 10 also reports the transmission range of a sample node for all the considered link sizes $L$, thus illustrating the set of neighbors of such node in the three scenarios.

Five random selections of $K = 10$ source/destination couples have been considered, and the results shown in Tables 9 and 10 represent the average over the five scenarios for Poisson and TCP traffic, respectively.

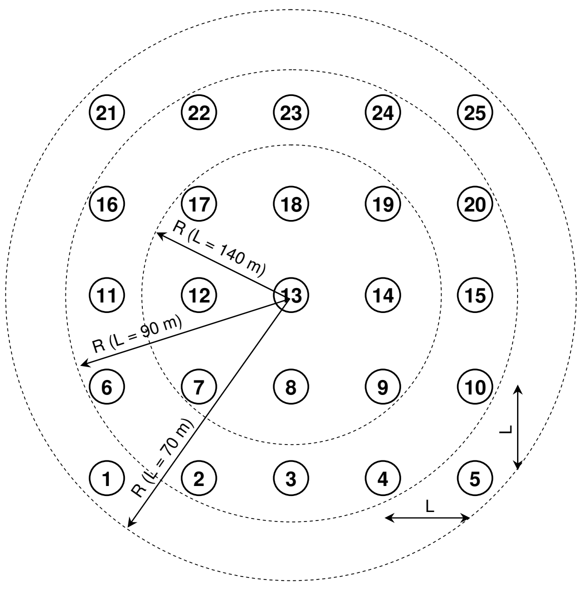



Figure 10: Grid network scenario with elementary link size $L$. $K$ connections are randomly established in this network. The transmission range $R = 215$ m of a sample node (node 13) is illustrated for different $L$ values ($L = 70$, 90 and 140 m), to show the set of neighbors of such node in the considered scenarios.

Table 9: Average goodput [Mbit/s] and Jain's fairness index for various MAC versions in the $5 \times 5$ grid network scenarios with inter-node spacing of 70, 90 and 140 m; 10 connections offer to the network a Poisson traffic. A single channel is available for transmitting data ($N_D = 1$).

| | **Grid 70 m** | | **Grid 90 m** | | **Grid 140 m** | |
|---|---|---|---|---|---|---|
| **MAC** | Goodput | Fairness | Goodput | Fairness | Goodput | Fairness |
| IEEE 802.11 MAC | 6.87 | 0.49 | 7.70 | 0.50 | 6.13 | 0.36 |
| PCD-MAC | 10.71 | 0.75 | 14.01 | 0.74 | 11.02 | 0.67 |
| MO-MAC | 6.75 | 0.70 | 7.63 | 0.64 | 8.28 | 0.41 |
| MPC-MAC | 7.45 | 0.72 | 9.11 | 0.62 | 9.05 | 0.47 |
| IU-MPCD-MAC | 14.13 | 0.71 | 15.74 | 0.76 | 14.55 | 0.65 |
| **MPCD-MAC** | **14.14** | **0.72** | **15.88** | **0.78** | **14.55** | **0.65** |

Table 10: Average goodput [Mbit/s] and Jain's fairness index for various MAC versions in the $5 \times 5$ grid network scenarios with inter-node spacing of 70, 90 and 140 m; 10 connections offer to the network FTP traffic. A single channel is available for transmitting data ($N_D = 1$).

| | **Grid 70 m** | | **Grid 90 m** | | **Grid 140 m** | |
|---|---|---|---|---|---|---|
| **MAC** | Goodput | Fairness | Goodput | Fairness | Goodput | Fairness |
| IEEE 802.11 MAC | 7.59 | 0.49 | 6.42 | 0.44 | 6.81 | 0.32 |
| PCD-MAC | 11.47 | 0.61 | 10.02 | 0.60 | 10.41 | 0.59 |
| MO-MAC | 6.61 | 0.71 | 5.98 | 0.63 | 7.25 | 0.55 |
| MPC-MAC | 7.28 | 0.71 | 6.81 | 0.64 | 7.52 | 0.60 |
| IU-MPCD-MAC | 12.21 | 0.63 | 11.43 | 0.65 | 11.13 | 0.69 |
| **MPCD-MAC** | **12.25** | **0.63** | **11.44** | **0.69** | **11.13** | **0.69** |

Numerical results demonstrate that MPCD-MAC performs consistently better than single-channel MAC protocols (IEEE 802.11 and PCD-MAC) and omnidirectional multi-channel MAC schemes (MO-MAC and MPC-MAC), both in terms of achieved throughput and fairness index. The performance gain of MPCD-MAC with respect to the other protocols is evident in all grid scenarios for both Poisson and TCP traffic.

We then considered a variation of the same network scenarios when $N_D = 2$ data channels are available. Tables 11 and 12 report the corresponding numerical results for Poisson and TCP traffic, respectively.

Table 11: Average goodput [Mbit/s] and Jain's fairness index for various MAC versions in the $5 \times 5$ grid network scenarios with inter-node spacing of 70, 90 and 140 m; 10 connections offer to the network a Poisson traffic. Two channels are available for transmitting data ($N_D = 2$).

| | **Grid 70 m** | | **Grid 90 m** | | **Grid 140 m** | |
|---|---|---|---|---|---|---|
| **MAC** | Goodput | Fairness | Goodput | Fairness | Goodput | Fairness |
| MO-MAC | 11.62 | 0.73 | 13.21 | 0.71 | 11.48 | 0.60 |
| MPC-MAC | 12.68 | 0.75 | 14.79 | 0.72 | 12.38 | 0.64 |
| IU-MPCD-MAC | 15.05 | 0.77 | 17.10 | 0.77 | 14.55 | 0.65 |
| **MPCD-MAC** | **15.05** | **0.77** | **17.10** | **0.77** | **14.55** | **0.65** |

The performance of MPCD-MAC increases with respect to the $N_D = 1$ case for dense grid topologies ($L$ = 70 and 90 m), while it is practically the same for sparse grid networks ($L$ = 140 m). In fact, in dense grid scenarios, several connections are spatially superposed and therefore benefit from the spatial reuse made possible by MPCD-MAC. On the other hand, in sparse networks the number of concurrent connections is very low, so that the utilization of two data channels does not improve consistently the

Table 12: Average goodput [Mbit/s] and Jain's fairness index for various MAC versions in the $5 \times 5$ grid network scenarios with inter-node spacing of 70, 90 and 140 m; 10 connections offer to the network FTP traffic. Two channels are available for transmitting data ($N_D = 2$).

| | **Grid 70 m** | | **Grid 90 m** | | **Grid 140 m** | |
|---|---|---|---|---|---|---|
| **MAC** | Goodput | Fairness | Goodput | Fairness | Goodput | Fairness |
| MO-MAC | 10.27 | 0.69 | 9.89 | 0.66 | 8.97 | 0.69 |
| MPC-MAC | 11.52 | 0.70 | 10.82 | 0.65 | 9.29 | 0.70 |
| IU-MPCD-MAC | 13.02 | 0.67 | 11.83 | 0.69 | 11.13 | 0.69 |
| **MPCD-MAC** | **13.02** | **0.67** | **11.83** | **0.69** | **11.13** | **0.69** |

performance of the MPCD-MAC protocol.

## Random networks

In this scenario, we generate a random network with $I$ 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. Figure 11 shows an example of such a network generated selecting $I = 30$ nodes on a 1 km square area and with $R = 215$ m.

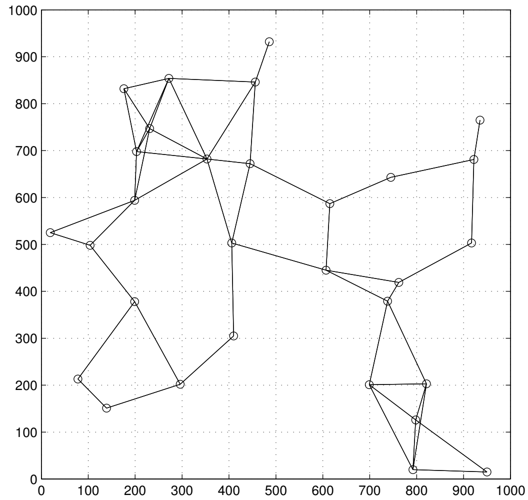



Figure 11: Instance of a generated random topology with $I = 30$ nodes uniformly distributed on a 1 km square area.

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 are averaged on 5 source/destination random selections, and also on 5 random feasible topologies. Both UDP and TCP traffics are considered.

Table 13 shows the numerical results obtained when only one data channel is available ($N_D = 1$). Also in this quite practical wireless mesh network scenario MPCD-MAC performs best for both UDP and TCP traffic, increasing the goodput of about 98 % (UDP traffic) and 48 % (TCP traffic) over the IEEE 802.11 standard MAC. Fairness is also greatly improved.

In this realistic scenario we further measured the performance of the LCAP protocol [13], reviewed in Section 2.1.1, which uses directional antennas and two separate channels, one for control frames, the other for DATA/ACK frames (i.e., $N_D = 1$). LCAP achieves better performance than the MO-MAC and MPC-MAC schemes, due to its directional transmission and power control features. However, its performance is worse than that of MPCD-MAC since LCAP transmits CTS frames only directionally, thus exacerbating the hidden terminal problem; furthermore, in LCAP each node uses only one NIC, and therefore the

Table 13: Average goodput [Mbit/s] and Jain's fairness index achieved by the various MAC schemes in the random network scenarios illustrated in Figure 11 with 30 nodes and 10 connections. A single channel is available for transmitting data ($N_D = 1$).

| | **Poisson Traffic** | | **FTP Traffic** | |
|---|---|---|---|---|
| **MAC** | Goodput | Fairness | Goodput | Fairness |
| IEEE 802.11 MAC | 10.18 | 0.46 | 9.63 | 0.50 |
| PCD-MAC | 17.02 | 0.62 | 12.79 | 0.55 |
| MO-MAC | 10.64 | 0.52 | 9.64 | 0.59 |
| MPC-MAC | 11.42 | 0.51 | 9.80 | 0.63 |
| IU-MPCD-MAC | 18.83 | 0.67 | 13.10 | 0.67 |
| LCAP | 17.46 | 0.64 | 12.82 | 0.62 |
| **MPCD-MAC** | **20.17** | **0.71** | **14.33** | **0.72** |

Table 14: Average goodput [Mbit/s] and Jain's fairness index achieved by the various MAC schemes in the random network scenarios illustrated in Figure 11 with 30 nodes and 10 connections. Two channels are available for transmitting data ($N_D = 2$).

| | **Poisson Traffic** | | **FTP Traffic** | |
|---|---|---|---|---|
| **MAC** | Goodput | Fairness | Goodput | Fairness |
| MO-MAC | 18.18 | 0.62 | 13.41 | 0.65 |
| MPC-MAC | 18.75 | 0.63 | 13.80 | 0.68 |
| IU-MPCD-MAC | 20.00 | 0.70 | 13.97 | 0.70 |
| **MPCD-MAC** | **20.25** | **0.68** | **14.42** | **0.72** |

control and data channels can never be used simultaneously, thus leading to the multi-channel hidden terminal problem.

Table 14 illustrates the results obtained in the same network scenario, where $N_D = 2$ data channels are available. Note that the performance of MO-MAC, MPC-MAC and IU-MPCD-MAC improves with respect to the single data channel case, while MPCD-MAC performs approximately the same as reported in Table 13. This is due to the fact that in such network scenario the average length of wireless links is about 140 meters, so that very few transmissions are spatially superposed (recall that the radio range $R$ is equal to 215 m). In this case, the availability of a second data channel does not improve significantly the performance of MPCD-MAC. As we observed in previous scenarios, in dense network topologies the performance of MPCD-MAC increases consistently due to its power control, directional antennas and interference-awareness features.

We then considered a variation of this network scenario, increasing the number of nodes, $I$, which are randomly deployed on the 1 km square area; the number of source/destination pairs is still $K = 10$. Figures 12(a) and 12(b) illustrate the goodput and fairness index, respectively, achieved by MPCD-MAC as $I$ varies in the 30 to 100 range, for both UDP and TCP traffic.

Figure 12(a) shows that the average goodput achieved by the connections increases with increasing $I$ values, until it reaches a saturation point. This is due to the fact that as the number of network nodes increases, it is more likely for the $K$ connections to share fewer common nodes in their path from source to destination. This is made even more likely due to the utilization of power control, multiple channels and directional transmissions in MPCD-MAC. For large $I$ values, all $K$ connections tend to pass through almost completely disjoint paths and therefore their throughput tends to be limited almost exclusively by the number of hops traversed by the connection.

Similar increasing trends were observed for the other multi-channel MAC protocols considered in this paper, which are not shown in the Figure for the sake of clarity.

The same trend can be observed in Figure 12(b) for the fairness index value, for both UDP and TCP traffics.

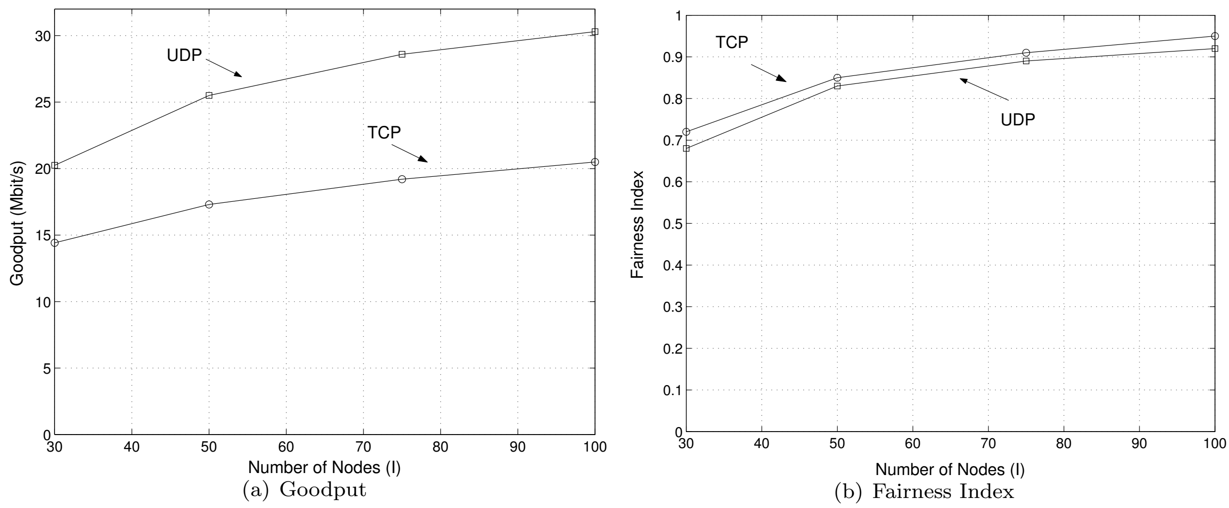



Figure 12: Average goodput [Mbit/s] and Jain's fairness index achieved by the MPCD-MAC protocol in the random network scenarios with 10 connections and $I$ nodes ($I$ ranges from 30 to 100 nodes). Two channels are available for transmitting data ($N_D = 2$).

# 5 Conclusion

In this paper we proposed MPCD-MAC, a novel multi-channel, power-controlled MAC for nodes endowed with directional antennas.

MPCD-MAC improves spatial reuse limiting the hidden terminal problem by spreading the information about wireless medium reservation in all directions on a separate signaling channel without interfering with the connections already established in the network. Then, data transmissions take place on orthogonal channels only directionally and at the minimum power necessary to reach the intended receiver. Furthermore, MPCD-MAC exploits the knowledge of neighbors location to limit the interference on already active connections.

Numerical results show that the use of MPCD-MAC increases remarkably both the total traffic accepted by the network and the fairness among competing connections, even when a very small number of orthogonal channels is available for data transmissions, thus representing a very effective solution for wireless mesh networking.

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