Channel Allocation and Routing in Wireless Mesh Networks: A survey and qualitative comparison between schemes

F. Kaabi[1], S. Ghannay[2], and F. Filali[1]
[1]Mobile Communications Department
Eurécom 2229, route des Crêtes BP193, 06904 Sophia-Antipolis, France
E-mail:{kaabi, filali}@eurecom.fr
[2]CRISTAL Laboratory, National School of Computer Sciences, Tunisia
E-mail:{sana.ghannay}@cristal.rnu.tn

Abstract

In order to avoid transmission's 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 have been conducted in the area of multi-channel allocation in order to improve the aggregate bandwidth of the hole network. In this paper, 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 on channel allocation proposals done at the MAC level independently to the other layers. The second one consists on 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.
Keywords: Channel allocation, Wireless Mesh Networks, Multi-Channel Multi-Transceiver, Cross-layer design, Joint-layer design.

1 Introduction

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 actual 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 [5]. For wireless metropolitan area networks (WMAN), i.e., IEEE 802.16 [3], a lot of proposals have been submitted for standardization [6, 7]. Also, for wireless local area networks (WLAN), an extension

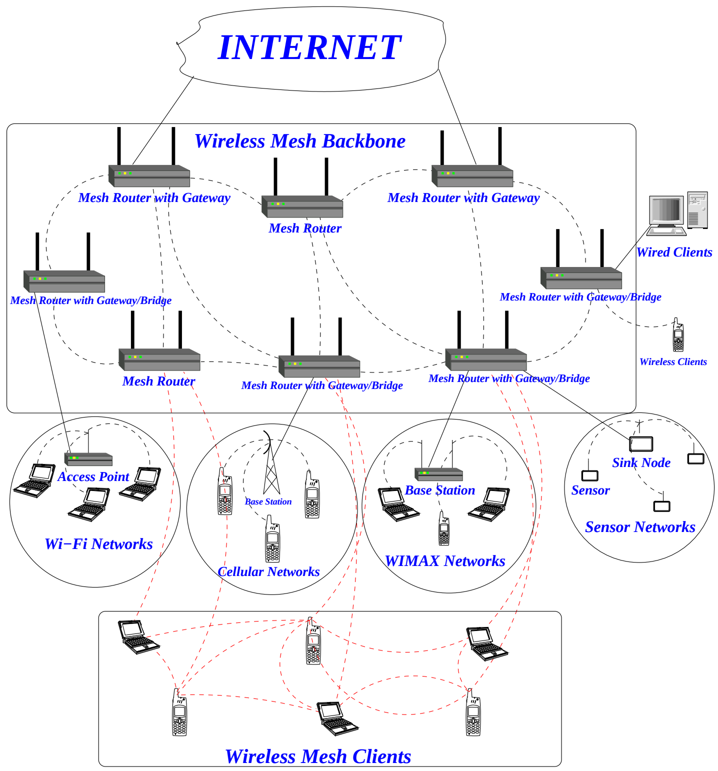


Figure 1: Architecture of a wireless mesh network (WMN)

called 802.11s, that could be called IEEE 802.11-based Wireless Mesh Networks, is still under discussions [4, 8].

A Mesh Network is defined as being an infrastructure network working with an ad hoc mode. The architecture shown in Figure 1 where dash and solid lines represents respectively wireless and wired links, depicts 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 [1, 2, 3] 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 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 providing such capacity. In order to improve WMNs capacity a good management of the available frequencies is necessary.

In this paper, 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 paper 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 [9] and [10] but the proposed techniques and approaches for channel allocations.

The rest of this paper 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.

2 Channel spectrum use in 802.11, 802.15 and 802.16

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 [1]. 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 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.

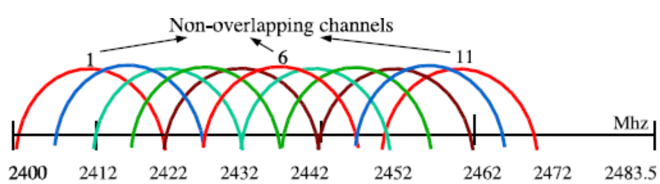


Figure 2: Channel spectrum use in IEEE 802.11 [21]

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 [2], 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 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.

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 1: Center frequency of CSS [2]

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

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

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 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.

2.3 Channel spectrum use in IEEE 802.16

The first IEEE 802.16 [3] 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. For this to be of use, 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 sub-carriers. The most promising, used and benefit channel allocation proposals is OFDMA.

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 2: UWB PHY band allocation [2]

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 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 sub-carriers 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 sub-carrier index.

3 Proposals for Channel Allocation in WMNs

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

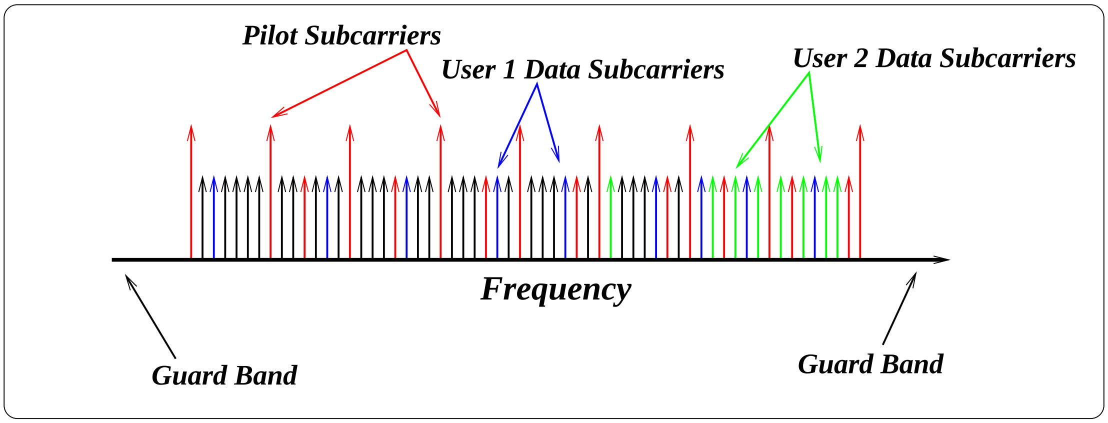
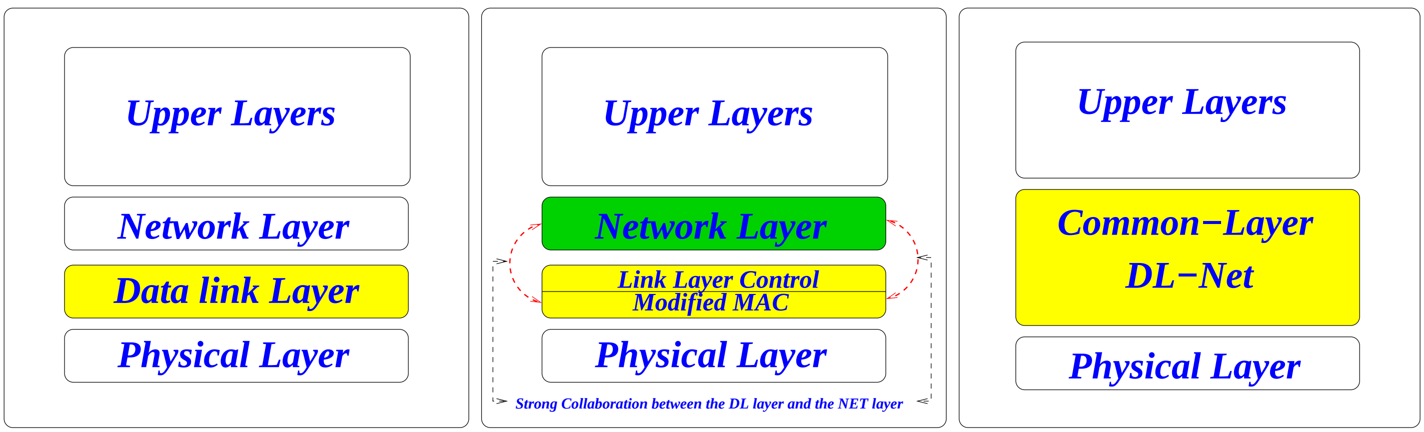


Figure 3: Channel spectrum use in IEEE 802.16 using OFDMA [3]



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

Figure 4: Approaches for channel allocation and dependency to routing protocols

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 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 4. The following subsections review and compare the most recent and promising proposals.

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

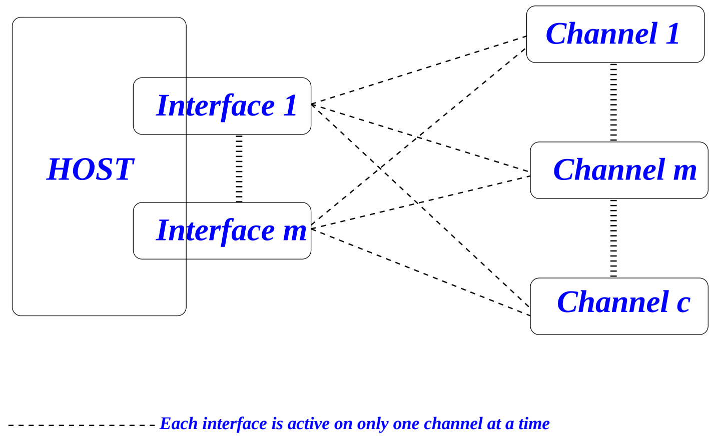


Figure 5: Case of Multi-Transceivers per node

The first category shown in Figure 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 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 [15], 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 [11, 12], that can be considered as an improvement of the first one [15], 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 [16] keeps some interfaces of each node fixed, while others can switch among channels. The Hybrid Multi-channel Protocol (HMCP) [16, 17] 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 [13] 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 [14] 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 [11, 13] to be less efficient than protocols for a single transceiver per node.

In [18], 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 [19]. The main equation in channel allocation and channel assignment in [18] 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 a channel. This equation represents a TDMA-type management inside a maximal clique.

The mathematical formulations expressed in [18] and explained in the previous paragraph model the relationship between the channel allocation, interface assignment, and MAC problems. [18] proposes to extend the MAC framework proposed in [20] 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 decompositions. 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 [18], 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 [18], 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 [21], 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 phase MAC protocol which is a TDMA-style protocol in mesh network [22, 23], 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 explores 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 [21], 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 [21], 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 [21], the author proofs 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 [35], have 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 [35] proof 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 author obtain a set of virtual communication links that can support simultaneous communications.

Table 3 provides a deeper analysis and comparison of the channel allocation techniques described and discussed in this section.

3.2 Cross-layer design for Channel Allocation and Routing

As depicted in Figure 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 [11, 25, 26, 27, 28, 29] 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 with 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 [24] 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 4 provides a deeper analysis and comparison of the channel allocation techniques described in this section.

3.3 Common-layer design for channel allocation and routing

The third and last category given in Figure 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 [30, 32, 33]. In [30], the authors propose an excellent problem formulation on which they explain clearly their approach. In [30], 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 NICs 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 on starting with one node, partitioning its neighbors into q groups and assign 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 allow 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 hole network.

The main idea of the "Load-Aware Channel Assignment" approach in [30] 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 to 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 [31] was proposed.

In fact, in [30], 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.(1).

$$X = \sum_{s,d} C\,(s, d) \tag{1}$$

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.(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.(2) is computed regardless to the number of NICs per node.

$$C_l = \frac{Q * C_Q}{L_l} \tag{2}$$

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.(3), where $P(s,d)$ is the number of acceptable paths between a pair of node (s,d), $P_l(s,d)$ is the number of acceptable paths between a pair of node (s,d) that pass a link l, $B(s,d)$ is the estimated load bandwidth between a pair of node (s,d) and ϕ_l is the expected load on a link l.

$$\phi_l = \sum_{s,d} \frac{P_l(s,d)}{P(s,d)} * B(s,d) \tag{3}$$

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.(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.

$$bw_i = \frac{\phi_i}{\sum_{j \in Intf(i)} \phi_j} * C \tag{4}$$

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 6.

The aggregate throughput advertised by the authors [30] 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 [32] and is presented in five steps but it has the same principles than [30]. Finally, another approach consists on minimizing a convex function [33], 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 [33] that this function can represent for example the power transmission or the link utilization. The performance of the Simultaneous Routing and Resource Allocation (SRRA) [33] 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 [34]. The approach mechanism (Figure 7) is composed by to phases. The first phase that is the initial

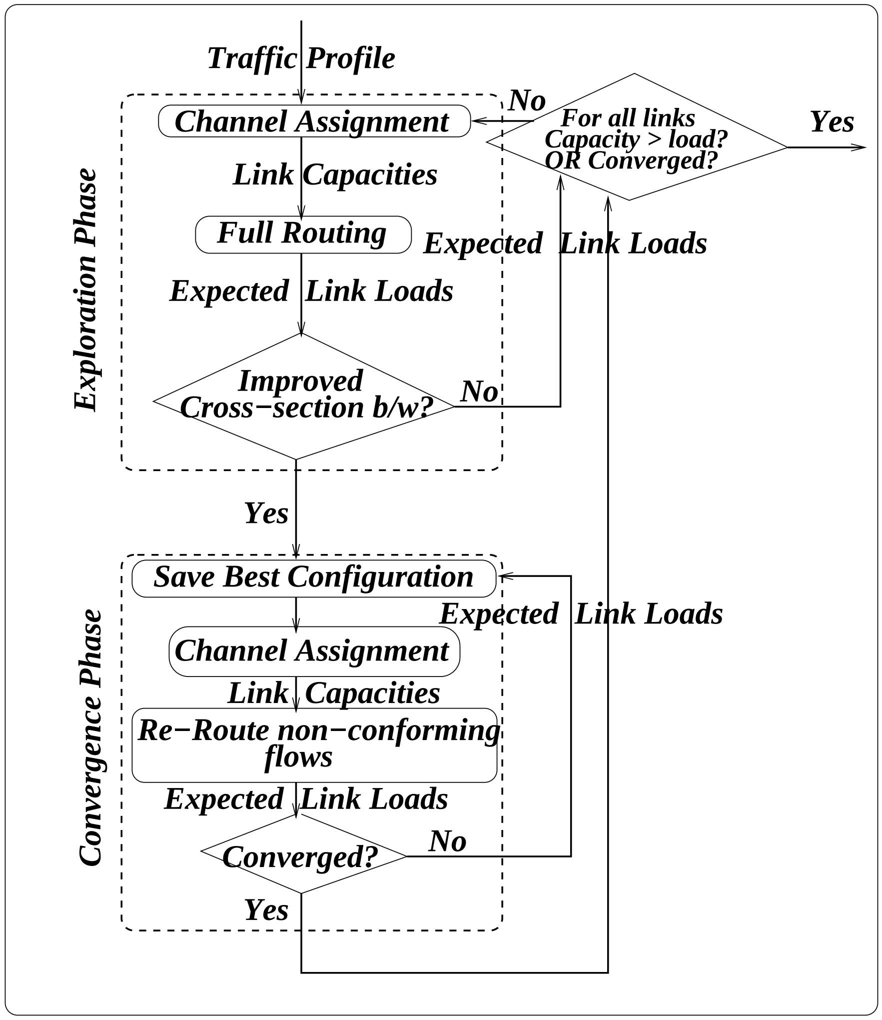


Figure 6: Load aware channel assignment [30]

phase consists on 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 evaluate 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 [34] 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 4.(c).

Finally, the differences between centralized and distributed approaches are done in the table 5.

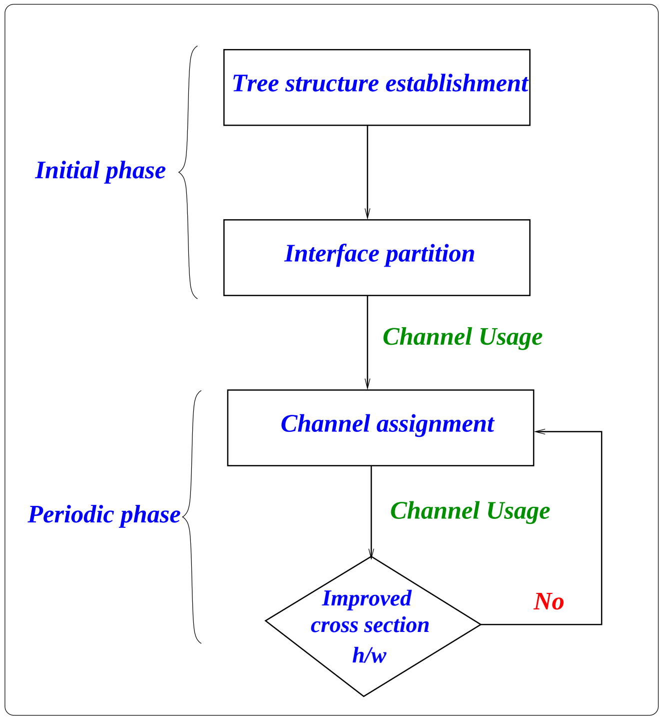


Figure 7: Load-aware channel assignment done by each node.

4 Conclusion and future directions

We have discussed in this paper 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 [18] and [21] where both use graph theory for modeling the problem of channel allocation and agree that it is an NP-Hard problem. [18] considers that the problem of optimizing channel allocation consists on the fact that the sum 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, [18] uses two methods where the first one consists in extracting binary linearization while the second uses an approximate dual decompositions. [21] considers that the problem of optimizing channel allocation consists on achieving zero-mismatch channel allocation (ZMCA) between the available bandwidth provided by the ISP and achieved on the network. In [21], several heuristics are tested and showed 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 [18] which consists on extracting binary linearization is the method to recommend because it is the less dependent on heuristics. Even the performances claimed by the authors seems 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 to 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 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 [24] 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 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 to 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 [30, 32, 33] 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 [36] have been done for multirate anypath 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 affect 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 paper will stimulate the activity in the research community working on wireless mesh networks.

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Techniques names	Descriptions	Advantages	Drawbacks	Performances Evaluation
Static channel allocation [15]	For each interface of each node, allocate a different Channel statically	each node knows the channel allocated to each interface of his 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 [11, 12]	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 strongly affected by Multi-hop
Hybrid Multi-channel Protocol (HMCP) [16, 17]	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 [18]	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 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) [21]	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 [35]	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 3: Comparison between the proposed techniques in case of independent channel allocation

Techniques names	Description	Advantages	Drawbacks	Performances Evaluation
Modifying MAC for multi-channel support [11, 25, 26, 27, 28, 29]	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 [24]	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 4: Comparison between the proposed techniques in case of cross layer design scheme

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