# A TDMA-based MAC Protocol for Wireless Mesh Networks using Directional Antennas

Ali El Masri, Lyes Khoukhi, and Dominique Gaiti
ICD/ERA, Troyes University of Technology
12 rue Marie Curie, 10010 Troyes Cedex , France
Email: {ali.el_masri, lyes.khoukhi, dominique.gaiti}@utt.fr

***Abstract*—Wireless Mesh Networks (WMNs) have emerged as a key technology for next generation wireless networks. It is expected that WMNs will support diverse kind of multimedia services. Hence, there is a vital need to conceive efficient and reliable MAC protocols that allows alleviating wireless MAC problems. In this paper, we develop a novel MAC scheme for Wireless Mesh Networks based on a TDMA approach and using directional antennas. Our main objective behind this proposal is to respond to the main directional MAC problems such as deafness and hidden terminal problems caused by the lack in knowledge at each wireless node about its neighboring transmissions. The contribution of our MAC scheme is twofold. First, in enabling parallel transmissions and second in maintaining a full knowledge at each wireless node about neighboring transmissions. Using parallel transmissions, a busy node will not miss the start of a neighboring transmission. A robust algorithm of mini-slot assignment is proposed to provide full-knowledge, collision-free, and a fair channel access between all the nodes in the network.**

***Index Terms*—Wireless Mesh Networks; Directional Antennas; Medium Access Control (MAC);**

## I. Introduction

Wireless mesh networks (WMNs) have emerged as a key technology for next-generation wireless networks. A WMN is a set of stationary wireless routers serving as access points for wireless clients and forming together a wireless mesh backbone (creating in effect, an ad hoc network).

One of the main challenges that are facing the deployment of WMN is how to ensure Quality of Service (QoS) to the real-time traffic. In fact, a properly designed MAC protocol is a key factor to maintain the reliability of transmissions, to satisfy the QoS requirements and to efficiently allocate the radio resources. Two main aspects distinguish WMNs from traditional multi-hop wireless networks such as mobile ad hoc and wireless sensor networks [1]. First, the routers are placed in fixed location with continuous power supply, and then there is no mobility or energy constraints. Second, the traffic aggregated at each local router is heavy due to the forwarded traffic from neighboring routers and the uploaded traffic from local wireless clients, and then contention-based MAC protocols suffer from serious collisions and great violations of QoS requirements. Hence, designing a properly MAC protocols continues to be critical problem in WMNs.

In the other hand, directional antennas have been successfully applied to increase spatial reuse, reduce interference, extend transmission range and optimize power consumption. Directional antennas seem then to be an appropriate technique to improve the performance of WMNs characterized by their heavy load traffic and their fixed wireless routers. The past few years have witnessed the special attention given by the wireless community to the directional antennas concept. A number of proposed MAC protocols based on directional antennas have been proposed, most of them are CSMA/CA-based protocols. However, the use of directional antennas introduces new MAC problems such as deafness problem, new kinds of hidden terminal problems and head-of-line blocking problem.

The deafness problem (Figure 1a) occurs when a node C tries to communicate with a node A while node A is beamformed to another direction than the direction of node C. In such scenario, node C loses many RTS (Ready-To-Send) packets while trying to establish the connections with A. It leads to the following: Increase the contention window of node C, lose the fairness between nodes, waste the bandwidth and cancel the spatial reuse, which it is the main benefit of directional antennas. The hidden terminal problem (Figure 1b) occurs when two nodes A (source) and B (destination) begin a communication while a neighboring node C is already communicating with other nodes. When node C becomes idle, it does not sense the communication between A and B due to the use of directional antennas. If node C has in the head of its queue a packet intended to node B, it starts the transmission of a series of unsuccessful RTS packets. Node C suffers then from the inconveniences of deafness problem explained above, and node B suffers from collisions between data packets received from A and RTS packets received from C. The head-of-line problem (Figure 1c) occurs when a node C has in the head of its queue a packet intended to a busy node A, while the next packet in the queue is intended to an idle node D. Hence, the packet intended to D suffers from unnecessary delay.

The main reason of these problems is the lack in awareness at a wireless node about the concurrent neighboring transmissions. This lack is due to one of the following two scenarios. First, when two nodes begin a communication, they do not inform all the nodes in their vicinity about the ongoing communication due to the use of directional RTS/CTS (Clear-To-Send) transmissions. Second, even if nodes in the vicinity of the communication are well informed, the RTS/CTS handshake cannot be heard by a busy node. In our opinion, parallel transmissions seem to be an optimal solution of these problems. We mean by parallel transmissions that the different concurrent transmissions have the same start and end times.

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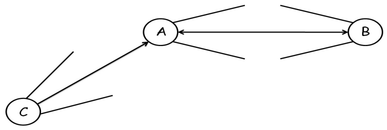
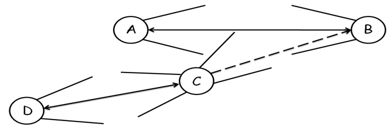
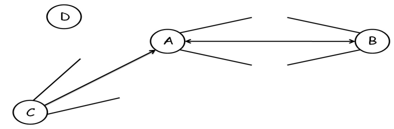



(a) Deafness problem




(b) Hidden terminal problem




(c) Head-of-line blocking problem

Fig. 1: Directional MAC problems

In this paper, we propose a new TDMA-based (Time Division Multiple Access) MAC protocol for wireless mesh backbone using directional antennas. Our proposal aims to handle directional MAC problems by enabling parallel transmissions. The proposed protocol provides a full knowledge about the concurrent transmission in the surrounding of each wireless router. Thus, the proposed protocol is designed to be collision-free, deafness-free and blocking-free. In addition, the proposed MAC protocol includes a new algorithm that offers a flexible and scalable way for assigning time-slots to wireless routers. The proposed time-slot assignment algorithm is applied at each node/neighborhood, to completely avoid the transmission of unsuccessful control messages, and hence to widely reduce the control overhead in WMNs. Moreover, the time-slot assignment changes dynamically to ensure a fair channel access. Benefiting from the transmission characteristics of directional antennas, the spatial reuse is greatly increased by our protocol.

The rest of the paper is organized as follows. The related work is reviewed in Section II. The antennas model is presented in Section III. In Section IV, we detail our proposed protocol. Finally, we draw our conclusion in Section V.

## II. Related Work

Several proposed MAC protocols for ad hoc and mesh networks using directional antennas exist in the literature. Most of them are based on the IEEE 802.11 DCF MAC protocol. In this section, we give our proper classification of MAC protocols using directional antennas. In our classification, protocols are divided into two groups: protocol with parallel transmissions and protocol with non-parallel transmission, each group is divided into several categories.

### *A. Non-Parallel Transmission*

This group includes three categories of protocols, pure directional RTS/CTS, circular directional RTS/CTS, and explicit control messages category.

In Pure Directional Category [2][3], all RTS/CTS/Data/Ack packets are transmitted in the directional mode. Since no additional control packets exists, the spatial reuse is improved. However any proposed mechanism doesn't handle the deafness or the hidden terminal problem.

In the circular directional category [4][5], RTS and CTS are circularly transmitted in the directional mode through all or part of the unblocked beams of the transmitter and the receiver. The goal is to alleviate the deafness problem and to inform all the directional-omni neighbors about the ongoing transmission. Although the deafness problem is largely alleviated with this category of protocols, the deaf nodes are not completely avoided. In addition, the control overhead is largely increased due to additional control packets (circular RTS/CTS), and further fields inserted into RTS/CTS packets.

In the category of explicit control messages, additional control messages are used, e.g., busy-tone signals [6] and receiver initiated messages [7]. The busy-tone signals [6] are sent after the transmission to notify nodes in deafness state to reset their contention window. RTR (Ready To Receive) packet is sent by a receiver to invite potential sender to begin the transmission. The mean weakness of these approaches is that they try to solve directional MAC problems at the end of transmissions. The fairness is improved, however the unsuccessful RTS packets and bandwidth wastage still exist in this kind of protocols.

### *B. Parallel Transmission*

Few works are proposed in the group of parallel transmission. These protocols are divided into two categories: CSMA-based [8], and TDMA-based [9]. In former case, the source-destination couple of the first successful exchange of RTS/CTS packets are considered as master nodes. Nodes in their vicinity are considered as slave nodes. After the successful exchange of control packets, master nodes wait for a duration before the beginning of transmission. Only the slave nodes, that win to exchange successful RTS/CTS packets during the waiting time, are allowed to transmit in parallel with the master nodes. Several limitations are observed: First, RTS/CTS packets are sent omnidirectionaly, hence the network connectivity is limited to OO-neighbors. Second, serious collisions may occur during the waiting time after the RTS/CTS exchange between the master nodes. Third, it is not clear how it will be the behavior of slave nodes if they are common neighbors of two couples of master nodes. To cope these issues, a directional TDMA-based MAC (RT-DMAC) protocol is proposed in [9]. However, RT-DMAC is designed only for uniform grid topologies where each node has four neighbors and is equipped with four beam antennas. The connectivity of RT-DMAC is also limited to OO-neighbors. This approach in not realistic in real WMNs and then the proposed protocol is not applicable.

## III. Antennas Set-up

Each wireless router is equipped with M non-overlapped directional antennas. Routers can transmit or receive using directional or omnidirectional mode. When using omnidirectional mode, a router can either transmit or receive through all directions at the same time with a gain of $G_o$. When using directional mode, a router can either transmit or receive through only one direction with a gain of $G_d \succ G_o$. Three sets of neighbors are used in our model: *OO-neighbors/DD-neighbors* when both the transmitter and the receiver use omnidirectional/directional mode respectively, and DO-neighbors when either the transmitter or the receiver uses the directional mode.

## IV. The proposed MAC Protocol

### A. Time Division

The time sequence in nodes is divided into slots. Each slot is divided into a control part and a transmission part. The goal of the control part is to decide which nodes will transmit in the following transmission part and which nodes will receive. In order to minimize the control overhead, the transmission part is much greater than the control part. The control part is divided into N mini-slot when N represents the number of nodes in the most load two-hop neighborhood. Each mini-slot is divided into three mini-parts. The two-hop neighborhoods of a given node consist of all nodes containing in the one-hop or the two-hop neighbors of this node. The time division is shown in Figure 2.

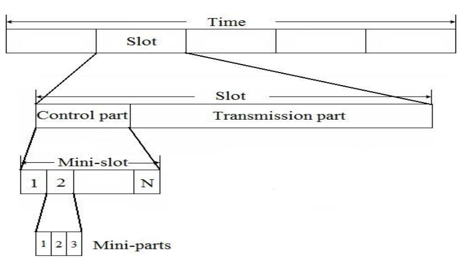



Fig. 2: Mini-slot Assignment

### B. Mini-Slot Assignment

The goal of the mini-slot assignment is to assign a number of nodes to each mini-slot. If the number of mini-slots is small, then the control overhead is small. Hence, the number of nodes into each mini-slot should be the largest as possible. The mini-slot assignment should take into consideration that two nodes in the same two-hop neighborhood cannot be assigned to the same mini-slot. As explained in Section III-C, a node wishing to transmit during the transmission part should send a jam signal during it corresponding mini-slot. Hence, in order to maintain a collision-free MAC protocol, two nodes in the same two-hop neighborhood cannot be assigned to the same mini-slot. In fact, if two nodes in the same two-hop neighborhoods begin a transmission at the same time, resulting in a situation where the receiver of one of them is a one-hop neighbor of the other, and then a collision will occur at this receiver. The algorithm of mini-slot assignment is shown in Algorithm 1.

**Algorithm 1** Mini-slot assignment

$N \leftarrow 1$; Number of mini-slots
$L_i$ = The set of 2-hop neighbors of node $i$
$S_j$ = The set of nodes in the mini-slot $j$
**for** $i$ = 0 to $Numberofnodes$ **do**
    $flag \leftarrow$ false;
    **for** $j$ = 0 to $N$ **do**
        **if** $L_i \cap S_j$ == ∅ **then**
            add $i$ to $S_j$;
            $flag \leftarrow$ true;
            break;
        **end if**
    **end for**
    **if** $flag$ == false **then**
        $N \leftarrow N + 1$;
        add $i$ to $S_N$;
    **end if**
**end for**

### C. Framework

At the beginning of each mini-slot, if a node S has a packet to transmit to node R and if S is assigned to this mini-slot, S will transmit a jam signal omnidirectionally during the first mini-part of the mini-slot. A jam signal is a busy-tone signal and it does not contain any information. The jam signal should be only sensed at the receiver but not decoded. When a receiver node R receives a jam signal during the first mini-part, it detects the direction of the received signal and it knows that the corresponding neighbor will be busy during the following transmission part. Note that since a jam signal only needs to be detected and not decoded, it will be sensed by all the nodes in the set of DO-neighbors of the sender S even if it is transmitted using the omnidirectional mode [10]. In the second mini-part, the node S transmits a jam signal toward the direction of R using the directional mode. Hence, when a neighbor node of S senses only the first jam signal, it knows that S will be busy during the following transmission part. In the other case, when a node receives a jam signal during the first and the second mini-slots, it knows that it will be the receiver node R during the following transmission part. In the result, all the one-hop neighbors of S are notified that S will be busy in the following transmission part. If one of the neighbors of S has in the head of its queue a packet intended to S, the transmission of this packet is deferred to the next slot. In the third mini-slot, the receiver R transmits a jam signal using the omnidirectional mode, and then the one-hop neighbors of R know that R will be busy during the following transmission part. In the following mini-slots, the assigned nodes can follow the same procedure if their corresponding receivers are not busy. In other words, the assigned nodes can follow this procedure if they have not received a jam signal from their corresponding receivers during the precedent mini-slots of the same slot. It is clear that using our protocol, all the nodes will have a complete knowledge about the concurrent transmission in their vicinity, and then no deafness, hidden, or blocking problem will take place since transmissions occur in parallel.

In the aim of better understating our proposed work, let's

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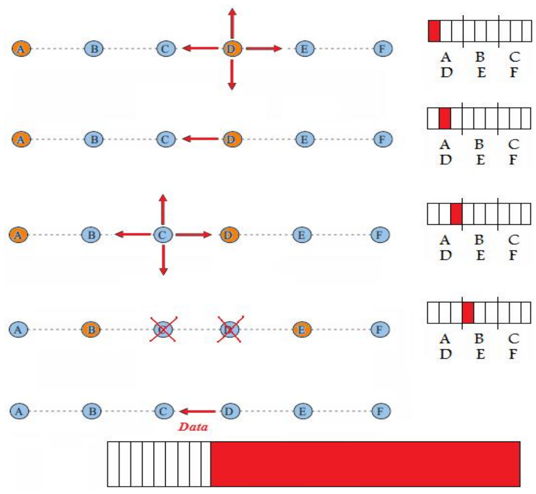


Fig. 3: The framework of our protocol

consider the example shown in Figure 3. It presents a chain topology of 6 nodes. In the first step, the model has to assign nodes to mini-slots. Let's consider the set of nodes A,B,C, since each node of this set is within the two-hop neighborhoods of the two other nodes, each one of them should be assigned to a separate mini-slot. Node D is not within the two-hop neighborhood of node A, and then node D is assigned to the same mini-slot of node A. For the same reasons, node E is assigned to the mini-slot of node B and node F is assigned to the mini-slot of node C. In the second step, we explain the operations realized by our protocol. Let's consider that at the beginning of the slot, the node D has in the head of its queue a packet intended to node C. During the first mini-part of the first mini-slot, node D transmits a jam signal using the omnidirectional mode. By sensing the direction of the receiving jam signal, node C and node E know that node D will be busy during the transmission part. During the second mini-part of the first mini-slot, node D transmits a jam signal toward node C using the directional mode. Hence, node C knows that it is the corresponding receiver of node D, and node E knows that it is not the corresponding receiver of node D. In the third mini-part, node C transmits a jam signal using the omnidirectional mode. By sensing the direction of the receiving jam signal, node B knows that node C will be busy during the transmission part. Nodes B and E are assigned to the second mini-slot. During the first mini-slot if node B has in the head of its queue a packet intended to node A, it follows the same procedure of node D. In the other case, if node B has in the head of its queue a packet intended to node C, it defers the transmission of this packet to the next mini-slot and it checks if it has another packet in the queue indented to node A. If such packet exists, node B follows the procedure of node D; otherwise B remains idle during its mini-slot. Node E follows the procedure of node B by preventing the transmission toward node D. The same procedure is repeated in the third mini-slot. The transmission will take place just after the end of the control part. The precedent mechanism is repeated at the beginning of each slot.

### D. Fairness

It is clear from the previous sections that the nodes assigned to first mini-slots have the higher priority to access the channel. Hence, in order to maintain the fairness in channel access, the mini-slot assignment is shifted at the beginning of each slot. In other words, if a node is assigned to the $i^{st}$ mini-slot in the current slot, it will be assigned to the $(i-1)^{st}$ mini-slot during the next slot. For instance, the nodes assigned to the second mini-slot in the current slot, will be assigned to the first mini-slot in the next slot. Hence, the priority of these nodes is incremented by one index. Also, the nodes assigned to the first mini-slot in the current slot will be assigned to the latest mini-slot in the next slot. Hence, the priority of these nodes will be changed from higher priority to lower priority.

## V. Conclusion and Future Work

In this paper we have proposed a new TDMA-based MAC protocol for WMNs using directional antennas. By providing a full knowledge for each node about its neighboring transmissions and by maintaining parallel communications, our protocol is able to alleviate the control access challenges encountering in many MAC protocols. Our protocol is collision-free, deafness-free, hidden-free and blocking-free. Our proposol also provides a full faireness between all the nodes in the network.

Our future works will be focused on implementing and deploying our model, and adding more functionalities such as congestion control and service differentiation. In addition, the performances evaluations of our work will be compared with some existing directional MAC protocols.

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