Wireless Mesh Networks Design — A Survey

Article *in* IEEE Communications Surveys & Tutorials · January 2012

DOI: 10.1109/SURV.2011.042711.00007 · Source: IEEE Xplore

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***Abstract*—With the advances in wireless technologies and the explosive growth of the Internet, wireless networks, especially Wireless Mesh Networks (WMNs), are going through an important evolution. Designing efficient WMNs has become a major task for networks operators. Over the last few years, a plethora of studies has been carried out to improve the efficiency of wireless networks. However, only a few studies are related to WMNs design and are mainly concerned with protocol design and routing metrics optimization. In this paper, we survey different aspects of WMNs design and examine various methods that have been proposed either to improve the performance of an already deployed network or to improve its performance by a careful planning of its deployment.**

Key Words: *Wireless Mesh Network, performance improvement, Design problem, Multi-radio multi channel network.*

I. INTRODUCTION

With the proliferation of Internet, Wireless Mesh Networks (WMNs) have become a practical wireless solution for providing community broadband Internet access services. These networks exhibit characteristics that are novel in the wireless context, and in many ways more similar to traditional wired networks [1]. In Infrastructure WMNs, Access Points (APs) provide internet access to Mesh Clients (MCs) by forwarding aggregated traffic to Mesh Routers (MRs), known as relays, in a multi-hop fashion until a Mesh Gateway (MG) is reached. MGs act as bridges between the wireless infrastructure and the Internet. Fig. 1 illustrates a typical WMN infrastructure. In such networks, it is possible to equip each infrastructure node with multiple radios, and each radio is capable of accessing multiple orthogonal channels, referred as Multi-Radio Multi-Channel transmissions. Fig.2 depicts the case of multiple radios routers where each router is equipped with two radio interfaces for the backhaul side communications and one radio interface for the client side communications; in a Multi-Radio Multi-channel network, simultaneous communications are possible by using non-interfering channels, which have the potential of significantly increasing the network capacity [2], [3], [4], [5].

WMNs can provide large coverage area, lower costs of backhaul connections, prolong end-user battery life, and more importantly provide no LOS (Line Of Sight) connectivity among users without direct LOS links. Recent commercial and academic deployments of WMNs in real world are beginning to demonstrate some of these advantages. However, several challenges remain so that a WMN performance in terms of throughput and delays match the performance of a wired network. Furthermore, earlier deployments of WMNs have been linked to a number of problems mainly related to connectivity problems (such as lack of coverage, dead spots or obstructions) and performance problems (low throughput and/or high latency) [6].

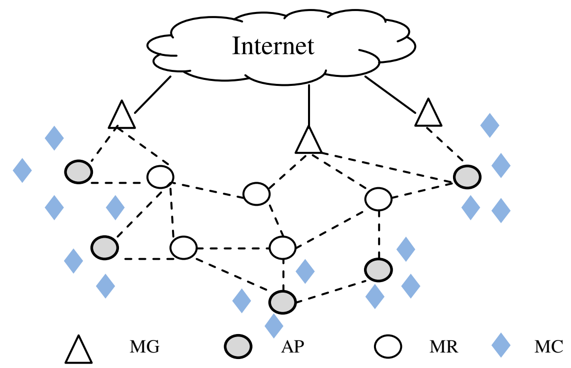


Fig. 1: Wireless mesh network infrastructure

Due to the scarce nature of wireless channel resources, network performance is highly impacted by wireless interference and congestion causing considerable frame losses and higher delays. Fig. 3 depicts situations where some communicating nodes are within the interference range r_i.

The most noticeable sources of performance degradation in WMNs, e.g., low throughput or high latency, are mainly due to poorly planned wireless networks. According to interviews and discussions conducted with network administrators and operations engineers of Microsoft's IT department [6], performance problems occur for many reasons: multi-path interference, traffic slow down due to congestion, large co-channel interference due to poor network planning, or due to poorly configured client/AP. The cause of the problems of wireless network performance can be traced back to the original design assumptions. Moreover, as individual protocols are typically specified with different assumptions in mind, the end-to-end performance of these protocols stacks in deployed wireless networks has not been always satisfactory.

We believe that a well planned and optimized wireless network can often provide extra capacity with the same infrastructure cost; for instance, this may result in more efficient use of radio frequencies (considered as scarce resources). In this survey, we focus on multi-channel WMNs most widely adopted techniques.

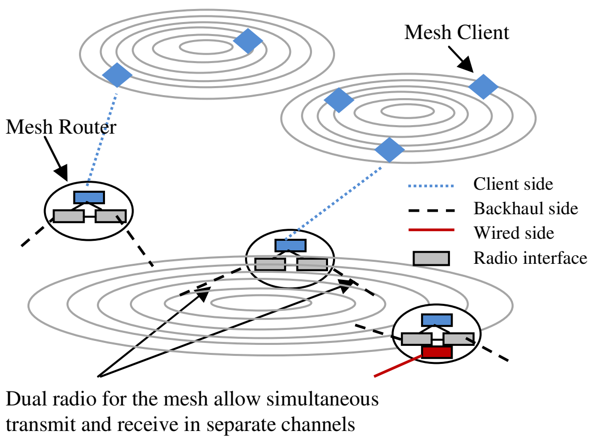


Fig. 2. Multi-radio Mesh Routers. Simultaneous communications are possible by using non-interfering channels.

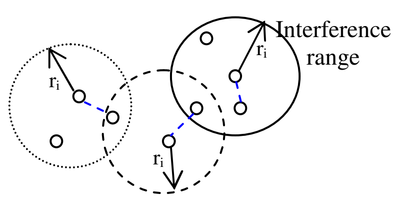


Fig. 3. Simultaneous communications interfere with each other.

Specifically, topology-aware MAC and routing protocols can significantly improve the performance of WMNs. Also, to increase the capacity and flexibility of wireless systems, approaches based on radio techniques have been proposed, the most noteworthy being directional and smart antenna [7][8], MIMO systems [9][10][69], and multi-radio/multi-channel systems [11][12]. To date, many contributions in the context of WMNs performance improvement have been proposed. Depending on what and how to optimize, we can classify these contributions into two broad classes, namely *fixed-topologies* and *unfixed-topologies* (as shown in Fig. 4).

Fixed-topologies based approaches aim at better exploiting and utilizing the network resources; they improve the channel spatial or temporal reuse and/or routing protocols/metrics together with possible admission control mechanisms. However, they assume a given topology, i.e., the position and the type of all mesh nodes are decided beforehand. On the other hand, unfixed-topologies based approaches are subdivided into two groups. The first group (partial design) encompasses all approaches that attempt to optimize the network performance by optimally selecting the position and type of each mesh node (either MR or MG) given a different set of pre-deployed nodes. The second group is more generic and uses more complex techniques to build a network from scratch; it requires the consideration of many factors prior to network deployment. Some of these factors are clients' coverage, optimal placement of MGs (for better throughput and less delay/congestion), and an optimal number of channels/radio per node.

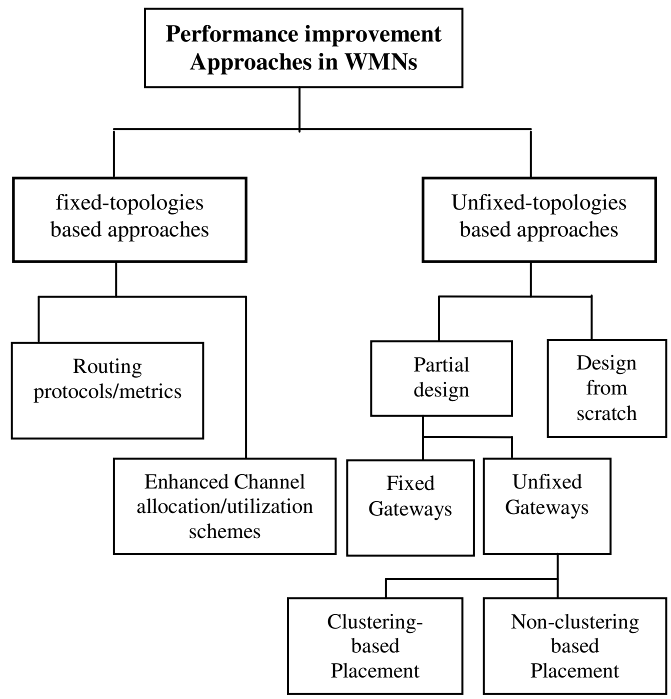


Fig. 4. Classification of approaches for WMN performance improvement

Because of the new and inventive applications WMNs can offer, most industries, unfortunately, introduced premature and not optimized solutions to avoid losing their market share. Furthermore, the solutions were not standardized, and each network offered different incentives for a particular application [13]. To optimize WMNs, a literature search already yields several design issues and solutions, but further research is still needed. The present article surveys existing WMNs performance improvement studies in a comprehensive taxonomy of WMN design approaches according to the categorization shown in Fig. 4. More specifically, for each category, we explore the most representative set of approaches and discuss the corresponding fundamental characteristics.

The rest of the paper is organized as follows. Section II is devoted to fixed-topologies based approaches, i.e., when the network is deployed *a priori*. Section III presents partial deployment based approaches, i.e., either mesh routers or MGs location and characteristics are not yet decided. Section IV encompasses all research efforts related to optimal design of WMNs when all mesh nodes locations and network description are unknown (design from scratch for total deployment). Section V discusses and presents potential/possible research avenues for the design of WMNs. Finally, Section VI concludes the paper.

II. FIXED-TOPOLOGIES BASED APPROACHES

In wireless networks, the network performance can be greatly improved by using multiple channels, as shown in [14][15]. In such networks, a simultaneous transmission is possible as long as different/orthogonal channels are used. Moreover, the probability of packet collision can be reduced because of traffic mitigation in each channel. A number of MAC protocols have been proposed for multi-channel transmission systems [16][17] in ad-hoc networks.

In wireless networks, two neighboring nodes can communicate with each other only if they are assigned a common channel; therefore, the channel assignment may restrict possible routes between any pair of nodes in the network topology. Thus, the effectiveness of multi-channel routing algorithms is closely related to the channel assignment scheme used.

In the last decade, numerous research efforts from around the globe have addressed the problems of routing and channel assignment in multi-channel WMNs. The majority of these studies could not dissociate the routing problem from the channel assignment problem leading to proposals of joint solution for both problems in the same study. A good survey on joint design approaches in WMNs can be found in [70]. Raniwala et al. [18] propose a dynamic channel assignment and routing techniques in multi-channel WMNs. They propose a set of distributed load-aware channel assignment and routing algorithms that can realize the raw performance potential of the multi-radio architecture in the context of multi-hop wireless access. They measure the traffic going through each node, and compute the available bandwidth on different links of a path as well as on the MG node to find a load-balancing route. They separate each channel load and use it to compute the residual bandwidth available to any link. It also supports fast failure recovery. The authors use three routing metrics to determine the final tree structure (the cost metric is carried in the ADVERTISE messages). These are the *hop count*, the *MG link capacity*, and the *Path capacity*. The *hop count* is the number of hops between a WMN node and the MG node; however, this metric does not contribute to balancing network load. The *MG link capacity* indicates the residual capacity of the uplink connecting the root MG of a tree to the wired network. The *Path capacity* is more general than the other two metrics since the bottleneck of a path can be any constituent link on the path rather than always being the MG link.

Draves et al. [19] propose a very interesting metric for routing in multi-radio multi-hop wireless networks. The goal of the metric is to choose a high-throughput path between a source and a destination. The metric WCETT (Weights Combination based on Expected Transmission Time- ETT) is defined as a combination of weights assigned to individual links based on the Expected Transmission Time, which is a function of the loss rate and the bandwidth of the link. The authors in [19] conducted experiments and concluded that a path that is made up of hops on different channels is better than a path where all the hops are on the same channel (interference problem consequences). They show that unlike shortest paths, the benefits are actually limited to the cases of longer paths and heavily-loaded networks. This metric avoid intra-flow interference as it considers all channels used along the route. Nevertheless routes in congested areas might be selected since WCETT does not avoid inter-flow interference [20]. The Metric of Interference and Channel switching (MIC), also based on the value of ETT, addresses the inter-flow issue [20]. Each node takes into account the number of interfering nodes in the neighborhood to estimate inter-flow interference. The iAWARE metric [21] also considers the inter-flow interference by estimating the average time the medium is busy because of transmissions from each interfering neighbor, moreover, it considers link-quality variation.

Alicherry et al. [2] propose a novel throughput optimization technique in multi-radio WMNs. They mathematically formulate the joint channel assignment and routing problem taking into account interference constraints, the number of channels in the network, and the number of radios available at each mesh router. The mathematical model is then used to develop a solution that optimizes the overall network throughput subject to fairness constraints on allocation of scarce wireless capacity among mobile clients. They used a linear program (LP) to find a flow that maximizes the throughput. The same LP is solved twice with different objective functions. The first objective function maximizes the fraction λ of loads that are effectively satisfied at all nodes; the resulting optimal value λ^* is then used to minimize the second objective of link schedulability which is an intuitive measure of network total interference. The solution technique they use is nothing but an instance of the well-known aggregated objective resolution. This is a classical technique to handle Multi-Objective Problems (MOPs). The major problem with the aggregate technique is its inability to find solutions in non-convex fronts as proved in [22] later referred in [23]. Basically, when the landscape of the single objective, resulting from aggregating two or more objectives, is not convex then the image of the solutions located on those non-convex regions might very well be overlooked (see Fig. 5 for a minimization case of two objectives). Moreover, the setting of the relative weights for the different objectives is very subjective and often leads to favoring some and penalizing others.

To improve the performance of WMNs, interference should be taken into account; indeed, it is the foremost factor that degrades the performance of a wireless network. In [24], Jain et al. conducted a thorough study to show the impact of interference on multi-hop wireless network. Besides collisions, they found that frame loss is another end-result of channels interference. Frame loss may occur due to the accumulative interference resulting from nodes lying outside the silence range of the transmitter. The silence set of a transmitter *A* is the set of nodes that will detect the channel to be busy if *A* transmits [25].

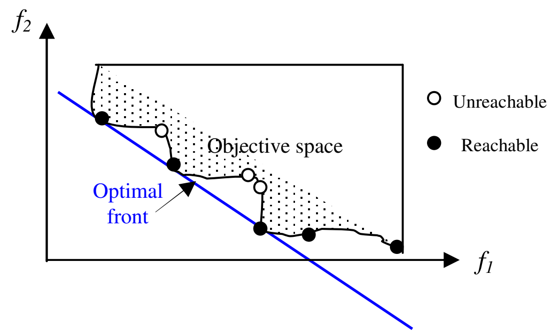


Fig. 5. Image of the solutions located on the non-convex regions might be overlooked.

Even though several interference models exist [26], [27], and [28], Xu et al. [29] suggest the use of a ***channel-bonding technique*** to realize a high-data-rate packet transmission by using a broadened channel. The channel-bonding technique is generally used in IEEE 802.11n, where multiple frequency channels are joined into a single broader channel. Simulation results indicate that when the traffic is low, the channel-bonding technique can achieve lower delay compared to the multi-channel technique, while under high-traffic conditions, the multi-channel technique can greatly mitigate the influence of packet collisions, and thus improve network performance.

Various methods have been proposed in order to enhance channel utilization by improving spatial reuse. A comprehensive survey for improving spatial reuse in multi-hop wireless networks is provided in [30].

Most of the current protocol optimization techniques, applied to achieve a better WMN performance, are layer based protocols for which "*layering as optimization decomposition"* is applied. The key idea of "*layering as optimization decomposition*" is to decompose the optimization problem into sub-problems, each corresponding to a protocol layer and functions of primal or Lagrange dual variables [31]. The Coordination between these sub-problems corresponds to the interfaces between layers.

Yet, ***cross-layer design*** is one of the most important tasks in protocol design for WMNs for performance optimization. Cross-layer design allows communications to take place even between non adjacent layers through additional entities introduced into the system's architecture. However, there is no reference model that specifies the functionality each new entity must realize in a cross-layer design solution [30]. Also, it comes with risks due to several factors such as: the loss of protocol-layer abstraction, incompatibility with existing protocols, unforeseen impact on the future design of the network, and last but not least difficulties in maintenance and management. Currently, several research efforts are aiming to integrate cross-layer design solutions into wireless communication standards with the objective to allocate resources to mobile users, schedule access to shared resources with higher throughput, and achieve better quality of service for multimedia applications [71]. Many of these solutions employ functional entities that support cross-layer processes for mobile devices. A good survey on cross-layer design in WMNs can be found in [32] and [71].

In addition to performance enhancement schemes (as seen above), there are some studies that are related to ***network topology control*** **design**. The main goal of the topology control is to identify a subset of possible wireless links that provide connectivity for wireless networks, with certain design criteria including power consumption [33], interference [34], broadcast [35][36], and quality-of-service (QoS) [37]. In WMNs, topology control can be used to reduce network interferences; in particular, Lu et al. [37] propose a topology control scheme such that the overall throughput can be maximized by taking into account traffic patterns in the network. The main idea of the proposed scheme is to establish multiple *wireless highways*, on both the horizontal direction and the vertical direction. Highways in each group can operate simultaneously because they are mutually parallel and can be placed away enough to reduce interference below a certain threshold. Consequently, horizontal and vertical highways will partition the whole geographical area into grids, in which nodes will try to forward their traffic to the nodes on neighbouring highways. To demonstrate the merits of the proposed framework, the authors also present scheduling schemes based on network coding and physical-layer network coding.

Other studies that could be classified as fixed topology design schemes, deal with the construction of networks' virtual backbones [38], [39], and [40]. The main objective of virtual backbone construction is to alleviate the Broadcasting Storm Problem by reducing the communication overhead and simplifying connectivity management. Thus, with virtual backbones, routing messages are only exchanged between the backbone nodes instead of being broadcasted to all the nodes. The problem of finding a virtual backbone is an instance of the problem of finding a Connected Dominated Set (CDS). The simplest approach for selecting the backbone nodes is to first find a minimum CDS, then construct the spanning forest and finally create the spanning tree, which connects the entire graph.

Most of the approaches discussed in this section aim to enhance the performance of a multi-channel WMN by solving one or many of the above issues, e.g. routing metric, channel assignment, routing protocol, and interference. Even though these approaches exhibit a significant diversity, they possess a considerable similarity in a sense that they address issues that are inevitably related to each other. The routing metrics serve as the basis for routing and significantly influence network performance, whereas, a different metric (e.g., hop-count, channel diversity, traffic load) leads to different routing results even if supported by the same routing protocol. Currently there is an increasing number of routing metrics and, a consensus on which should be used has not yet been reached. Most of actual routing protocols implementations, generally, prefer metrics with simpler designs as those in [18] and [19]. Channel assignment and routing are mutually dependent to the extent that a well designed routing algorithm for multi-channel WMNs may become useless with an improper channel assignment. With respect to interferences, link scheduling guarantees free-interference communications by scheduling the links sharing the same channel within the interference range to use different time slots. Thus, the link scheduling problem is solved after the routes are defined and channels are assigned accordingly.

Although these approaches (seen in this section) combine some or all of the above issues, which are formally converted to NP-hard formulations, they differ in the solution approach adopted to solve the problem and the QoS constraints to satisfy. A subset of these approaches model the multi-channel WMN by a flow network and propose heuristics to solve their optimization models, mainly based on greedy searches. Some of them rely only on local information to quickly adapt to network dynamics (distributed approach); however, the results obtained may be far from optimality because of the partial nature of the information they rely on. Others use the entire network information (centralized approach) but assume a static traffic pattern. Notice that this kind of approaches can effectively lead to optimal or near optimal solutions since global network information is available, though, they are not applicable during network operation (since they do not support network changes).

Additionally, the performance improvement based schemes surveyed in this section are aimed at selecting the best routing metric to route the traffic with higher throughput and/or to better utilize/allocate the channels in order to minimize packets collisions and losses or to control the topology with certain design criteria (such as power consumption, interference, broadcast, and quality of service). Nevertheless, all these contributions assume, in one way or another, a priori fixed topologies with the position and type of nodes known in advance.

III PARTIAL DESIGN OF WMN TOPOLOGIES

Another way to achieve a better network performance is to optimize the placement and characteristics of either APs or MGs before network deployment. A careful placement of MGs, may lead to less congestion, low delay and eventually better throughput if the distances AP-MG and the links capacity are taken into account. Additionally, with optimal placement of APs for a required coverage, the network setup becomes more flexible in case of addition of news APs. We classify partial design schemes into two classes, namely fixed-gateways [41], [42] and unfixed-gateways [43], [44], [45], [46], [47], [48].

A. *Fixed gateways*

In the fixed gateways subcategory, the WMN design problem is viewed as the problem of looking for strategic locations to optimally place the APs and/or MRs given a set of positioned MGs and a set of connectivity, geographic coverage and financial constraints to satisfy.

Sen et al. [41] propose a planning solution for rural area networks to provide a set of villages with network connectivity from a given landline node (a positioned MG). The authors study the optimization problem as the minimization of the total cost affected by the multi-hop network topology and the antenna tower heights under the constraints of throughput, power, and interference. The problem is broken down into four sub-problems: topology search, optimum height assignment, antenna assignment, and power assignment. For each sub-problem, they provide a formulation and apply a different solution technique.

Chen & Chekuri [42] consider the deployment plan for mesh routers that are equipped with directional antennas to form the mesh backbone (an urban WMN is considered). They assume that the placement of MGs is already given. The goal is to maximize the deployment profit (profit representing the amount of services a location can provide if it is deployed with a router) and maintain the cost within the budget while providing sufficient accessibility (connectivity) and guaranteeing a robust backbone. They propose a greedy-based algorithm to solve the optimization problem, however, the power/channel assignment problem is not considered.

B. *Unfixed gateways*

The MGs placement problem concerns where to locate MGs and how to minimize their number as well as the AP-MG path length while satisfying the APs Internet demand. MGs constitute Internet traffic sinks/sources to WMNs and consequently a WMN may be unexpectedly congested at one or more of them if MGs are not adequately located. Basically, the placement of these mesh nodes (MGs) determines the hop-length of the communication paths in the network, the amount of congestion, and the availability bandwidth to and from the Internet.

Due to the impact of MG placement on network performance and network scalability handling, there has been a recent surge of interest in the optimal placement of MGs in WMNs. Some of the key studies can be found in [43], [44], [45], [46], [47], and [48]. Network scalability is highly affected by the geographical expansion and the increase of aggregated demand (when the demand per user increases and/or the number of users increases) and is drastically influenced by the way MGs are placed. If network nodes are divided into groups/clusters and MGs locations are set so that each cluster is served by one MG, the problems of MG placement and network scalability could be effectively solved both at once, as shown in [43] and [49]. We categorize MG placement schemes into clustering-based placement and non-clustering based placement classes.

1) *Clustering-based placement*

Placing MGs based on a clustering approach has a number of benefits including more importantly, the tight relationship between the resulting MGs placement and network throughput [49]. When the network is partitioned into clusters, then independently of the network size, each node can send to nearby MGs within a fixed radius. Consequently, all nodes in a cluster have a bounded distance (in terms of number of hops) to reach a MG.

In multi-radio wireless networks, if traffic is routed on shorter communication paths then the impact of inter-path (or co-cannel) interference on network performance is reduced and. therefore a substantial increase in network throughput can be expected. The research studies in this sub-category can be subdivided into tree-based and non-tree based approaches, depending on whether the placed MGs are following a tree-structure or not.

Tree-based clustering

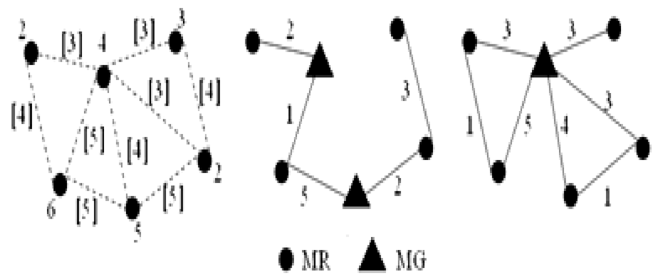
The studies in [43] and [46], make use of different clustering techniques to optimally place MGs in a WMN infrastructure. The clusters generated in these studies are represented by trees rooted at the MGs. Although, these techniques have a number of benefits (e.g., low routing overhead and efficient flow aggregation), they suffer from the well-known problem in tree-based structures, namely reliability degradation – a tree topology uses a smaller number of links than a mesh topology where there are at least two nodes with two or more paths between them to provide redundant paths to be used in case a link in one of the paths fails. Furthermore, as shown in [48], topologies restricted to tree structures, may require, under the link capacity constraint (the amount of traffic routed on a link is less than or equal to its capacity) a larger number of MGs and thus may increase the network deployment cost. Fig. 6 shows how a tree-based topology tends to deploy more MGs than a mesh topology (2 MGs Vs. 1 MG). Every potential link (a dashed line) is associated to a capacity link (the value between brackets) and a traffic demand is associated to every node.

The MG placement technique proposed in [43] consists of placing a minimum number of MGs, such that the three constraints of throughput, power, and interference are satisfied. The technique consists of using a recursive algorithm to divide the WMN into clusters of bounded radius under relay load and cluster size constraints. In this approach, a one-hop dominating set of the original graph is greedily found at first then this result is used as the input of next recursion; the greedy dominating-set searching operation continues until the cluster radius reaches the pre-defined upper bound of cluster radius. Nonetheless, more faraway routers could be attached to the MGs since the hop length from each router to the MG is not considered during the cluster formulation, leading to long communication path length.

Chandra et al. [46] address the problem of minimizing the number of MGs while satisfying the traffic demands by using a network flow model. They formulate the problem in the context of community mesh networks where the mesh routers (installed in clients' houses) are fixed, leaving only the placement of MGs to be decided. The main drawback of the iterative greedy approach that they apply is the unbalanced load of the MGs; indeed, new MGs are placed whenever existing ones are fully loaded.

Non-tree based clustering

To our best knowledge, the sole contribution that proposes a non-tree based clustering scheme for the MGs placement problem is reported in [48]. Hsu et al. [48] model the MG placement problem as a combinatorial optimization problem. They propose two algorithms namely, Self-Constituted Gateway Algorithm (SCGA) and Predefined Gateway Set Algorithm (PGSA). Both algorithms make use of a genetic search algorithm to search for feasible configurations coupled with a modified version of Dijkstra's algorithm to look for paths with bounded delays. In PGSA, the number of MGs (initially set to one) is iteratively incremented by one until a feasible configuration is obtained. On the other hand, the number of MGs in SCGA is set up dynamically when needed. The design problem solved by both search algorithms does not consider bounded delay in terms of communication hops. Instead, delay is seen as the ratio packet size over link capacity.



Initial network Tree-based topology Mesh toplogy

Fig. 6. Impact of network topology on MG deployment. The tree-based topology deploys more MGs than the mesh topology because of the capacity link constraint.

It is worth noting that the network partitioning problem (clustering) is not an NP-hard problem; it requires a simple scheme as a solution. However, when adapted to the characteristics of WMNs, the clustering solution becomes more difficult to implement because of the capacity and connectivity constraints and QoS requirements, if considered. Thus, heuristics/approximation methods are needed to solve the non-tree based clustering MGs placement problem.

2) Non-clustering based placement

Robinson et al [47] study the MG placement problem as facility location and k-median problems. They propose two local search algorithms (minhopcount, mincontention) with different approaches to estimate the unknown MGs capacities. In the "minhopcount" algorithm, the MG placement problem is regarded as a facility location problem,; while in the "mincontention" solution, it is interpreted as a k-median problem; however, the authors' focus is only on a single-radio, single-channel architecture.

Li et al. [49] studied the MG placement for throughput optimization in WMNs using a grid-based deployment scheme. More specifically, given a mesh infrastructure and a number of MGs to place, the authors investigate how to place the MGs in the mesh infrastructure in order to achieve optimal throughput. They first formulate mathematically the throughput optimization problem for a fixed mesh network and propose an interference-free scheduling method to maximize the throughput. The basic idea behind the proposed solution is to sort the links based on some specific order and then process the requirement for each link in a greedy manner. Then, they use their solution as an evaluation tool to decide on the optimal MG placement scheme. The proposed approach to place exactly *k* MGs has achieved better throughput in the grid scheme than in random and fixed schemes.

IV. DESIGN OF WMN TOPOLOGIES FROM SCRATCH

There have been plenty of planning network solutions developed for Cellular Networks (CNs) and WLANs, and one would be tempted to tailor these solutions to WMNs. However, these solutions cannot possibly be applied to planning WMNs. Network planning in CNs is almost entirely driven by geographical coverage. More precisely, the positions/configurations of wireless transceivers, which are also MGs towards the wired backbone, depend only on local connectivity constraints between end-users and the closest network device [49]. In WLANs, wireless communications are one-hop length whereas in WMNs end-users' traffic is forwarded in multi-hop fashion, starting from APs, jumping from one MR to another MR via point-to-point wireless link until a MG is reached. WMNs present unique characteristics, thus, new design solutions specially designed for WMNs are required.

A good planning task of a WMN essentially involves a careful choice of the installation's locations, an optimal selection of the types of network nodes, and a good decision on a judicious channel/node interface assignment, while guaranteeing users coverage, wireless connectivity and traffic flows at a minimum cost. In optimization terms, this is translated into determining: the optimal number of wireless routers required to cover the area under consideration, the optimal number of MGs for efficient integration of WMNs with Internet, the optimal initial channel assignment, and an optimal number of wireless interfaces per router, while taking into account all physical and financial constraints of the network provider. In what follows, we survey the attempts made for solving the WMNs design problem. The solutions proposed are divided into two different classes of optimization approaches: *single-objective* optimization and *multi-objective* optimization.

Amaldi et al. [50] construct and formulate the planning model of WMNs as an Integer Linear Problem (ILP) based on user-coverage satisfaction. But QoS requirements such as delay and throughput are not considered. The system is solved using a heuristic optimizer based on greedy selection. Beljadid et al. [51] propose a unified model for WMN design formulated as an ILP problem. The objective is to minimize the total installation cost by tuning all the network parameters; they consider the delay as a constraint. Some noteworthy drawbacks are: (1) Users' coverage is not considered in the model; and (2) the problem is solved for small-size instance networks because of the exponential number of constraints and variables.

WMN design problems in [50] and [51] belong to the set of optimization problems over a cost function (*single-objective* optimization). In such problems, we are given a cost function $f: X \rightarrow Y$ where Y is totally ordered. Let F be the set of such mappings. Given f, the problem is to find a $x^* \in X$ which minimizes f.

However, when planning for cost-effective networks, the deployment cost is not necessarily not the sole objective to optimize. In such networks, the quality can be constrained by multiple criteria such as the signal level received by the mesh clients, the performance quality in terms of throughput or delay, and the installation cost. When considering the optimization of many criteria at the same time, the objective functions are to be optimized simultaneously within the same problem formulation (multi-objective optimization problem formulation). However, it is impossible to optimize all the objectives, usually conflicting with each other, at once. In such situations, one would be content with solutions that "trade-off" the conflicting objectives. There are two ways to deal with this kind of optimization problems. Either aggregate the conflicting objectives into a single, usually, weighted objective, or apply a Pareto based optimization approach [52]. We refer to the first approach as *aggregated multi-objective* approach and the second one as *pure multi-objective* approach.

The approaches applied in [3] and [53] are instances of the aggregated multi-objective approach. The main drawback of this approach, as discussed in Section II, is the difficulty to set the weights when the *a priori* knowledge is not trivial. In this case, the cooperation of the optimizer and the designer is a must. Moreover, as stated in Section II, this technique is unable to generate proper Pareto-optimal solutions found in the presence of non-convex fronts.

Kodialam et al. [3] show that the design of WMNs is by nature a multi-objective optimization problem where multiple design criteria need to be taken into account. They proposed two link channel assignment schemes based on a linear programming formulation. Their proposal allows optimizing only a single objective function at a time. The optimization technique applied is a special instance of the aggregated multi-objective approach called a lexicographic ordering technique.

Vanhatupa et al. [53] propose a model to estimate the performance of an IEEE802.11s WMN based on a set of parameters that describe the network and its configuration. The output of the performance model is *seven metric*s to estimate individual physical characteristic of the WMN performance. The model also provides a weighted combination of the metrics for a simultaneous use of multiple evaluation criteria in WMN optimization.

In the context of pure multi-objective optimization, Benyamina et al. [54] propose a multi-objective formulation for the WMN design problem. Two conflicting objectives of deployment cost and network throughput are to be optimized simultaneously while guaranteeing full coverage to mesh clients. The throughput function is maximized by computing the utilization ratio of all links carrying flows; formally, it is specified as follows;

$$\max \sum_{j \in L} \sum_{l \in L} \sum_{q \in C} \frac{f_{jl}^{q}}{u_{jl}} \qquad (1)$$

f^{q}_{jl} denotes the traffic flow routed from node j to node l using channel q. u_{jl} is the traffic capacity of the wireless link (j,l). However, with such formulation, the throughput is not calculated properly since we may have a higher value of throughput corresponding to longer paths, which in reality does not reflect the true throughput value. The above formulation is enhanced and two other bi-objective models are proposed by the same authors in [55] with a comprehensive comparative study presented in [56]. The models in [54] and [55] are solved using a nature inspired meta-heuristic algorithm based on Multi-Objective Particle Swarm

Optimization (MOPSO) [57]. A set of good "trade-off" solutions for real-sized networks is provided to network operators where each solution can be used in a different decision making scenario.

Another category of studies focuses on network topology layout to select for a total design in order to achieve better performance. Robinson et al. [58] studied the performance of deployment factors in WMNs where the benefits of adopting grid topologies over other topologies are shown. The authors considered three regular tessellations as their baseline grid topology: triangular, square and hexagonal tessellation (see Fig. 7). To determine which topology factors strongly influence mesh performance, they used three performance metrics: client coverage area, backhaul tier connectivity, and fair mesh capacity.

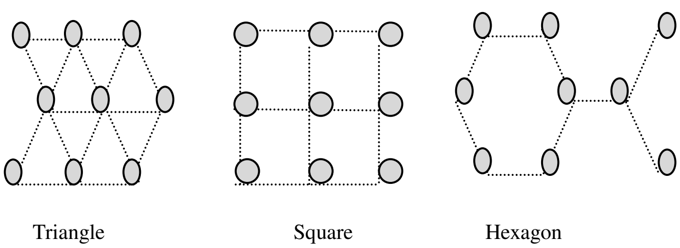


Fig. 7. Triangle, square and hexagonal tessellations for mesh nodes placement.

The study in [58] did show that the hexagonal grid topology results in more uncovered spots than a square or triangular grid and therefore requires twice the node density to achieve worst-case coverage guarantees, resulting in more expensive topologies. Regarding backhaul tier connectivity, the connectivity in regular grid based topologies outperforms the random topologies for networks with high density. Finally, the average fair capacity in a random network is less than half the fair mesh capacity in a grid topology.

V. SYNTHESIS AND DISCUSSIONS

Although the existing studies provide some possible solutions to alleviate the problem of performance degradation in wireless mesh networks, several significant points that need to be properly addressed by future researchers are identified below.

1. Layering/cross-layering as optimization approach

Most of protocol optimization techniques (see Section II) apply *layering as optimization decomposition technique* to improve the performance of WMNs. However, up to date, there has been no documented study analyzing the optimality of the layering technique.

The network global optimization problem can be formulated as a general network utility maximization problem [31]:

$$\text{maximize} \quad \sum_s U_s(x_s, P_{e,s}) + \sum_j V_j(w_j)$$

$$\text{subject to} \quad \mathbf{Rx} \le \mathbf{c}(\mathbf{w}, \mathbf{P}_e)$$

$$x \in \mathcal{C}_1(\mathbf{P}_e),\ x \in \mathcal{C}_2(\mathbf{F}),\ \text{or } x \in \boldsymbol{I}$$

$$\mathbf{R} \in \mathcal{R},\ \mathbf{F} \in F,\ \mathbf{w} \in \mathcal{W}$$

In this formulation, the user utility function $U(.)$ and resources $V_j(.)$ are maximized. x_s and w_j denote the rate of source s and the physical layer resources at network element j, respectively. **R** is a routing matrix, and **x** denotes the link capacity as a function of physical layer resource **w** and the desired error probability $\mathbf{P}_e$ after decoding. The function **c** captures all physical layer factors, such as interference, power control, etc. The first constraint represents the behavior perceived at the routing layer. The function $\mathcal{C}_1(.)$ captures the coding and error-control mechanisms versus the rate, while function $\mathcal{C}_2(.)$ and $\boldsymbol{I}$ capture the contention-based MAC and scheduling based MAC, respectively.

More specifically, in this formulation, network performance has to be optimized at the transport layer which is subject to routing, MAC, and physical layers constraints. In this way, we can see that *layering as optimization decomposition* involves many other layers to perform optimization at a specific layer. The MAC, routing, and transport layer have to collaborate among themselves and work together with the physical layer to provide optimal performance for WMNs. Authors in [32] argue that *layering as optimization decomposition* technique does not eliminate the need for cross-layer optimization; moreover, the specific features pertained by WMNs also illustrate the need of cross-layer.

Actually, cross-layer optimization schemes are supposed to be more accurate and optimal than their counterpart, the conventional layered optimization schemes; but, strict guidelines need to be followed [32] in order to minimize the risks that come with the cross-layer design. However, a clear understanding of the relationships between WMNs capacity and the factors impacting this capacity (such as network architectures, network topologies, traffic patterns, network node densities, number of channels used in each node interface, transmission power level, and nodes' mobility) may provide guidelines for protocol development, architecture design, and deployment, and finally, operation of the network.

2. Directional antennas

Another category of alternative performance improvement schemes focus on the optimization of the location of some mesh nodes so that QoS requirements are met. More, specifically, the studies in [41] and [42] attempt to plan for the deployment of WMNs by fixing the MGs positions and equipping routers with directional antennas. Although many proposals in the literature did show the benefits of using directional antennas, related research has been suspended in many research institutes (see Alaweih et al. in [30]). The main reason is that directional antennas require line of sight (LOS) environments while relevant applications that can provide high LOS components can be hardly found.

3. A wise placement of gateways

Existing solutions that address the optimal MG placement problem can be found in [43], [44], [45], [46], [47], and [48].

They differ mainly in terms of the set of constraints that the placed MGs have to satisfy; thus, the resulting placements influence differently the network quality of service (QoS).

A new clustering-based approach for optimal placement of MGs is proposed in [60]. The aim of the approach is to attain three objectives: (1) Constructing clusters in a way such that every MG is reachable within *h* hops; (2) Forcing each node to send traffic to its nearby MG (scalability handling); and (3) Deploying the minimum number of MGs without sacrificing performance.

Even though there have been considerable research efforts in optimizing the MG placement problem, we believe that it would be interesting to pair these algorithms with complementary techniques addressing other criteria, such as optimal placement of APs and/or MRs, in order to improve network performance. The models proposed in [50] and [51] take into account these criteria; however, their approaches for optimal WMN planning do consider the deployment cost as the sole concept to optimize -subject to many constraints to satisfy.

4. Design trade-offs

From a network designer's point of view, the goal is usually to satisfy as many users as possible by providing an all-around high QoS. Providing predictable QoS to the users should also be considered as a key objective beside the deployment cost, in addition to the service area, the number of users and the resource utilization. It may be argued that it seems logical to overestimate the number of mesh nodes (routers, MGs) to avoid lack of coverage and to increase throughput. However, this choice strongly impacts the complexity of the channel assignment problem and provides high interference levels, worsening final network performance.

Essentially, WMN planning problem is an optimization problem where the two most important objectives are the deployment cost (to minimize) and the network performance (to maximize). Minimizing the deployment cost is mainly achieved by deploying less network devices (routers/MGs); however, this may cause longer traffic delays and bottlenecks, which undermine network performance. Similarly, maximizing network performance can be achieved by strategically placing extra network devices, which fattens the deployment cost budget. This shows that objectives in a Multi-objective Optimization Problem (MOP) do conflict with each other in the sense that an increase in one objective dimension undermines another objective. This clearly plays in favor of adopting heuristic multi-objective optimizers as they are the best methods to return a spectrum of trade-off solutions.

In a wireless multi-hop network, the network capacity, usually represented by throughput, is not the only concern for users. In fact, QoS is equally important. Usually QoS metrics include delay, jitter, and packet loss ratio. In order to increase the network capacity, authors in [59] suggest two rules to follow: (1) reducing the number of hops that a packet shall travel; and (2) reducing the interference range of transmissions. However, scheduling schemes that satisfy these rules usually improve throughput but increase delay. Thus, it seems interesting to perform resources-throughput and/or throughput-delay tradeoffs when designing efficient WMNs.

More generally, design decisions involving trade-offs greatly impacts the quality of the planned network. This requires additional research to devise a generic multi-objective optimization framework that captures and reflects the essence of the true nature of WMNs planning problems.

5. Rate adaptation

Rate adaptation is another important factor in improving network performance that should be considered when designing WMNs. In [61], [62], [63], [64], and [65] analytical models were presented to investigate the goodput under rate adaptation for 802.11a-based WLANs. The basic idea is to select appropriate transmission rates according to the channel condition. With a good channel condition, the network efficiency (throughput) could be improved by using higher rates.

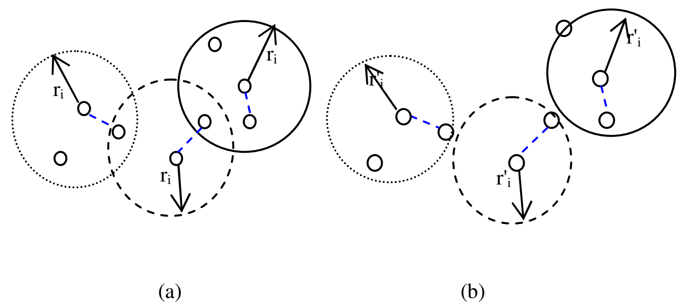


Fig. 8. Impact of rate adaptation on simultaneous communications, (a): transmissions occurring at the same time are interfering with each other. (b): successful simultaneous communications after changing transmission rate from r_i to r'_i ($r_i > r'_i$).

Conversely, in the presence of channel impairments, transmission reliability may be improved by lowering the transmission rate. Moreover, lowering this rate reduces the transmission power (case of 802.11) which is equivalent to reducing the interference range, thus allowing more concurrent transmissions to coexist without corrupting each other (see Fig. 8). Surprisingly, with the exception of the studies in [50] and [51], there has been little interest in the literature that considers rate adaptation while designing WMNs. Authors in [50] and [51] propose rate adaptation models to formulate WMN design problem; however, they did not take into account in the proposed model formulations other essential design criteria (see Table I).

6. Design of reliable networks

Another fundamental criterion in networking study is network reliability, translated as the availability of communications paths between network pairs in the presence of node failures. The reliability and deployment cost are important and are largely determined by network topology. One could argue that adding redundant network components increases the reliability of a network; however, this also increases the cost substantially. To our best knowledge, the only work that integrates network reliability in the design of WMNs is presented in [66] and [67]. Beljadid et al. [66] define a reliability cost function that allows maximizing the reliability of the whole WMN. The approach is based on iterative policy that is performed until a reliable and satisfactory (cost-effective) solution is found.

It must be noted, however, that in constrained optimization problems (e.g., WMN design problem), it is already costly and very hard to compute a good feasible solution; so when looking only for reliable solutions, the "iterative" optimization process becomes much over-burden. Moreover, the reliability of the network has to be jointly considered with network QoS requirements while designing WMNs. It is therefore essential to devise a converging algorithm that constructs reliable WMNs.

Authors in [67] propose a novel algorithm to construct a bi-connected WMN infrastructure based on the *Ear decomposition* theoretical approach [68]. An interesting new direction of research is to consider the construction of reliable networks at the same time when designing cost-effective WMNs.

Table I: List of Different WMN design characteristics

Code	*Design aspect*
Topl_F	Topology is fixed a priori (layered/cross- layer design)
MG_F	Only MGs have fixed positions (planning problem, partial deployment)
MR_F	Only mesh routers have fixed positions (planning problem, partial deployment)
Scrat.	All mesh nodes positions/characteristics are not decided (network design, deployment from scratch)
Cov	Full coverage of mesh clients criteria
QoS	QoS constraints (throughput/ delay/hop counts/congestion) satisfaction
Interf	Interference model application
RA	Rate adaptation
Rsize	Design problem solved for real-sized networks
MO	Multi-objective optimization
RC	Reliability consideration
OpRC	Optimal reliability scheme application
Clust	Design based on a clustering approach
OpClust	Clusters are free from a tree-structure
SqGrid	Square-grid layout deployment

Table II: Features of references related to performance improvement in WMNs.

Reference	*Design category*	*Design aspects*										
		Cov	*QoS*	*Interf*	**RA**	*Rsize*	*MO*	*RC*	*OpRC*	*Clust*	*OpClust*	*SqGrid*
[2],[18],[18],[24],	**Top_F**	**S**	**+**	**S**	**-**	**S**	**-**	**S**	**-**	**NA**	**NA**	**-**
[41]-[42]	**MG_F**	**+**	**-**	**+**	**-**	**-**	**-**	**+**	**-**	**NA**	**NA**	**-**
[43],[46]	**MR_F**	**-**	**+**	**+**	**-**	**-**	**-**	**+**	**-**	**+**	**-**	**-**
[47], [49]	**MR_F**	**-**	**+**	**+**	**-**	**+**	**-**	**-**	**-**	**-**	**-**	**S**
[48]	**MR_F**	**-**	**+**	**+**	**-**	**+**	**-**	**+**	**-**	**+**	**+**	**-**
[50]	**Scrat.**	**+**	**-**	**+**	**+**	**+**	**-**	**-**	**-**	**-**	**-**	**-**
[51]	**Scart.**	**-**	**+**	**-**	**+**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
[54], [55], [56]	**Scrat.**	**+**	**+**	**+**	**-**	**+**	**+**	**-**	**-**	**-**	**-**	**+**
[60]	**Scrat.**	**+**	**+**	**+**	**-**	**+**	**+**	**-**	**-**	**+**	**+**	**+**
[66]	**Scrat.**	**-**	**+**	**-**	**+**	**-**	**-**	**+**	**-**	**-**	**-**	**-**
[67]	**Scrat.**	**+**	**+**	**+**	**-**	**+**	**+**	**+**	**+**	**-**	**-**	**+**

7. State of current WMNs design studies

To compare existing design solutions, we determine/identify the key design aspects, as shown in Table I. Then we assess the most representative contributions surveyed in this paper against these aspects; the result of this assessment process is shown in Table II.

In Table II, if an approach satisfies/dissatisfies a design aspect/ property, the corresponding table entry is marked with +/- respectively. If an aspect or a property cannot be applied, then the corresponding entry is marked "NA" (Not Applicable); for example, the *Clust* entry for approaches that use a clustering approach to place MGs is marked N/A for all studies that have MGs position already fixed. We use the letter "S" for entries for which the property holds only for some of the studies being assessed together (a group of contributions).

Table II provides valuable information for new ideas to investigate and exploit when designing WMNs. Notice that most of the design aspects are not applicable in fixed-topologies and partial design topologies, because of the nature of the topology under study; however, some other applicable aspects that may improve the actual performance of the network are not yet fully utilized. For instance, rate adaptation, multi-objective optimization and grid layout deployment received little interest from current performance improvement research. Thus, more studies/investigations are needed to explore the use of these aspects to improve performance of WMNs. Notice also that the design of topologies from scratch provides more open slots of possible design aspects to be applied; nevertheless, none of the surveyed approaches in this category considers all these aspects at the same time. More specifically, non-tree clustering based MGs placement, multi-objective optimization, rate adaptation, grid layout deployment, and efficient reliability consideration receive very limited attention from existing approaches. To sum up, we believe that network planning/design optimization will continue to be a challenging research topic for WMNs.

VI. CONCLUSION

This study surveys the most relevant research contributions in the open literature dealing with performance improvement of WMNs. We define a taxonomy in which we classify and survey these contributions by carefully discussing their strengths and weaknesses.

The fixed topology category includes all approaches where the positions and the types of all mesh nodes are decided beforehand. In the *unfixed topology* category, approaches are further categorized into two sub-classes, *partial design* (some mesh nodes are setup a priori) and *design from scratch* (positions and types of all mesh nodes are unknown). In the *partial design* category, WMNs can be deployed around a set of a priori fixed MGs (*fixed gateways* sub-category) or find the optimal MGs locations based on a set of a priori fixed APs and MRs (*unfixed gateways* subcategory), which is more scalable if a clustering approach is applied.

In the *design from scratch* category, all mesh nodes are unknown and the WMN deployment problem is to find the type and the location of each mesh node. This is more generic than all the preceding categories. All related studies use an optimization algorithm to determine the best type selection and location of the mesh nodes taking into account network QoS constraints. Most of the surveyed work in this category optimizes the deployment cost of a single-objective problem formulation; only very few adopt a multi-objective approach to optimizing the WMNs planning problems either using an aggregated or Pareto dominance based optimization policy.

According to Table I and II, there are many challenges and research opportunities in optimizing WMNs planning problem. Layered protocols and cross-layer design have been successfully applied for many applications; we believe that network efficiency could be achieved at a higher level if efficient planning/design of the network resources characteristics is performed prior to any deployment.

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