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Modeling and Enhancement of Wireless Access and Mesh Infrastructure Vehicular Networks

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Maillée pour les Réseaux Véhiculaires

Faouzi KAABI

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DÉDICACES

À ma famille et à tous mes amis

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Abstract

A major technological breakthrough to improve road safety and traffic efficiency will be cooperative communications for transport systems. Through the use of wireless communications, cooperative systems will allow the dynamic exchange of messages between transportation systems such as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. Cooperative Vehicular Systems are composed by Road Side Units (RSUs) and On Board Units (OBUs). OBUs provide network connectivity to the users and are inside their cars whereas the RSUs are fixed and deployed equipment on the public roads.

The RSUs can be connected to each other and to the Internet using Wireless Mesh Network backbone. We call "service level/access of the vehicular network" the network composed by the RSUs and the OBUs and we call "backbone level/infrastructure of the vehicular network" the network connecting the RSUs to the Internet.

In this thesis, we develop several contributions to improve the vehicular network performances at both service level and backbone level. For the service level, 802.11p defines a control frequency channel for control and most critical data packets and one or several service frequency channels for less critical packets.

As a first step, we propose an analytical model for the 802.11p operations in the control frequency. It captures all suggestedenhancements important for exchanging data packets generated by road safety applications. The model is a simple tool that is able to reproduce expected results. This is an important step toward the improvement of vehicular networks performances. The model is then combined with optimization criteria for optimal placement of roadside units.

For the backbone level, we conduct a rich study to identify what are the significant factors and mechanisms that have the most important impact on the WMNs backbone performances. We concluded that investigating on channel allocation and routing is the best answer to that issue. After that, we focused and classified the most challenging approaches and proposals for channel allocations and routing. As a conclusion, we can say that the most interesting work are those proposing a common-layer design between MAC layer and network layer and are mostly concerning a centralized manner. However, in a wireless environment, presenting a centralized approach is not too realistic. Our contributions in this area concern the development of two interesting approaches to solve the addressed problem in a distributed fashion.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Wireless network is the underpinning communication of the future. During the last couple of decades, the wireless network has evolved from an academic research project into thousands of independently administered, public and private networks that can be interconnected via the Internet Protocol (IP). Several standards have been defined by standardization organisms depending on the coverage area of each wireless network. For wireless personal area network (WPAN), wireless metropolitan area networks (WMAN), and wireless local area networks (WLAN), respectively the IEEE 802.15, IEEE 802.16, and IEEE 802.11 standards have been defined.

Nowadays, IEEE 802.11, IEEE 802.15 and IEEE 802.16 standards are facing several deployment limitations like the throughput degradation and the unfairness between network nodes, the IEEE community decided to extend the actual standards in order to improve the network performances and to extend its coverage area. Several working group committees are established to improve the current standards. Many of these groups are proposing new promising amendments. Some of these amendments are still expected to be approved by their task groups. For instance, extensions aim to define new working modes for the wireless local area networks and even to explore new area of applications of IEEE 802.11 to include some urban increasing needs. In fact, since the middle of the twentieth century the car park is witnessing a significant increase, all over the world. The population rate that has access to a car is also increasing causing a significant traffic load of the roads. This huge traffic, unfortunately, causes pollution and a lot of accidents that cost thousands of lives each year in each country. This new significant problem emphasizes the urgency to have new applications that will be provided by new technologies to rescue and help people whenever they drive a car. The research community decided to provide a solution to this urgency. One of the proposals was by creating the IEEE Task Group P. This task group aims at providing an amendment for wireless local area network that will be called 802.11p to enable communication between vehicles. This amendment will define two types of possible communications that are symetric Vehicul to Infrastructure and Vehicul to Vehicul. The vehicular network protocol provides the use of different frequency channels. In fact, several channels are used for transmitting and receiving non critical data while only one is used for exchanging control and critical packets.

Besides data exchange, vehicular network should play an important role in safety. In fact, one of the most significant use of wireless technology in general and vehicular network in particular remains the public safety. The vehicular networks are composed of Road Side Units (RSUs) and On Board Units (OBUs) that correspond respectively to the infrastructure and the vehicular part. Hence, two issues are addressed in this thesis. First, how can we model the IEEE 802.11p and how can we provide an efficient deployment of this network? Then, how the RSUs are connected to the Internet and between them?

In this thesis, we aim to improve the vehicular network performances. For this, our contributions are done on the two levels of the general network topology. The first level is the service level and is composed of the RSUs and the OBUs. The second level is the backbone level and is composed of the network that connects the different RSUs.

In the service level and as a first step, we have to provide a mathematical model for evaluating the performances of the IEEE 802.11p MAC layer working on the control channel. This model must take into consideration outdoor environmental constraints that are external parameters consisting of device features and signal processing laws. In fact, by considering environmental constraints, we provide a realistic model that can be used later as a reference for the IEEE 802.11p network deployment. As we consider safety applications as being prior to other applications and they run over the control channel, our model will focus on the control channel of the IEEE 802.11p. Transmissions over control channel are done in a broadcast manner without acknowledgments. The exchange of information is done between the OBUs, on the one hand, and the RSUs, on the other hand.

In this step, we propose an adapted model for the MAC layer of the control channel for 802.11p. The model we present does not only consider the MAC features, but it also includes approximations of the physical layer characteristics. In this step, we present a simple and approximate model of the IEEE 802.11p protocol modeling the IEEE 802.11e MAC layer taking into consideration the physical characteristics. Despite the fact that our model is not exhaustive of all the physical layer features, we succeed in obtaining a simple approach of the behavior of the IEEE 802.11p that is validated against simulations. Our objective consists in achieving convergence between model and simulation results. This model will have a significant impact on network IEEE 802.11p based design. In fact, this model can be used for the analysis of the strategies for IEEE 802.11p Road Side Units deployment.

One of the major problems when using a wireless technology remains how to take the maximum of benefit from this technology and how to provide for its users performances closed to the theoretical advertised ones. To provide an answer to this issue, we strongly believe that a good network deployment remains the most significant approach. In the case of IEEE 802.11p, the RSUs provide the only access to the network and maintain the OBUs connected. Therefore, to look for an optimal deployment of these RSUs is mandatory. The attempt of improvement of the performances of the Vehicular networks, at the service level, is the objective of the second step of our thesis which consists in finding the best deployment of the RSUs in this network. Our contribution has as objective to resolve the problem of RSUs deployment by proposing a technique allowing to find the best place of one or several RSUs in a vehicular network so as to obtain the best performances of the network (one better network coverage, a better total and average throughput for OBUs, a better fairness between OBUs and a better stability of the network when there is mobility of the OBUs). For this step, we will use the model proposed in the previous step to find the best network configuration.

We focused to know how to improve the vehicular network performances by acting on the service level, but we also believe that such a task can be done also at an upper level of the network topology. In fact, the RSUs can be connected between them using another wireless technology. The resulting network composed of the RSUs will be the backbone level. We believe that the most adapted network technology for providing connectivity at the backbone level is the Wireless Mesh Network (WMN).

A Mesh Network is defined as being an infrastructure network working with an ad hoc mode. The architecture provides the possibility of interconnecting several heterogeneous networks. In fact, the Mesh Network is composed of two levels. A backbone level that includes the Mesh routers and service level that correspond to the different networks connected to the backbone level via a Mesh router (with Gateway or Bridge).

Communications in WMNs are multi-hop and multipoint-to-multipoint, the network is self-organized and its performances are affected by mobility even if it is low that's why designing a scalable MAC for WMNs is an issue. This scalability can be addressed by the MAC layer in two ways. The first way is to enhance existing MAC protocols or to propose new MAC protocols to increase end-to-end throughput when only single channel is available in a network node. When several communication channels are available in the network, a second way is to allow transmission on multiple channels in each network node.

As IEEE 802.11, IEEE 802.15 and IEEE 802.16 basic standards [23, 24, 25] provide the support of multi-channel, IEEE (802.11, 802.15, 802.16)-based Wireless Mesh Networks may have single-channel or multi-channel configuration. In wireless mesh network backbone, one node can have one or more transceivers. The traffic in WMNs is mainly directed between nodes and the Internet but we believe that also traffic may exist between nodes themselves. High-bandwidth applications need sufficient network capacity so it is challenging to make the network providing such a capacity. In order to improve WMNs capacity a good management of the available frequencies is necessary. More precisely, a reliable and efficient medium access control (MAC) protocol and a good channel allocation are needed. Allowing multiple channels use in the same network is often presented as a possible way to improve the network capacity. A lot of research work have been conducted in the area of multi-channel allocation in order to improve the aggregate bandwidth of the whole network.

In this third part of the thesis, we focus our attention on the proposals to solve the channel allocation problem for Multi-Transceiver per node in the backbone level using the IEEE 802.11s technology. We classify these proposals into three categories. The first one consists in channel allocation proposals done at the MAC level independently of the other layers. The second one consists in a channel allocation approaches done by a modified MAC collaborating with upper layers. Finally, the third category concerns channel allocation methods implemented in a new layer resulting from a common-layer design between MAC and Network layer. For each category, the existing multi-channel protocols and their channel allocation approaches are identified. A qualitative comparison is conducted according to the advantages that they present, the limitations and problems they are facing, and the performances they are claiming to offer. After a deep study of the proposed solutions to the issue of using all the network capacity for each category, the best network use is only achieved by a common-layer design MAC Network.

The most interesting previous work done by the different research bodies presented approaches done for a common-layer design between MAC layer and network layer that are mostly concerning a centralized manner. However, in a wireless environment, presenting a centralized approach is not too realistic because of who can supervise such a distributed network and how well, this supervisor does it? We strongly believe that these questions should be answered before presenting a centralized approach. By the next two steps, we will propose two distributed solutions for this problem.

After the previous conclusions, and under the scope to improve the vehicular network performances by acting at the backbone level, we propose two possible alternatives to solve the problem of channel allocation and routing at this level. In this fourth step of the thesis, we propose to divide the whole network on clusters. Each cluster is managed by a cluster-head. The cluster-head is elected by its neighbors as being, for example, the node which has the highest number of neighbors. A cluster is formed by a cluster-head and all neighbors that are, for example, on a maximum of two hops of distance from it. Each cluster-head knows the topology and the network features of its cluster. All the clusters of the whole network are connected by relay nodes that are on the borders of each cluster and provide connectivity with a neighbor cluster. A relay node is a member of only one cluster. All the cluster-heads of the whole network are connected and advertised their clusters topologies periodically between them. If a node wants to reach another node, it sends a message for communication request to its cluster-head over a fixed channel. If the destination is inside the same cluster, the cluster-head will choose the path and the channel of communication and will advertise its choice to both source and destination. Otherwise, if the source and the destination are in different clusters, the cluster-head of the source will send a message to the cluster-head of the destination and to the other cluster-heads of the different clusters through which the communication in-between source and destination will occur. A communication path is, then, created between the relay nodes from the source to the destination and each cluster-head decides on the path and the channel of communication between the nodes members of the path source/destination and inside its cluster.

A second alternative, for solving the problem of joint channel allocation and routing, is to create a WMN topology control over a distributed network. This last step introduces another approach to manage a distributed network and tries to create a distributed virtual structure over the mesh backbone that will work like a Centralized Channel Allocation Entity. Such a structure will have three tasks that are network features and future traffic collection, network management and the advertisement of the decided network configuration. To create this structure, we propose that, inside a neighborhood, nodes (wireless mesh routers) elect a master. As an election result, the node which has the highest connectivity inside its neighborhood becomes the master (dominant node) and advertises its decision to its neighborhood. A Connected Dominating Set (CDS) that connects the masters (dominant nodes) can be fulfilled by the masters from each neighborhood. Such a CDS inside the mesh network would be used to manage the whole network and limit the retransmissions and the overhead number.

The following steps are done for the creation of the distributed topology control :

- Implementation of a neighbor discovery mechanism that will collect the neighborhood information.
- Election of a local dominant that will represent its neighborhood.
- Advertisement of the neighborhood information between local dominants.
- Each local dominant computes best Connected Dominating Set (CDS) that includes the least number of participant nodes.
- Each local dominant advertises the CDS features to its neighborhood.
- Network management inside the CDS.

This approach will limit the number of management messages inside the network and will allow the use of centralized approaches to manage the network.

This dissertation presents the motivation of the high level goals, the detailed description of the design of each mechanism and protocol, and the performance evaluation from a set of computer simulations. The following section summarizes the key contributions of this thesis.

1.1 Thesis Contributions

Regarding the several issues addressed in this dissertation, we were able to make some contributions, which are summarized here and discussed in more details in the subsequent chapters:

- **Performance analysis of IEEE 802.11p control channel:** We have proposed and extensively evaluated a simple and scalable approximation of the IEEE 802.11p control channel to achieve the requested model for the realistic behavior of IEEE 802.11p control channel. IEEE 802.11 is composed of two parts. An infrastructure part that is the deployed Road Side Units (RSUs) and a non infrastructure part that is the mobile On Board Units (OBUs). For each OBU, we first propose a model of the MAC layer as described in the successive drafts for the expected Standard IEEE 802.11p. Then, we approximate the physical layer features in order to have a closed approach to a real deployment. In our approach, and from the model of the MAC layer that we express as a Markov Chain, we complete the model to express the average throughput of the OBUs. To guarantee a more realistic approach, we define a probability of failure of transmission for a given OBU dependent on its transmitted signal power. First, the received signal power decreases with the increase of the distance between the RSU and the OBU. The chosen attenuation factor value of α in the model is 3 and is corresponding to the urban environment. Second, we define the interaction power for an OBU given by the sum of the powers out-coming from the other OBUs and received at the same RSU, and thus, we define the signal to noise rate expression for a given OBU as being the value of its received signal at the RSU divided by the sum of the thermal noise and the value interaction power value. Finally, we introduce the physical layer constraints to the expressions extracted from the model of the MAC layer and we obtain an expression of the throughput for an OBU closed to the one that would be obtained by real deployment. Simulation results demonstrate that our presented model achieves the expected approximation of the behavior of the IEEE 802.11p control channel. In fact, comparing the obtained results from the implementation of our model against those obtained with Qualnet results leads to the validation of our model. Furthermore, we believe that our model is a simple and efficient tool for future design and turning of IEEE 802.11p based network.

- **A better deployment of IEEE 802.11p Road Side Units:** We have designed, developed, and evaluated a simple and scalable approach for the IEEE 802.11p deployment. Our contribution has as objective to resolve the problem of deployment of IEEE 802.11p RSUs by finding a technique allowing us to find the best position of one or several RSUs in a vehicular network. We mean by best position of RSUs, the geographical deployment of the RSUs that provide the best performances of the network (best network cover, a best total and average throughput available for the OBUs, a best fairness between the OBUs, and a best network stability). We utilized our proposed model for the IEEE 802.11p control channel to express the throughput of the different OBUs in the network. We have also identified and discussed the optimization techniques that will be used and the criteria of optimality that has to be respected. We implemented these techniques and run simulations for the case where we have to deploy a single RSU in the network and for the case we have several RSUs to deploy. The simulation results that we obtained for the different adopted optimization techniques for either a single or several RSUs to deploy allows us to find the best strategy of the network according to the features that we expect the network to satisfy. This contribution provides, on the one hand, a simple and realistic tool for the IEEE 802.11p RSUs deployment, and on the other hand, it allows to adapt the network deployment to the expected requirements in term of coverage and throughput.

- **Channel allocation and routing in Wireless Mesh Networks:** After our contributions for modeling the IEEE 802.11p control channel and for the IEEE 802.11p RSUs deployment, we try to improve the vehicular network performances by acting on an upper level of the network topology. As the RSUs can be connected between them using the backbone level of the Mesh Network, in this contribution, we aim to study how to improve network performances in wireless mesh networks (WMNs). After a deep study of mesh networks, we have concluded that in order to avoid transmission's collision and improve the network performances, a reliable and efficient medium access control (MAC) protocol and a good channel allocation are needed. Indeed, allowing multiple channels use in the same network is a possible way to improve the network capacity. By this contribution, we propose a deep study comparing the different channel allocation proposed techniques that we classify into three categories. The first one consists in channel allocation proposals done at the MAC level independently of the other layers. The second one consists in a channel allocation approaches done by a modified MAC collaborating with Network layer. Finally, the third category concerns channel allocation methods done by a common-layer design between MAC and Network layer. We related, for this contribution, many excellent approaches for channel allocation which ultimate objective is to take the maximum of benefit from the available channels in wireless mesh network. These techniques have been proved by their authors to improve the network performances, however, the common-layer design is the approach that provides the best network performances. In fact, the proposed solutions to the issue of using all the network capacity is only achieved by a common-layer design MAC Network where the performances that the authors claim to achieve are nearly the theoretical optimum of use of the network capacity.

- **Proposals for an efficient distributed joint channel allocation and routing approach:** After studying the different techniques of channel allocation, we introduce in this contribution two approaches to achieve an efficient channel allocation and routing. In the first approach, we propose to divide the whole network on clusters where each cluster is composed of a cluster-head and all neighbors that are on a maximum of two hops of distance from it. Each cluster-head is elected to manage its cluster and exchange information with the cluster-heads. The connectivity between clusters is provided by relay nodes that are always on the borders of each cluster. If a node wants to reach another node, the selected path and communication channel are given by its cluster-head. In the second approach, we try to solve the problem by finding a technique to manage a distributed network and to create a distributed virtual structure over the mesh backbone that will work like a Centralized Channel Allocation Entity. Such a structure will have the task to manage the network. To creating this structure, we propose that, inside a neighborhood, the nodes elect a local master. The node which has the highest connectivity inside its neighborhood becomes the master. A Connected Dominating Set (CDS) that connects the masters can be fulfilled by the elected masters.

1.2 Dissertation Outline

The remainder of this dissertation is organized as follows. Chapter 2 reviews the work related to this dissertation. We first discuss the current proposed techniques for modeling the behavior of IEEE 802.11p control channel and the possible differences with a real deployment. Then, we discuss possible techniques that could be adopted for RSUs placement. Also, and at an upper layer of the network topology, recent researches in network resource allocation for wireless mesh network at a backbone level are presented. After that, we introduce the related work to our proposals for a joint channel allocation and routing. Finally, we derive the remaining challenges to improve the performances of vehicular networks that are the main research problems addressed in this thesis.

Chapter 3 and Chapter 4 focus on the first research problem namely: the improvement of vehicular network performances at client level.

In Chapter 3, we consider a vehicular network protocol where there are several OBUs connected to RSUs. We propose and evaluate a new model of the IEEE 802.11p control channel that we compare against simulations done with the professional simulator Qualnet. The comparison between the results given by the analytical model we propose and those given by the simulator leads to the validation of our model.

In Chapter 4, we address the problem of vehicular network deployment. We present and discuss several possible techniques to resolve the problem of deployment. Then, we introduce the selected approach for the placement of the RSUs in the network. After that, we define the optimality criteria that have to be respected by each technique. Finally, we implement and evaluate the adopted models for the RSUs placement.

In Chapter 5, we investigate the challenge of improving the Vehicular network performances at the backbone level of the network topology. As the RSUs can be connected between them using the wireless mesh network, we investigate how we can improve the WMN performances, therefore. After a deep study, we conclude that for improving the WMNs performances, we have to consider the multiple channel use and focus on how to achieve the best channel allocation on the network. We believe that for such a task, we have to answer the question if a good channel allocation can be fulfilled regardless of the other layer. We review in this chapter the most challenging and the most recent proposed approaches to answer the question and conclude that the best way to improve the wireless mesh network is to propose a common-layer for channel allocation and routing.

In Chapter 6, we consider the conclusions of the Chapter 5 and we propose two solutions that aim to improve the wireless mesh network capacity. The two proposed solutions are detailed and explained theoretically.

In Chapter 7, we present a general summary of the work achieved and the conclusions concerning the results obtained during this thesis. Some perspectives and open questions are given for the continuation of this work in the area of vehicular and wireless mesh networks.

Chapter 2

State of the Art

The vehicular networks are mainly composed of Road Side Units (RSUs) and On Board Units (OBUs). The OBUs are integrated equipments into the users' cars where the RSUs are fixed and deployed equipments on the public roads. The RSUs provide the network access and connectivity to the OBUs. The service level of the vehicular network is composed of the RSUs and the OBUs. RSUs can be connected between them at the backbone level with a Wireless Mesh Network (WMN). Our contributions are given at the two levels of the vehicular network that are the service level and the backbone level. In this chapter, we presente the related works in the topic addressed in this thesis, namely vehicular communication and wireless mesh networks.

2.1 Topics related to contributions at the service level

At the service level, we split the contributions into two main topics. The first topic concerns the approaches for modeling the MAC layer of IEEE 802.11p standard, whereas the second one concerns the proposals related to Road Side Units deployment.

2.1.1 Analytic model model for 802.11p

A fundamental work on the performance analysis of IEEE 802.11 distributed coordination function (DCF) was presented by Bianchi [1]. The proposed Markov model provides expressions for the saturation throughput and the probability that a packet transmission fails due to a collision as a function of the number of stations, retransmissions and back-off states. However, it does not consider physical layer conditions nor the actual DCF required by the standard. Despite its simplicity, the Bianchi model attracted lots of interest and was considered in a number of works that improved the model by considering clear channel assessment and physical characteristics. Moreover, other works adapted the model to comply with the standards, e.g. Robinson et al. adapted it for the IEEE 802.11e amendment. Other works, such as the one presented by Duffy et al. [2], presented an analysis in non-saturated conditions. In particular, with respect to previous models in saturation, Duffy introduced an additional level in the Markov chain to represent the states were the packet has not arrived at the MAC layer. Although this model allows to represent the transmission in both non-saturated and saturated conditions, the random backoff counter is decremented despite the medium condition. The analysis presented by Engelstad [3] allows to address this inconsistency with the standard, by decrementing the back-off counter only when the medium is idle. Nevertheless, Engelstad's model does not consider the case when a packet arrives at the MAC layer and the medium is busy. In our proposed model we will consider also this case, thus describing more closely the behavior of the packet transmission. All the models presented above assume that all stations have the same physical layer (same transmission power, same coding...) and that if more than one station transmits a packet in a certain slot time, all the packets will be lost. This might be not true, as presented by Kochut [4]. In fact, when a station is close to the receiving station and the other transmitting station is not, the packet transmitted by the closest station has higher chances to be correctly received. A step further toward a realistic description of the packet transmission was done by Manshaei [5], who proposed to add the physical layer constraints to the MAC model for expressing the MAC throughput saturation and the packet loss probability. More recent works have focused on vehicular communication characterization and on proposing mechanisms to improve the IEEE 802.11p performance, e,g. by changing the Enhanced Distributed Channel Access parameters. In [6], the authors presented results that show that, whereas vehicle density has a significant impact on aggregate throughput, average delay and packet loss, vehicle speed is not a significant factor. The authors of [7] and [8], showed that STDMA allows higher performance with respect to CSMA in the considered scenarios. In [9], the authors investigated the channel access scheme and propose to extend the service channel interval. They showed that their approach increases the channel bandwidth and decreases the channel bit error. In [10] the author proposed to reduce the number of high priority messages. In [11], the authors proposed to assign priority according to either the number of neighbors that a node can have or its speed. Finally, in [12], the authors proposed to dynamically adjust the backoff window size according to the channel condition. Although literature presents a number of works on IEEE 802.11p transmission models, they mainly consider point-topoint traffic with retransmissions. In this work, instead, we focus on safety scenarios that consider broadcast messages without retransmission. For such scenarios, we propose an analytical Markov model that accurately describes the access to the CCH.

2.1.2 Road Side Units deployment

Although many projects and research works considered already the deployment of dedicated infrastructure as an essential part of vehicular networks, only very few proposals have been done for the road side units deployment. In fact, a lot of research projects have to be considered where their authors claim that they are innovative and bring a significant solution to the vehicular network infrastructure deployment. In this section, we will review only few of them. In [16], the authors propose to measure the access to the Internet by deploying access points along a road. This work has been done to study the behavior of the connection with regard to vehicles speed. They conclude that the higher the speed is, the lower the performances are (association to an access point, number of scanned access points, average throughput,...). In [16], the authors did not propose a scalable mathematical model for the deployment. In [17], the authors propose some measurement scenarios to evaluate the performances of the network but in this proposal there was no deployment model proposed. In [18], the authors propose a mechanism that can be used for exchanging data contenant between cars based on peer to peer algorithm. In the described mechanism, a car arrives in the range of a gateway, initiates downloading a block of the file. After getting out of range, it starts looking for the missing blocks of the file from its neighbors until being connected to the next gateway to resume the download. This proposal is interesting, however, it is limited when real time information are expected and do not provide any useful result for the network deployment. Similar proposals are described in [19, 20] where the authors introduce techniques to provide connectivity to users that are out of range of the RSUs.

In the previous work, there were no mathematical model provided. Today, many task groups and projects are motivating the urgency of contributions to improve the vehicular networks. Safespot [21] motivates the use of vehicular network by emphasizing the need of such a network in the real life. In fact, vehicular network would work first for public safety. Awareness of the traffic light, the traffic situation in intersections, and accident avoidance are advertised reasons in Safespot [21] for adopting and generalizing the use of vehicular network. To take the maximum of benefit from the vehicular network, deployment strategies have to be adopted. For this many systems and projects are created to provide solutions for deployment. However, only few techniques try to conduct a realistic study on the organization and deployment of RSUs. Some people think that placing the RSUs at the intersections can be seen to be the most useful approach where others claim that by splitting the deployment area into geographical clusters is a serious approach. However, adopting such an approach is not realistic. In fact, a geographical simplification of the problem does not take into consideration the reality of the traffic and its real constraints. A more realistic approach is proposed in [22] where the authors propose a RSUs deployment based on the metric of centrality. In [22], the authors propose to adopt a deployment based on the situation of traffic. In fact, they claim that the idea of placing the RSUs according to the criteria of centrality and regular distance between the RSUs is improving the network performances. However, in [22], the algorithm does not guarantee the time constraint for services but guarantees the availability of the RSUs at constant distance. As a conclusion, we can see that the problem of the access to services is often considered to be a problem of availability of access points. In fact, to give such a conclusion regardless of a deep study of the traffic density is meaningless because a RSU can provide access to a limited number of cars and being in range of the RSU does not mean having the expected bandwidth for some services.

2.2 Contributions at the backbone level

2.2.1 Techniques for channel allocation and routing in WMN backbone

Several works have been conducted in the area of channel allocation and routing in wireless mesh network. In this section, we brievely present most of them. We can split the proposals into three categories of philosophical and technical thinking way.

2.2.1.1 Independent channel allocation and routing

The first category concerns people who believe that we have only to manage the channel allocation in a network and the routing comes after. Many proposals have been done in case of a single NIC per node and consists that each node follows a well known sequence , or to periodically rendez-vous on a common channel , where a protocol designed named Muti-channel MAC (MMAC) has been described and detailed. Even designed for a single NIC per node, the MMAC protocol is shown in [51] to be improving considerably the network performances more than the IEEE 802.11 DCF [23] or the multi-channel protocol DCA which need at least two NICs per node. Also, and in the case of multiple NICs per node, many proposals have been done. In this case, a node includes multiple parallel RF front-end chips and base-band processing modules to support several simultaneous channels. On top of the physical layer, only one MAC layer module is needed to coordinate the functions of multiple channels. A node may operate on several channels simultaneously by affecting a different channel to each one of its NICs. Under this situation, distributed and centralized protocols have been proposed to improve coordinations and channel allocations. However, the theoretical capacity is achieved with centralized algorithms, and assumptions of steady traffic. Developing an accurate distributed protocol is still a challenge. Statically configuring the NICs of different nodes on pre-known channels simplifies protocol implementation but it is too limited to static network and may affect the network connectivity. Frequently switching the NICs of a node among different channels requires coordination and a strong synchronization between the sender and receiver nodes before transmission and may incur delay. A hybrid approach is made with The Hybrid Multi-channel Protocol (HMCP) [38, 39] that consists in keeping some NICs of each node fixed, while others can switch among channels. This approach is shown to be efficient in [38, 39] when the number of the available channels increases. However, the increase of the number of hops seriously affects the performances. Other approaches are proposed using analytical resolution. These approaches use graph theory for modeling the problem of channel allocation.

2.2.1.2 Cooperative channel allocation and routing

A second category concerns people who believe that both link layer and routing layer should collaborate. This category concerns either Single NIC or multiple NICs per node. For this, several proposals have been done where a vast amount of research like [33, 47, 48, 49, 50, 51] are modifying the MAC layer to support multi-channel ad hoc network. The common approach of these works is to find the best channel for a single packet transmission under the collaboration with the network layer and they don't consider the importance of a cross layer design. Even though the performance of these works seems to be improving the network capacity, these improvements are not enough and the strategies adopted are shown to be strongly suffering from the number of hops from source to destination. Also, the used MAC is either protected or not free, so it is limiting the research knowledge to the simple modifications or specially designed to a specific hardware and so the portability is limited.

2.2.1.3 Common channel allocation and routing

A third category concerns people who believe that when multi-channel wireless mesh nodes are considered, new routing protocols are needed for two reasons. First, the routing protocol not only needs to select a path in-between different nodes, it also needs to select the most appropriate channel on the path. Second, common-layer design becomes a necessity because the change of a routing path involves the channel switching in a mesh node. Without considering cross-layer design, the switching process may be too slow to degrade the performance of WMNs. Under this situation and consideration, several works have been also done. Most of the past work proposed solution for a centralized manner. An excellent knowledge of the network is so required to make theirs proposal realistic and scalable. Excellent work has been proposed in [52, 54, 55]. In [52], the authors propose an excellent problem formulation on which they explain clearly their approach. The main idea in [52] is to evaluate the traffic profile between source and destination and then to assign channels over the logical link between nodes. The paths are established using simple routing algorithms regardless of the channel allocation constraints and taking into consideration the load balancing between selected paths where an excellent survey on algorithms for convex multicommodity flow problems [53] was proposed. The performances advertised by the authors [52] yield a factor 8 of possible improvement which is higher compared to other approaches blamed for not fulfilling the maximum potential of the offered hardware. A similar broadband fixed wireless access system approach is done in [54] and is presented in five steps but it is the same approach as [52]. Finally, another approach consists in minimizing a convex function [55], which depends on the networks flow and communication variable under the constraints of the network flow and communications model. The objective function depends on the user's need when designing the network and it is shown in [55] that this function can represent, for example, the power transmission or the link utilization. The performances of the Simultaneous Routing and Resource Allocation (SRRA) [55] are underlining the importance of the model for planning and designing network.

2.2.1.4 Conclusion

After presenting the most interesting previous work done by the different research bodies, we can say that the presented approaches done for a common-layer design between datalink layer and network layer are mostly concerning a centralized manner management. These approaches are promoted by their authors to be improving the network performances up to a factor of 8 [24] compared to a single channel network. However, in a wireless environment, presenting a centralized approach is not too realistic because of who will be the supervisor of a such network and how will, this supervisor do it. We hardly believe that these questions should be answered before presenting a centralized approach.

In a distributed environment and in large scale multihop wireless networks, flat architectures are not scalable. In order to overcome this major drawback, clustering is introduced to support self-organization and to enable centralized approaches for the network management. Clustering algorithms are already proposed. We can quote the density-based algorithm proposed by [59]. This algorithm is based on the density of the neighborhood of a node. It's the ratio between the number of edges between a node and its neighbor, the number of edges between the node's neighbors and the number of nodes inside the node's neighbor. As a result, the network is partitionned into different clusters where each cluster has a cluster-head. Clusters can be connected by relay nodes that are the nodes on the borders of sub-networks forming the cluster. We can also manage a distributed wireless network by creating a virtual structure that will work as a centralized management network entity.

Chapter 3

Performance Analysis of IEEE 802.11p control channel

The IEEE Task Group has approved recently the 802.11p amendment to enable efficient short range communications for vehicular networks by introducing multiple enhancements at the physical and MAC layer. It defines a control frequency channel for control and most critical data packets and one or several service frequency channels for less critical packets. In this chapter, we propose an analytical model for the 802.11p operations in the control frequency including approximations of the physical layer characteristics. It captures all suggested enhancements important for exchanging data packets generated by road safety applications. We showed through diverse simulations scenarios that our proposed model is able to reproduce expected results. We consider this work as an important step toward understanding the performance of 802.11p based vehicular communications and the model can be employed in the simulations of safety applications in large scenarios.

3.1 Introduction

The emerging WAVE standard defines the communication specifications for wireless communication in vehicular environments. These specifications include the use of several channels, one dedicated for control and most critical data packets and the others for value-added services. The target applications for this technology are the ones concerning Intelligent Transportation Systems. Among these, the most important and critical is safety. Safety messages, such as collision warning, are specifically broadcast with low delay and high reception probability constraints. In order to investigate the performance of such applications in vehicular environment, it is necessary to perform realistic simulations. However, large scale simulations are very expensive in term of time processing and some large scenarios could not be simulated. Moreover, simulations fail to describe the capacity bounds of this technology which are fundamental to assess if the constraints of safety messages are satisfied. In order to address this problem analytical models are required. Literature presents a number of analytical models but none of them considers the case of safety message transmission. In this chapter we present an analytical model for IEEE 802.11p that describes the behavior of the communication on the control channel (CCH) and that allows to simplify simulations in safety scenarios. The proposed model is simple, captures some physical layer conditions (such as radio capture effect and modulation and coding robustness) and is validated against simulations under typical safety scenario conditions. In particular, we compare the behavior of the model by varying the channel load and the distance between communicating stations. The results showed that our simple model can quite accurately describes the behavior for the considered scenarios.

The rest of this chapter is organized as follow. Section 3.2 gives a deep description of our model. The simulation results and interpretations are provided in section 3.3. Finally, section 3.4 concludes the chapter.

3.2 Model analysis

3.2.1 Model description

Assumption

The model concerns non-saturated channel condition. A packet can be en-queued in the buffer at any time. The packet arrival time in the buffer can be described by a Poisson distribution. The back-off is decremented after a slot if the sensed medium is idle.

Mechanism description

- When the back-off is 0 a packet is transmitted whatever the medium state is.
- CSMA/CA is the selected MAC access mode.
- Retransmission (if any) is not provided at the MAC layer.

3.2.2 Mechanism mathematical interpretation

Packet arrival

- A packet arrives to the MAC buffer with probability q.
- The arrival follows a Poisson manner with an exponentially distributed inter-packet arrival time with rate λ.
- $1 - q$ is the probability that no packet arrives in a typical slot of length T.

Thus

- $1 - q = \exp(-\lambda T)$

and

- $q = 1 - \exp(-\lambda T)$

Transition modeling between MAC States

Assumptions:

- Each station can buffer only one packet.
- Transmission can occur if, and only if, the back-off counter $k = 0$.

- A station back-off counter is decremented when the medium is idle and whether it has or not a packet to transmit to reach a value of 0.
- If a station back-off counter reaches the value of 0 and a packet is still expected by the MAC, the MAC station remains at that state until the packet arrives.
- If the back-off counter reaches the value of 0 and in the buffer there is a packet to transmit, the station transmits the packet.
- If a station that does not have a packet to send and has the back-off counter equal to 0, receives a packet, it will sense the medium. If the medium is idle, the station will send the packet in the following slot, else, the station launches a random back-off counter.
- The probability to find the medium idle is p'.
- The network is composed by n stations.
- The probability that a station transmits on a slot is τ.
- The probability of collision is p.

Resulting transitions probabilities:

- probability to have already a packet to transmit and to remain at the same state is $P\left[(0,k)\,|\,(0,k)\right] = 1-p'$.
- probability to have already a packet to transmit and to decrement the back-off counter is $P\left[(0,k-1)\,|\,(0,k)\right] = (1-\tau)^{n-1} = p'$.
- probability not to have already a packet to transmit, to not receive a packet, and to decrement the back-off counter is $P\left[(0,k-1)_e\,|\,(0,k)_e\right] = (1-q)\,p'$.
- probability not to have already a packet to transmit, to receive a packet, and to decrement the back-off counter is $P\left[(0,k-1)_e\,|\,(0,k)\right] = q.p'$.
- Probability that a packet arrives just after the back-off counter reaches the value of 0 and to find the channel idle is $P\left[(0,0)\,|\,(0,0)_e\right] = q.p'$.
- Probability that no packet arrives after the back-off counter reaches the value of 0 is $P\left[(0,0)_e\,|\,(0,0)_e\right] = 1-q$.
- Probability to find the medium idle is $(1-\tau)^{n-1} = p'$.
- Probability to find the medium busy is $1-(1-\tau)^{n-1} = 1-p'$.
- Probability that just after a packet transmission the MAC buffer receives a packet to transmit is $P\left[(0,k)\,|\,(0,0)\right] = \frac{q}{W_0}$.
- Probability that just after a packet transmission the MAC buffer doesn't receive a packet to transmit is $P\left[(0,k)_e\,|\,(0,0)\right] = \frac{(1-q)}{W_0}$.
- Probability that a packet arrives just after the back-off counter reaches the value of 0 and to find the channel busy is $P\left[(0,0)\,|\,(0,0)_e\right] = \frac{q(1-p')}{W_0}$.

3.2.3 Resulting Markov chain model

The resulting Markov chain is given by the figure 3.1.

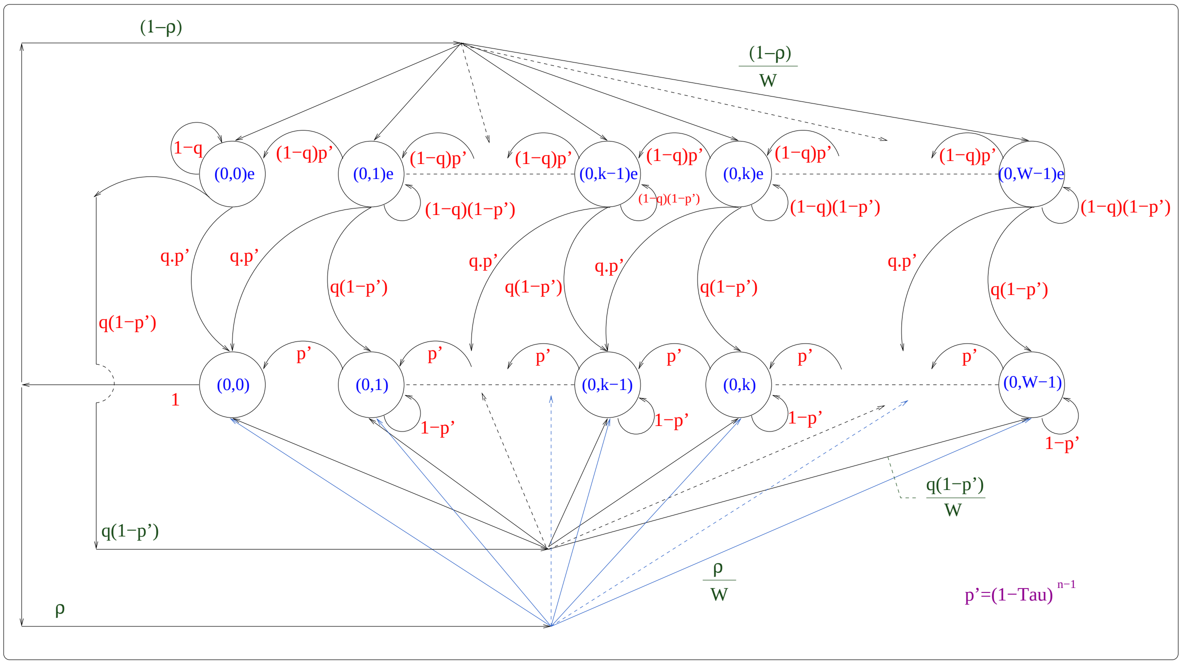

Figure 3.1: Markov chain model

3.2.4 Model mathematical interpretation

From the analysis of the Markov chain that models the access to the channel of mobile nodes for the control channel in 802.11p, we can write the equations that describe the probability distribution of the states.

The system is determined by the following parameters :

- q is the probability to have a packet to send at the MAC layer during a certain time slot.
- p' is the probability that the channel is detected free during a certain time slot.
- W_0 is the number of back-off stages.

The Markov chain has two different types of states

- $b\left(0,k\right)_e$ represents the states when no packet is waiting to be transmitted.
- $b\left(0,k\right)$ represents the states when a packet is waiting to be sent.

The states $b\left(0,k\right)_e$ can be described as a function of the state $b\left(0,k\right)$ as follows:

$$b\left(0,k\right)_e = \frac{\left(1-\rho\right)}{1-\left(1-q\right)\left(1-p'\right)} \frac{b\left(0,0\right)}{W_0} \left(\frac{1-T^{W_0-k}}{1-T}\right) \tag{3.1}$$

where $k = [1, ..., W_0 - 1]$ and

$$T = \frac{(1-q)\,p'}{1-(1-q)\,(1-p')} \tag{3.2}$$

The state $b\,(0,k)_e$ has a different formulation from the other states. In particular, it can be written as follows:

$$b\,(0,0)_e = \frac{(1-\rho)}{q}\frac{b\,(0,0)}{W_0}\left(\frac{1-T^{W_0}}{1-T}\right) \tag{3.3}$$

After writing the expressions for the states when the buffer is empty, we need to write the expression that represents the probability for the states $b\,(0,k)$ with $k = [1, ..., W_0 - 1]$.

$$b\,(0,k) = \frac{W_0 - k}{W_0}\frac{1}{p'}\left[b\,(0,0) + q\left(1-p'\right)b\,(0,0)_e\right] - b\,(0,k)_e \tag{3.4}$$

Once we write the expressions of all the states (as a function of the basic state $b\,(0,k)$), we need to impose the normalization as:

$$1 = \sum_{i=0}^{W_0-1}\left[b\,(0,i)_e + b\,(0,i)\right] \tag{3.5}$$

The normalization allows to write the state $b\,(0,k)$ as function of the fundamental parameters of the Markov chain p', q, W_0. Hence, the expression of $b\,(0,0)$ is done by equation 3.6.

$$b\,(0,0) = \frac{1}{1 + \frac{W_0-1}{2p'} + \left(1 + \frac{W_0-1}{2p'}q\,(1-p')\right)\frac{1-q}{q}\frac{1}{W_0}\frac{1-T^{W_0}}{1-T}} \tag{3.6}$$

According to our Markov chain, there is one possibility to transmit a packet and to be at the state $b\,(0,0)$. Hence the probability τ that a station transmits a packet is defined by the equation 3.7.

$$\tau = b\,(0,0) \tag{3.7}$$

3.2.5 Model throughput expression

Device parameters

Let N_0 be the power of thermal noise

$$N_0 = N_f.KTW \tag{3.8}$$

Where : N_f denotes the circuit noise value, K the Boltzmann constant, T the temperature in Kelvin and W is the frequency bandwidth.

The bit error probability for BPSK modulation P_b^{BPSK} and for QPSK modulation P_b^{QPSK} are respectively given by equations 3.9 and 3.10.

$$P_b^{BPSK} = Q\left(\sqrt{2.\frac{E_b}{N_0}}\right) \tag{3.9}$$

$$P_b^{QPSK} = Q\left(\sqrt{2.\frac{E_b}{N_0}}\right) - \frac{1}{2}Q^2\left(\sqrt{2.\frac{E_b}{N_0}}\right) \tag{3.10}$$

Where $\frac{E_b}{N_0}$ denotes the average signal to noise ratio per bit. The $\frac{E_b}{N_0}$ of a received signal is derived from the SNR as follows:

$$\frac{E_b}{N_0} = SNR.\frac{W}{R_b} \tag{3.11}$$

Where R_b is the maximum bit rate of transmission mode and W is the unspread bandwidth of the signal.

Protocol parameters

A data packet is composed of two parts :

- A PLCP Header sent with Basic Rate
- A MAC Header + Payload sent with the rate indicated in PLCP

Hence, the resulting probability of error of a packet is given by equation 3.12.

$$p = PER = 1 - \left(1 - P_e^{PLCP}\right).\left(1 - P_e^{Payload}\right) \tag{3.12}$$

Where P_e denotes the probability of error of PLCP or Payload and is defined as:

$$P_e = 1 - (1 - P_b)^{Length} \tag{3.13}$$

Model parameters

Let τ be the probability that a station transmits in a slot time. According to our model, a transmission can occur only in the state $b\left(0,0\right)$, and as a result, we obtain equation:

$$\tau = b\left(0,0\right) \tag{3.14}$$

Network parameters

We denote p_c, the probability that a transmitted packet collides with other transmissions. Hence, for n stations, we obtain the equation

$$p_c = 1 - (1 - \tau)^{n-1} \tag{3.15}$$

From the analysis of the Markov Chain corresponding to our model:

As, it is a non saturated model, we obtain two types of states modeling a MAC station. In fact, a MAC station buffer can be either empty or containing a packet to transmit and can be modeled respectively by $b\left(0,k\right)_e$ and $b\left(0,k\right)$, therefore.

From equations 3.12 and 3.13, we obtain the equation that a transmitted packet from a station k located on a distance d_k from the road side unit is lost.

$$P_k = 1 - \left(1 - p_b^{PLCP}\right)^{L_{PLCP}}\left(1 - P_b^{Payload}\right)^{L_{Payload}} \tag{3.16}$$

where L_{PLCP} and $L_{Payload}$ design respectively the PLCP and the Payload length.

Let $L(D_i)$ be the power of the signal of a transmitting station i located with a distance D_i from the Road Side Unit (RSU), the expression of the received signal power is done in equation

$$L(D_i) = \frac{P_0}{D_i^{\alpha}} \tag{3.17}$$

where P_0 and α denote respectively, the initial power of the transmitted signal and path loss exponent.

In case of collision, each signal of station k located on a distance d_k from the road side unit will interfere with the other signals coming from the other station and hence I_k denotes the interfering signals with the signal of the transmitting station k on the RSU and is given by equation 3.18.

$$I_k = \sum_{i \neq k}^{n} Y_i.L(D_i) \tag{3.18}$$

Where Y_i is a Bernoulli random variables and is equal to 1 when a station transmits and 0 else.

This allow to write the expression of SNR as shown in the equation

$$SNR_k = \frac{L(d_k)}{N_0 + I_k} = \frac{L(d_k)}{N_0 + \sum_{i \neq k}^{n} Y_i.L(D_i)} \tag{3.19}$$

So, we can see that to compute equation 3.16, the only random variable is I_k. Hence, having the *pdf* of I_k which we denote by $f_{I_k}(x)$, we can compute $p_k(d_k) = E[P_k]$. Assuming independence of Y_i, $f_{I_k}(x)$ can be expressed as $n-1$ convolution as denoted in equation 3.20.

$$f_{I_k}(x) = f_{X_1} \otimes ... \otimes f_{X_{k-1}} \otimes f_{X_{k-2}} \otimes ... \otimes f_{X_n}(x) \tag{3.20}$$

In the next step, we suppose, we are given the vector $\overline{D} = \{d_1, ..., d_n\}$, where d_i describes the distance of a On Board Unit (OBU) i to the Road Side Unit (RSU). For a OBU k, we aim to find the *pdf* of I_k. I_k gives the interfering power of all other OBUs at the RSU. To compute I_k, we need $f_{I_k}(x)$, the *pdf* of the power at the RSU of an individual OBU. For an OBU i, $f_{X_i}(x)$ can be written as given in equation 3.21,

$$f_{X_i}(x) = \delta_x(0)(1-\tau_i) + \delta_x(L(d_i))\tau_i \tag{3.21}$$

Where $\delta_x(x_0)$ is a Dirac pulse at $x = x_0$ and τ_i denotes the transmission probability of an OBU i. Finally, $f_{I_k}(x)$ can be computed using equation 3.20, while the value τ_i in $f_{I_k}(x)$ are left unknown. Using equation 3.16 and tacking expectation, we get the packet loss probability p_k of an OBU in equation 3.22.

$$p_k = E\left[1 - \left(1 - P_b^{PLCP}\right)^{L_{PLCP}} . \left(1 - P_b^{Payload}\right)^{L_{Payload}}\right] \tag{3.22}$$

This expression of p_k, is a function of the transmission probabilities of the other OBUs via the *pdf* functions f_{X_i}.

Throughput expression

We now derive the throughput of an OBU k, at a given distance d_k from the RSU. This throughput depends on the position of all other OBU and their transmission probabilities τ_i. Finally, the throughput of an OBU k is given by the function $Z(p_k, \tau_k)$ as defined in the equation 3.23.

$$Z(p_k, \tau_k) = \frac{\tau_k (1 - p_k) L}{(1 - P_{tr}) \sigma + P_{tr} P_s T_s + P_{tr} (1 - P_s) T_c} \tag{3.23}$$

In the numerator of the throughput expression, we put the average number of useful bits transmitted in a slot time whereas the denominator corresponds to the average duration of a slot. σ is the physical slot time of 802.11 MAC layer. T_s and T_c are respectively the duration of a slot when a packet is successfully transmitted and the duration of a slot when two or more packets collide. L is the payload size. With P_{tr}, we denote the probability that at least one of the n OBU is transmitting and is defined in equation 3.24. P_s denotes the probability that such transmission is successful and is defined in equation 3.25.

$$P_{tr} = 1 - \prod_{i=1}^{n} (1 - \tau_i) \tag{3.24}$$

$$P_s = \frac{\sum_{i=1}^{n} \tau_i (1 - p_i)}{P_{tr}} \tag{3.25}$$

3.3 Performances analysis

3.3.1 Protocol validation

For the Validation of the protocol we implemented it on Qualnet 4.5 [13] using as a physical layer the 802.11a that we upgraded to correspond to the specifiaction of 802.11p with the corresponding parameters of the standard and the 802.11e MAC layer.

Protocol specific parameters

We have set our simulation parameters to the values reported in the ETSI specification draft corresponding to the European channel allocation. The height, gain, and transmitting power of the antennas have been based on commonly recommended values in white papers and technical reports related to both technologies. The path loss fading model has been set to a two-ray Ricean fading model with a high line-of-sight component ($K = 10$) which is quite realistic in a context of highway (unlike in an urban environment where this assumption is not valid anymore)

Physical layer set value:

- Frequency $5.87GHz$
- Channel bandwidth $10MHz$
- RSU Tx power $23dBm(= 200mW)$
- RSU antenna height $2.4m$

- RSU antenna gain $3dBi$
- MS Tx power $23dBm (= 200mW)$
- MS antenna height $1.5m$
- MS antenna gain $0dBi$
- Type of antenna Omnidirectional
- Pathloss Two-ray
- Fading model Ricean ($K = 10$)

MAC layer set value:

- MAC protocol IEEE 802.11e
- Short Packet Transmit Limit 1 (no retransmission)
- Long Packet Transmit Limit 1 (no retransmission)

Scenarios and validation

In this Section we present a number of scenarios that validate our model. The performance of all the scenarios were investigated by using the network simulator Qualnet 4.5 and the obtained results have a confidence interval of 95%. In the scenarios we investigate the reception throughput that a RSU obtains with respect to other stations that are transmitting messages for an increasing channel load.

First scenario: We placed two OBUs at 50 meters and one at 200 meters from the RSU, we changed the frequency of transmitting a packet in $[1..10000]Hz$ while keeping the channel basic rate at 3 Mbps. The resulting throughput evolution is given by the figure 3.2. We notice in this configuration the throughput value for each station is the same. In fact, the implemented mechanism in the protocol leads to an imposition of the throughput of the farest OBU that makes the throughput of the two closed OBUs lower.

Second scenario: We placed one OBU at 50 meters and two at 200 meters from RSU, we changed the frequency of transmitting a packet in $[1..10000]Hz$ while keeping the channel basic rate at 3 Mbps. The resulting throughput evolution is given by the figure 3.3. For this scenario, we observe the same behavior of the network keeping the same throughput value for the same reasons than the previous scenario.

Analysis of the first and second scenario: For the two previous scenarios, we did not implement any mechanism of auto-rate fallback and, hence, the throughput is equal for all OBUs whatever the distance from the RSU. This corresponds to the conclusion of the work done by M. Heusse and all [15].

Third scenario: We placed two OBUs at 50 meters and one at 200 meters from RSU, we set the frequency of transmitting a packet at $1Hz$ for both OBU-1 and OBU-3 and we changed it in $[1..10000]Hz$ for the OBU-2 while keeping the channel basic rate at 3 Mbps. The resulting throughput evolution is given by the figure 3.4. For this scenario the OBU-2 obtains all the network throughput. In fact, OBU-1 and OBU-3 are limited in transmission to $1Hz$.

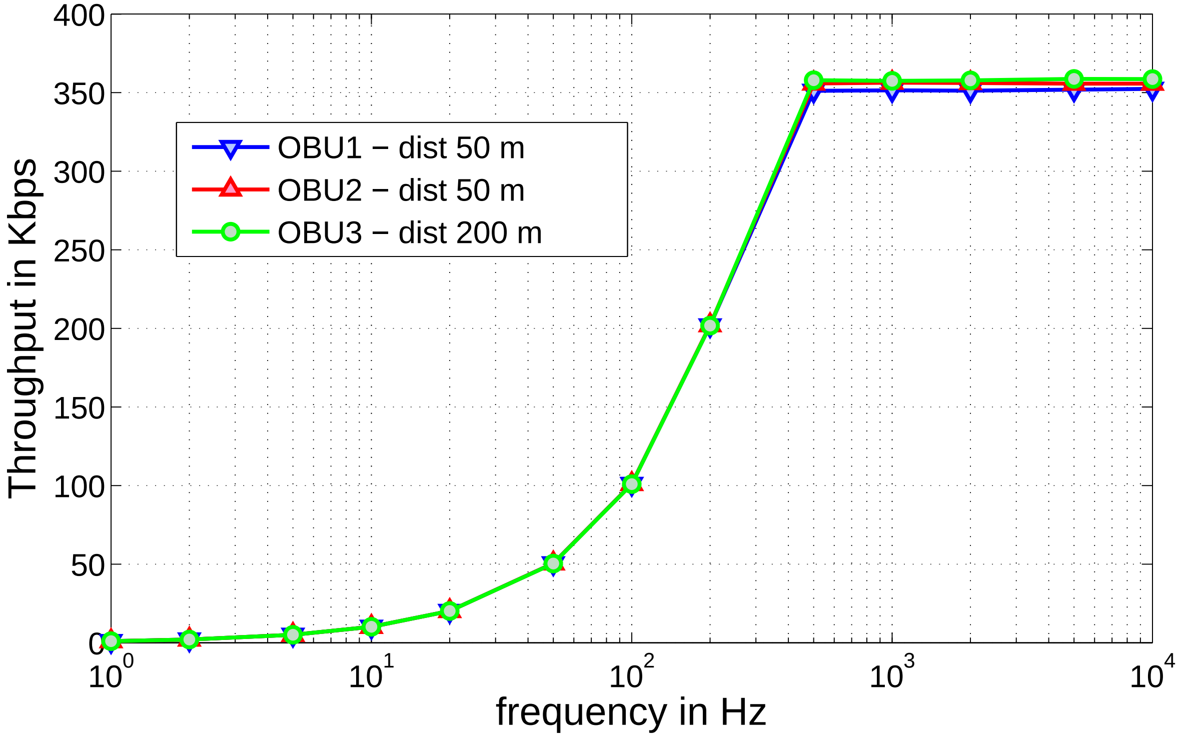

Figure 3.2: Evolution of the throughput for the first scenario

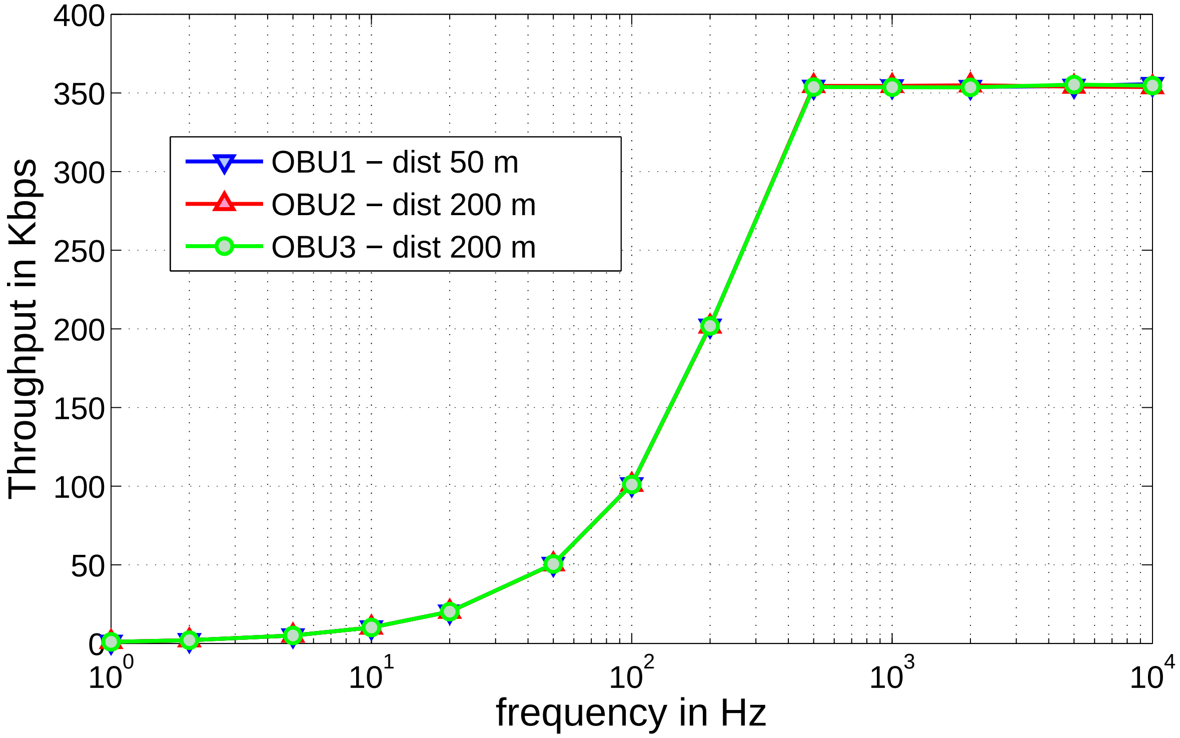

Figure 3.3: Evolution of the throughput for the second scenario

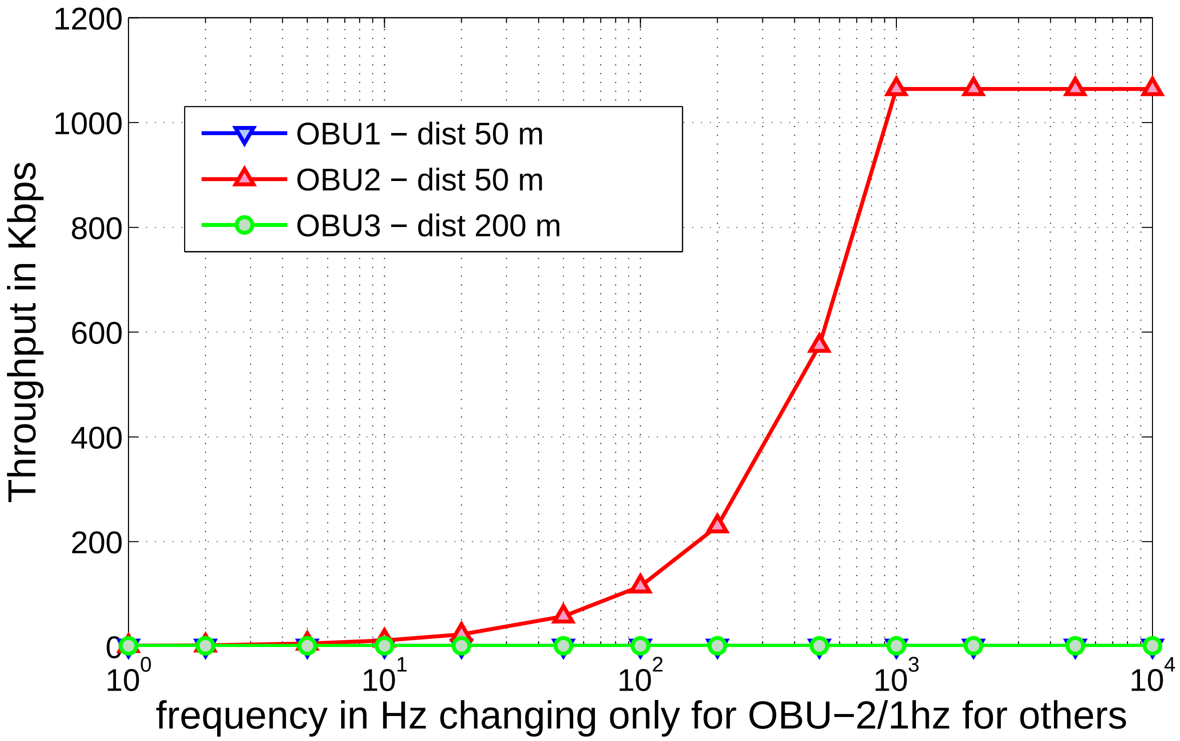

Figure 3.4: Evolution of the throughput for the third scenario

Fourth scenario: We placed two OBUs at 50 meters and one at 200 meters from RSU, we set the frequency of transmitting a packet at $1Hz$ for both OBU-1 and OBU-2 and we changed it in $[1..10000]Hz$ for the OBU-3 while keeping the channel basic rate at 3 Mbps. The resulting throughput evolution is given by the figure 3.5. In this scenario, the throughput evolution we have the same conclusion as for the previous scenarios. In fact, the distance does not impact the throughput and as OBU-1 and OBU-2 are limited in transmission to $1Hz$, then, OBU-3 obtains all the available network throughput.

Analysis of the third and fourth scenario: For the two previous scenarios, we did not implement any mechanism of auto-rate fallback. However, the throughput at the transmission is not the same for all OBUs and so will be at the RSU. In this case there is no influence due to the distance.

Fifth scenario: We placed two OBUs at 50 meters and one at 200 meters from RSU, we changed the frequency of transmitting a packet in $[1..10000]Hz$ while setting the channel basic rate at 24 Mbps for OBU-1 and OBU-2 and at 3 Mbps for OBU-3. The RSU radio type is set on Auto Rate Fallback to be able to exchange messages with different channel encoding modes corresponding to the two encoding modes (OBU-1 and OBU-2 on the one hand, and OBU-3 on the other hand for this configuration). The resulting throughput evolution is given by the figure 3.6. We obtain in this figure that one of the OBU having the highest data rate obtain the totality of the throughput available in the network.

Sixth scenario: We placed two OBUs at 50 meters and one at 200 meters from RSU, we changed the frequency of transmitting a packet in $[1..10000]Hz$ while setting the radio type on Auto Rate Fallback to be able to exchange messages with different channel encoding

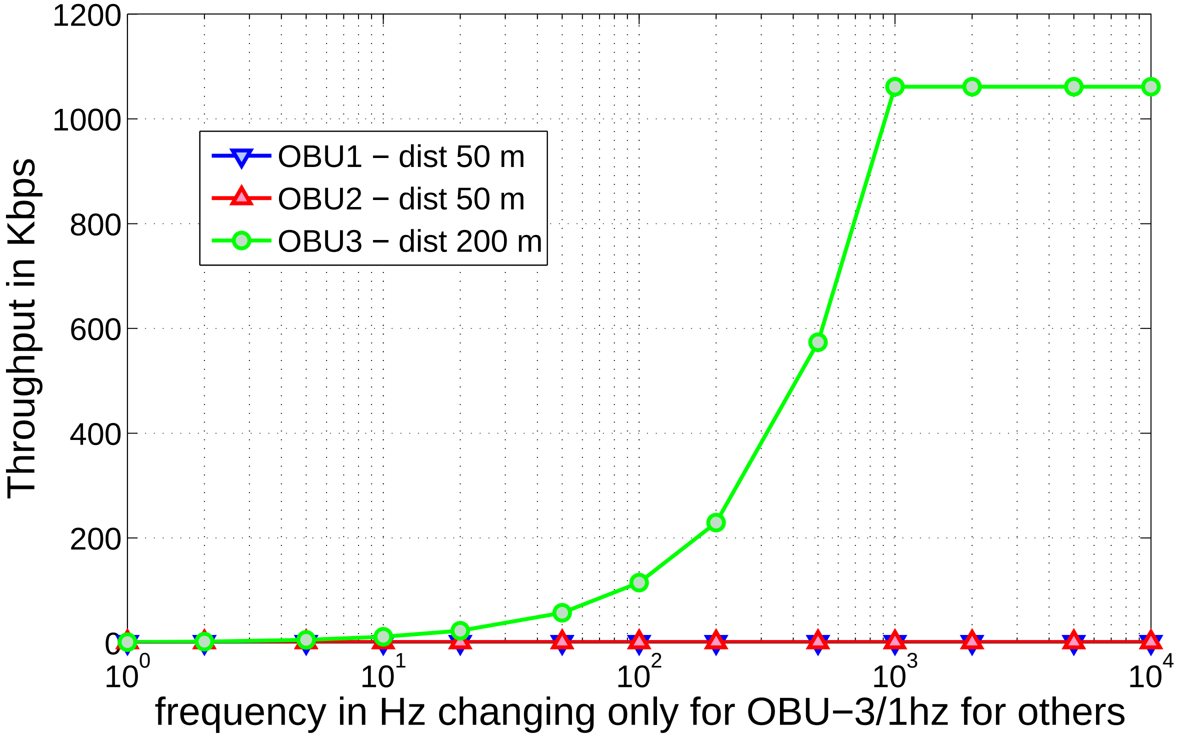

Figure 3.5: Evolution of the throughput for the fourth scenario

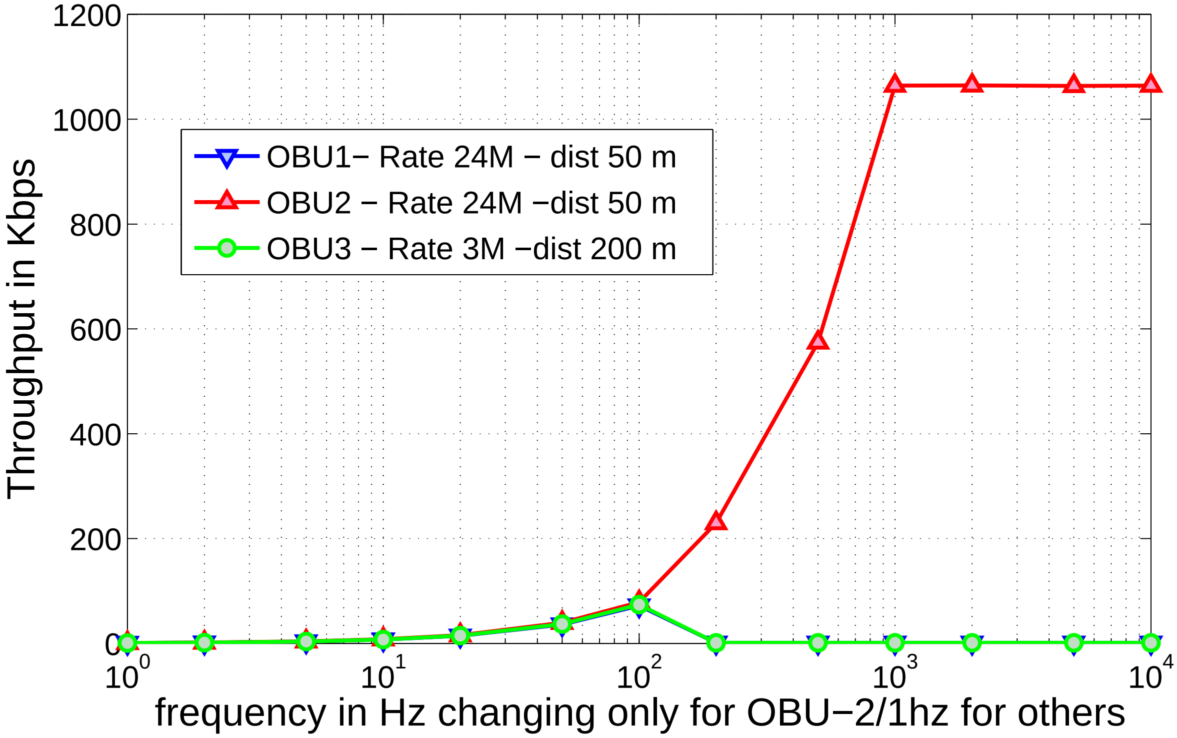

Figure 3.6: Evolution of the throughput for the fifth scenario

mode channel basic rate for OBU-1, OBU-2, OBU-3, and the RSU. The resulting throughput evolution is given by the figure 3.7. This configuration is so far the best. In fact, in this case we have penalty due to the distance. OBU-3 as being the farest from the RSU obtains the less throughput in saturation phase where OBU-1 and OBU-2 obtain the same throughput but higher than the throughput available for OBU-3 as being the closest in distance. This is explained by the implementation of the Auto-Rate Fallback mechanism that adapt both the modulation and, hence, the resulting coding approach which occurs a less throughput available for the farest stations but less packet probability error.

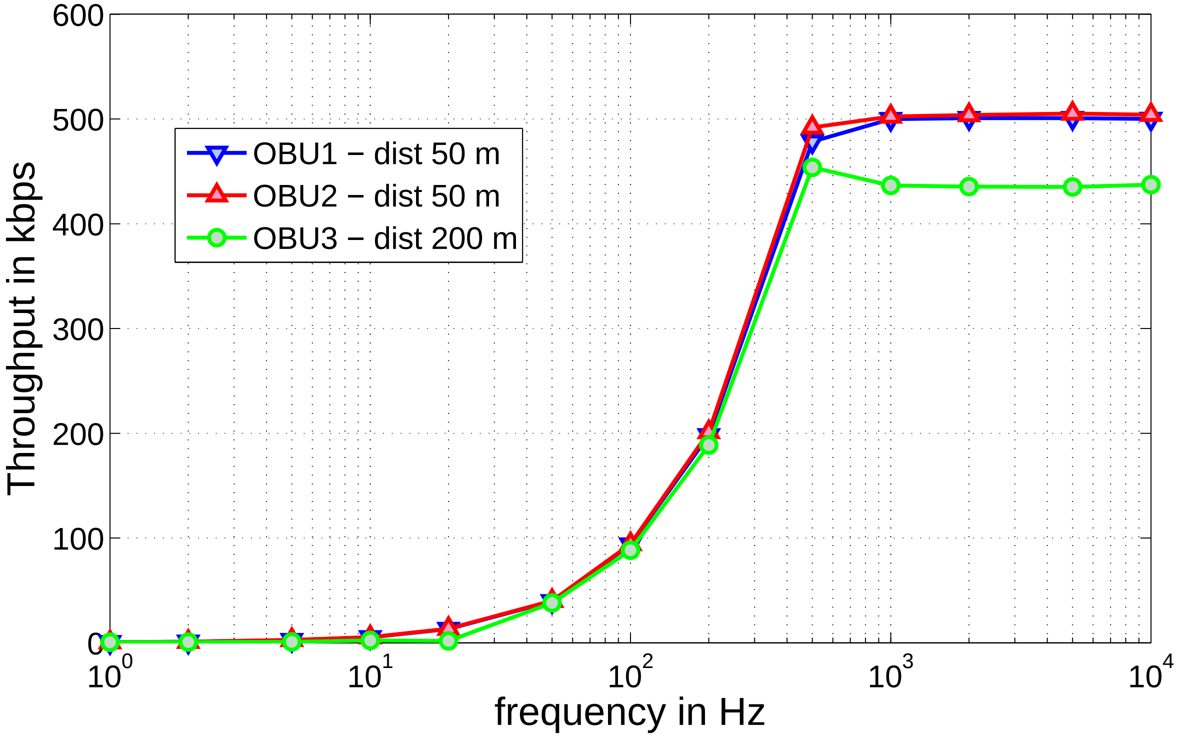

Figure 3.7: Evolution of the throughput for the sixth scenario

Seventh scenario: We placed ten OBUs at 50 meters and ten at 200 meters from RSU, we changed the frequency of transmitting a packet in $[1..10000]Hz$ while setting the radio type on Auto Rate Fallback to be able to exchange messages with different channel encoding mode channel basic rate for OBU-1, OBU-2, OBU-3, and the RSU. The resulting throughput evolution is given by the figure 3.8. In this scenario we observe that, on the one hand, the closest OBUs have a highest available throughput than the farest ones. On the other hand, after a certain load of the network corresponding to the frequency of transmitting a packet of $200Hz$, the network auto adapt by providing a lower throughput. However, this network behavior needs further investigations and a deeper study to be better understood.

3.3.2 Model implementation and results

Implementation environment

We implemented our model on Matlab 7.9.0 (R2009b) for Linux environment.

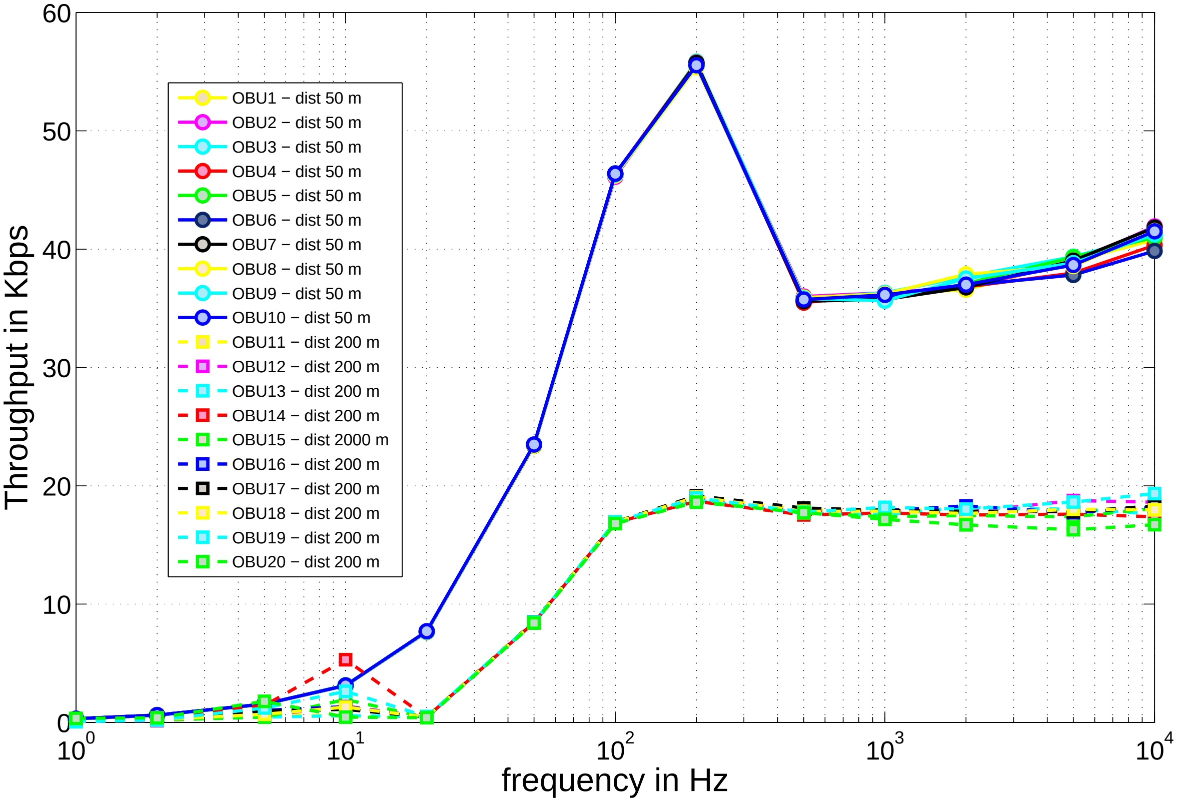

Figure 3.8: Evolution of the throughput for the seventh scenario

Obtained results

Implemented scenario

After implementing our Model, we placed two OBUs at 3 meters and one at 100 meters from the RSU. We changed the frequency of transmitting a packet in $[1..10000000]Hz$. We obtained the figure 3.9.

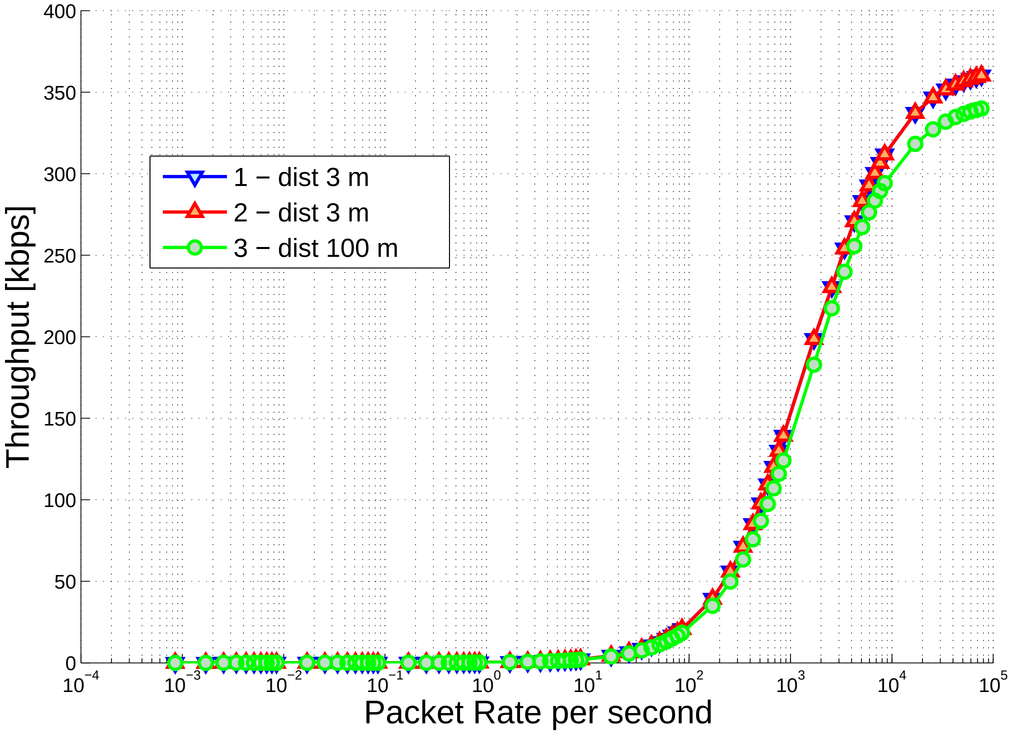

Figure 3.9: Evolution of the throughput according to our model

The result depicted in 3.9 corresponds to the results depicted in 3.7. In fact, both graphics are composed of three parts: a part in which the throughput value is low, a second part where it increases exponentially, and a third part of saturation in which the throughput reaches its maximum value.

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3.4 Conclusion and future directions

In this chapter we presented a simple and approximated model of the IEEE 802.11p protocol by modeling the IEEE 802.11e MAC layer and by taking into account the physical characteristics of the protocol. Despite the fact that our model is not exhaustive since it does not consider all the physical layer features, nor unicast transmission, it still describes the behavior of the transmission on IEEE 802.11p. This means that this model can be used as a simple tool in the cases where vehicular transmission on the control channel does not need to be accurately described. For example, this tool can be used in the study of the optimal placement of roadside units. In fact, for this problem, transmission performance is just one of the multiple metrics (e.g., deployment plan, user's service satisfaction analysis, etc...) to consider and an accurate description of the communication part might not be needed. In the following chapter, we will propose a better deployment for IEEE 802.11p RSU strategies based on our model detailed in this chapter.

Chapter 4

A better deployment of IEEE 802.11p Road Side Units

4.1 Introduction

The wireless networks serve generally to provide a connection where it is impossible to use wired network . However, they begin however to include the mobile stations on large areas. In urban environment, vehicular networks have been proposed as future solution to connect mobile users to the network. A wireless network is composed of network adapters and access points, which are connected to high broadband network . For vehicular network, the On Board Units (OBUs) that represent the mobile part of the wireless network are connected to fixed Road Side Units (RSUs). One of the key issues which must be settled is the location of the RSUs in order to maximize the network range and throughput.

To provide a solution to this issue, several approaches can be adapted. In the rest of this chapter we will first detail the different approaches and then propose the best approch to solve this problem.

4.2 Simulations and experimental appoach

In this approach, the optimal placement of the RSUs is a process based on empirical rules stemming from a human expertise. A way of helping in the conception of network consists in developing simulation programs in order to quantify the phenomena of interferences between stations and the path loss signals. A description of the deploying environment can be proposed and, hence, the level of realism is dependent on the used waves propagation model.

As a first step, we can decompose the model of the signal attenuation as a sum of two terms. The first term corresponds to the distance between the RSU and the OBU and the second represents the losses due to the met obstacles, the type of materials is considered for each of these obstacles. The model will be empirical and the values of the corresponding coefficient to the types of materials can be defined from real measures. In this step, we do not consider neither interferences between stations nor phenomena of signal reflexion.

As a second step, we can consider OBUs positions by using statistical data. The phenomena of interferences and signal attenuation can be then considered and estimated.

For a set of OBUs that we know the positions, we can propose via a numerical simulation, an estimation of the coverage of the network. To optimize the RSUs placement, we have to define the objective functions and the parameters defining the positions of the OBUs

4.3 Modeling based on simulations and experimentations approach

In this approach, the conception of a VANET network contains the following steps:

- Definition of the map of the local demands: we divide this area into points of service demand where we observe the signal of the RSUs and where the number of users and the needed thoughput are estimated.
- Selection of the possible positions for the RSUs according to the constraints.
- Measurements of the signal at the demand area, which has to be above a certain threshold to guarantee an acceptable throughput.
- Choice of the position of the RSUs in order to maximize the coverage and the throughput, then choice of channels for the RSU that avoid the interferences which strongly reduce the network performances
- Reconfiguration based on statistical use of the network.

In a wireless network composed of several mobile nodes, the coverage is not the only issue. It is also necessary to distribute suitably the load between the RSUs. Otherwise a RSU can be overloaded while its neighbors are unused. It is, thus, necessary to try to place RSUs so as to maximize the throughput by OBUs by distributing the load on all available RSUs.

To provide a solution to this issue, we have to know first the following elements:

- A set of points of service demand area N_d.
- The average volume of traffic of every service demand T_i.
- A set of candidate points to be a RSU N_a.
- The matrix of signal $S = \{S_{ij}\}$.

From these elements, we build the graphs of distribution of the RSUs and channels:

- Graph of distribution of the RSUs: $G = (N, E)$, where N is composed by N_d and N_a. A link exists between i and j if S_{ij} is bigger than certain thresholds.
- Graph of distribution of channels: $G_a = (N_a, E_a)$, where a link exists between two OBU if they are at a distance of interference.

Finally, we formulate the problem of minimization of the maximum of the use of the channel of one RSU while satisfying the demand traffic.

This variable will be noted α. It is a good metric for this kind of problem that emphasizes, indeed, the congestion of the network. The choices to adopt in order to minimize this variable are:

- Determine to which RSU, we connect every demand point.

- Determine which channels must be used for every RSU.
- Determine which RSU to select.

We, thus, want to minimize α by satisfying the conditions:

- Every demand point must be connected with a RSU.
- The total request traffic of points connected with to a given RSU must be lower than the available bandwith of RSU.
- All the RSU which connect at least a point of demand which must be selected.
- A channel must be assigned to all selected RSU.
- We have to avoid overlapping channels while assigning channels to selected RSUs.

We deduce from these constraints a linear programming problem, which is necessary to optimize in order to have the wished results.

4.4 RSUs placement based on an independent model

In this section, we are going to propose models based on the model of channel proposed in Chapter 3. We opt for two phases of resolution of the problem. The first one where we deal with a single RSU and the second in the case of some RSUs to place. We also ask some questions in particular on the criteria of optimality and optimization of the place of the RSU. The criteria of optimality concern the metrics of the network which we have to optimize and here we have to optimize the throughput of the network while improving the fairness between OBUs. The criteria of optimization tend to find the application level of the optimality criteria that starts from the global vision of the network at the level of the OBUs: That's to say we aim at maximizing the total throughput of the network or rather maximizing the minimum throughput which can have any OBU of the network.

4.4.1 Case of a single RSU in the network

We are going, first, to distribute uniformly the OBUs on a surface limited, for example, X and Y the coordinates of a given OBU vary respectively between X_{min} and X_{max}, Y_{min} and Y_{max} in a uniform way, we can start from the random numbers x_1 and y_1 varying between 0 and 1, we can write:

$$X = X_{min} + x_1 \left(X_{max} - X_{min} \right) \tag{4.1}$$

$$Y = Y_{min} + y_1 \left(Y_{max} - Y_{min} \right) \tag{4.2}$$

Then, we consider equation (3.23) presented in the Chapter 3:

This equation gives the value of the throughput of an OBU K distant from the RSU of a distance D.

We propose four models of optimization:

- Maximization of the sum of the throughputs of the OBUs (4.3):

$$D_1\left(RSU_x, RSU_y\right) = Max \sum_n Z\left(p_k, \tau_k\right) \tag{4.3}$$

- Maximization of the sum of the log of throughputs of the OBUs (4.4):

$$D_2\left(RSU_x, RSU_y\right) = Max \sum_n log\left(Z\left(p_k, \tau_k\right)\right) \tag{4.4}$$

- Maximization of the median of throughputs of the OBUs (4.5):

$$D_3\left(RSU_x, RSU_y\right) = Max\left(Med_n\left(M_{1\times n}\left(Z\left(p_k, \tau_k\right)\right)\right)\right) \tag{4.5}$$

With:

$$M_{1\times n}\left(Z\left(p_k, \tau_k\right)\right) = \left(Z\left(p_1, \tau_1\right), Z\left(p_2, \tau_2\right), ..., Z\left(p_i, \tau_i\right), ..., Z\left(p_n, \tau_n\right)\right)$$

And

$$Med_n\left(X_{1\times n}\right) = X_{i/i\in[1,n]} : Min \sum_{k=1}^{n} Abs\left(X_i - X_k\right)$$

- Maximization of the minimum of throughputs of the OBUs (4.6):

$$D_4\left(RSU_x, RSU_y\right) = Max\left(Min\left(Z\left(p_k, \tau_k\right)\right)\right) \tag{4.6}$$

where D_i represents the best solution given by its position(RSU_x, RSU_y).

The validation of the results of the four models presented above is done mainly according to two metrics: throughput of the network and fairness between OBU. A priori, the model of the equation (4.3) will present the highest average throughput of the network and guarantee no faireness between OBUs where the model of the equation (4.6) is the model which guarantees the best faireness but not guarantees high average throughput of the network.

It remains to focus on the models of the equations (4.4) and (4.5) if they present a good compromise between average network throughput and fairness between OBUs.

4.4.1.1 Mathematical used tool

Let $\overline{D}$ be the average throughput computed for n OBUs and expressed in the equation (4.7)

$$\overline{D} = E\left[Z\left(p_k, \tau_k\right)\right] = \frac{1}{n}\sum_n Z\left(p_k, \tau_k\right) \tag{4.7}$$

Concerning the measure of the fairness, we have two mathematical tools to do it that are the variance of the throughput and the Jain Fairness Index.

The variance informs us on the distance of distribution of the throughput so allowing to give one information about the importance of these distances. However, Jain Fairness Index informs us about the fairness of the distribution of the throughputs.

Let V be the variance of the throughputs as given by the equation (4.8).

$$V = \frac{\sum_n \left(D_i - \overline{D}\right)^2}{n} \tag{4.8}$$

We note JFI the Jain Fairness Index that is computed as shown in equation (4.9).

$$JFI\left(D_1, D_2, ..., D_n\right) = \frac{\left(\sum_{i=1}^{n} D_i\right)^2}{n\sum_{i=1}^{n} D_i^2} \tag{4.9}$$

The computed JFI value is always between 0 and 1 as explained in equation (4.10).

$$0 \leq JFI\left(\right) < 1 \tag{4.10}$$

The value of the JFI is interpreted as:

- If the throughput distribution is fair between the n OBUs, then the JFI value is close to 1
- If there is only k from n OBUs that share fairly the totality of the available throughput, then the JFI value is equal to $\frac{k}{n}$.

Afterwards, and to be able to validate the obtained results, we have to do many simulations and calculate the confidence intervals in which the values of total throughput and of Jain Fairness Indexes have to be with a confidence rate equal to 95%. These confidence intervals are obtained as follows:

Let $X = \{X_1, X_2, ..., X_N\}$ be the vector of the obtained results from repeated measures. We approximate the measured quantity by the average of the results: $Y = \frac{1}{N}\sum X_i$.

- If the values of X_i are closed, then it's good, we have a good measure of expected quantity.

- But, if this is not the case? How to know if we are closed from the exact value of the measured quantity? (The higher N is, the closer we are to the exact value of the measured quantity)

- Let μ be the exact value of the measured quantity ($= E\left[X_i\right]$). We want to approximate μ.

- The X_i can be considered as independents and their average Y can be assumed as following a normal distribution.

- $E\left[Y\right] = \mu$

- We approximate the variance of Y by : $s = \frac{1}{N-1}\left(X_i - Y\right)^2$.

- $\frac{y-\mu}{\sigma/\sqrt{N}}$ can be considered as following a standard normal distribution Φ.

- The function of density of probability *pdf* (Φ) is equal to $f_\Phi\left(x\right) = \frac{1}{\sqrt{2\pi}}e^{-\frac{1}{2}x^2}$.

- *pdf* (Φ) is equal to $P\left(\Phi < a\right) = \frac{1}{2} + \frac{1}{2}erf\left(\frac{a}{\sqrt{2}}\right) = \frac{1}{2} - erfc\left(\frac{a}{\sqrt{2}}\right)$

with

$$erfc\left(b\right) = \frac{2}{\sqrt{\pi}}\int_b^\infty e^{-u^2}du$$

$$erfc\left(0\right) = 1$$

and

$$erfc\left(\infty\right) = 0$$

There are several tables that give the values for the functions erf and $erfc$.

- Then, we can write :

$$P\left(-a < \Phi < a\right) = erf\left(\frac{a}{\sqrt{2}}\right) = 1 - erfc\left(\frac{a}{\sqrt{2}}\right)$$

- As a consequence, we have

$$P\left(y - a\frac{\sigma}{\sqrt{N}} < \mu < y + a\frac{\sigma}{\sqrt{N}}\right) = 1 - erfc\left(\frac{a}{\sqrt{2}}\right)$$

- Thus, the exact value is in the interval $y \pm a\frac{\sigma}{\sqrt{N}}$, with a probability of $1 - erfc\left(\frac{a}{\sqrt{2}}\right)$.

- Finally, we draw y and we draw around it a vertical interval $y \pm a\frac{\sigma}{\sqrt{N}}$ and we can predict that the exact value of y is in this interval with a probability $1 - erfc\left(\frac{a}{\sqrt{2}}\right)$.

- The smaller the interval is, the better the results are.

- For a given approximation, the more number of sample (N) is, the smaller confidence interval is.

- The smaller σ is , the smaller the confidence interval is .

- An increase of level of confidence leads to an increase of the value of a and, hence, the confidence interval becomes larger.

4.4.2 Case of multiple RSUs in the network

This part is a natural extension of the one that precedes and in which we present possible models for the resolution of the problem. But, first of all, we are going to expose the general problem and for this, indeed, let us note that for the case of multiple RSUs we are confronted with two difficulties that are the optimization of the deployment of RSUs and especially the affectation of the OBUs to them.

An OBU can be connected to single RSU at the given time. The RSU will use different frequency bands to avoid interference problems. Let us focus again on the equation (3.23):

This equation gives the value of the throughput of an OBU k placed at a distance d from the RSU. For this part, we introduce a matrix of affectation A: this matrix has a dimension of

$1 \times RSUnumber$ where $RSUnumber$ indicates the number of RSUs in the network. As an OBU is connected to a one and only one RSU at a given time, we can write the following constraint on A:

For a given OBU, the constraint of affectation is given by the equation (4.11).

$$\sum_{RSUnumber} A\left(1, i\right) = 1 \tag{4.11}$$

Then, for adapting the equation of the throughput of an OBU (4.11), we first introduce, the following modifications on our model:

The equation of the power of the signal of a transmitting OBU i located with a distance D_i from the RSU changes to its new expression given in equation (4.12).

$$L\left(D_i\right) = A\frac{P_0}{D_i^{\alpha}} \tag{4.12}$$

This change has an impact on the values of equations (3.18), (3.19) ,(3.20), and (3.23) but does not change their expressions.

The four models introduced above for finding the best position of a single RSU can be written here for the case of multiple RSUs as follows:

For:

$$RSU = \begin{pmatrix} RSU1_x & RSU2_x & RSUi_x & ... & RSUn_x \\ RSU1_y & RSU2_y & RSUi_y & ... & RSUn_y \end{pmatrix}$$

Where RSU represents the matrix of best solutions given by the positions of the involved Road Side Units.

- Maximization of the sum of the throughputs of the OBUs (4.13):

$$D_5\left(RSU_x, RSU_y\right) = Max \sum_n A.Z\left(p_k, \tau_k\right) \tag{4.13}$$

Under the constaints

$$\sum_{RSUnumber} A\left(1, i\right) = 1 \ \ (4.11)$$

- Maximization of the sum of the log of throughputs of the OBUs (4.14):

$$D_6\left(RSU_x, RSU_y\right) = Max \sum_n A.log\left(Z\left(p_k, \tau_k\right)\right) \tag{4.14}$$

Under the constaints

$$\sum_{RSUnumber} A\left(1, i\right) = 1 \ \ (4.11)$$

- Maximization of the median of throughputs of the OBUs (4.15):

$$D_7\left(RSU_x, RSU_y\right) = Max\left(Med_n\left(M_{1\times n}\left(A.Z\left(p_k, \tau_k\right)\right)\right)\right) \tag{4.15}$$

Under the constaints

$$\sum_{RSUnumber} A\left(1, i\right) = 1 \ \ (4.11)$$

With:

$$M_{1\times n}\left(Z\left(p_k, \tau_k\right)\right) = \left(Z\left(p_1, \tau_1\right), Z\left(p_2, \tau_2\right), ..., Z\left(p_i, \tau_i\right), ..., Z\left(p_n, \tau_n\right)\right)$$

And

$$Med_n\left(X_{1\times n}\right) = X_{i/i\in[1,n]} : Min \sum_{k=1}^{n} Abs\left(X_i - X_k\right)$$

- Maximization of the minimum of throughputs of the OBUs (4.16):

$$D_8\left(RSU_x, RSU_y\right) = Max\left(Min\left(A.Z\left(p_k, \tau_k\right)\right)\right) \tag{4.16}$$

Under the constaints

$$\sum_{RSUnumber} A\left(1, i\right) = 1 \ \ (4.11)$$

Because of the complexity of the problem, we can apply heuristics to simplify it. We present the following simplification scenarios that are an eventual solution for the problem:

4.4.2.1 Scenario1:

For this scenario, the simplification of the problem consists in the fact that we do not have to optimize any more the affectation here because the OBUs will be connected according to their distance to the RSU as the distance is an important criterion . This scenario contains three steps: first of all, we are going to consider the same models as for a RSU. Afterwards, we are going to introduce the following modifications on these models to find the best places of the RSUs.

For:

$$RSU = \begin{pmatrix} RSU1_x & RSU2_x & RSUi_x & ... & RSUn_x \\ RSU1_y & RSU2_y & RSUi_y & ... & RSUn_y \end{pmatrix}$$

- Maximization of the sum of the throughputs of the OBUs (4.17)

$$D_9\left(RSU_x, RSU_y\right) = Max \sum_n Z\left(p_k, \tau_k\right) \tag{4.17}$$

- Maximization of the sum of the log of throughputs of the OBUs (4.18)

$$D_{10}\left(RSU_x, RSU_y\right) = Max \sum_n log\left(Z\left(p_k, \tau_k\right)\right) \tag{4.18}$$

- Maximization of the median of throughputs of the OBUs (4.19)

$$D_{11}\left(RSU_x, RSU_y\right) = Max\left(Med_n\left(M_{1\times n}\left(Z\left(p_k, \tau_k\right)\right)\right)\right) \tag{4.19}$$

With:

$$M_{1\times n}\left(Z\left(p_k, \tau_k\right)\right) = \left(Z\left(p_1, \tau_1\right), Z\left(p_2, \tau_2\right), ..., Z\left(p_i, \tau_i\right), ..., Z\left(p_n, \tau_n\right)\right)$$

And

$$Med_n\left(X_{1\times n}\right) = X_{i/i\in[1,n]} : Min \sum_{k=1}^{n} Abs\left(X_i - X_k\right)$$

- Maximization of the minimum of throughputs of the OBUs (4.20)

$$D_{12}\left(RSU_x, RSU_y\right) = Max\left(Min\left(Z\left(p_k, \tau_k\right)\right)\right) \tag{4.20}$$

Finally, the allocation will be done according to the distance of the OBUs to the RSUs.

4.4.2.2 Scenario2:

This scenario is similar to the previous one, the simplification of the problem consists in the fact that we do not have to optimize any more the affectation here because the OBUs will be connected according to their throughput. In this scenario, we suggest to divide the network on N_i groups of OBUs and each time we introduce a RSU in the network, we optimize with regard to N_k OBUs every time. We obtain the following models:

For N OBUs:

$$\sum N_k = N$$

- Maximization of the sum of the throughputs of the OBUs (4.21)

$$D_{13}\left(RSU_x, RSU_y\right) = Max \sum_{N_k \in N} Z\left(p_k, \tau_k\right) \tag{4.21}$$

- Maximization of the sum of the log of throughputs of the OBUs (4.22)

$$D_{14}\left(RSU_x, RSU_y\right) = Max \sum_{N_k \in N} log\left(Z\left(p_k, \tau_k\right)\right) \tag{4.22}$$

- Maximization of the median of throughputs of the OBUs (4.23)

$$D_{15}\left(RSU_x, RSU_y\right) = Max\left(Med_{N_k \in N}\left(M_{1\times N_k}\left(Z\left(p_k, \tau_k\right)\right)\right)\right) \tag{4.23}$$

With:

$$M_{1\times n}\left(Z\left(p_k, \tau_k\right)\right) = \left(Z\left(p_1, \tau_1\right), Z\left(p_2, \tau_2\right), ..., Z\left(p_i, \tau_i\right), ..., Z\left(p_n, \tau_n\right)\right)$$

And

$$Med_n\left(X_{1\times n}\right) = X_{i/i\in[1,n]} : Min\sum_{k=1}^{n} Abs\left(X_i - X_k\right)$$

- Maximization of the minimum of throughputs of the OBUs (4.24)

$$D_{16}\left(RSU_x, RSU_y\right) = Max\left(Min_{N_k \in N}\left(Z\left(p_k, \tau_k\right)\right)\right) \tag{4.24}$$

Each time we select N_k OBUs, we affect them to a RSU and we continue with the remaining $N - N_k$ OBUs until we affect all the N OBUs.

4.4.2.3 Scenario3:

This scenario aims at finding a graphical simplification to the problem. An approach would consist in dividing the network composed by OBUs on clusters where every cluster is composed of a minimum spanning tree. We consider our problem as being a problem of a minimum spanning tree:

Let G be a graph and w the weight function on its edges. We have to find a minimum spanning tree T for the graph G for which $\sum_{e\in T} w\left(e\right)$ is minimum.

Note that the resulting minimum spanning tree is a partial and connected graph of minimum weight. The algorithms to find a minimum spanning tree are based on the fact that a transverse edge of minimum weight is contained in a minimum spanning tree.

Definition: Let S be included in $V\left(G\right)$. An edge e connects x and y is $S - transverse$, if $x \in S$ and $y \in \overline{S}$.

Lemma: Let $G = (V, E)$ be a graph, w be weight function on the edges, and S be a part of V. If e is an edge between S and $\overline{S}$, of minimum weight, thus, a minimum spanning tree containing e exists. In particular, if e is an edge of minimum weight for which $w\left(e\right) = min_{f\subset E(G)} w\left(f\right) = w_{min}$, then a minimum spanning tree containing e exists.

Proof: Let T be a tree that does not contain the edge e. A path p connects S and $\overline{S}$ in this tree. There is at least an edge e' is $S - transverse$. Hence, the tree $T' = T/\left\{e'\right\} \cup \left\{e\right\}$

has the weight $w(T') = w(T) + w(e) - w(e') \leq w(e')$. Thus, if T was a minimum spanning tree, so is T' and $w(e) = w(e')$.

Kruskal's algorithm: The Kruskal algorithm is similar to the Prim algorithm and its validity is assured by the Lemma above. The idea of the algorithm of Kruskal is to start from spanning forest and to make its number decrease of constituents until we obtain a tree. At the beginning, the forest has no edges and in every stage we add one edge of minimum weight which connects two constituents. The algorithm is similar to that giving a covering tree except the fact that one edge chosen among the possible edges that do not form a cycle. This supposes that we sorted out, for example, edges to avoid comparing them every time. We can improve the algorithm by stopping as soon as we obtaine a spanning tree. In the following algorithm j represents the label of the current edge (choosen in the list sorted out) and i the number of edges already in T.

Kruscal's algorithm

```
1. Sort out the egdes according to their weight ($w(e_j) \leq w(e_{j+1})$)
2. Initialize $i = 0$, $j = 0$, and $T = \oslash$.
3. While ($i \leq n - 2$) do
        If ($T \cup e_j$) has a cycle
          $j = j + 1$
        Else $T = T \cup e_j$ and $i = i + 1$
      End (if)
   End (While)
```

For dividing the network into two clusters, we can stop at the step before the last step of the algorithm iteration. Then, we use the four models described above for a single RSU in network for each cluster.

4.4.2.4 Scenario4:

The main idea in this scenario is to affect the OBUs to the RSUs by repeating a reconfiguration of the nework until we find the best configuration. This approach may have a high algorithmic complexity, however, we strongly believe that is the best, so far.

Let us focus again on the equation (3.23) of our model.

$$Z(p_k, \tau_k) = \frac{\tau_k (1 - p_k) L}{(1 - P_{tr}) \sigma + P_{tr} P_s T_s + P_{tr} (1 - P_s) T_c} \quad (3.23)$$

This equation gives the throughput value of a given OBU in the network. The network is composed of several OBUs uniformly distributed on a limited area. We have proposed four optimization models for the case where the network contains a single RSU given in the equations (4.3), (4.4), (4.5), and (4.6).

As a first step for this scenario, we will affect all the OBUs of the network on a same RSU. Then and for each optimization model, we will compute the throughput matrix (4.25).

$$M = \begin{pmatrix} Z(p_1, \tau_1) & Z(p_2, \tau_2) & ... & Z(p_n, \tau_n) \end{pmatrix} \tag{4.25}$$

After that, we will take the OBU that has the least throughput and we will have two groups S_1 and S_2 where the first contains all the OBUs except the one that has the least throughput value as given by the equations (4.26) and (4.27).

$$S_2 := S_2 \cup Index\left(Min\left(M\right)\right) \tag{4.26}$$

$$S_1 := S_1 - S_2 \tag{4.27}$$

Then, we resolve again the optimization models (4.3), (4.4), (4.5), and (4.6) for each group S_1 and S_2.

For the validation of the results of the models presented above, we consider two metrics that are the throughput and the fairness between the OBUs. For the measurement of the average throughput for the n OBUs, we use the method given by the equation (4.7). For the fairness measurement, we dispose of two mathematical tools that are the variance (4.8) and the Jain Fairness Index (4.9). If we are looking for maximizing the total throughput, we have to redo the iterations until obtaining the $Max\left(\overline{D}\right)$. However, if we are looking to find the best fairness between the OBUs, we have to redo the iterations until obtaining the $Min\left(V\right)$ and $Max\left(JFI\right)$.

In case we have several RSUs, we have to continue each time until finding the solution for N RSUs. Then, we take the OBU which has the lowest throughput between the n OBUs in the network and do as for the previous model described for the case of two RSUs. We can stop when the evolution of the gain in throughput of the network becomes unimportant.

4.4.2.5 Choice of the scenario to implement:

The first scenario seems to be the easiest to implement but it does not give us a real solution to the problem because an OBU can only be connected to a single RSU at a given time. Thus we decided to spread this scenario and not implement it. The second scenario also seems to be well but the problem is that according to which heuristics are we going to decide on the number of the OBUs that will be connected to each RSU and that's why we will not implement this scenario. The third scenario considers neither the parameters of the physical layer nor those of the MAC layer that's why we will not be able to judge the realism and the exactness of the results and it is a scenario that we will not consider any more. The fourth scenario is a very good alternative and is one of the best approaches for the solution of the problem because it manages at the same time the optimization of the RSUs placement and the affectation of the OBUs to them.

4.4.3 Obtained results

4.4.3.1 Case of a single Road Side Unit in the network:

In this section, we are going to compare the four models of optimization according to two criteria of comparison that are the total throughput of the OBUs of the network and the fairness between these OBUs. We realized for this issue several simulations for networks composed of 5, 7, 10, 12, and 15 OBUs then we computed the confidence intervals for 95% to be able to make general conclusions from the obtained results. The obtained results are given in table 4.1.

4.4.3.1.1 Interpretation of the results On the one hand, we notice that both the model of maximization of the sum of the throughput and the model of maximization of the sum of the log of the throughput are better in terms of total throughput of the network while that of

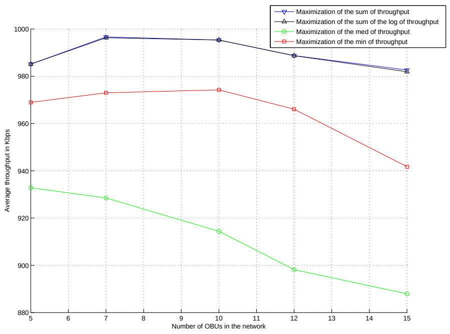
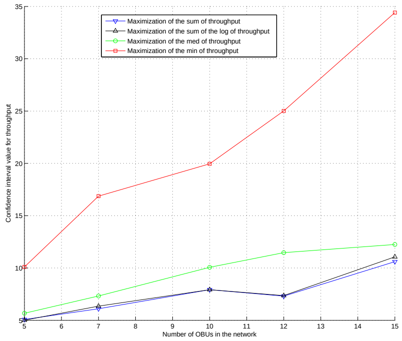
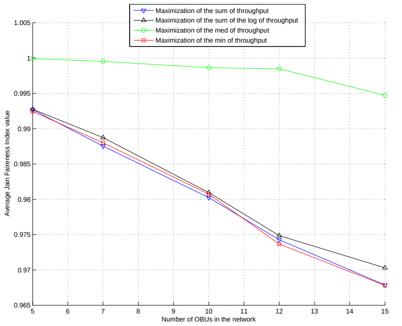
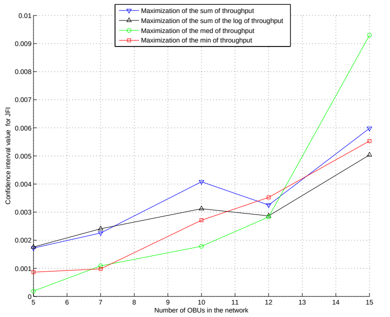
	Optimization Criteria	Confidence Intervals
Throughput		
Jain Fairness Index		

Table 4.1: Comparison between the adopted model for the RSU placement

maximization of the median of the throughput of the network provide the worst performances of the network. We can say also that the more we add OBUs in the network the more the total throughput of the network decreases and this phenomenon is due to the increase of the overhead in the network. On the other hand, after focusing on the figure of JFI for the four model, we are able to say that the model of maximization of the median is the best one for the fairness between the connected OBUs to the RSU. Finally, and after considering the two figures of confidence interval for both JFI and evolution of the throughput, we are able to conclude that the models of maximization of the sum and maximization of the sum of the log of the throughput are so far from the models that provide the best global network bandwidth where the model of maximization of the medium is the one that provides a fair distribution among the OBUs at 95%. We can also conclude that the model of maximization of the minimum of the throughput is useless.

4.4.3.2 Case of multiple Road Side Units in the network

In this section, we are going to to compare the obtained results for the case where we are looking for placing one, two or three RSUs in a network connecting ten OBUs for the four optimization models that we defined previously. As a first step, we will present the obtained results for each optimization model following three criteria that are:

- Deployment of RSUs providing connectivity to the OBUs: A1
- Evolution of the gain in throughput while optimizing the RSUs placement: A2
- Distribution of the available throughput to the connected OBUs of the network: A3

As a second step, the comparaison will be done between the four optimization models according to:

- Representation of the OBUs throughput: A4
- Comparison between the networks throughput: A5
- Comparison between the variances of the throughput of networks: A6
- Comparison between the standard deviation of the throughput of networks: A7
- Comparison between the JFI of networks: A8

4.4.3.2.1 Results for each optimization model

Results and interpretation for the model: maximization of the sum of the throughputs The results are given in the table 4.2.

Results and interpretation for the model: maximization of the sum of the log of throughputs The results are given in the table 4.3

Results and interpretation for the model: maximization of the mediane of the throughputs The results are given in the table 4.4

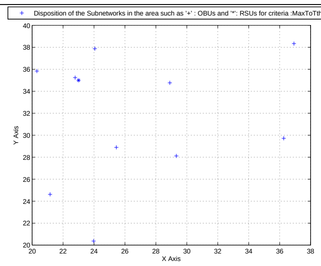
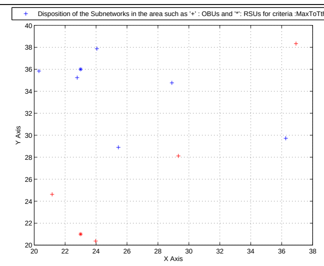
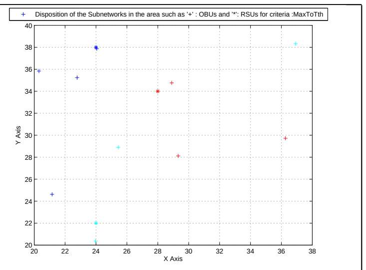
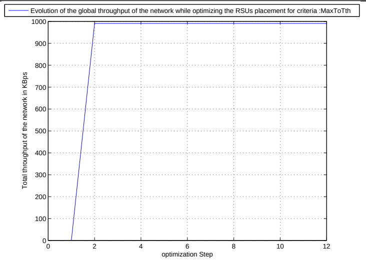
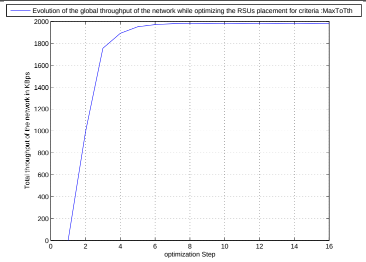
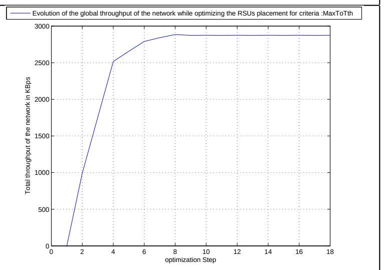
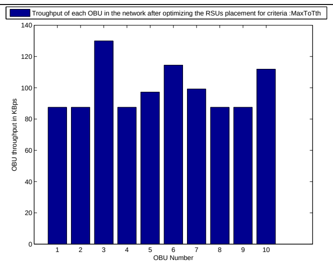
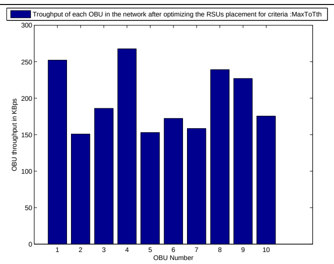
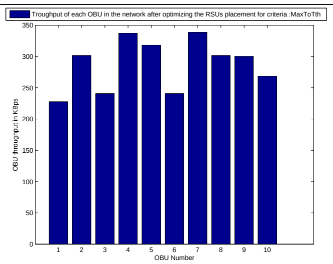
10 OBUs	1 RSU in the network	2 RSUs in the network	3 RSUs in the network
A1			
A2			
A3			

Table 4.2: Results for the optimization model: maximization of the sum of the throughputs

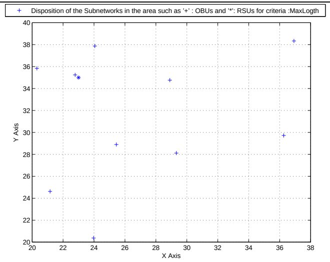
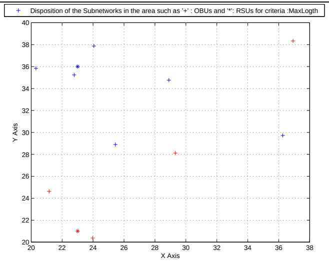
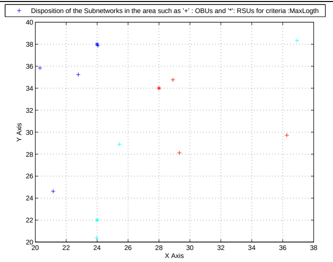
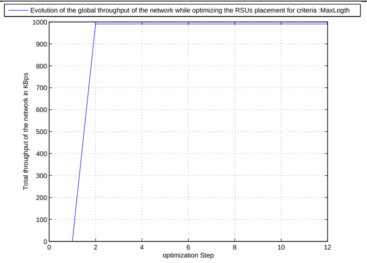
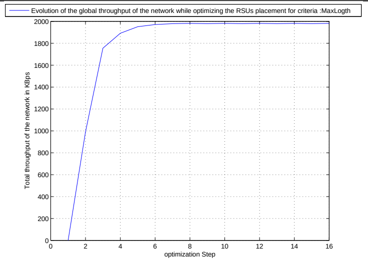
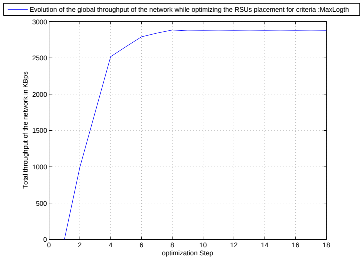
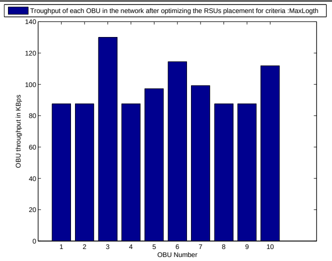
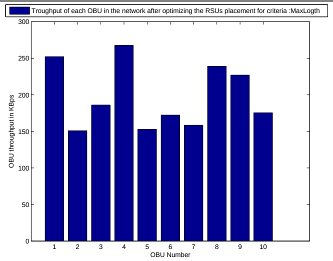
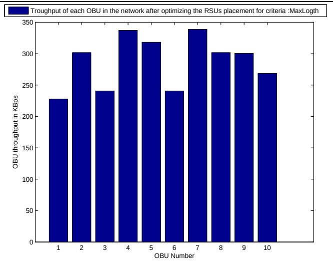
<table>
<tr><th>10 OBUs</th><th>1 RSU in the network</th><th>2 RSUs in the network</th><th>3 RSUs in the network</th></tr>
<tr><td>A1</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>A2</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>A3</td><td>
</td><td>
</td><td>
</td></tr>
</table>

Table 4.3: Results for the optimization model: maximization of the sum of the log of the throughputs

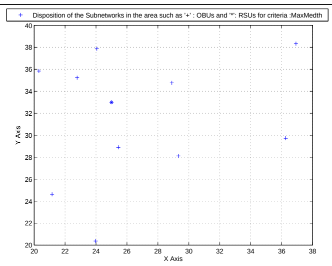
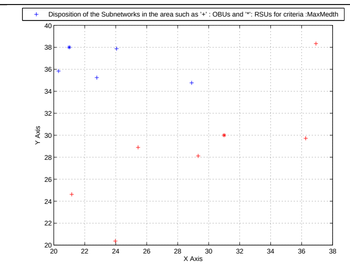
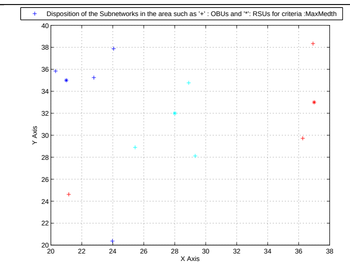
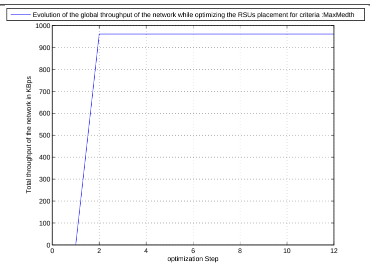
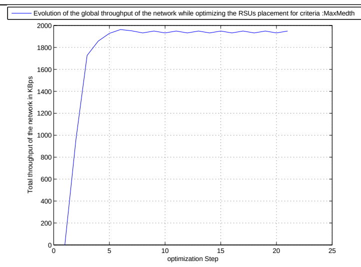
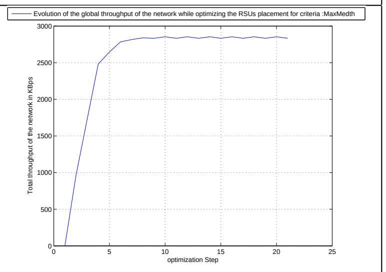
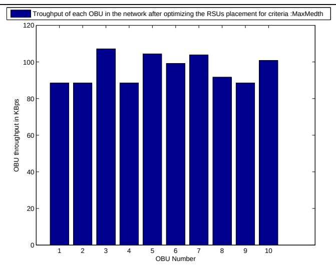
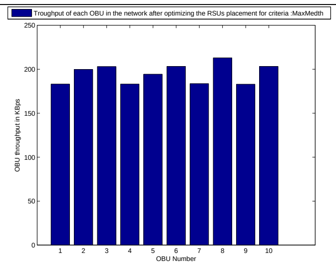
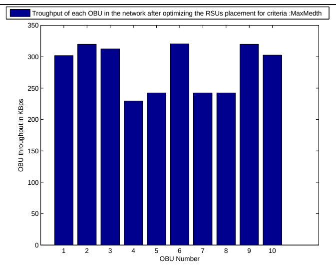
10 OBUs	1 RSU in the network	2 RSUs in the network	3 RSUs in the network
A1			
A2			
A3			

Table 4.4: Results for the optimization model: maximization of the mediane of throughputs

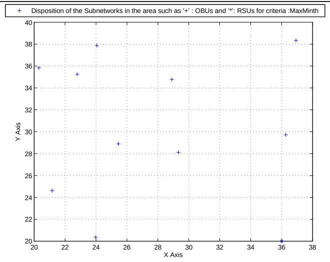
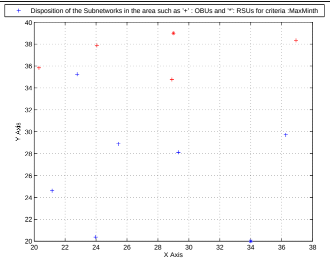
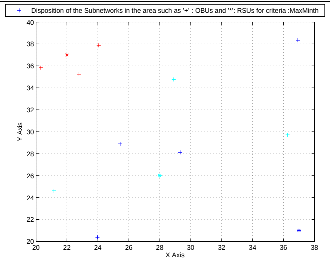
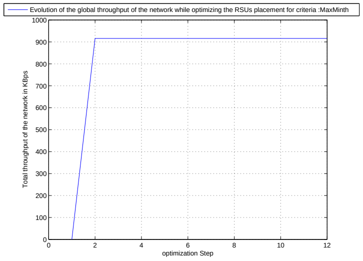
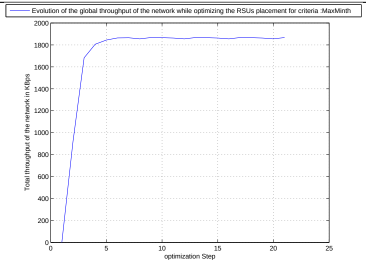
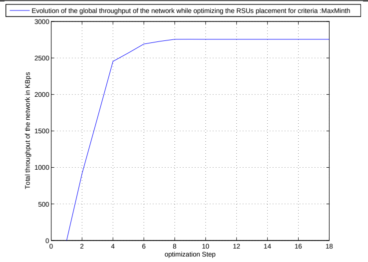
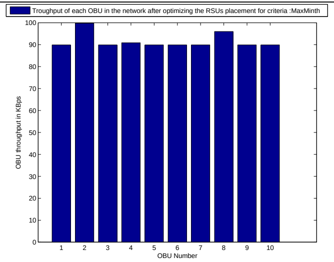
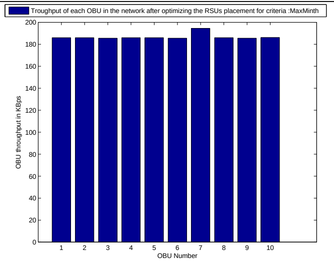
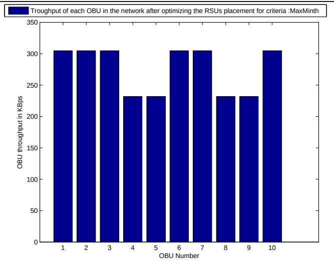
10 OBUs	1 RSU in the network	2 RSUs in the network	3 RSUs in the network
A1			
A2			
A3			

Table 4.5: Results for the optimization model: maximization of the minimum of throughputs

Results and interpretation for the model: maximization of the minimum of the throughputs The results are given in the table 4.5

Interpretation of the ressults

4.4.3.2.2 Comparison between the four optimization models

Obtained results for the four optimization models The results are given in the table 4.6

4.4.3.2.3 Interpretation of the obtained results As a conclusion we can say that adding of a RSU in the network allows to have a better network global throughput. The model of maximization of the sum of the throughputs and the one of maximization of the sum of the logarithms of the throughputs allow to obtain the best throughput of network followed by the model of maximization of the median of the throughput to have lastly the model of maximization of the minimum of the throughputs. Certainly the model of maximization of the median of the throughput display weaker performances, but this model allow indisputably an excellent level of faireness between the OBUs of the networks and hence is a good compromise throughput and faireness. The addition of RSU in the network considerably improve the faireness between OBUs.

Note that the model of maximization of the sum of the throughputs and the one of maximization of the sum of the logarithms of the throughputs are the fastest to solve in terme of number of operations as they cost less than the two others in term of complexity. Aslo, adding a RSU has a weak impact on the needed number of operation to solve the models.

4.5 Conclusion

The RSUs are fixed and deployed equipments on the public roads and they are providing network connectivity to the OBUs. Hence, they are the most important equipments in the vehicular networks. We strongly believe that a carelessness or a bad deployment of the RSUs in the network lead to a weak and bad use of the available network resources and that is prior to develop an efficient approach for the RSUs deployment.

We introduced in the previous chapter a model that is able to reproduce the expected results for IEEE 802.11p control channel. This model is an important step toward the improvement of vehicular networks performances. In fact, in this chapter we combined our model with optimization criteria for optimal placement of RSUs. We defined four model of optimization of the placement of RSUs that are the maximization of the sum of the throughput, the maximization of the sum of the logarithms of the throughput, the maximization of the median of the throughput, and the maximization of the minimum of the throughput. The validation of these models was done according to two criteria that are the real throughput of the network and the fairness between the OBUs inside it.

In this work, we were able to propose an efficient approach to the problem of deployment of the RSUs in vehicular network. Our contribution is scalable and can be adapted for any vehicular network environment.

As the RSUs can be connected to each other and to the Internet using Wireless Mesh Network backbone. We call "backbone level/infrastructure of the vehicular network" the

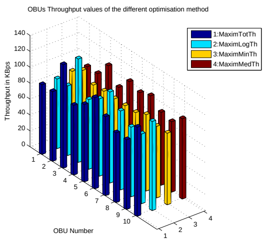
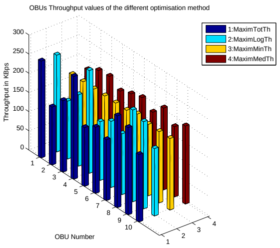
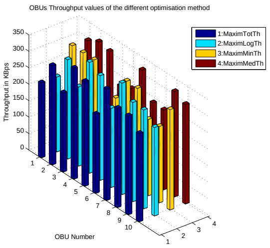
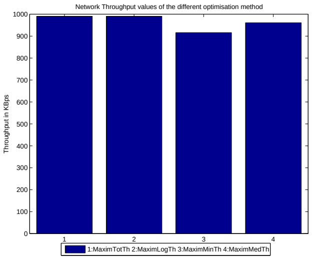
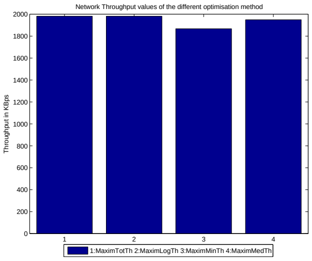
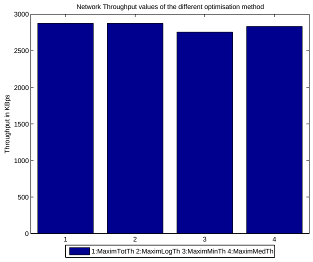
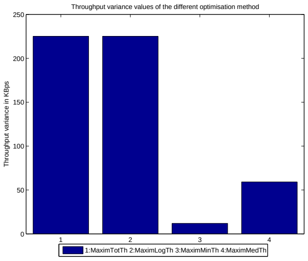
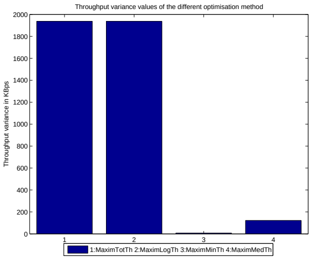
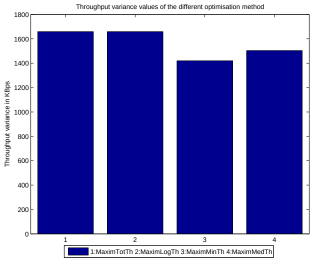
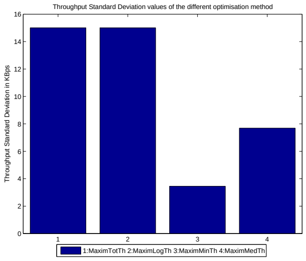
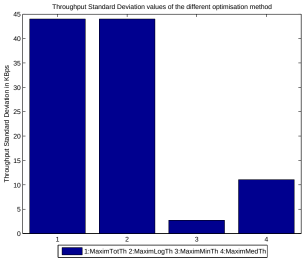
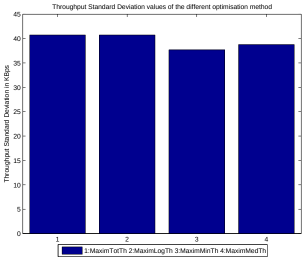
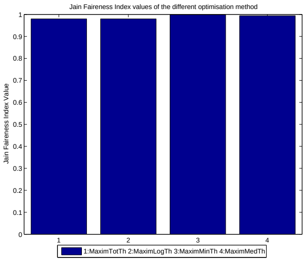
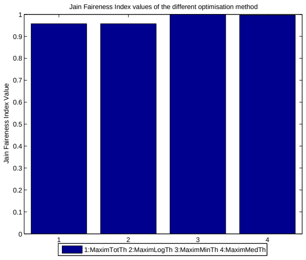
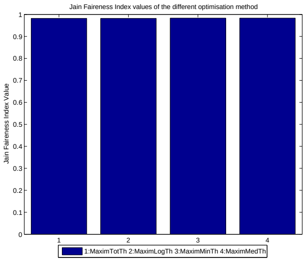
10 OBUs	1 RSU in the network	2 RSU in the network	3 RSUs in the network
A4			
A5			
A6			
A7			
A8			

Table 4.6: Comparison between the performances of the networks for the four optimization models

network connecting the RSUs to the Internet. In this next chapter, we investigate several contributions to improve the vehicular network performances at backbone level.

Chapter 5

Channel Allocation and Routing in Wireless Mesh Networks

5.1 Introduction

In order to avoid transmission collisions and improve network performances in wireless mesh networks (WMNs), a reliable and efficient medium access control (MAC) protocol and a good channel allocation are needed. Allowing multiple channels use in the same network is often presented as a possible way to improve the network capacity. As IEEE 802.11, IEEE 802.15 and IEEE 802.16 standards provide more than one channel, thus a trivial way to improve the network performances is to allow transmission on multiple channels in each network node. A lot of research work has been conducted in the area of multi-channel allocation in order to improve the aggregate bandwidth of the whole network. In this chapter, we focus our attention on the proposals for solving the channel allocation problem for Multi-Transceiver per node in the backbone level using the IEEE 802.11s technology. We classify these proposals into three categories. The first one consists of channel allocation proposals done at the MAC level independently of the other layers. The second one consists of a channel allocation approaches done by a modified MAC collaborating with upper layers. Finally, the third category concerns channel allocation methods implemented in a new layer resulting from a common-layer design between MAC and Network layer. For each category, the existing multi-channel protocols and their channel allocation approaches are identified. A qualitative comparison is conducted according to the advantages that they present, the limitations and problems they are facing, and the performances they are claiming to offer.

As IEEE 802.11, IEEE 802.15 and IEEE 802.16 standards faces several deployment limitations like the throughput degradation and the unfairness between network nodes, the IEEE community decided to extend the current standards in order to improve the network performances and to extend its coverage area.

For wireless personal area network (WPAN), a new working group, i.e., IEEE 802.15.5, is established to determine the necessary mechanisms in the physical and MAC layers to enable mesh networking in wireless PANs [27]. For wireless metropolitan area networks (WMAN), i.e., IEEE 802.16 [25], a lot of proposals have been submitted for standardization [28, 29]. Also, for wireless local area networks (WLAN), an extension called 802.11s, that could be called IEEE 802.11-based Wireless Mesh Networks, is still under discussions [26, 30].

A Mesh Network is defined as being an infrastructure network working with an ad hoc

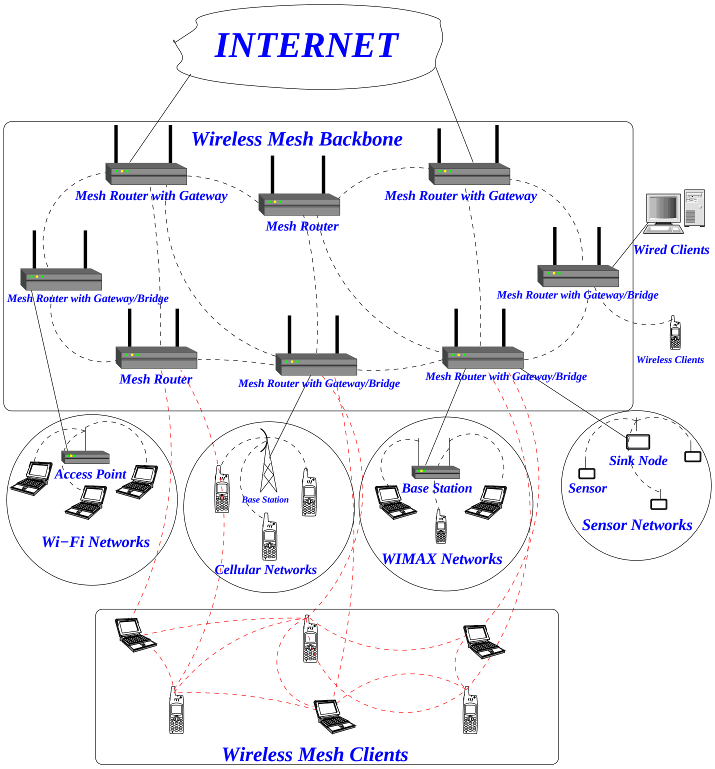


Figure 5.1: Architecture of a wireless mesh network (WMN)

mode. The architecture shown in Figure 5.1 where dash and solid lines represent respectively wireless and wired links, depict the possibility of interconnecting several heterogeneous networks.

Communications in WMNs are multi-hop and multipoint-to-multipoint, the network is self-organized and its performances are affected by mobility even if it is low that's why designing a scalable MAC for WMNs is an issue. This scalability can be addressed by the MAC layer in two ways. The first way is to enhance existing MAC protocols or to propose new MAC protocols to increase end-to-end throughput when only single channel is available in a network node. When several communication channels are available in the network, a second way is to allow transmission on multiple channels in each network node.

As IEEE 802.11, IEEE 802.15 and IEEE 802.16 basic standards [23, 24, 25] provide the support of multi-channel, IEEE (802.11, 802.15, 802.16)-based Wireless Mesh Networks may have single-channel or multi-channel configuration. As shown in Figure 5.1, one node can have one or more transceivers (backbone level). The traffic in WMNs is mainly directed between nodes and the Internet but we believe that also traffic exists between nodes themselves. High-bandwidth applications need sufficient network capacity so it is challenging to make the network provide such capacity. In order to improve WMNs capacity a good management of the available frequencies is necessary.

In this chapter, we focus on multi-channel allocation techniques for WMNs. Enabling a network node to work on multiple channels instead of only one fixed channel improves network performances and increases network capacity for WMNs. Depending on hardware platforms, different multi-channel allocation protocols are developed and can be classified into three categories. The channel allocation for the first one is done without taking into account the network needs and constraints, while the second one is given as a result of a cross-layer design between MAC and network layers. Finally, the third category is made by a new layer that is a common-layer between MAC and routing. Additionally, in this chapter we will not consider the case when there are multiple radios per node because in a such scenario, each radio has its own MAC and physical layer. The communications using these radios are totally independent and it is not in the scope of our work. Our work does not focus on the proposed MAC protocols for wireless mesh network which are covered by other works like [31] and [32] but the proposed techniques and approaches for channel allocations.

The rest of this chapter is organized as follows. In Section 2, we present a short view of the channel spectrum use in 802.11, 802.15 and 802.16. Section 3 gives a description of the proposals for channel allocation, over which a qualitative comparison is conducted after. Conclusions and future directions are provided in Section 4.

5.2 Channel spectrum use in 802.11, 802.15 and 802.16

5.2.1 Channel spectrum use in IEEE 802.11

This subsection tries to summarize the use of the available channel frequency spectrum in IEEE 802.11 [23]. The number of transmit and receive frequency channels used for operating the Physical Medium Dependent (PMD) entity is 79 for the USA and Europe, and 23 for Japan. But not all of these channels can be used simultaneously because of the overlapping problem. The hop sequence for used channel is defined by the geographic features and is given by the authorities of where will be implemented the network. In practice, IEEE 802.11 /b/g defines at least 11 channels and of these, at least three are completely non-overlapping (channels 1 [2402 MHz, 2422 MHz] , 6 [2427 MHz, 2447 MHz], and 11 [2452 MHz, 2472 MHz]) as depicted in Figure 5.2. Now, the issue of medium contention arises only when we are using the same channel or overlapping channels. An important observation in a wireless network is that if two links are allocated independent (non-overlapping) channels, they can be scheduled independent of one another. A node in WMNs can have one or more physical interfaces but the number of interfaces per node (often 3 at maximum) is less than the number of the available channels in the network. To each link, we associate a unique channel. The question now is how to optimize the channel allocation in order to improve the performances of the network?

Section 3 describes the proposals for the issue of channel assignment in 802.11-based WMNs and provides a qualitative comparison of these proposals.

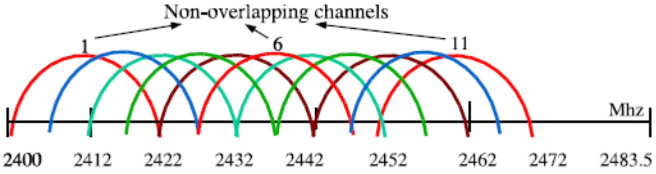


Figure 5.2: Channel spectrum use in IEEE 802.11 [23]

Frequency channel number	Frequency in megahertz
0	2412
1	2417
2	2422
3	2427
4	2432
5	2437
6	2442
7	2447
8	2452
9	2457
10	2462
11	2467
12	2472
13	2484

Table 5.1: Center frequency of CSS [24]

5.2.2 Channel spectrum use in IEEE 802.15

In this subsection, we try to summarize the use of the available channels for the IEEE 802.15 [24], according to the two physical technologies approved for the medium use that are the Chirp Spread Spectrum (CSS) and the Ultra Wide Band (UWB). When a CSS Physic is in concern, a total of fourteen channels, numbered 0 to 13 are available across the 2.4 Ghz band as depicted in Table 5.1. Different subsets of these frequency channels can be selected so that the non-overlapping frequency channels are used. A channel frequency defines the center frequency of each band for CSS.

$$F_c = 2412 + 5(k-1) \text{ in megahertz, for } k = 1, 2, ..., 13$$

$$F_c = 2484 \text{ in megahertz for } k = 14$$

where k is the band number.

Fourteen different frequency bands in combination with four different subchip sequences from a set of $14 \times 4 = 56$ complex channels. When a UWB Physic is in concern, a total of sixteen channels, divided into three bands, are defined as depicted in Table 5.2. A compliant UWB device shall be capable of transmitting in at least one of the three specified bands. A UWB device that implements the flow band shall support channel 3. The remaining low-band are optional. A UWB device that implements high band shall support channel 9. The remaining high-band channels are optional. A total of $16 \times 2 = 32$ complex channels are assigned for operation, two channels in each of the 16 defined operating frequency bands. A compliant implementation should support at least the two logical channels for one of the mandatory bands.

Band group (decimal)	Channel number	Center frequency, f_c(MHZ)	Bandwidth (MHz)	Mandatory/Optional
0	0	499.2	499.2	Mandatory below 1 GHz
1	1	3494.4	499.2	optional
1	2	3993.6	499.2	optional
1	3	4492.8	499.2	Mandatory in low band
1	4	3999.6	1331.2	optional
2	5	6489.6	499.2	optional
2	6	6988.8	499.2	optional
2	7	6489.6	1081.6	optional
2	8	7488.0	499.2	optional
2	9	7987.2	499.2	Mandatory in high band
2	10	8486.4	499.2	optional
2	11	7987.2	1331.2	optional
2	12	8985.6	499.2	optional
2	13	9484.8	499.2	optional
2	14	9984.0	499.2	optional
2	15	9484.8	1354.97	optional

Table 5.2: UWB PHY band allocation [24]

5.2.3 Channel spectrum use in IEEE 802.16

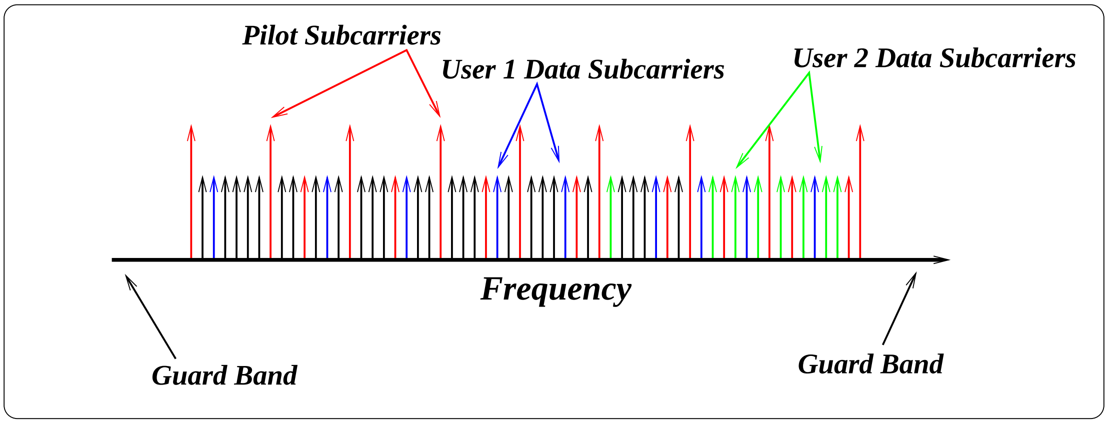


Figure 5.3: Channel spectrum use in IEEE 802.16 using OFDMA [23]

The first IEEE 802.16 [25] standard was approved in December 2001. It delivered a standard for point to multipoint Broadband Wireless transmission in the 10-66 GHz band, with only a line-of-sight (LOS) capability. It uses a single carrier (SC) physical (PHY) standard.

IEEE 802.16a was an amendment to 802.16 and delivered a point to multipoint capability in the 2-11 GHz band. To make use of this, it also required a non-line-of-sight (NLOS) capability, and the PHY standard was therefore extended to include Orthogonal Frequency Division Multiplex (OFDM) and Orthogonal Frequency Division Multiple Access (OFDMA). IEEE 802.16a was ratified in January 2003 and was intended to provide "last mile" fixed broadband access. IEEE 802.16e, another amendment to IEEE 802.16, uses Scalable OFDMA to carry data, supporting channel bandwidths of between 1.25 MHz and 20 MHz, with up to 2048 subcarriers. The most promising, used and benefit channel allocation proposals is OFDMA.

The Orthogonal Frequency-Division Multiple Access (OFDMA) is a multi-user version of the popular Orthogonal frequency-division multiplexing (OFDM) digital modulation scheme. Multiple access is achieved in OFDMA by assigning subsets of subcarriers to individual users as shown in Figure 5.3. This allows simultaneous low data rate transmission from several users.

Based on feedback information about the channel conditions, adaptive user-to-subcarrier assignment can be achieved. If the assignment is done sufficiently fast, this further improves the OFDM robustness to fast fading and narrow-band cochannel interference, and makes it possible to achieve even better system spectral efficiency.

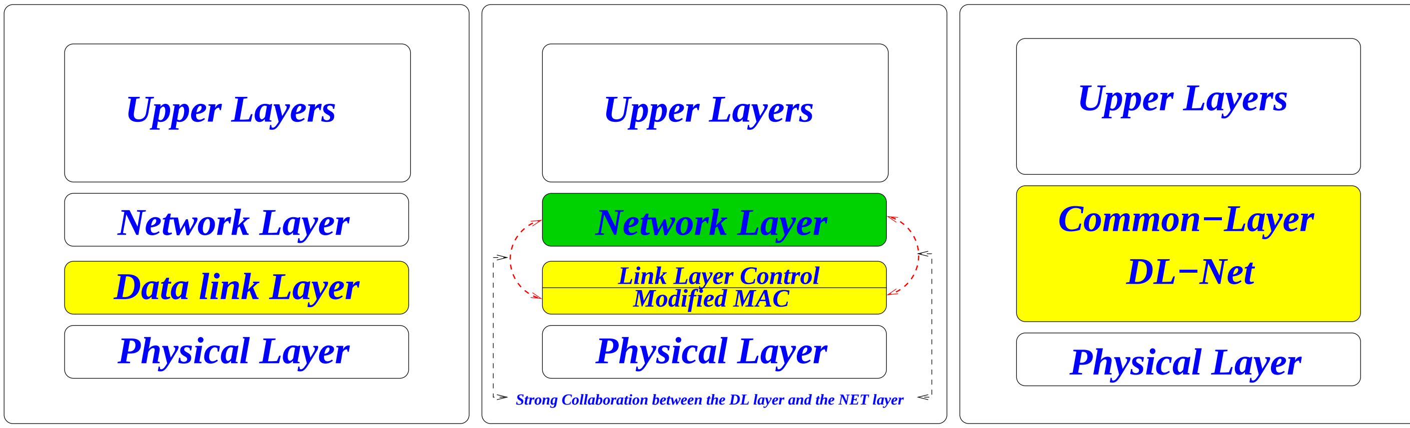
Different number of subcarriers can be assigned to different users, in view to support differentiated Quality of Service (QoS), i.e. to control the data rate and error probability individually for each user.

OFDMA resembles code division multiple access (CDMA) spread spectrum, where users can achieve different data rates by assigning a different code spreading factor or a different number of spreading codes to each user.

OFDMA can also be seen as an alternative to combining OFDM with time division multiple access (TDMA) or time-domain statistical multiplexing, i.e. packet mode communication. Low datarate users can send continuously with low transmission power instead of using a "pulsed" high-power carrier. Constant delay, and shorter delay, can be achieved.

However, OFDMA can also be described as a combination of frequency domain and time domain multiple access, where the resources are partitioned in the time-frequency space, and slots are assigned along the OFDM symbol index as well as OFDM subcarrier index.

5.3 Proposals for Channel Allocation in WMNs



(a) Layered scheme (b) Cross-layer scheme (c) Common-layer scheme

Figure 5.4: Approaches for channel allocation and dependency to routing protocols

A multi-channel allocation protocol can be implemented on different hardware platforms which impacts the design of the MAC. Each node of the network, can have one or more transceivers but if cost and compatibility are the concern, one transceiver by node is a preferred hardware platform that's why multi-transceivers are often implemented on nodes from the wireless mesh backbone as depicted in Figure 5.1. However, when multi-channel wireless mesh nodes are considered, new routing protocols are needed for two reasons. First, the routing protocol needs to select not only the optimal path in-between different nodes, but also the most appropriate communication channels on the path. Second, cross-layer and common-layer design become a necessity because changes in routing paths involve channel switching in a mesh node. Without considering cross-layer or common-layer design, the switching process may be too slow to degrade the performance of WMNs. The existing routing protocols treat all network nodes in the same way. However, such solutions may not be efficient for WMNs, because mesh routers in WMNs backbone and mesh clients have significant differences in power constraint and mobility. More efficient routing protocols that take into account these differences are desired for WMNs.

Several proposals concerning multi-channel allocation strategies for multi-transceiver per node have been suggested and we can split them into three categories with regard to their philosophical and technical approaches as depicted in Figure 5.4. The following subsections review and compare the most recent and promising proposals.

5.3.1 Independent multi-channel allocation strategies for nodes with multi-transceiver

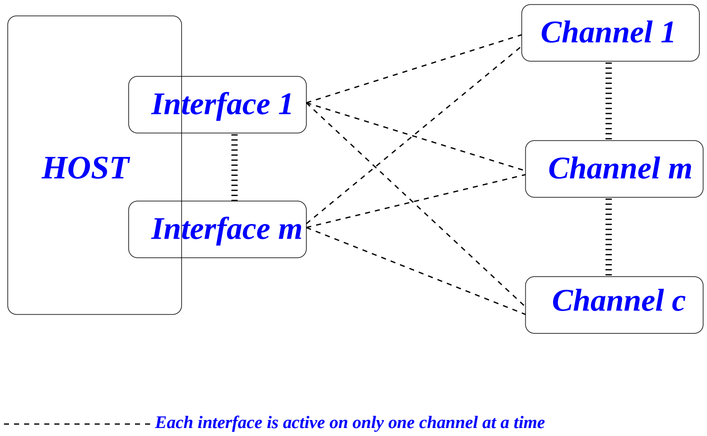


Figure 5.5: Case of Multi-Transceivers per node

The first category shown in Figure 5.4.(a) concerns people who believe that we have only to manage the channel allocation in a network while the routing comes after. As shown in Figure 5.5 where m and c represent the number of transceivers and the number of available channels in the network, respectively, a node includes multiple parallel RF front-end chips and base-band processing modules to support several simultaneous channels. On top of the physical layer, only one MAC layer module is needed to coordinate the functions of multiple channels. A node may operate on several channels simultaneously by affecting a different channel to each one of its transceivers. Consequently, a strong collaboration between nodes is needed to avoid channel interfering. In reality and as we mentioned in Section 2, IEEE

802.11 b/g provides three non overlapping channels and hence, it is useless to have more than three transceivers per node. Under this situation, distributed and centralized protocols have been proposed for improving coordination and channel allocation. However, the theoretical capacity is achieved with centralized algorithms, and assumptions of steady traffic. Developing an accurate distributed protocol is still a challenge.

Several strategies have been proposed. In [37], the authors propose to statically configure the interfaces of different nodes on pre-known channels. This approach simplifies protocol implementation but it is too limited to static network. Also, a node can send (or receive) data over only m channels where m is the number of its interfaces and, as a result, a network can be splitted into non communicative sub-networks because, naively keeping interfaces fixed on different channels may affect network connectivity.

A second possibility [33, 34], that can be considered as an improvement of the first one [37], is to frequently switch the interfaces of a node among different channels. This approach requires coordination between the sender and receiver nodes before transmission and a strong synchronization between them is necessary. Also, switching from one channel to another incurs delay.

A hybrid approach [38] keeps some interfaces of each node fixed, while others can switch among channels. The Hybrid Multi-channel Protocol (HMCP) [38, 39] is a link-layer protocol where the node's interfaces are either "fixed " or "switchable". The fixed channels can be explicitly advertised to neighbors by broadcasting "Hello" messages. Whenever a sender needs to send packets to a receiver, it can switch its channel to the receiver's fixed channel and send packets. Thus, once the fixed channel of a node is discovered through the reception of a "Hello" message, explicit channel synchronization is not needed. This protocol is shown in [35] to be efficient when the number of available channel increases. However, the increase of the number of hops affects seriously the performances. Moreover, in this scheme, single broadcast performances are limited since each node can listen to a different channel. A similar proposal is the DCA [36] algorithm that needs at least two interfaces per node where one can be dedicated to stay on a fixed channel and exchange control messages which can lead to a bottleneck problem in this interface as shown in [33, 35] to be less efficient than protocols for a single transceiver per node.

In [40], the authors consider the backbone level of the network, the problem studied is only concerning the router or gateway's level where each router can have more than one network interface card (NICs) because of cost constraint. They first, gave a model of the routers communications using the graph theory tools with the constraint that we can not have more than one logical link between each two routers. A logical link is modeled as a vertice of a graph. If and only if two communications represented by two vertices may interfere, then in the correspondent graph, these vertices are connected with an edge. After that, they focused on the set of all maximal cliques. A maximal clique in a graph is a maximal complete sub-graph where a complete graph is a graph with all vertices fully connected to the others. This set of maximal cliques denotes the possible interfering logical links. The maximum link layer flow capacity is limited for a maximum clique such as the normalized flow rate remains feasible. This limitation is strongly dependent on the characteristics of the set. However, to use clique capacity constraints, we need to design and express the maximum cliques of the graph in term of channel allocation and interfaces assignment. Besides, finding the maximal cliques in an arbitrary graph is NP-Hard [41]. The main equation in channel allocation and channel assignment in [40] is expressed as the limitation of the sum of time of all links chairing the same channel by the link layer flow capacity that represents the possible transmission time on

techniques names	descriptions	advantages	drawbacks	performances evaluation
static channel allocation [37]	for each interface of each node, allocate a different Channel statically	each node knows the channel allocated to each interface of its neighbors at a given time, easy to implement	may cause division of the network into multiple non communicating sub-networks	if two interfaces have the same channel, the performances above the logical link are very good, when different channels are assigned to interfaces they will never be able to establish a logical link and then communication between the two nodes could never be possible
frequently switching frequency assignment [33, 34]	nodes negotiate frequently the channel to use depending on the communication need	adapted to communication needs, support of broadcast	need of collaboration between nodes, incurs delay	incurring delay, performances depend on the number of nodes and are strongly affected by multi-hop
hybrid multi-channel protocol (hmcp) [38, 39]	interfaces can be fixed or switchable where the fixed are used for receiving and the switchable for sending information	benefit when number of available channels increase	limited broadcasting	depends on the number of available channels and performance decrease with the increase of hops
maximizing link layer flow inside a set of interfering channels [40]	resolving the maximization of the link layer flow in each group of interfering logical links by extracting binary linearization and using an approximate dual decompositions with practical assumptions	extracting binary linearization provides a unique maximum and the optimality is granted	with using an approximate dual decompositions with practical assumptions, optimality is not granted and is dependent on the assumption choice	significant increase of the network average utility for all different values of the set of interfering logical links capacity
minimizing the zero-mismatch channel allocation (zmca) [43]	uses graph theory for modeling the network and the zero-mismatch channel allocation and several techniques like the coloring problem and associated heuristics	the (zmca) is mathematically expressed and minimized for each technique	resolution of the problem of minimizing zmca is proofed to be np-hard and use of heuristics is mandatory	performances depend on the used heuristics but are improved for any heuristic
polynomial-time approximation scheme [57]	portioning the network space into small grids and doing computations over the obtained grids	no heuristics needed	obtained result from an approximation of the problem	the obtained configuration is the optimal

Table 5.3: Comparison between the proposed techniques in case of independent channel allocation

a channel. This equation represents a TDMA-type management inside a maximal clique.

The mathematical formulations expressed in [40] and explained in the previous paragraph model the relationship between the channel allocation, interface assignment, and MAC problems. [40] proposes to extend the MAC framework proposed in [42] to obtain a joint channel allocation, interface assignment, and MAC algorithm. This extension is formulated as non linear mixed-integer problem which is not easy to solve. This problem's objective is to maximize the sum of continuously differentiable, increasing and strictly concave utility function of the link-layer flow rate per logical link. The problem is resolved according to two methods. The first one consists in extracting binary linearization while the second uses an approximate dual decomposition. By relaxing all the binary constraints, the problem becomes a strictly concave problem with a unique maximum. This approach can lead to obtaining the global optimal solution of the joint channel allocation, interface assignment and MAC problem in a centralized manner. Resolving the dual problem of the original primal problem with practical assumptions makes the optimality of the joint algorithm not granted. In [40], numerical tests are done and the simulation results show that the proper value for the clique capacity parameter should be selected depending on some specific characteristics of the network contention graph. In the experiments, the authors conclude that their proposed schemes are efficient, regardless of the selected value for the clique capacity and the average network utility changes as the clique capacity changes. In [40], it is also observed that the multi-channel multi-interface deployment, significantly increases the network average utility for all different values of the clique capacity. In addition, the second proposed joint design efficiently finds the optimal or near-optimal solutions.

Finally, in [43], the author considers a network composed by directional antennas and long distance point-to-point communication. Then, he focus on the channel assignment to each interface. Based on the two phases MAC protocol which is a TDMA-style protocol in mesh network [44, 45], the author formulates first the problem of minimizing the mismatch between link capacities desired by the network operator and that achieved under a channel allocation using the graph theory. The approach adopted is to translate the real problem to a problem of coloring-3-edges because IEEE 802.11 provides three non overlapping channels where each edge corresponds to a communication link and a channel. Then, by using the problem formulation of 3-coloring-edges, the authors show that this problem is NP-hard. Finally, the authors explore several heuristics for achieving Zero-Mismatch Channel Allocation (ZMCA) for a graph. A set heuristics achieve the optimal allocation in most scenarios. Those heuristics are for color choice, edge ordering and local search. For example in [43], heuristics for color choice are two. The Greedy-col heuristics consists of, at each stage, to greedy try to pick a color that would add the minimum mismatch cost to the graph. The second one is the Match-DF heuristic witch consists of preferring colors according to the degree of match between edges. In [43], the author achieves simulations by generating 100 random graphs with 50 nodes and concludes that the Match-DF heuristic improves the network performances better than the Greedy-col heuristics and both are good. In [43], the author proves that solving the problem of channel allocation in WMNs is not a P-problem but NP-hard and could not be solved without introducing heuristics but here, we are facing another big problem which is how to choose heuristics?

A recent work [47], has been done for two interference models for channel scheduling that are under the physical constraint and under the hop constraint. This interference models are considered by the authors to be the most significant. The authors in [47] proves that channel scheduling is NP-Hard for Multi-Radio (Multi-NIC per node) Multi-Channel and propose a polynomial-time approximation scheme. This approximation is done by partitioning the network space into small grids and doing computations over the obtained grids. As a result the authors obtain a set of virtual communication links that can support simultaneous communications.

Table 5.3 provides a deeper analysis and comparison of the channel allocation techniques described and discussed in this section.

5.3.2 Cross-layer design for Channel Allocation and Routing

As depicted in Figure 5.4.(b), the second category concerns people who believe that both link layer and routing layer should coordinate. This category concerns either Single NIC or multiple NICs per node. For this, several proposals have been done where a large amount of research like [33, 47, 48, 49, 50, 51] are modifying the MAC layer to support multi-channel ad hoc network. The common approach of these works is to find the best channel for a single packet transmission with the collaboration of the network layer considering the importance of a cross layer design. Even the performances of these works seem to be improving the network capacity, but this improvement is not enough and the strategies adopted are shown to be strongly suffering from the number of hops from source to destination. Also, the used MAC are either protected or not free, so it is limiting the research knowledge to the simple modifications or specially designed to a specific hardware and so the portability is limited.

Another approach called MESTIC [46] aims to improve the aggregate throughput of the network, where the authors claim that they propose an innovative scheme which stands for mesh-based traffic and interference aware channel assignment. The MESTIC is a fixed, rank-based, polynomial time greedy algorithm for centralized channel assignment, which visits every node once. The node's rank computation depends on its link traffic characteristics, topological properties, and number of its network interface cards (NICs). For this, a common default channel, assigned to a dedicated NIC on each node, is used for ensuring the connectivity and the network management.

The main idea of MESTIC is to assign channels to the transceivers based on the rank of the node and the load expected on the links a priori between nodes. As MesTiC a rank-based algorithm, thus nodes that are expected to carry heavy loads have more flexibility in assigning channels. The gateway node in this configuration obtains the highest rank in order to avoid congestion in the gateway as most of the expected traffic is in-between users and the Internet where some works speak about 95%. We classified this approach as a cross-layer design for channel allocation and routing because the expected load and traffic in the network is done a priori and not dynamically. In fact, if a node decides to send data over the network using a specific path to the destination, the channel allocation strategy will not be changed or negotiated to ensure the optimal configuration scheme because even the collaboration exists between MAC and network layer, it is not Strong enough to solve this problem and we can not talk about a common-layer design between MAC and network layer. The authors claim that there is a strong benefit in terms of improving the aggregate bandwidth is obtained by using the MESTIC algorithm, however, their approach is strongly limited by the apriori known traffic. Table 5.4 provides a deeper analysis and comparison of the channel allocation techniques described in this section.

Techniques names	Description	Advantages	Drawbacks	Performances Evaluation
Modifying MAC for multi-channel support [33, 47, 48, 49, 50, 51]	Adapting MAC to support multi-channel in ad hoc mode	easy to implement	adapted to specific scenario and not scalable to any network	improving the network aggregate throughput with a high factor
MESTIC [46]	Affecting of channels to NICs based on the a priori traffic	Good load balancing	Not scalable for dynamic traffic changes	improves the network performance with the high factor for any configuration

Table 5.4: Comparison between the proposed techniques in case of cross layer design scheme

5.3.3 Common-layer design for channel allocation and routing

The third and last category given in Figure 5.4.(c), concerns people who believe that, when multi-channel wireless mesh nodes are considered, new routing protocols are needed for two reasons. First, the routing protocol needs to select not only the optimal path in-between different nodes, but also the most appropriate channels on the path. Second, a common-layer design becomes a necessity because change of a routing path involves the channel switching in a mesh node. Without considering a common-layer design, the switching process may be too slow and degrade the performance of WMNs. Under this situation and consideration, several works have been also done. Most of the previous works proposed solutions with a centralized vision. An excellent knowledge of the network is so required for making their proposals realistic and scalable. Promising works have been proposed in [52, 54, 55]. In [52], the authors propose an excellent problem formulation on which they explain clearly their approach. In [52], the authors propose two approaches that they claim are improving the aggregate bandwidth. Two novel channel assignment algorithms for a given multi-channel wireless mesh network are given therefore. The first algorithm “Neighbor Partitioning Scheme” performs channel assignment based only on network topology. The second algorithm “Load-Aware Channel Assignment” reaps the full potential of proposed architecture by further exploiting traffic load information. For this, the authors argue first that the main constraints that a channel assignment algorithm needs to satisfy are the limitation of the number of distinct channels that can be assigned to a wireless mesh node to the number of NICs on it, a communication could occur between two nodes only if at least one common channel is shared between one NIC from each node, the majoration by the channel raw capacity of the sum of the expected load on the links interfering on it and the total of available radio is limited. Then, they present the “Neighbor Partitioning Scheme” as the first approach. This consists in starting with one node, partitioning its neighbors into q groups and assigning one group to each of its interfaces and then each of this node’s neighbors, in turn, partitions its neighbors into q groups. This process is repeated until all nodes have partitioned their neighbors. The “Neighbor Partitioning Scheme” approach allows to use more channels in the network than the number of NICs per node. However this scheme would work if all the virtual link in the network have the same traffic load what is not always true in the reality. This motivates the authors to think about introducing the traffic load as a constraint for the channel allocation process and to introduce further the “Load-Aware Channel Assignment” approach.

Taking a real common-layer design, let us introduce the problem, its constraints and the objective to fulfill. The channel assignment phase should give more bandwidth to the link that might need to support load traffic, and should depend on the expected load on each virtual link, which depends in turn on routing. Moreover, given a set of communications node pairs, the expected traffic between them, and the virtual link capacities, the routing algorithm determines the route through the network for each communicating pair of nodes and the evaluation metric is then to maximize the overall traffic goodput in the whole network.

The main idea of the "Load-Aware Channel Assignment" approach in [52] is to evaluate the traffic profile between source and destination and, then, to assign channels over the logical link between nodes. The paths are established using simple routing algorithms regardless of the channel allocation constraints and taking into consideration the load balancing between selected paths where an excellent survey on algorithms for convex multicommodity flow problems [53] was proposed.

In fact, in [52], the authors first defined the evaluation metric as being the overall traffic goodput of the network that is formalized by using the cross-section goodput X of a network which is defined as the sum of the useful network bandwidth assigned between a pair of ingress-egress nodes (s, d) as defined in Eq.(5.1).

$$X = \sum_{s,d} C\left(s, d\right) \tag{5.1}$$

Because routing depends on the virtual Link's capacity, that is determined by channel assignment, and channel assignment depends on the virtual Link's expected load, which is affected by routing, there is a circular dependency between radio channel assignment and packet routing and, then, to break this circular dependency, the authors propose an initial link load estimation as the first step of their algorithm.

For this, they assume that all interfering links in the same neighborhood equally split the combined bandwidth of all radio channels as detailed in Eq.(5.2) where C_l is the capacity of a link l, C_Q is the capacity of the channel number Q and L_l is the number of link interfering with the link l including itself. Eq.(5.2) is computed regardless of the number of NICs per node.

$$C_l = \frac{Q * C_Q}{L_l} \tag{5.2}$$

To compute initial expected link loads, the authors assume a perfect load balancing across all acceptable paths between each communicating node pair. Then the expected load on a link l is given by Eq.(5.3), where $P\left(s, d\right)$ is the number of acceptable paths between a pair of node (s, d), $P_l\left(s, d\right)$ is the number of acceptable paths between a pair of node (s, d) that pass a link l, $B\left(s, d\right)$ is the estimated load bandwidth between a pair of node (s, d) and ϕ_l is the expected load on a link l.

$$\phi_l = \sum_{s,d} \frac{P_l\left(s, d\right)}{P\left(s, d\right)} * B\left(s, d\right) \tag{5.3}$$

While the resulting estimates of this approach are not 100% accurate, it provides a good starting point to kick off the iterative refinement process.

The next step of the algorithm given by the authors concerns the channel assignment step and for this, the goal is to assign channels to network interfaces such that the resulting available bandwidth on these interfaces is at least equal to their expected traffic load. As the problem is proofed to be NP-hard, the authors propose a greedy load-aware channel assignment algorithm. For evaluating the effectiveness of a channel assignment algorithm, the computation of the capacity of each virtual link and its comparison against the link expected load are needed. An approximation of a virtual link i' capacity bw_i is done in Eq.(5.4) where ϕ_i is the expected load on link i, $Intf\,(i)$ is the set of all virtual links in the interference zone of link i, and C is the substained radio channel capacity. The accuracy of this formula decreases as $\sum_{j \in Intf(i)} \phi_j$ approaches C.

$$bw_i = \frac{\phi_i}{\sum_{j \in Intf(i)} \phi_j} * C \tag{5.4}$$

Besides, the characteristic of the load-aware channel assignment is that it can work with any routing algorithm. Finally, the authors give how to combine the channel assignment and routing algorithms as depicted in Figure 5.6.

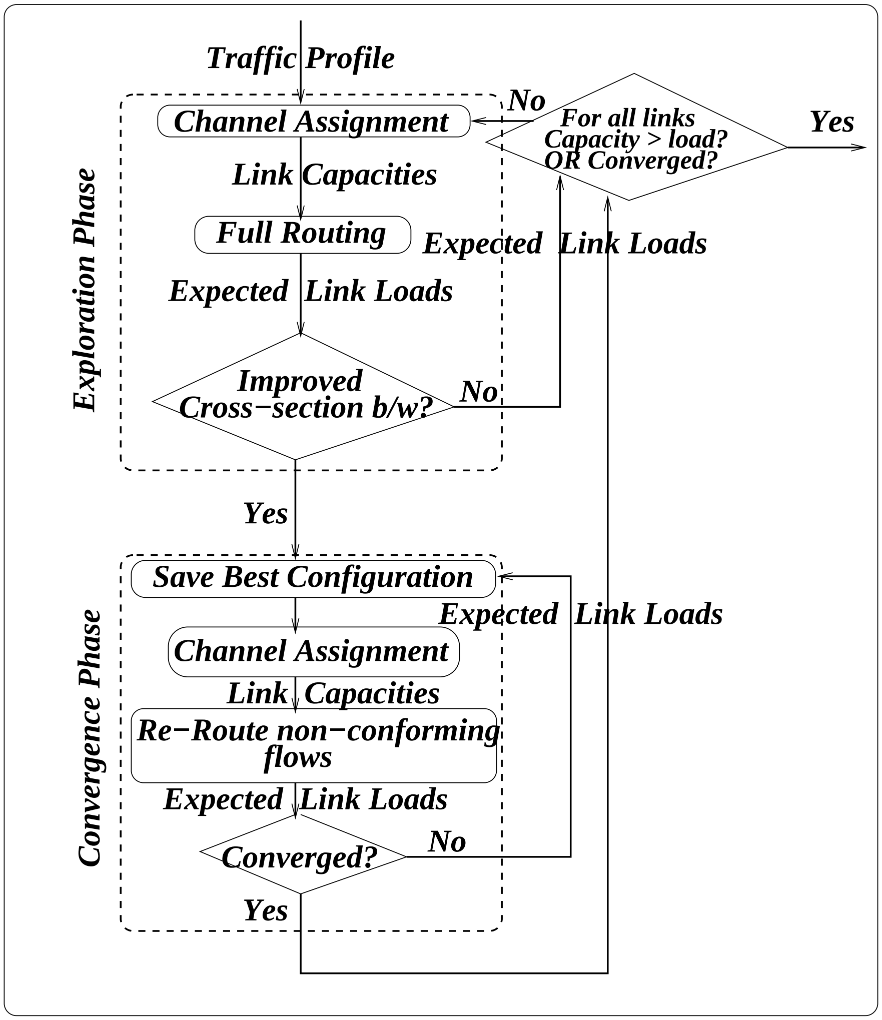


Figure 5.6: Load aware channel assignment [34]

The aggregate throughput advertised by the authors [52] yield a factor 8 of possible improvement which is higher compared to other approaches blamed to not fulfilling the maximum potential of the offered hardware. A similar for broadband fixed wireless access system approach is done in [54] and is presented in five steps but it has the same principles than [52]. Finally, another approach consists on minimizing a convex function [55], which depends on the networks flow and communication variable under the constraints of the network flow and communications model. The objective function depends on the user needs when designing the network and it is shown in [55] that this function can represent for example the power transmission or the link utilization. The performance of the Simultaneous Routing and Resource Allocation (SRRA) [55] are underlining the importance of the model for planning and designing network.

An enhancement of the previous described solutions is a distributed load channel assignment solution [56]. The approach mechanism (Figure 5.7) is composed by to phases. The first phase that is the initial phase consists of a distributed route discovery update protocol developed to establish routes between multi-channel WMN nodes and wired Gateway. Then, the second and periodic phase is the distributed load aware channel assignment. In fact, each node separates its set of interfaces into UP-NIC(s) that will be affected by their parents and DOWN-NIC(s) that involves only the node itself for affectation(s). To assign channel(s) to its DOWN-NIC(s), each node periodically exchanges its individual channel usage information as a CHNL_USAGE packet with all its interfering neighbors. The aggregated traffic load of a particular channel is estimated by summing up the loads contributed by all the interfering neighbors that happen to use this channel. A WMN node evaluates periodically its current channel assignment based on the channel usage information it receives from neighboring nodes. As soon as the node finds a relatively less loaded channel after accounting, it moves one of its DOWN-NIC(s) operating on a heavy-loaded channel to use the less-loaded channel, and send a message (CHNL_CHANGE) message with the new channel information to the affected child nodes, which modify the channels of their UP-NICs accordingly. It also sends an update CHNL_USAGE to its interfering neighbors to update their information about the usage of channels. Even this approach [56] is not really a cross-layer design between Mac and Routing layers, it remains, for the best of our knowledge, the closest to the third and last category given in Figure 5.4.(c).

Finally, the differences between centralized and distributed approaches are done in the table 5.5.

Technique	Description	Advantages	Drawbacks	Performances Evaluation
Centralized channel assignment and routing	Load balancing using multi-channel and routing	Find best and scalable solution	Centralized Not realistic	Goodput could be increased to a factor of 8
Distributed algorithms for channel assignment and routing	Channel assignment over routing	Distributed Scalable Realistic	High overhead Hard to implement	Throughput can be improved by a factor of 6 to 7

Table 5.5: Comparison between the proposed techniques for a common-layer design for channel allocation and routing

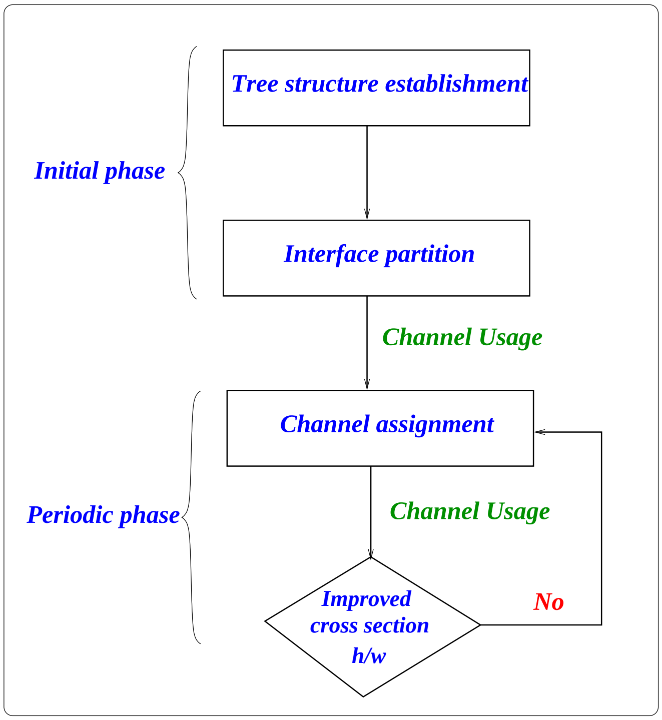


Figure 5.7: Load-aware channel assignment done by each node.

5.4 Conclusion and future directions

We have discussed in this chapter, recently proposed, techniques and approaches for channel allocation WMNs backbone where each node has at least two network interface cards. Many excellent approaches for channel allocation have been reported in the literature. The ultimate objective of these techniques is to take the maximum of benefit from the available channels in wireless mesh network. These techniques have been proved by theirs authors to improve the network performances. By this work, we classified the proposed techniques into three categories according to the dependence degree between channel allocation and routing proposed by their authors.

For the case of independent channel allocation, we have presented techniques for channel allocation and the most interesting are proposed by [40] and [43] where both use graph theory for modeling the problem of channel allocation and agree that it is an NP-Hard problem. [40] considers that the problem of optimizing channel allocation consists in the fact that the amount of time of all links sharing the same channel is limited by the link layer flow capacity and tries to maximize the sum of continuously differentiable, increasing and strictly concave utility function of the link-layer flow rate per logical link. To solve this issue, [40] uses two methods where the first one consists in extracting binary linearization while the second uses an approximate dual decompositions. [43] considers that the problem of optimizing channel allocation consists in achieving zero-mismatch channel allocation (ZMCA) between the available bandwidth provided by the ISP and achieved on the network. In [43], several heuristics are tested and shown to improve the network performances. Most of the proposed methods optimizing channel allocation uses heuristics but the choice of heuristics is not so easy to do. In fact, choosing a bad heuristic can considerably decrease the network performances that's why we believe that the method proposed by [40] which consists in extracting binary linearization is the method to recommend because it is the less dependent on heuristics. Even the performances claimed by the authors seem to be good, we strongly believe that such approach allocating channel to the different interface cards of the nodes is naive and not scalable because it is done regardless of the network traffic, however it is the easiest to implement. In Subsection 3.2 we proposed another survey of the most interesting techniques under the situation of cross-layer design between MAC and network layer when allocating channels to the different NICs. These techniques are mainly modifying the MAC layer to support multi-channel ad hoc network. The common approach of these works is to find the best channel for a single packet transmission under the collaboration with the network layer considering the importance of a cross layer design. Even the performance of these works seems to be improving the network capacity, these improvements are far to be enough and the strategies adopted are shown to be strongly suffering from the hop number from source to destination. Also, the used MAC is either protected or not free, so it is limiting the research knowledge to the simple modifications or specially designed to a specific hardware and so the portability is limited. However, and for the second category, few algorithms like MESTIC [46] are scalable and independent of the Hardware devices. In fact, MESTIC is the simplest one and the most efficient one but we strongly disagree with the idea of limiting the collaboration between MAC and Routing to a "A priori" estimation of the network traffic and thus, changing the network traffic might have very bad impact on the network aggregate bandwidth.

Finally and in Subsection 3.3, we focused on the third category that concerns people who believe that only the common-layer design between MAC and Network provides the best network performances. In fact, the proposed solutions to the issue of using all the network capacity is only achieved by a common-layer design MAC Network where promising works have been proposed in [52, 54, 55] and the performances that the authors claim are nearly the theoretical optimum of use of the network capacity. However, the best performances are provided by solutions done in a centralized manner.

Based on our survey on channel allocation strategies for WMNs, it is clear that many research issues remain to be solved. Indeed, we believe that the following questions remain without answers:

1. Promising works like [58] have been done for multirate any path routing, so can we extend a common-layer design MAC/Network to include some of these techniques?
2. Can we extend the common-layer design Mac/Network to include techniques?
3. Can we find a distributed dynamic strategy that affects channels dynamically according to the need? Could we add in the MAC frame a field called "next frequency" on which the transmitter can inform the receiver that it is switching from channel?
4. Can we create a distributed virtual structure over the mesh backbone that will work like a Centralized Management Entity? How this could be feasible?
5. Can we rely on smart antenna and beam-forming techniques to allow nodes to use the same channel without creating interference?

Finally, we hope that the discussions given in this chapter will stimulate the activity in the research community working on wireless mesh networks.

Chapter 6

A distributed architecture for 802.11s mesh networks

After presenting in Chapter 5, the most interesting previous work done by the various research bodies, we can say that the presented approaches done for a common-layer design between data link layer and network layer are mostly concerning a centralized manner management. These approaches are advertised by their authors to be improving the network performances significantly compared to a single channel network. However, in a wireless environment, presenting a centralized approach is not too realistic because of how will we be able to implement it in a distributed network? We strongly believe that we have to provide a solution to this issue before presenting a centralized approach. In this chapter, we will propose and discuss two possible distributed solutions for this problem.

6.1 Problem statement

In this section, we introduce the target network and the constraints that are imposed on both channel allocation and routing.

6.1.1 Network model

The considered network is composed of wireless mesh routers equipped with multiple wireless IEEE 802.11 network interface cards (at least two NICs per node) as depicted in Figure 6.1 and Figure 6.2. This network is working on an ad hoc mode where each node may relay traffic from a source to a destination if it is a member from the multi-hop path. The increase of the number of hops is affecting the end-to-end (traffic source to traffic destination) performances. On this network, we suppose that all the NICs have the same capabilities in terms of transmission power and transmission rate. Also, we suppose that the mobility of nodes is very low and the topology is not changing. In the rest of this section and by the next subsections, we will describe our model constraints step by step.

6.1.2 Multichannel environment constraints

In our network (Figure 6.1), we consider that a logical link may happen between two nodes if they are in the coverage area of each other and they have at least one NIC switched on a common channel. Given the eventual communication between nodes and the possible traffic

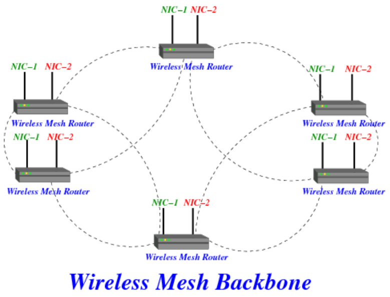


Figure 6.1: Wireless Mesh Backbone

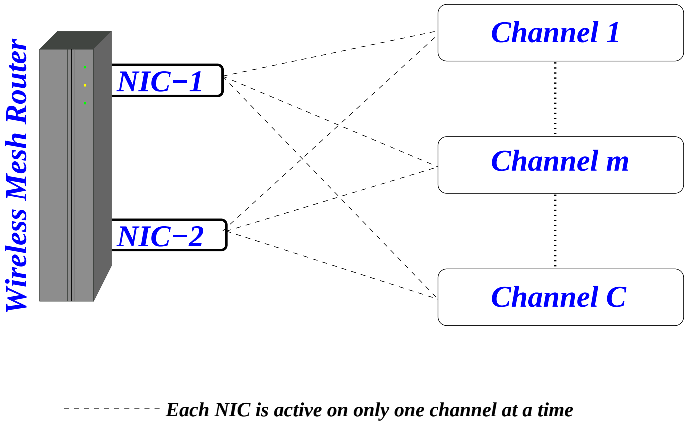


Figure 6.2: Wireless Mesh Router

between a source and a destination, each source has to determine how to assign a channel on each network interface card. When assigning the channels to the NICs, we have to consider some important constraints:

- The number of distinct channels assigned to a network node can never exceed, at a given time, the number of NICs that it has.
- Two nodes involved to a virtual link must have at least two NICs (one by node) bound to a common channel to make the communication possible.
- The sum of the traffic load routed on a interfering links can not exceed the channel capacity.
- The available network non overlapping channels are limited (three at least for IEEE 802.11 standard).
- Apart from the good channel allocation, also routing is playing an important role for improving the network performances.
- Necessity of providing a load balancing to minimize the penalty of the virtual links to avoid bottlenecks.

6.1.3 Path definition and constraints

A path is a sum of logical links that are involved to relay traffic from a source to a destination node. Then, inside a path, each logical link has a capacity. The capacity of a link C_L, as given in equation (6.1), depends on the capacity per channel C_c, the number of the available channels A_c, and the number of the logical link that may interfere N_{IL}.

$$C_L = \frac{C_c.A_c}{N_{IL}} \tag{6.1}$$

The available capacity on a logical link can, then, be determined and is the remaining non used capacity from the available link capacity C_L. The link cost L_C is expressed in equation (6.2).

$$L_C = \frac{1}{C_L} \tag{6.2}$$

A path selection is conditionned by an initial estimation for the needed bandwidth over it regardless the networks features. we note this estimated bandwidth between source and destination EB_{SD} that denotes the end-to-end estimated needed capacity.

For this, there might be a set of possible paths that satisfy the end-to-end needed capacity and minimize the load on each virtual (6.3) link to avoid bottleneck creation.

$$\frac{E_L}{C_L} \tag{6.3}$$

Where E_L denotes the expected load on a logical link L and is done by (6.4) where T_{paths} denotes the total paths from source to destination

$$E_L = \sum_{I \in T_{paths}} P_I.Load_I \tag{6.4}$$

Based on the needed load on a virtual link (6.4), the channels have to be allowed so that if we need only 20% from a logical link capacity, we only have to choose for this logical link a channel shared by four other interfering links. Any end-to-end connection should be done based on the previous configuration under the constraint that will not decrease the path end-to-end capacity of the other connections.

6.2 First Approach: Joint routing and channel allocation protocol

As depicted in the Figure 6.3, a joint routing and channel allocation approach involves both channel allocation and routing to collaborate and to be on a circular dependency. In fact, on the one hand, routing depends on the virtual Link's capacity, that is determined by channel assignment. On the other hand, channel assignment depends on the virtual Link's expected load, which is affected by routing. To resolve this circular dependency, we propose a protocol called JRCAP which combines both routing and channel allocation.

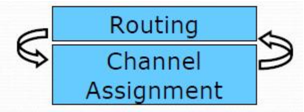


Figure 6.3: Dependency between channel allocation and routing

6.2.1 Mechanism description

The boot sequence of the algorithm is done as follows:

1. Clustering : dividing the whole network into clusters.
2. Advertising the root identity.
3. Building a cluster heads table by the root by collecting the cluster heads identity and distance.
4. Configuring the intra-cluster fixed channels.
5. Configuring the cluster's relay nodes inside each cluster.
6. Configuring routing mechanism.

6.2.2 Configuration phase

The configuration phase is an initial and static phase to configure some node interfaces.

6.2.2.1 Clustering phase

Several clustering algorithms are already proposed in the litterature, in most of them, the design of clusters selection appears to be similar to few variants where each node locally computes its own value of a given criteria (degree, mobility, ...) and then node that have the highest criteria will be the cluster head. In case of multiple winner, other criteria (node Id,

...) are, then, used to choose the cluster-head. In this chapter, we adopt another approach [59] based on density metric to build clusters and elect cluster-head. This approach is based on the density of the neighborhood of a node. The density aims to characterize the node's importance inside the wireless network and in its neighborhood. As the network's topology slightly changes, a node's degree changes are much more important than its density. The density notion should absorb small changes.

As usual, we use the graph theory to model a wireless mesh network. We model such a network by a graph $G = (V, E)$ where V (Vertices) model a set of n mobile nodes ($|V| = n$) and $e = (u, v) \in E$ represents a wireless link between the pair of nodes u and v when they are in communication range with each another. Let $d(u, v)$ be the euclidean distance between the pair of nodes u and v. We note $C(u)$ the cluster to which belongs the node u and $H(u)$ its cluster head. The k-neighborhood of a node u is $\Gamma_k = \{v \in V | 0 < d(u, v) \leq k\}$ and $\delta_k(u)$ the number of nodes included in k-neighborhood of u and is done by$\delta_k(u) = |\Gamma_k(u)|$. The eccentricity of a node u inside its cluster is $e(u/C) = max_{v \in C(u)}(d(u, v))$ while the diameter of a cluster will be defined as $D(C(u)) = max_{v \in C(u)}(e(v/C))$.

The density metric is directly related to both the number of nodes and links in a k-neighborhood and is the ratio between the number of links in the neighborhood of a given node u and the number of nodes inside u's neighborhood. The k-density of a node $u \in V$ is done by equation (6.5)

$$\rho_k = \frac{|e = (v, w) \in E \; v \in \{u, \Gamma_k(u)\} \;\; w \in \Gamma_k(u)|}{\delta_k(u)} \tag{6.5}$$

To elect a cluster head, each node computes its k-density value and broadcasts it locally to all its k-neighbors. By receiving this value, each node is able to know which node will be the cluster head. Once a cluster head is elected, the cluster head Id and its density are locally broadcast by all nodes that decided to join that cluster. A cluster can then extend itself until it reaches a cluster frontier of another cluster head.

In the clusters' organization resulting from density heuristics, cluster-heads are closer to the middle of the cluster which leads to a less control exchange inside a cluster. The number of nodes in clusters are balanced which reduces intra-cluster interferences. The network is partitioned into different clusters, each of them has a cluster head and a fixed channel. Different clusters are linked by relay nodes that are the nodes on the borders of clusters.

6.2.2.2 Cluster features configuration

A particular node called the Root selected from MPP affects fixed channels to cluster heads according to the distance between the cluster head and the Root in terms of hops. MP nodes that are inside the same cluster assign one of their interface to the advertised intra-cluster channel advertised by the Root. After the initial assignment, MP nodes may still have idle interface. These interfaces will be configured in the routing phase.

The root sends a message to declare itself as a root RDEC (Root DEClaration) in the mesh network. After reception of RDEC, each cluster-head sends a unicast RREG (Route REGistration) to the Root via the MP following the same path of the reception of the RDEC. The RREG message contains a hop count field metric to compute the number of hops between the Root and a cluster head. The Root saves in a cluster heads table, the cluster head address and its distance in number of hops. After that, the Root node affects to each cluster head a fixed channel.

The Root runs the following steps:

1. Wait to receive all RREG messages from cluster heads.
2. Begin with the closest cluster head to the Root, then choose a free channel which is not attributed yet or a channel involving the fewest conflicts.
3. If there is no free channel and there are two cluster head at the same level (neighbors), the Root computes the distance between each neighbor cluster-heads at the same level and assigns the channel used by the most distant cluster heads.

Each cluster-head assigns a single common channel to all nodes inside its cluster. Thus, nodes can communicate with each other using the same channel.

6.2.2.3 Relay node configuration

The cluster-head starts the configuration of the relay node interfaces. If there are two nodes that might be relay to the same clusters, the cluster-head keeps one relay by default and the other will have its interface free. Also, any relay node to a cluster configures its free interface to the fixed channel of that cluster.

After all the steps are completed, the connectivity within the cluster is maintained by the fixed channel and neighbor clusters are linked with relay node using default and fixed channels.

6.2.3 Routing phase

The total load of a channel is a weighted combination of the aggregated traffic load and the number of nodes using the channel.

6.2.3.1 Routing protocol

It is well recognized that channel assignment and routing can be efficiently executed only if the traffic patterns are taken into account. Considering that the global traffic load information is sometimes impossible to get, we will use some local information in our channel switching. Each node sends to the cluster-head, the channel utilization value. The channel utilization is calculated as follows : On each time slot, a node listens on it's channel and gets an estimation of free time percentage. The estimation can be simply done by subscribing the channel busy time from the entire time slot.

The cluster-head diffuses a message called channel list containing all channels used in the cluster ordered by channel utilization.

6.2.3.2 Routing metric

In this section, we propose a new routing metric MRC (Maximum Residual Capacity expressed in equation (6.6)) and adapt JRCAP routing protocol to support MRC. There are two goals for MRC designing. First, it should take the channel diversity of a path into account because the interference along the path is a main factor that decreases the throughput. Second, the link capacity of link should be explicitly considered.

$$MRC = \underset{Possible\,P}{Max}\left(\underset{l\in P}{Min}\left(Bw_l\right)\right) \tag{6.6}$$

Where Bw is the bandwidth of a link l. Bw is expressed as a function of MLC (Maximum Link capacity expressed in equation(6.7)) and LCD (Link Channel Diversity expressed in equation(6.8)). MLC is the maximum capacity of link l belonging to a path P. MLC is expressed as:

$$MLC = U * C \tag{6.7}$$

Where C represents the channel capacity and U, the rate of the unused capacity. LCD is

$$LCD_l = \sum_{i \in \{I_l \cap P\}} I\left(C\left(i\right) = C\left(l\right)\right) \tag{6.8}$$

$$I = \begin{cases} 1\, if\, C\left(i\right) = C\left(j\right) \\ 0\, if\, C\left(i\right) \neq C\left(j\right) \end{cases}$$

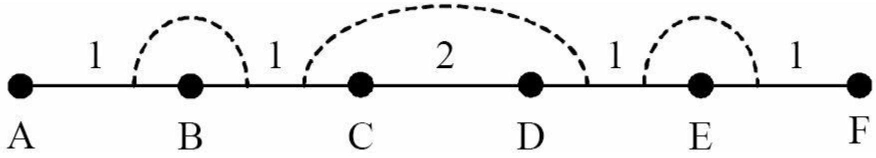


Figure 6.4: LCD Example

$$LCD_{AB} = 2 \quad LCD_{BC} = 3 \quad LCD_{CD} = 1 \tag{6.9}$$

The bandwidth on a link l is expressed in equation (6.10)

$$BW = \frac{MLC}{LCD} \tag{6.10}$$

RREQ carries the load information at a previous hop and the partial path information. The format of partial path information is composed of : Identification of i^{th} relay node, Channel used at i^{th} hop, Value MLC on link at i^{th} hop. When a node receives RREQ, it checks if its id appears in partial path. If so, it discards packet Otherwise, it attaches its information to a partial path and rebroadcasts RREQ on a control channel. After receiving RREQ, destination selects route which has maximum residual capacity and unicasts RREP.

6.2.4 Maintenance phase

A MP node evaluates its current channel assignment based on the channel utilization of its interfaces. As soon as the node finds a heavily loaded interface, it sends a channel request CREQ message to its cluster-head. The cluster-head choses a less loaded channel and sends back a message to the node. The message will be sent in the cluster with the new channel information to the affected neighbor. These neighbors modify their channels if it's possible, or else they consider that the node is reachable on the common interface.

6.3 Second Approach: A virtual structure to manage the network

6.3.1 Introduction

In this section we give the main steps to build the virtual structure. This one will manage a distributed network and will provide a centralized global view of the whole network.

6.3.2 Neighbor Discovery

Classical neighbor discovery algorithms operate by periodically transmitting beacon (HELLO message). The beacon contains the identifier of the node and possibly the location of the node. All nodes that receive the beacon update their respective neighbor lists to include the sender of the beacon. Using classical neighbor discovery algorithms, a node is able to obtain a complete knowledge of the neighbors inside its transmission range. We propose that rhe nodes discover their neighbors by sending the "Hello" messages on a single hop in which are mentioned information such it's NICs MAC addresses. Then, in each neighborhood, the node which has the highest NIC MAC address becomes dominant and the others dominated. Note that a node can be dominant in a neighborhood and dominated in another at the same time. The dominant nodes of each neighborhood are distant of two hops at most. For the network discovery phase, the dominant nodes broadcast their neighborhood table with a high TTL (Time to live). After reception of neighborhood tables by a dominant node, it first establishes its network table and then broadcasts it with a TTL equal to one to inform its neighborhood. This mechanism is realized in a distributed manner and allows easy and fast neighbor and network features discovery. The network features are concerning each logical link capacity, between nodes and the possible interfering links computed whith neighbor discovery.

6.3.2.1 Neighbor Discovery Approach

In this Section, we will propose a simple concept to achieve an efficient neighbor discovery for WMN backbone as depicted in Figure 6.5 where dash lines design wireless communication between wireless routers. For this, we need to focus on the MAC Frame in IEEE 802.11. The MAC frame designed for IEEE 802.11 is one of the most important elements to take into account. In Fact, the fields' sizes and order have to be respected while transmitting a message to make that information understood by the neighbors. Also, a good and efficient channel allocation is a big issue that we will discuss later to make neighbors able to send and receive data from each other.

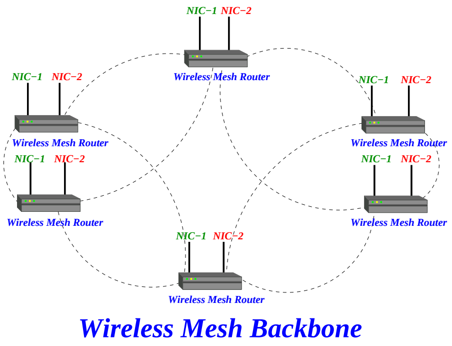


Figure 6.5: Wireless Mesh Backbone

Our study concerns the wireless mesh backbone as depicted in Figure 6.5, and we can consider this backbone as being a set of Independent Basic Service Set (IBSS) where each IBSS is a neighborhood depending on the coverage. Note that an IBSS is a BSS (set of stations) without a coordination function implemented on a specific device that can be the Access Point in a BSS. The stations inside the IBSS are working on an ad hoc mode where each station can exchange information with any other station of the IBSS. The connectivity between the IBSS is provided by a Distribution System (DS) that we will introduce later.

6.3.2.2 IEEE 802.11 MAC Frames

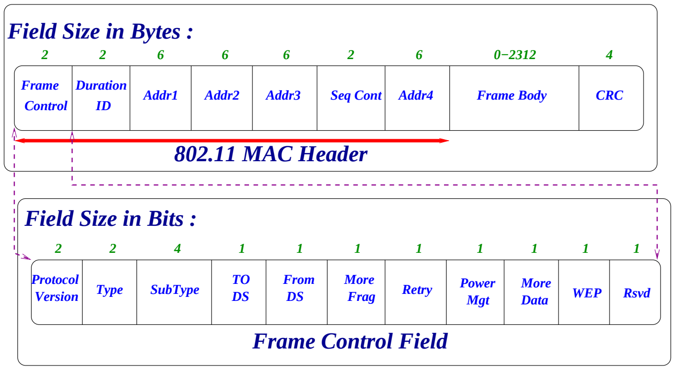


Figure 6.6: IEEE 802.11 MAC Frame

The frame formats proposed for 802.11 is shown in Figure 6.6 and it has different uses that differ per type described in the second field of the frame control field. The field Type size is two bits and indicates one of the three types of frame that is actually in use:

- Type = 00 for MAC Management Frame
- Type = 01 for MAC Control Frame
- Type = 10 for MAC Data Frame

The MAC Management Frame and the MAC Control Frame also include types called subtypes and specified in the Subtype Field of the Frame Control Field. The MAC control frame can be used for the Carrier sense Multiple Access with collision avoidance protocol (CSMA/CA):

- Request To Send (RTS)
- Clear To Send (CTS)
- Acknowledgment (ACK)

Finally, the MAC Data Frame is used to transmit data between Stations.

6.3.2.3 Neighbor Discovery Mechanism

To DS	From DS	Address1	Address2	Address3	Address4
0	0	DA	SA	BSSID	N/A
0	1	DA	BSSID	SA	N/A
1	0	BSSID	SA	DA	N/A
1	1	RA	TA	DA	SA

Table 6.1: Address Field Description for IEEE 802.11 MAC Frame

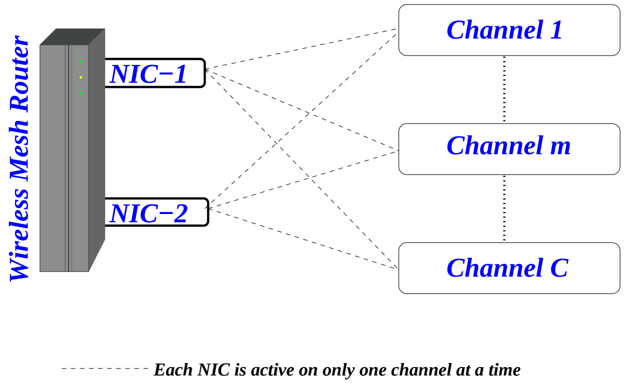


Figure 6.7: Wireless Mesh Router presenting two NICs

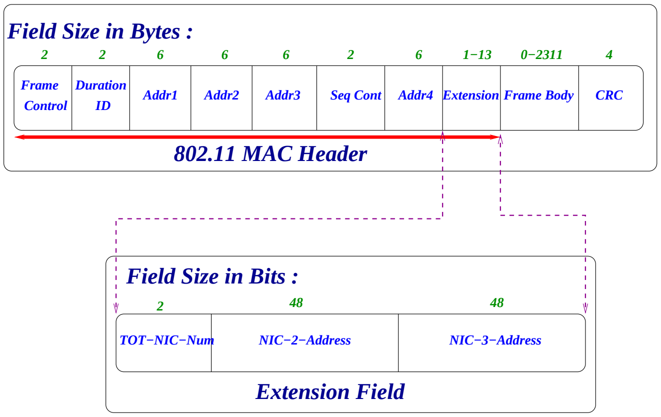


Figure 6.8: Extended 802.11 MAC Frame

After presenting the IEEE 802.11 MAC Frames, we propose to adjust the frame to our need. First, for neighbor discovery, we will need a MAC Management Frame. Thus, the field "Type" will be turned on 00. Also, we have to choose an addressing schema from the available four addressing proposals defined in Table 6.1.

There are four address fields in the MAC frame format (Figure 6.6). These fields are used to indicate the BSSID, source address, destination address, transmitting station address, and receiving station address. The usage of the four address fields in each frame type is indicated by the abbreviations BSSID, DA, SA, RA, and TA, indicating basic service set identifier (BSSID), Destination Address, Source Address, Receiver Address, and Transmitter Address, respectively. Certain frames may not contain some of the address fields. Certain address field usage is specified by the relative position of the address field (1 to 4) within the MAC header, independent of the type of address present in that field. For example, receiver address matching is always performed on the contents of the Address 1 field in received frames, and the receiver address of CTS and ACK frames is always obtained from the Address 2 field in the corresponding RTS frame, or from the frame being acknowledged.

The use of which addressing schema is done by the fields "To DS" and "From DS" as:

1. To DS $=0$ and From DS $=0:$ A data frame direct from one STA to another STA within the same IBSS, as well as all management and control type frames.

2. To DS $=1$ and From DS $=0:$ Data frame destined for the DS.

3. To DS $=0$ and From DS $=1:$ Data frame exiting the DS.

4. To DS $=1$ and From DS $=1:$ Wireless distribution system (WDS) frame being distributed from one AP to another AP.

For our neighbor discovery approach the appropriate address schema is the first where To DS $=0$ and From DS $=0$.

For wireless mesh network, some wireless mesh routers of the network backbone can have more than one network interface card (Figure 6.7). Each NIC has its MAC address and can be affected to only one channel at a given time. The IEEE 802.11/a/b/g Standard provides at least three non overlapping channels (channels 1, 6 and 11). So, its logical to have at maximum, for each router, three NICs. Our approach concerns the neighbor discovery and for this, each network station (Backbone Router for our case) has to advertise its NIC MAC addresses. As a solution we propose to extend the MAC Frame Header as depicted in Figure 6.8. The extension is done by adding an extension field in the data field. The first two bits from the extension field advertises how many NICs has a router. If the total NICs Number is more than one, say two, so the second field of the extension fields will be the last extension fields and will contain the second router NIC MAC address. If the router has three NICs, the first extension field will be equal to 11 and in the second and third will contain respectively the second and the third NIC MAC Address. The field Addr1 will contain the highest NIC MAC address of the router. Each router advertises to each neighbors its NICs MAC addresses. The router which has the highest NIC MAC address among its neighbors will be the dominant (the master in its neighborhood) and the others dominated and then, the field Addr3 of the whole neighborhood will be equal to the highest NIC MAC address that Will be used as a BSSID. A neighborhood list is established on each router.

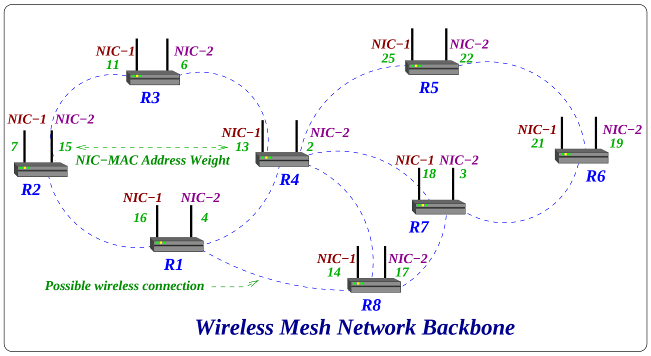


Figure 6.9: Sample of wireless mesh backbone

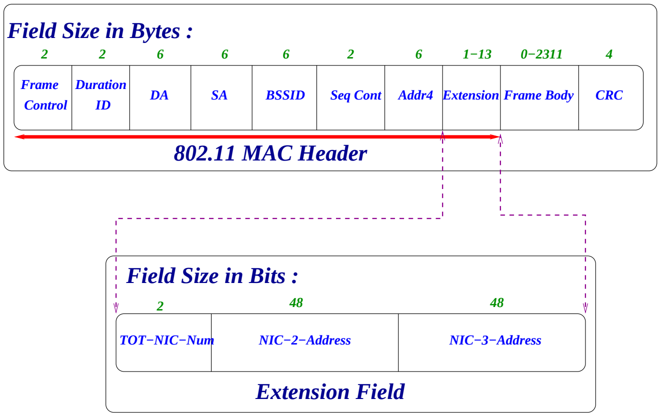


Figure 6.10: Used MAC Frame

6.3.2.4 Illustration of the neighbor discovery mechanism

In this subsection, we will give an example of how would work our algorithm for neighbor discovery in wireless mesh backbone. The network of the Figure 6.9 illustrates a sample for our study where dash lines design the possibility of communication between wireless routers. Two wireless routers can communicate when they are in the transmission range of each other. In this network, we have eight wireless routers ("R_1" to "R_8"). Each router can have, as we said before, one, two or three network interface cards. For our sample, each router has two network interface cards. According to each network interface card MAC address value, we assign a value to each NIC. Since the MAC address of a network interface card is unique in the world, so are the values affected to those network interface cards. According to the IEEE 802.11 standard, the MAC field "Type" Frame will be turned on 00 to obtain a management frame. Also, there are four address fields in the MAC frame format (Figure 6.6). The precision of the use of the addresses is done by the fields "To DS" and "From DS". For our use those fields will be equal to 0 (To DS = 0 and From DS = 0). Thus, the correspondant MAC frame will be the MAC frame depicted in Figure 6.10. In the reminder of this subsection, we will try to detail our example.

1. A node (wireless router) say R_1 can intiate the phase of neighbor discovery. It sends the following MAC frame
   i) DA= FFFFFFFFFFFF for broadcasting to its neighborhood
   ii) SA = its highest NIC MAC address which value is 16
   iii) BSSID = its highest NIC MAC address which value is 16
   iv) Extension TOT-NIC-Num=10 as it has two NICs
   v)NIC-2-Address= Second NIC MAC address (value =4)

2. R_2, R_4, R_8 receive the frame from R_1 and compare their highest NIC MAC addresses to the one advertized by R_1

3. Only R_8 has its highest NIC MAC address higher to the one advertized by R_1. R_2 and R_4 launch intern timers while R_8 sends the following MAC frame
   i) DA= FFFFFFFFFFFF for broadcasting to its neighborhood
   ii) SA = its highest NIC MAC address which value is 17
   iii) BSSID = its highest NIC MAC address which value is 17
   iv) Extension TOT-NIC-Num=10 as it has two NICs
   v)NIC-2-Address= Second NIC MAC address (value =14)

4. R_1, R_4, R_7 receive the frame from R_8 and compare their highest NIC MAC addresses to the one advertized by R_8

5. Only R_7 has its highest NIC MAC address higher than the one advertized by R_8. R_1 and R_4 launch intern timers while R_7 sends the following MAC frame
   i) DA= FFFFFFFFFFFF for broadcasting to its neighborhood
   ii) SA = its highest NIC MAC address which value is 18
   iii) BSSID = its highest NIC MAC address which value is 18
   iv) Extension TOT-NIC-Num=10 as it has two NICs
   v)NIC-2-Address= Second NIC MAC address (value =3)

6. R_4, R_6 and R_8 receive the frame from R_7 and compare their highest NIC MAC addresses to the one advertized by R_7

7. Only R_6 has its highest NIC MAC address higher than the one advertized by R_7. R_8 and R_4 launch intern timers while R_6 sends the following MAC frame
   i) DA= FFFFFFFFFFFF for broadcasting to its neighborhood
   ii) SA = its highest NIC MAC address which value is 21
   iii) BSSID = its highest NIC MAC address which value is 21
   iv) Extension TOT-NIC-Num=10 as it has two NICs
   v)NIC-2-Address= Second NIC MAC address (value =19)

8. R_2 intern timer expires so it sends the following MAC frame
   i) DA= FFFFFFFFFFFF for broadcasting to its neighborhood
   ii) SA = its highest NIC MAC address which value is 15
   iii) BSSID = its highest NIC MAC address which value is 16 as a response to accept to be dominated by R_1
   iv) Extension TOT-NIC-Num=10 as it has two NICs
   v)NIC-2-Address= Second NIC MAC address (value =7)

9. R_1 intern timer expires so it sends the following MAC frame
   i) DA= FFFFFFFFFFFF for broadcasting to its neighborhood
   ii) SA = its highest NIC MAC address which value is 16
   iii) BSSID = its highest NIC MAC address which value is 17 as response to accept to be dominated by R_8
   iv) Extension TOT-NIC-Num=10 as it has two NICs
   v)NIC-2-Address= Second NIC MAC address (value =4)

10. R_5 and R_7 receive the frame from R_6 and compare their highest NIC MAC addresses to the one advertized by R_6

11. Only R_5 has its highest NIC MAC address higher than the one advertized by R_6. R_7 launch intern timer while R_5 sends the following MAC frame
    i) DA= FFFFFFFFFFFF for broadcasting to its neighborhood
    ii) SA = its highest NIC MAC address which value is 25
    iii) BSSID = its highest NIC MAC address which value is 25
    iv) Extension TOT-NIC-Num=10 as it has two NICs
    v)NIC-2-Address= Second NIC MAC address (value =22)

12. R_4 and R_6 receive the frame from R_5 and compare their highest NIC MAC addresses to the one advertized by R_7

13. R_1 and R_3 receive the frame from R_2 and only R_3 compares its highest NIC MAC addresses to the one advertized by R_2

14. R_4intern timer expires so it sends the following MAC frame
    i) DA= FFFFFFFFFFFF for broadcasting to its neighborhood
    ii) SA = its highest NIC MAC address which value is 13
    iii) BSSID = its highest NIC MAC address which value is 25 as a response to accept to be dominated by R_5
    iv) Extension TOT-NIC-Num=10 as it has two NICs
    v)NIC-2-Address= Second NIC MAC address (value =2)

15. R_3 intern timer expires so it sends the following MAC frame
    i) DA= FFFFFFFFFFFF for broadcasting to its neighborhood
    ii) SA = its highest NIC MAC address which value is 11
    iii) BSSID = its highest NIC MAC address which value is 15 as a response to accept to be dominated by R_2
    iv) Extension TOT-NIC-Num=10 as it has two NICs
    v)NIC-2-Address= Second NIC MAC address (value =6)

16. R_6 intern timer expires so it sends the following MAC frame
    i) DA= FFFFFFFFFFFF for broadcasting to its neighborhood
    ii) SA = its highest NIC MAC address which value is 21
    iii) BSSID = its highest NIC MAC address which value is 25 as a response to accept to be dominated by R_5
    iv) Extension TOT-NIC-Num=10 as it has two NICs
    v)NIC-2-Address= Second NIC MAC address (value =19)

After the previous steps, the neighborhor discovery phase was done and its node can establish its neighborhood list. Note that a node can be dominant and dominated at the same time (R_2, R_1, R_8, R_6 and R_7). Thus, the list of nodes that are in dominant list and determining the different BSSID are R_2, R_1, R_8, R_6 and R_7.

6.3.3 Network Discovery Approach

In this Section, we will give an example of how would work our algorithm for network discovery in wireless mesh backbone. The network discovery phase starts from the begining of building the connected dominating set (CDS) inside the backbone network.

We propose that, inside a neighborhood, nodes (wireless mesh routers) elect a master for the network. Then, the node which has the highest NIC MAC address becomes the master (dominant node) and advertises its decision to its neighborhood. A Connected Dominating Set (CDS) that connects the masters (dominant nodes) can be fulfilled between masters from each neighborhood. A such CDS inside the mesh network would be used to collect the control traffic limiting the retransmission number.

6.3.3.1 Mathematical explanation of a CDS

A CDS can be represented using the graph theory as follows.

Let V' being the set of vertices from $G(V, E)$ such that V represents the vertices and E the edges of the graph Grepresented by (6.11) and (6.12).

$$\forall u \in V, \exists v \in V'/v \in N(u) \tag{6.11}$$

$$\forall (u, v) \in V'^2, \exists c = path_{u \longrightarrow v}/\forall w \in c, w \in V' \tag{6.12}$$

A node is called dominant if it is a member of the CDS, else it is dominated. By (6.11) we can say that each node from the network is distant from the connected dominating set at maximum of $N(u)$ hop(s) and in this case the maximum hop number is one where (6.12) is for ensuring the connectivity of the CDS. In fact, (6.12) guarantees, that every node from the CDS can be reached from each node from the CDS. Let's extend this concept to obtain the

K-CDS by modifying the proposition (6.11) and, thus, we obtain (6.13). By this extension, we can say that each node from the network is distant from the connected dominating set at maximum of $N_k(u)$ hop(s) and in this case the maximum hop number is k

$$\forall u \in V, \exists v \in V'/v \in N_k(u) \tag{6.13}$$

Also, we call a MCDS (Minimum Connected Dominating Set) a CDS with a minimum cardinality. Building such a structure with either centralized or distributed schema is a NP-Hard problem. Many algorithms aim to approximate the MCDS and some of them propose two steps for that.

1. Election of the dominant nodes such that each dominated node be a neighbor of a dominant node and the resulting set is the total dominant set
2. Connection between dominants while minimizing the final set

6.3.3.2 Network discovery principle

Node ID	NIC-2	NICC-3	BSSID	Relation
Highest MAC Address	NIC-2 MAC Address	NIC-3 MAC Address	ID of the BSSS	F/S/B/O

Table 6.2: Neigborhood List Structure

The network discovery aims to make the channel allocation and the network management easier. Such a knowledge, will improve the network performances such as end-to-end delay and quality of services. Our approach consists in the creation of a sub-network inside the backbone network. This sub-network is done for the management and would be used for collecting traffic management. The sub-network will be composed of the set of the elected dominant of Section 2. One dominant has been elected inside each neighborhood. Now the issue is how to connect those dominants to make a connected dominating set (CDS). A CDS can be represented as a set V' of vertices from $G(V, E)$ such that V represents the vertices and E the edges of the graph G and responding to (6.11) and (6.12). (6.11) provides the respect of the maximum distance of any node to the connected dominating set at maximum of $N(u)$ hop(s) and in this case the maximum hop number is one where (6.12) is to ensure the connectivity of the CDS. In fact, (6.12) guarantees, that every node from the CDS can be reached from each node from the CDS.

Using (6.11) allows us to say that two dominants of two adjacent neighborhoods are separated by a maximum of $2 \times N(u) + 1$ hops. In the beginning, each dominant is a member of a connected dominating subset that includes it only with a subset ID equal to its highest NIC MAC address (IBSS ID). Each dominant from the network knows the distance in terms of hops between it and the adjacent dominants from the neighbor discovery phase. Thus, and for optimizing the creation of connected dominating set (CDS), each dominant sends a request of connectivity to the closest dominant that will respond by connectivity accepted and then a connected dominated subset is achieved between the two dominants. The Subset ID will be the highest NIC MAC address of the two dominant. The dominated nodes that are member of the shortest path between these two dominants become dominants. This operation is repeated so as one connectivity is done at a given time where we will choose the closest dominant to the subset. This operation ends when all subset has the same ID which means that all the subset are connected and then we can say that we have a connected dominating set.

On the CDS the dominant will exchange the network features among a common channel and use the CSMA/CA. We propose to keep this channel for the CDS. Note that nodes with single NIC can not be dominants or members of the CDS.

The resulting CDS is an optimized tree (Minimum Spanning Tree between dominants) so it no presents cycles.

<table>
<tr><td colspan="5">Neighborhood List For Node (R_1)</td></tr>
<tr><td>(R_2) ID</td><td>(R_2) NIC-2</td><td>N/A</td><td>(R_1) ID</td><td>Child</td></tr>
<tr><td>(R_4) ID</td><td>(R_4) NIC-2</td><td>N/A</td><td>(R_5) ID</td><td>Other</td></tr>
<tr><td>(R_8) ID</td><td>(R_8) NIC-2</td><td>N/A</td><td>(R_7) ID</td><td>Father</td></tr>
<tr><td colspan="5">Neighborhood List For Node (R_2)</td></tr>
<tr><td>(R_1) ID</td><td>(R_1) NIC-2</td><td>N/A</td><td>(R_8) ID</td><td>Father</td></tr>
<tr><td>(R_3) ID</td><td>(R_3) NIC-2</td><td>N/A</td><td>(R_2) ID</td><td>Child</td></tr>
<tr><td colspan="5">Neighborhood List For Node (R_3)</td></tr>
<tr><td>(R_2) ID</td><td>(R_2) NIC-2</td><td>N/A</td><td>(R_1) ID</td><td>Father</td></tr>
<tr><td>(R_4) ID</td><td>(R_4) NIC-2</td><td>N/A</td><td>(R_5) ID</td><td>Other</td></tr>
<tr><td colspan="5">Neighborhood List For Node (R_4)</td></tr>
<tr><td>(R_1) ID</td><td>(R_1) NIC-2</td><td>N/A</td><td>(R_8) ID</td><td>Other</td></tr>
<tr><td>(R_3) ID</td><td>(R_3) NIC-2</td><td>N/A</td><td>(R_2) ID</td><td>Other</td></tr>
<tr><td>(R_5) ID</td><td>(R_5) NIC-2</td><td>N/A</td><td>(R_5) ID</td><td>Father</td></tr>
<tr><td>(R_7) ID</td><td>(R_7) NIC-2</td><td>N/A</td><td>(R_6) ID</td><td>Other</td></tr>
<tr><td>(R_8) ID</td><td>(R_8) NIC-2</td><td>N/A</td><td>(R_7) ID</td><td>Other</td></tr>
<tr><td colspan="5">Neighborhood List For Node (R_5)</td></tr>
<tr><td>(R_4) ID</td><td>(R_4) NIC-2</td><td>N/A</td><td>(R_5) ID</td><td>Child</td></tr>
<tr><td>(R_6) ID</td><td>(R_6) NIC-2</td><td>N/A</td><td>(R_5) ID</td><td>Child</td></tr>
<tr><td colspan="5">Neighborhood List For Node (R_6)</td></tr>
<tr><td>(R_5) ID</td><td>(R_5) NIC-2</td><td>N/A</td><td>(R_5) ID</td><td>Father</td></tr>
<tr><td>(R_7) ID</td><td>(R_7) NIC-2</td><td>N/A</td><td>(R_6) ID</td><td>Child</td></tr>
<tr><td colspan="5">Neighborhood List For Node (R_7)</td></tr>
<tr><td>(R_4) ID</td><td>(R_4) NIC-2</td><td>N/A</td><td>(R_5) ID</td><td>Other</td></tr>
<tr><td>(R_6) ID</td><td>(R_6) NIC-2</td><td>N/A</td><td>(R_5) ID</td><td>Father</td></tr>
<tr><td>(R_8) ID</td><td>(R_8) NIC-2</td><td>N/A</td><td>(R_7) ID</td><td>Child</td></tr>
<tr><td colspan="5">Neighborhood List For Node (R_8)</td></tr>
<tr><td>(R_1) ID</td><td>(R_1) NIC-2</td><td>N/A</td><td>(R_8) ID</td><td>Child</td></tr>
<tr><td>(R_4) ID</td><td>(R_4) NIC-2</td><td>N/A</td><td>(R_5) ID</td><td>Other</td></tr>
<tr><td>(R_7) ID</td><td>(R_7) NIC-2</td><td>N/A</td><td>(R_6) ID</td><td>Father</td></tr>
</table>

Table 6.3: Network Neighborhood Lists

6.3.3.3 Connected Dominating Set creation algorithm

After the establishment of the neighborhood list on each network node as shown in Table 6.3, we propose the following algorithm to connect the dominant node. This algorithm aims to obtain, as a result the CDS structure and the principle is that each dominant node initiates the creation of the CDS. Each dominant node (wireless mesh router) knows that it is a dominant node so it chooses from its neighborhood list the closest dominant and, then, sends a message to that dominant to invite it to join the CDS structure. The association obtained from the two dominants is a new IBSS. Then, the nodes from the association elect the closest dominant to join them. This operation finishes when all the dominant nodes join the new IBSS. The final IBSS obtained is thus CDS. Note that if two dominant nodes are separated by a dominated node, the latter becomes dominant and joins the CDS.

6.3.3.4 Illustration example of network discovery mechanism

After the network discovery phase, we obtain on each node a neighbor list. The structure of the neighbor list is done in the table 6.2 and we can explain each field as follows:

- Node ID includes the ID of the neighbor that is its highest NIC MAC address
- NIC-2 includes the second NIC MAC address if the neighbor has at least two NICs
- NIC-3 includes the third NIC MAC address if the neighbor has three NICs
- BSSID includes the ID of the neighbor's dominant highest NIC MAC address
- Relation includes the relation with the neighbor which can be Father, Son or Brother. (Father if it is dominating this node, Son if it is dominated by this node, Brother if it is dominated by the same node or Other if they are just neighbors with different dominants)

For our example, the resulting neighborhood list is done in the table 6.3.

After the application of our algorithm, described in the previous subsection, we obtain:

1. R_2 invites R_1, R_7 invites R_8 and R_5 invites R_6 to create the CDS
2. R_1, R_8, and R_6 accept the invitation of respectively R_5, R_7 and R_2.
3. Three IBSS are obtained and are $[R_2, R_1]$, $[R_7, R_8]$ and $[R_5, R_6]$
4. $[R_2, R_1]$ invite $[R_7, R_8]$ to create the CDS
5. $[R_7, R_8]$ accept the invitation of $[R_2, R_1]$
6. Two IBSS are obtained and are $[R_5, R_6]$ and $[R_2, R_1, R_7, R_8]$
7. $[R_5, R_6]$ invit $[R_2, R_1, R_7, R_8]$ to create the CDS
8. $[R_2, R_1, R_7, R_8]$ accept the invitation of $[R_5, R_6]$
9. One IBSS is obtained and is $[R_5, R_6, R_2, R_1, R_7, R_8]$
10. The CDS is, then, $[R_5, R_6, R_2, R_1, R_7, R_8]$

6.3.4 A better Connecting Dominating Set establishment

After presenting the approach for a fast network discovery, we propose by this section, a better CDS for the network management. Let us consider the network of figure 6.9. In this network, we apply the following sequences:

1. Dominants election.
2. Dominants connection.
3. CDS creation.

We present, in the following subsection the adopted approches.

6.3.4.1 Dominants election

There are a lot of proposals in the litterature where a leader declares itself dominant. Its neighbors become dominated and the neighbors of the dominated become active. The active node possessing at the end of the round the strongest weight among its active neighbors becomes dominant. The metrics of election can be the degree of a node, the address, or a generic weight and is not clarified. Under the scope of creating the most efficient and a minimum cardinality CDS, we propose that the node that has the highest degree (number of neighbors) starts the dominant election phase and if there are many nodes that have the same degree, the node that has the highest NIC address among them starts the election phase. Then, we divide the network nodes in two groups. Let GrD, be the group of nodes that are explored and can be either dominant or dominated. Let $\overline{GrD}$, be the group of the nodes that are unexplored yet. Hence as a first step, the dominant node and the dominated nodes inside the $Kcds$, join the group GrD. For the next step, we focus on nodes from the group GrD that have the biggest neighbors in the group $\overline{GrD}$. If there is more than one node, we chose the node that has the highest NIC address. We continue up to the group $\overline{GrD}$ become empty. The table 6.4 illustrates an example for the dominant election.

6.3.4.2 Dominants connection

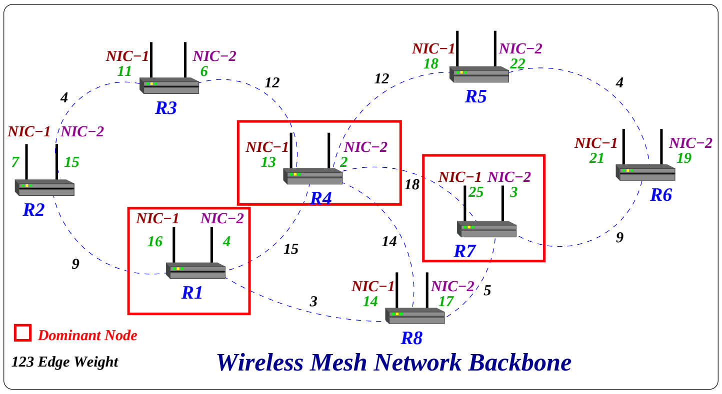


Figure 6.11: Network with weight on the edges

We consider the network of the figure 6.11. To have the best perfoming connection of the dominant, we propose to procede as follows:

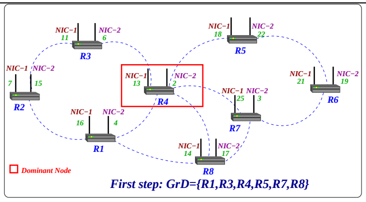
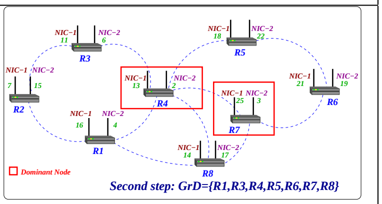
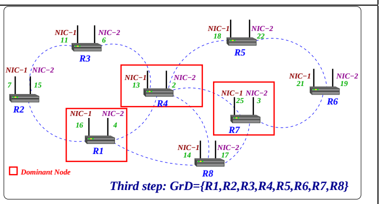
Step	Description	GrD	$\overline{GrD}$	Network
1	$deg\overline{GrD}\,(R4) = 5$	$\{R4, R1, R3, R5, R7, R8\}$	$\{R2, R6\}$	
2	$deg\overline{GrD}\,(R7) = 1$	$\{R4, R1, R3, R5, R6, R7, R8\}$	$\{R2\}$	
3	$deg\overline{GrD}\,(R1) = 1$	$\{R1, R2, R3, R4, R5, R6, R7, R8\}$	$\{\}$	

Table 6.4: Example of dominants election

1. From each Dominant node, we compute the shortest paths to each other dominant node.
2. We create a new graph that connects the dominant nodes with the value of connection the value of the shortest paths.
3. We select from this graph the minimum spanning tree that we consider as a new graph.

6.3.4.2.1 Shortest path: For the shortest path computaion we decide to utilize the Dijkstra's algorithm:

Let the node N_I at which we are starting be called the initial node. Let the distance of node N_x be the distance from N_I to N_x. Dijkstra's algorithm will assign some initial distance values and will try to improve them step by step.

1. Assign to every node a distance value. Set it to zero for our initial node and to infinity for all other nodes.
2. Mark all the nodes as unvisited. Set the initial node as current.
3. For current node, consider all its unvisited neighbors and calculate their tentative distance (from the initial node). For example, if current node N_1 has distance of 6, and an edge connecting it with another node N_1 is 2, the distance to N_2 through N_1 will be 6+2=8. If this distance is less than the previously recorded distance (infinity in the beginning, zero for the initial node), overwrite the distance.
4. When we are considering all the neighbors of the current node, mark it as visited. A visited node will not be checked ever again; its recorded distance is now final and minimal.

5. If all nodes have been visited, finish. Otherwise, set the unvisited node with the smallest distance (from the initial node) as the next "current node" and continue from step 3.

The table 6.5 illustrates the evolution of the computation of the shortest paths between the dominants.

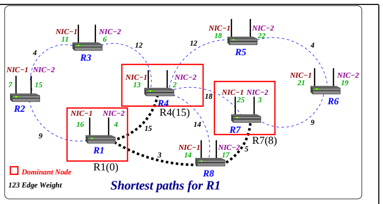
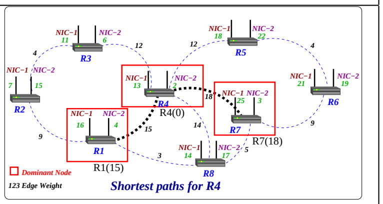
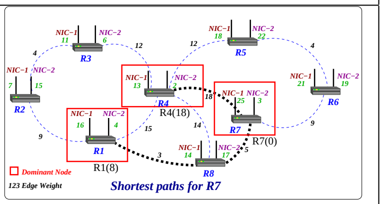
Intitial Node	Nodes Distance	Paths	Network
$R1$	$\{R4\,(15)\,,R7\,(8)\}$	$\{R4, R7\,(R8)\}$	
$R4$	$\{R1\,(15)\,,R7\,(18)\}$	$\{R1, R7\}$	
$R7$	$\{R4\,(18)\,,R1\,(8)\}$	$\{R4, R1\,(R8)\}$	

Table 6.5: Connection between the dominants

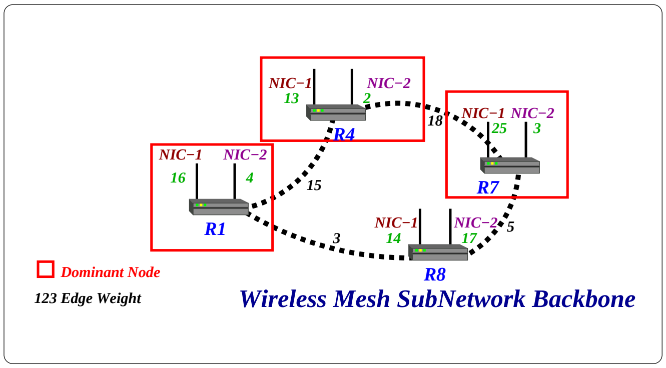


Figure 6.12: Resulting Subnetwork

6.3.4.2.2 Minimum Spannig Tree over the shortest paths: For the minimum spanning tree over the shortest path, we create a subnetwork from the previous network that includes only the involved nodes (Dominant nodes and dominated nodes belonging to at least one shortest path between two dominant nodes) as depicted in Figure 6.12. Then, we utilize the prim's algorithm :

The algorithm continuously increases the size of a tree, one edge at a time, starting with a tree consisting of a single vertex, until it spans all vertices.

1. Input: A non-empty connected weighted graph G with vertices V and edges E (the weights can be negative).
2. Initialize: $Vnew = \{x\}$, where x is an arbitrary node (starting point) from V, $Enew = \{\}$
3. Repeat until $Vnew = V$:
   i) Choose an edge (u, v) with minimal weight such that u is in $Vnew$ and v is not (if there are multiple edges with the same weight, any of them may be picked).
   ii) Add v to $Vnew$, and (u, v) to $Enew$
4. Output:$Vnew$ and $Enew$ describe a minimal spanning tree.

The Figure 6.13 gives the less cost way to connect the dominant nodes.

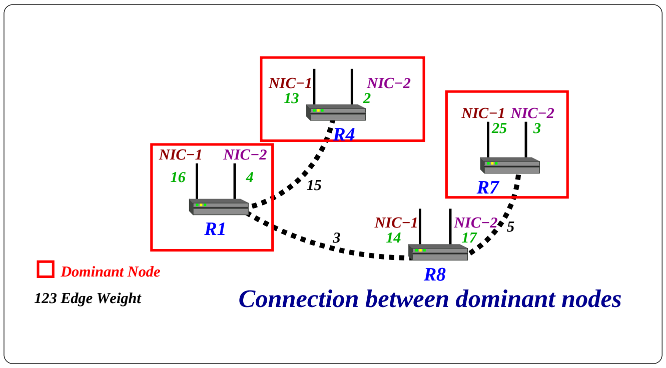


Figure 6.13: The Connection of the dominant node

6.3.4.3 Connecting Dominating Set creation

The node $R8$ was not elected as dominant. However, this node belongs to the communication paths between dominants, the $R8$ will be switched to dominant state therefore. The Figure 6.14 depicts the created CDS inside the WMN backbone.

6.3.5 Clustering and routing

6.3.5.1 Clustering

For clustering, each dominant proposes to the dominated nodes that are in a range of $Kcds$ hops from it to join the cluster it created. This step starts from the dominant node that has the highest NIC MAC address to avoid the case where one dominated node can belong to two different clusters. A dominant node that has not dominated nodes in a range of $Kcds$ hops from it joins the cluster of the closest dominant node that has the highest NIC MAC address. Finally, the less cost wireless link between two nodes that belong to different clusters has for consequence that these two nodes become two relay nodes.

The Figure 6.15 depicts the final configuration of the network.

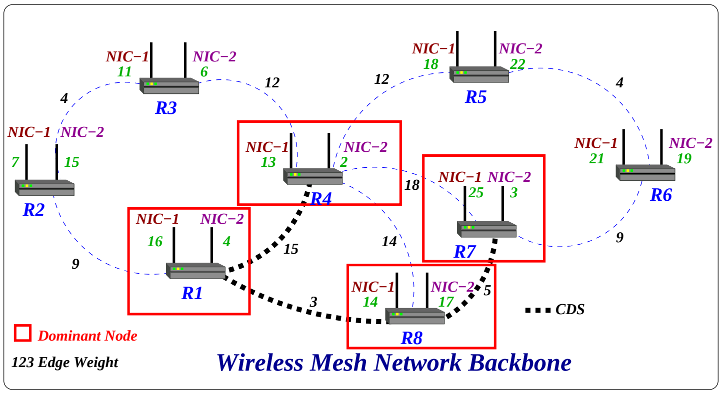


Figure 6.14: Connecting Dominating Set over WMN backbone

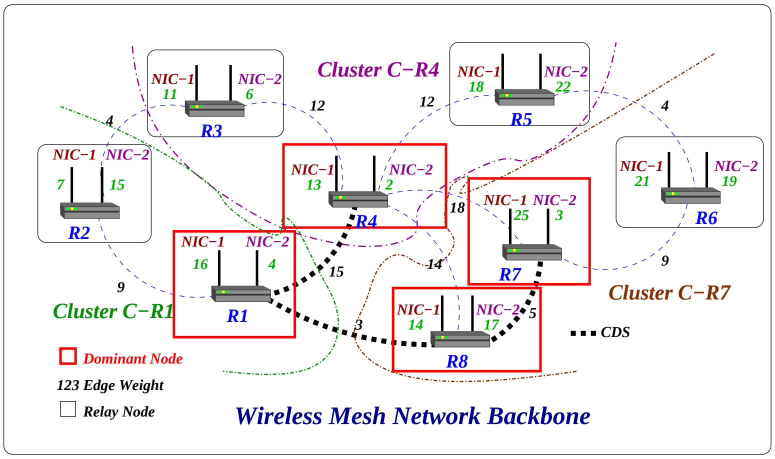


Figure 6.15: Wireless Mesh Network Backbone

6.3.5.2 Routing

For routing we propose that:

- If the source and destination are inside the same cluster, the source reaches the destination by using the shortest path algorithm.
- If the source and the destination belong to two different clusters, the source asks the CDS to know the relay node to which the source will give the message. The source reaches the relay node by using a shortest path algorithm. The realy node forwards the message to its correspondant relay node. The correspondant relay node will act as being the source of the message. These steps are repeated until the message arrives to the destination.

6.4 Conclusion

In this chapter, we have introduced two different approaches that aim to deal with a large distributed network. The first approach consists on dividing a large network into small clusters which are handled by an elected cluster-head. The second approach consists on creating a virtual structure that will work as a centralized entity of management. Both approaches target large distributed networks by making their management easier. A future work would be to evaluate the performances of both approaches.

Chapter 7

Conclusion and Outlook

In this chapter, we first briefly summarize the contributions of this thesis in Section 7.1. In Section 7.2, we discuss extensions of this work that will provide interesting challenges for future research. We also give a more long-term vision which we believe research will be able to make significant contributions in the field of wireless vehicular and mesh networks.

7.1 Summary of Contributions

Recent years have witnessed an enormous increase in the use of the Internet over wireless networks for a large variety of applications such as e-commerce, software distribution, multimedia streaming, video conference, data communication, and of course, safety applications . The emergence of such applications has created the need to provide a permanent access to Internet services wherever we are. New technologies have been developed to provide solutions to this actual need. A major technological breakthrough to improve road safety and traffic efficiency will be cooperative communications for transport systems. Through the use of wireless communications, cooperative systems will allow the dynamic exchange of messages between transportation systems such as vehicle-to-vehicle (V2I) and vehicle-to-infrastructure (V2I) communications. Cooperative Vehicular Systems are composed of Road Side Units (RSUs) and On Board Units (OBUs). OBUs provide a network connectivity to the users inside their cars whereas the RSUs are fixed and deployed equipment on the public roads. The vehicular networks are defined by the new amendment IEEE 802.11p that has been just approved of by its responsible task group.

In this context, we are interested in answering the following questions: “How can we use this technology for safety applications?” “How can we design a deployable and scalable network for urban and extra-urban environment?” “How can we connect vehicular networks to the different heterogeneous networks?” “How can we improve the performances of these networks?”

The RSUs can be connected to each other and to the Internet using Wireless Mesh Network backbone. We call "service level/access of the vehicular network" the network composed of the RSUs and the OBUs and we call "backbone level/infrastructure of the vehicular network" the network connecting the RSUs to the Internet. In this thesis, we develop several contributions to improve the vehicular network performances at both service level and backbone level.

In the first chapter, we have described the context of the work described in this dissertation. In chapter 2, we have given an overview of the trends and issues in the general context of deployment, interconnection, and performance improvements of vehicular networks. Then, we have pointed out the main problems that we have addressed in this thesis.

Chapter 3 has focused on the first component concerning the better use of vehicular networks for safety applications. For the service level, 802.11p defines a control frequency channel for control and most critical data packets and one or several service frequency channels for less critical packets. As a first step, we propose an analytical model for the 802.11p operations in the control frequency. It captures all suggested enhancements important for exchanging data packets generated by road safety applications. The model is a simple tool that is able to reproduce expected results. This is an important step toward the improvement of vehicular network performances.

The second component of our proposal for the service level is the optimal placement of road side units which has been presented in Chapter 4. The main idea behind this contribution is to provide an efficient vehicular network deployment. Our approach is to combine the model we introduced in Chapter 3 with optimization criteria for optimal placement of roadside units. A set of performance results in simulation environment using the *Matlab* environment show that the choice of the optimization criteria can closely achieve the expected bandwidth sharing among all the connected OBUs.

Note that in order to rapidly deploy our proposed new mechanisms over the public roads, we kept the model as simple and scalable as possible while maintaining its original intentions.

The second part of this dissertation focused on the possible contributions at the backbone level. We conduct a rich study to identify what are the significant factors and mechanisms that have the most important impact on the WMNs backbone performances. We concluded that investigating on channel allocation and routing is the best answer to that issue. After that, in Chapter 5, we investigated and classified the most challenging approaches and proposals for channel allocations and routing. We concluded that the most interesting work is proposing a common-layer design between MAC layer and network layer and are mostly concerning a centralized manner. However, in a wireless environment, presenting a centralized approach is not too realistic. We addressed the challenging issues concerning the channel allocation and routing for a distributed network. Our contributions in this area concern the development of two interesting approaches to solve the addressed problem in a distributed fashion.

In Chapter 6, we were first interested in studying and proposing a solution to divise the huge network on interconnected clusters. We identified some possible approaches to achieve efficient network clustering. Then, we adopted the most appropriate method based on density metric to build clusters and elect cluster head. Finally, we adopted two routing mechanisms depending on whether the source and destination are inside the same cluster or not. A second approach is to create over the distributed network a Connected Dominating Set (CDS). This CDS will work as a virtual structure for the network resource management.

We believe that the **complexity** of protocols for distributed networks will be the main challenge for networking in the coming years. Application and equipment developers face an environment of harsh competition and a great diversity of protocols, vendors, service providers, and applications. The researchers perspective should take this into account by focusing less on global solutions that assume global control over the infrastructure; the design space should rather be restricted to solutions that are viable in this dynamic, heterogeneous marketplace.

One very important lesson that we have learned from the impressive success of the wireless networks is the power of its service model simplicity. Offering only connectivity as a largest common denominator of possible services has allowed the wireless networks to spread rapidly. Monolithic solutions proposing more elaborate service models have more trouble becoming de-facto standards. Research should recognize this by focusing less on complete solutions that are hard to deploy in practice, simply because a global networking infrastructure is not, and probably never will be, a fixed homogeneous structure under centralized model.

7.2 Future Directions

There are several promising and important extensions to the research problems addressed in this thesis. Indeed, a number of issues remain open in the design of efficient schemes to use the network resource well in a vehicular environment. We will continue our approach of gaining insight using a combination of network use and ISP (Internet Service Provider) point of view.

First, in the proposed model in Section 3, we assumed that the main function for vehicular networks remains safety application. However, vehicular networks will also provide an attractive environment for commercial application. We plan to develop a generic model that will consider the commercial and personal applications that are running on the other channels. we have already introduced in Section 3 a generic model that can be used for any channel including environmental features by taking into account an approximation of the physical layer. Future work in this topic could also propose to extend the model of Section 3 to include retransmissions and load balancing over the available channels. An initial investigation on this topic has been already addressed in Section 5 where we reviewed the available techniques for the backbone level of Wireless Mesh Networks.

Second, there exist many possible areas for future work in the theme of bandwidth sharing between stations on a vehicular network. Recent research focused on the impact of changing some standard parameters and concluded that an improvement of the network performances occur. Future work could develop a dynamic control mechanism that provides an efficient help to switch the network protocol parameters to the best configuration depending on the network situation.

Third, in Chapter 5 and 6 as we are acting on the backbone level of WMN composed of already expensive equipment, we could be able to integrate equipments for geographical localization like GPS and implement a geographical routing protocol to improve the network performances. It is worthwhile to mention that these extensions will be useful for many other networks that use the WMN backbone to be connected to the Internet.

To summarize, we believe that this dissertation provides valuable insights and opens up a number of research directions for vehicular network deployment. The focus was on the safety applications support at service level and resource sharing between WMN backbone routers at backbone level for vehicular networks.

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