Radio Planning for Wireless Mesh Networks

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Abstract

As the demand for wireless service provisioning keeps increasing, new wireless technologies are required to extend the coverage capabilities of classical wireless access networks like WLANs, WMANs and cellular systems. In this field, Wireless Mesh Networking (WMN) seems to be the most promising solution. WMNs comprise three types of devices: mesh routers, mesh access points and mesh clients. The functionality of both the mesh routers and the access points is twofold: they act as classical access points towards the mesh clients, whereas they have the capability to set up a wireless backbone by connecting to other mesh routers through point to point wireless links. Further on, the mesh access points act as gateways toward the wired backbone.

The classical approach of coverage planning in wireless access network is often tailored as a set covering problem. Such approach is no longer suited for the WMNs, where the problem of planning the network is tightly coupled with the one of routing the traffic on wireless links towards a mesh access point. In this paper we propose a novel optimization model for the planning of WMNs whose objective is to minimize the network installation cost, while providing full coverage to the wireless mesh clients. Since coverage might be provided through multi-hop wireless links towards a mesh access point, our model takes into account the traffic routing and the capacity availability on the way to the wired realm.

1 Introduction

Wireless mesh networking is one of the most promising solution for the provision of wireless connectivity in a flexible and cost effective way. The *Wireless Mesh Networks* (WMNs) comprise a mix of fixed and mobile nodes interconnected via wireless links to form a multihop ad hoc network.

The main differences between WMNs and Mobile Ad Hoc NETworks (MANETs) are in the general network architecture. The classical MANET paradigm endorses a flat architecture with all the mobile nodes cooperating with the same functionalities to build up self sustained and fully distributed wireless networks. On the other hand, the network devices participating in WMNs are hierarchically organized in terms of internetworking functionalities and hardware capabilities.

Roughly speaking, the network devices composing WMNs are of three types: *Mesh Routers* (MRs), *Mesh Access Points* (MAPs) and *Mesh Clients* (MCs). The functionality of both the MRs and the MAPs is twofold: they act as classical access points towards the MCs, whereas they have the capability to set up a *Wireless Distribution System* (WDS) by connecting to other mesh routers or access points through point to point wireless links. Both MRs and MAPs are often fixed and electrically powered devices. Furthermore, the MAPs are geared with some kind of broadband wired connectivity (ADSL, fiber, etc ...) and act as gateways toward the wired backbone. MCs may be classical MANET ad hoc nodes which eventually can extend the connectivity provided by the WDS through ad hoc links.

The success of the aforementioned WMN architecture is mainly due to its flexibility and cost viability. In fact, different from the wireless access network paradigm where all the wireless access points are directly connected to the wired backbone, in WMNs the MAPs only act like gateways with the wired realm, consequently a potentially low number of MAPs can provide connectivity to a potentially high number of MCs through the wireless distribution system.

The mesh paradigm can be easily applied to different network scenarios and technologies. To this end, the IEEE has recently promoted several working groups for the standardization of specific mesh solutions for *Wireless Personal Area Networks* (WPANs) [1], *Wireless Local Area Networks* (WLANs) [2] and *Wireless Metropolitan Area Networks* (WMANs) [3, 4]. Besides the standardization effort many companies are proposing proprietary solutions [5, 6] providing off-the-shelves wireless mesh technology to build up general commodity networks.

The aforementioned flexibility in the network architecture makes the WMNs well suited to support a wide spectrum of applications ranging from *Intelligent Transportation Systems* services for vehicle traffic management to municipal networks for security and territory surveillance purposes (fire brigades and police patrols coordination). Eventually, the wireless mesh technology can represent a competitive alternative to wired solutions for the provision of cheap and reliable broadband access to city neighborhoods. [7] and [8] provide rather exhaustive overviews of the applications to WMNs.

Even if commercial solutions are already available, many aspects of WMNs are still under analysis with the purpose of enhancing the performance of such technology. The intrinsic flexibility of the WMNs poses stringent research challenges at different layers and a huge research effort is nowadays ongoing on the optimization of protocols and algorithms to support mesh networking.

The most popular research fields on mesh networking are related to the design of Medium Access Control and routing protocols, to mobility management and security issues. Since WMNs are wireless multi hop networks relying on a *Wireless Distribution System* to transport the information, the impact of the interference among different wireless links may dramatically affect the overall network capacity [9]. To this end, the most of the research effort is devoted in finding effective solutions for coping with interference.

Within this field, it is commonly recognized that the use of wireless devices (routers and access points) with wireless Network Interface Cards (NICs) highly reduce the impact of the interference consequently increasing the capacity of the wireless mesh network [10]. Furthermore, even a single NIC might be configured to transmit/receive on different channels[1].

As to routing aspects in WMNs, classical routing paradigms based on shortest paths might not be well suited in the new network scenario, where the choice of the best paths should account also for the available wireless link bandwidth and the available channels along the chosen path given a specific channel assignment; within this field, Draves *et al.* [11, 12] propose a new metric for choosing routes in multihop mesh networks.

As clear from the discussion above, many parameters concur to the determination of a general wireless mesh network effectiveness including the number of radio interfaces for each device, the number of radio channels per interface, the access mechanism, the routing strategies and the specific wireless technology used to implement the mesh paradigm. All these parameters are de facto degrees of freedom the network designer can exploit to deploy an effective WMN, thus optimization criteria are needed for the tuning of such parameters.

To this end, many works have appeared in the literature with the purpose of providing optimized protocols for WMNs. So *et al.* propose in [13] a multichannel MAC protocol in the case single interface transceivers are used, whereas reference [14] analyzes those networks where even multiple radio interface per wireless node can be used adapting the channel access protocol. Das *et al.* propose two Integer-Linear programming models to solve the fixed channel assignment problem with multiple NICs, whilst [16] and [17] address the problems of channel assignment and routing jointly, providing different formulations to the optimization problem.

To the best of our knowledge, the most of the previously published work assumes a given network topology, i.e., the general approach tends to optimize the channel assignment and/or the routing assuming given positions for the MRs and the MAPs. On the other hand, the purpose of the present work is to model the problem of determining where MRs and MAPs should be installed, that is, providing quantitative methods to optimize the topology of WMNs.

Whatever the application scenario is, the deployed WMNs should have good features in terms of coverage and conveyed throughput both in the uplink and in the downlink segments. To this end, a wise planning of the MRs and MAPs positions is of utmost importance to determine the effectiveness of the overall deployed network. The problem of deciding the positions of wireless transceivers has been widely analyzed in the literature for different wireless technologies and systems ranging from 2G and 3G cellular networks to Wireless LANs hot spots. However, the WMNs planing issue is different from all the studied case.

In fact, in all the aforementioned systems the wireless transceivers (base stations, WLAN access points) are also gateways towards the wired backbone and the decision on their posi-

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[1] Channels can be defined in frequency, time and code domains

tioning is almost completely driven by *local connectivity* requirements, that is, the connectivity which is due to be provided is the one between each mobile user and the closest[2] wireless transceiver. On the other side, in the WMNs planning problem, two connectivity constraints must be fulfilled: the first one is the same local connectivity between MCs and one closest MR or MAP, the second is a *multihop connectivity* between each MC and a MAP. In other words, the problem of planning a WMS is strictly related to the problem of defining routes in the WDS.

In this work we propose an optimization model for the problem of planning WMNs based on mathematical programming which takes into account both the *local* and the *multihop connectivity* requirements.

Our work is organized as follows: in the next section 2 we highlight the differences among the general approaches of planning wireless networks (2G/3G systems and WLAN hot spots) revising some of the proposed approaches for 2G/3G systems and WLAN hot spots. Section 3 gives the formulation of the proposed model and comments on its main features, whilst Section 4 reports some results obtained applying the model to synthetic instances of WMNs. Concluding remarks and given in Section 5.

2 Radio planning of wireless networks

Planning a wireless network involves selecting the locations in which to install the base stations (BS) or access points (AP), setting their configuration parameters (emission power, antenna height, tilt, azimuth, etc.), and assigning channels so as to cover the service area and to guarantee enough capacity to each cell [18].

A two-phase approach is commonly adopted for second generation cellular systems [19, 20, 21]. First coverage is planned so as to guarantee that a sufficient signal level is received in the whole service area from at least one BS. Then available frequencies are assigned to BSs considering *Signal to Interference Ratio* (SIR) constraints and capacity requirements.

For third generation systems, a two-phase planning approach is not appropriate since in CDMA (Code Division Multiple Access) systems the bandwidth is shared by all transmissions and no frequency assignment is strictly required. The network capacity depends on the actual interference levels which determine the achievable SIR values. As these values depend in turn on traffic distribution, as well as on BSs location and configuration, coverage and capacity must be jointly planned [22, 23]. Even if the radio planning of WLANs is somehow similar to that of TDMA-based second generation cellular networks, some peculiarities of these networks, such as the low cost of APs and the effect of interference, suggest the use of optimization approaches that focuses on network efficiency rather than on its cost [24].

The common approach to the coverage problem is based on discrete mathematical programming models. A set of *Test Points* (TPs) representing the users are identified in the service area. Each TP can be considered as a traffic centroid where a given amount of traffic (usually expressed in Erlang) is requested [25]. Instead of allowing the location of BSs in any position, a set of *Candidate Sites* (CSs) where BSs can be installed is identified. Since we can evaluate (or even measure in the field) the signal propagation between any pair of TP and CS, the subset

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[2] The one received with the strongest signal

of TPs covered by a sufficiently strong signal is assumed to be known for a BS installed in any CS. The coverage problem results in the classical minimum cost set covering problem [26, 27].

Let $S = \{1, \ldots, m\}$ denote the set of CSs and c_j the associated installation cost, $j \in S$. Let $I = \{1, \ldots, n\}$ denote the set of test points. The propagation information is summarized in the attenuation matrix G. Let g_{ij}, $0 < g_{ij} \leq 1$, be the attenuation factor of the radio link between test point i, $i \in I$, and a BS installed in j, $j \in S$. From the attenuation matrix G, we can derive a 0-1 incidence matrix containing the coverage information that is needed to solve the BS location and configuration problem. The coefficients for each pair TP i and BS j are defined as follows:

$$a_{ij} = \begin{cases} 1 & \text{if a BS installed in CS } j \text{ covers TP } i \\ 0 & \text{otherwise.} \end{cases}$$

Introducing the following binary variable for every pair of candidate site j:

$$y_j = \begin{cases} 1 & \text{if a BS is installed in CS } j \\ 0 & \text{otherwise,} \end{cases}$$

the problem of covering all the test points at minimum cost can be formulated as:

$$\begin{aligned} \min \quad & \sum_{j \in S} c_j y_j && (1) \\ & \sum_{j \in S} a_{ij} y_j \geq 1 \quad \forall i \in I && (2) \\ & y_j \in \{0,1\} \quad \forall j \in S. && (3) \end{aligned}$$

Objective function (1) aims at minimizing total cost, while constraints (2) ensure that all TPs are within the service range of at least one BS.

The above model provides coverage to all the TPs, but does not consider assignment of TPs to BSs. Since BSs are capacity limited adding assignment variable is important to include capacity constraints in the model. These binary variables are defined for every pair of TP i and CS j :

$$x_{ij} = \begin{cases} 1 & \text{if TP } i \text{ is assigned to BS } j \\ 0 & \text{otherwise.} \end{cases}$$

The formulation of the full coverage problem becomes:

$$\begin{aligned} \min \quad & \sum_{j \in S} c_j y_j && (4) \\ & \sum_{j \in S} x_{ij} = 1 \quad \forall i \in I && (5) \\ & x_{ij} \leq a_{ij} y_j \quad \forall i \in I, \forall j \in S && (6) \\ & y_j \in \{0,1\} \quad \forall j \in S && (7) \\ & x_{ij} \in \{0,1\} \quad \forall i \in I, \forall j \in S. && (8) \end{aligned}$$

The crucial constraints of the above model are (6) stating that a TP i can be assigned to a CS j only if it is covered by j and a BS is actually installed in j. Since now a cell is defined by the set of TPs assigned to it and it is not predefined by the incidence matrix, it is possible to add BS capacity constraints:

$$\sum_{i \in I} d_i x_{ij} \leq q_j y_j \quad \forall j \in S, \tag{9}$$

where d_i is the traffic generated in TP i and q_j the capacity of BS j.

In real wireless systems, freely assigning TPs to BSs is not possible since mobile terminals usually select BSs autonomously according to the strongest received signal. A possible way to express this constraint for a given TP i is to consider all the CSs that would allow connection with i and sort them in decreasing order of signal strength. Let $\{j_1, j_2, \ldots, j_L\}$ be the ordered set of BSs, the constraints enforcing the assignment of TP i to the strongest activated BS are:

$$y_{j_\ell} + \sum_{h=\ell+1}^{L} x_{ij_h}, \leq 1 \qquad \ell = 1, \ldots, L-1. \tag{10}$$

According to the above constraints, if a BS is activated in configuration ℓ, then TP i cannot be connected to a less convenient BS. These location-allocation models can be solved efficiently with known exact and heuristic methods (see e.g. [28]).

3 Wireless MESH network planning

The coverage models commonly adopted for the radio planning of radio access networks are not appropriate for WMNs. In fact, in WMNs each CS can host either MAPs or MRs with different installation costs. Installing a MAP is more expensive mainly due to the costs related to the connection with the wired backbone, even if, depending on the technology, the cost of the devices may also be slightly different.

Moreover, when a MR is installed in a candidate site, traffic related to its users must be routed through wireless multi-hop connections. In particular, the traffic to/from the wired backbone has to be routed on a path connecting the MR to a MAP at least. In this context, capacity limits of radio links among MRs and between MRs and MAPs play a key role since the traffic routed on a link must not exceed its capacity. Therefore, planning decisions on where to install network nodes and which type (either MAP or MR) to select depend on several issues including users coverage, wireless connectivity between MRs and MAPs, and traffic flows.

The resulting planning problem is a completely new one since it must consider at the same time both the radio coverage of users like in classical radio planning problems of wireless access networks [18], and the traffic flows management like in network design problems of wired networks [29].

In order to define a model for the WMN planning problem, let us consider the network description presented in Figure 1.

Similarly to the coverage problems presented in the previous section, let $S = \{1, \ldots, m\}$ denote the set of CSs and $I = \{1, \ldots, n\}$ the set of TPs. A special node N represents the wired

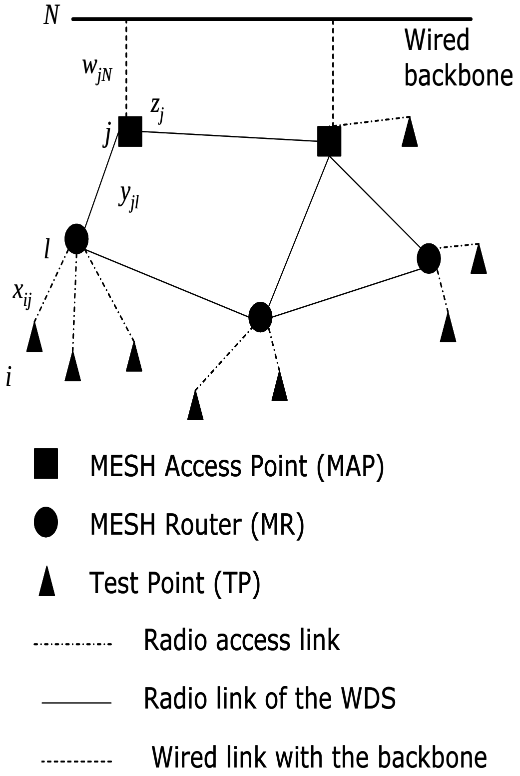

Figure 1: WMN planning problem description.

backbone network. The cost associated to installing a MR in CS j is denoted by c_j, while the additional cost required to install a MAP in CS j is denoted by p_j, $j \in S$. The total cost for installing a MAP in CS j is therefore given by $(c_j + p_j)$.

Traffic generated by TP i is given by parameter d_i, $i \in I$. The traffic capacity of the wireless link between CSs j and l is denoted by u_{jl}, $j, l \in S$, while the capacity of the radio access interface of CS j is denoted by v_j, $j \in S$. The sequence S_i of CSs that can cover TP i is calculated for all TPs considering a non increasing order of received signal strength, $S_i = \{j_1^{(i)}, j_2^{(i)}, \dots, j_{L_i}^{(i)}\}$, $i \in I$.

According to TPs and CSs location and propagation information the connectivity parameters can be calculated. Let a_{ij}, $i \in I, j \in S$, be the coverage parameters:

$$a_{ij} = \begin{cases} 1 & \text{if a MAP or MR in CS } j \text{ cover TP } i \\ 0 & \text{otherwise,} \end{cases}$$

and b_{jl}, $j, l \in S$, the wireless connectivity parameters:

$$b_{jl} = \begin{cases} 1 & \text{if CS } j \text{ and } l \text{ can be connected with a link} \\ 0 & \text{otherwise.} \end{cases}$$

Decision variables of the problem include TP assignment variables x_{ij}, $i \in I, j \in S$:

$$x_{ij} = \begin{cases} 1 & \text{if TP } i \text{ is assigned to CS } j \\ 0 & \text{otherwise,} \end{cases}$$

installation variables z_j, $j \in S$:

$$z_j = \begin{cases} 1 & \text{if a MAP or a MR is installed in CS } j \\ 0 & \text{otherwise,} \end{cases}$$

wired backbone connection variables w_{jN}, $j \in S$ (if $z_j = 1$, w_{jN} denote if j is connected to the wired network N, i.e. if it is a MAP or a MR):

$$w_{jN} = \begin{cases} 1 & \text{if a MAP is installed in CS } j \\ 0 & \text{otherwise,} \end{cases}$$

wireless connection variables y_{jl}, $j, l \in S$:

$$y_{jl} = \begin{cases} 1 & \text{if there is a wireless link between CS } j \text{ and } l \\ 0 & \text{otherwise,} \end{cases}$$

and finally flow variables f_{jl} which denote the traffic flow routed on link (j, l), where the special variable f_{jN} denotes the traffic flow on the wired link between MAP j and the backbone network.

Given the above parameters and variables, the WMN planning problem can be stated as follows:

$$\min \sum_{j \in S} c_j z_j + p_j w_{jN} \tag{11}$$

s.t.

$$\sum_{j \in S} x_{ij} = 1 \qquad \forall i \in I \tag{12}$$

$$x_{ij} \leq z_j a_{ij} \qquad \forall i \in I, \forall j \in S \tag{13}$$

$$\sum_{i \in I} d_i x_{ij} + \sum_{l \in S} (f_{lj} - f_{jl}) - f_{jN} = 0 \qquad \forall j \in S \tag{14}$$

$$f_{lj} + f_{jl} \leq u_{jl} y_{jl} \qquad \forall j, l \in S \tag{15}$$

$$\sum_{i \in I} d_i x_{ij} \leq v_j \qquad \forall j \in S \tag{16}$$

$$f_{jN} \leq M w_{jN} \qquad \forall j \in S \tag{17}$$

$$y_{jl} \leq z_j \qquad \forall j, l \in S \tag{18}$$

$$y_{jl} \leq z_l \qquad \forall j, l \in S \tag{19}$$

$$y_{jl} \leq b_{jl} \qquad \forall j, l \in S \tag{20}$$

$$y_{j_\ell^{(i)}} + \sum_{h=\ell+1}^{L_i} x_{ij_h^{(i)}} \leq 1 \qquad \ell = 1, \dots, L_i - 1, i \in I \tag{21}$$

$$x_{ij} \in \{0,1\} \quad i \in I, j \in S \tag{22}$$

$$z_j \in \{0,1\} \quad j \in S \tag{23}$$

$$y_{jl} \in \{0,1\} \quad j,l \in S \tag{24}$$

$$w_{jN} \in \{0,1\} \quad j \in S. \tag{25}$$

The objective function (11) accounts for the total cost of the networks including installation costs c_j and costs related to the connection of MAP to the wired backbone p_j. Constraints (12) provide full coverage of all TPs, while constraints (13) are coherence constraints assuring respectively that a TP i can be assigned to CS j only if a device (MAP or MR) is installed in j and if i is within the coverage set of j.

Constraints (14) define the flow balance in node j. These constraints are the same as those adopted for classical multicommodity flow problems. The term $\sum_{i \in I} d_i x_{ij}$ is the total traffic related to assigned TPs, $\sum_{l \in S} f_{lj}$ is the total traffic received by j from neighboring nodes, $\sum_{l \in S} f_{jl}$ is the total traffic transmitted by j to neighboring nodes, and f_{jN} is the traffic transmitted to the wired backbone. Even if these constraints assume that traffic from TPs is transmitted to the devices to which they are assigned and that this traffic is finally delivered by the network to the wired backbone, we can assume that d_i accounts for the sum of traffic in the uplink (from TPs to the WMN) and in the downlink (from WMN to the TPs) since radio resources are shared in the two directions.

Constraints (15) impose that the total flow on the link between device j and l does not exceed the capacity of the link itself (u_{jl}). As already mentioned above, these constraints account for the flows in either directions (f_{jl} and f_{lj}) since they share the same radio resources.

Constraints (16) impose for all the MCs' traffic serviced by a network device (MAP or MR) not to exceed the capacity of the wireless link used for the access, whilst constraints (17) forces the flow directed from device j to the wired backbone to zero if device j is not a MAP. The parameter M is used to limit the capacity of the installed MAP.

Constraints (18), (19) and (20) defines the existence of a wireless link between CS j and CS l. Namely (18) and (19) force to zero the decision variables y_{jl} (defining the existence of a wireless link between CS j and l) if no device is installed either in CS j or in CS l, and (20) state that a wireless link between CS j and l cannot exist if CS j and l are out of transmission range.

The constraints expressed by (21) define the assignment of a TP to the closest CS, whilst constraints (22), (23), (24) and (25) defines the decision variables of the model to assume binary values only.

The model defined above considers fixed transmission rates for both the wireless access interface and for the wireless distribution system, and it will be referred to as *Fixed Rate Model* (FRM) throughout the paper. On the other side, in real wireless systems, the capacity of a given wireless link depends on the distance between transmitter and receiver. To this end, the FRM can be easily extended to endorse transmission rate adaptation.

As to the wireless distribution system, the rate adaptation to the distance can be accounted directly in the variables u_{jl}, which can be calculated in in the new model as a function of the distance between CS j and CS l. No other modification to the model formulation is required. On the other side, rate adaptation in the wireless access network can be accounted in the model with a slight modifications of constraints 16.

The basic idea is to consider several circular regions centered in each CS, assigning to each region a maximum rate value. All the TPs falling in one of these regions can "talk" with the device installed in the CS using the specific rate of the region.

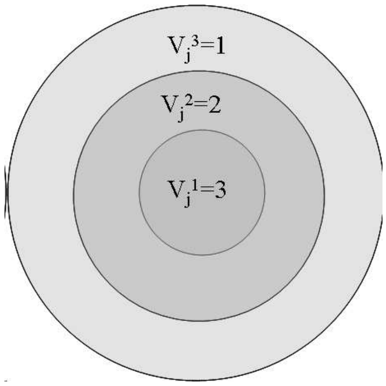

Figure 2: Rate adaptation regions around CS j.

Formally, we can define the set of regions for a given CS j $R_j = 1, ..., K$ and the set $I_j^k \subset I$ containing all the TPs falling in region k of CS j. Such sets can be determined for each CS j using the incidence variables a_{ij}^k defined as:

$$a_{ij}^k = \begin{cases} 1 & \text{if a TP } i \text{ falls within region k of the CS j} \\ 0 & \text{otherwise,} \end{cases}$$

Each of these regions of a given CS j is assigned a maximum capacity defined by the variables v_j^k.

In Figure 3 three capacity regions are defined around CS j; the nearest region to the CS has a maximum capacity $v_j^1 = 3$, whilst for the most eternal one the maximum capacity drops to $v_j^3 = 1$.

Using such definitions, the FRM can be extended to the case of rate adaptation in the wireless access part of the network by substituting the constraints (16) with the following new constraints:

$$\sum_{k \in R_j} \frac{\sum_{i \in I_j^k} d_i x_{ij}}{v_j^k} \leq 1 \qquad \forall j \in S \tag{26}$$

The new defined model with constraints (26) will be referred to as *Rate Adaptation Model* (RAM) throughout the paper.

4 Numerical Results

In this section we test the sensitivity of the two versions of the model with fixed rate (FRM, Section 4.1) and with rate adaptation (RAM, Section 4.2) to different parameters like the number of candidate sites, the traffic demands from the MCs and the capacity of the MAP in terms of traffic convoyed into the wired network.

To this end, we have implemented a generator of WMN topologies which takes as input the following parameters:

- the dimension of the square area to be covered (L [m])
- the number of CS (m), i.e., the number of positions where either a MAP or a MR can be installed
- the number of Test Points (n), i.e., the number of the MCs
- the coverage range in the wireless access part of the network (MC-MR) (R_A [m])
- the coverage range of the wireless backbone links (MRs, MRs), (R_B [m])
- the common traffic demand of the MCs:

$$d = d_i, \forall i \in I$$

- the ratio between the installation cost of a MR (c_j) and a MAP ($c_j + p_j$):

$$\beta = \frac{c_j}{c_j + p_j}, \forall j \in S$$

.

Each MR is assumed to have two interfaces on disjoint radio channels: one for the communications with the MCs and the other for the wireless link of the WDS. The connectivity in the wireless access part of the network (between MRs and MCs) is assumed to be a circular coverage region with radius R_A, whilst the connectivity among MRs and between MRs and MAPs is assumed to be a circular region with radius R_A. The assumption here is that $R_A \geq R_B$ which can be easily the case if the wireless backbone is assigned higher capacity than the access part[3].

The parameter β endorses the cost difference when installing a MR or a MAP in a candidate site. Such difference is mainly due to two factors: firstly, MAP are network devices which may tentatively handle a larger amount of traffic with respect to MRs, thus requiring more powerful and expensive hardware (CPUs, smart antennas, multiple interfaces, etc…); secondly, the installation of a MAP requires additional expenses for the provision of a wired network access for each installed MAP (cabling, wired connectivity lease etc…).

According to the above parameters, the generating tool randomly draws the positions for the m candidate sites and of the n test points. A network topology is not feasible when no solution covering all the TPs can be found. In order to generate feasible instances, the generator does the following: firstly, the positions of the CS are randomly generated within the simulated area, secondly each TP is forced to belong to the coverage range of one CS at least.

Table 1 summarizes the *standard setting* of the topological parameters which is widely used throughout the remaining part of the paper unless otherwise specified.

All the results commented hereafter are obtained formalizing the model in AMPL [31] and solving it with CPLEX [30] using workstations equipped with a AMD Athlon (TM) processors with CPUs operating at 1.2GHz, and with 1024Mbyte of RAM.

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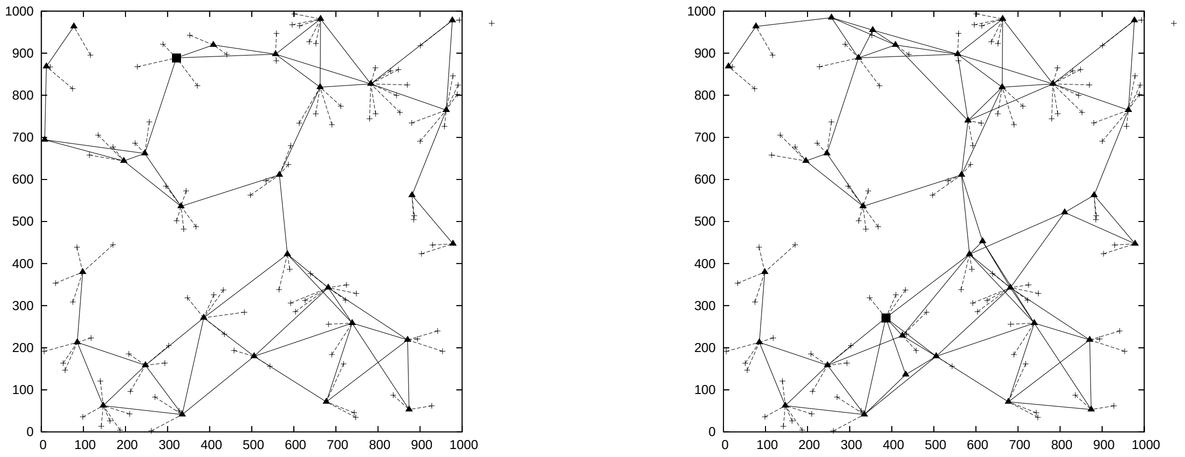
[3] Such capacity differentiation can be achieved either using different technologies, e.g. IEEE802.16 for the backbone and IEEE 802.11 for the access, or adopting smart antennas for the wireless links of the backbone when a single technology like 802.11 is adopted

Table 1: Standard setting of the network parameters.

Parameter	**Value**
L	1000m
n	100
R_A	100m
R_B	200m
β	1/10
$v_j, \forall j \in S$	54Mb/s
$u_{jl}, \forall j, l \in S$	54Mb/s

4.1 Fixed Rate Model

Once assigned the number and the positions of either CS and TP, the quality of the deployed WMN and consequently the overall installation cost depends on two parameters: the traffic demand d of the MCs and the ratio between the MR and MAP installation costs β. In this section we analyze the sensitivity of the proposed model to these parameters.



(a) d=600Kb/s

(b) d=3Mb/s

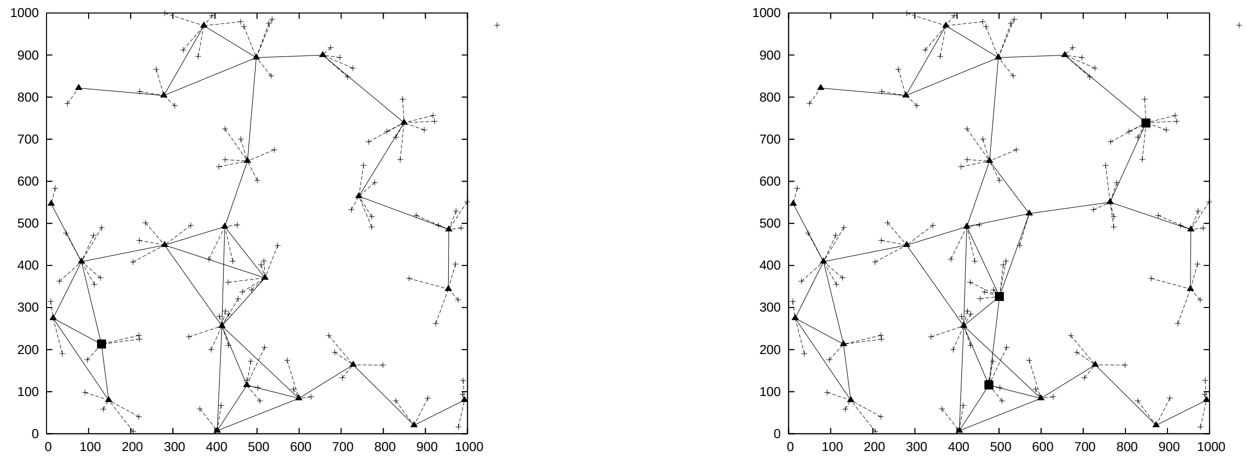
Figure 3: Sample WMNs planned by the FRM with increasing traffic demands of the MCs and infinite capacity of the installed MAPs ($M \rightarrow \inf$). Standard setting of the topological parameters.

Effect of the Traffic Demands Figure 3 reports the planned network when applying the FRM to the same network topology with two different requirements on the end user traffic and infinite capacity of the installed MAPs ($M \rightarrow \inf$). Namely, we consider the cases where all the MCs have a traffic demand of $d = 600Kb/s$ and $d = 3Mb/s$ respectively. In the Figure, squares represent the installed MAPs, triangles the installed MRs and crosses the MCs positions. Dotted line express the association of a MC to a MR, whilst solid lines connect MRs and MAPs in range.

As expected, increasing the traffic demands forces the model to install a higher number of MRs to convoy the MCs' traffic towards the MAPs; 33 MRs are needed with the highest traffic ($d = 3Mb/s$), whilst 29 MRs are installed with lowest one ($d = 600Kb/s$). Similarly, the number of wireless links of the WDS increases with the increase of the traffic.

On the other side, the number of installed MAPs remains insensitive to the MCs's traffic. This is due to the fact that the FRM with $M \rightarrow \inf$ does not endorse the limited capacity of MAPs, consequently the bottleneck here is on the wireless distribution system only and not on the connection with the wired realm.

However, since it is practical to have a finite bandwidth for the wireless/wired gateways, Figure 4 shows the planned network layout in the very same cases of Figure 3 but considering a finite capacity for the MAPs ($M = 128Mb/s$). Again, an increase in the traffic demands d requires an higher number of installed MRs as in the previous case. However, since the capacity of the MAPs is now limited, also a higher number of MAPs is installed to convoy the MCs' traffic into the wired domain.



(a) d=600Kb/s

(b) d=3Mb/s

Figure 4: Sample WMNs planned by the FRM with increasing traffic demands of the MCs and finite capacity of the installed MAPs ($M = 128Mb/s$). Standard setting of the topological parameters.

Tables 2 and 3 analyze the characteristics of the solutions of the FRM when varying the number of candidate sites. The results presented in the two tables are obtained averaging each point on 10 instances of network topology. For each couple (m, d) the tables report the number

Table 2: *Quality of the solutions provided by the FRM with three types of traffic demands with infinite capacity ($M \rightarrow \inf$) of the installed MAPs. Standard setting of the topological parameters.*

	$d = 600Kb/s$				$d = 2Mb/s$				$d = 3Mb/s$			
	MAP	**MR**	**Links**	**Time (s)**	**MAP**	**MR**	**Links**	**Time (s)**	**MAP**	**MR**	**Links**	**Time (s)**
m=30	2.3	23.4	18.6	1.28	2.6	23.8	19.6	1.61	2.8	24.2	20.7	0.63
m=40	1.4	27.4	26.2	2.2	1.5	28	27.5	2.75	1.8	28.1	27.8	5.47
m=50	1.1	28.4	29	18.16	1.1	29.6	31.7	4.63	1.1	31	35.5	4.72

Table 3: *Quality of the solutions provided by the FRM with three types of traffic demands with finite capacity ($M = 128Mb/s$) of the installed MAPs. Standard setting of the topology parameters.*

	$d = 600Kb/s$				$d = 2Mb/s$				$d = 3Mb/s$			
	MAP	**MR**	**Links**	**Time (s)**	**MAP**	**MR**	**Links**	**Time (s)**	**MAP**	**MR**	**Links**	**Time (s)**
m=30	2.3	23.5	18.6	1.59	3.2	23.9	19.5	3.16	4	24.3	20.2	0.39
m=40	1.4	27.2	25.6	10.53	2.4	27.7	26.7	5.38	3.4	27.6	27.1	7.02
m=50	1.1	28.7	30.1	16.7	2.1	28.8	29.6	4.34	3.1	29	30.4	17.81

of installed MRs, the number of installed MAPs, the number of wireless links of the WDS and the processing time to get the solution.

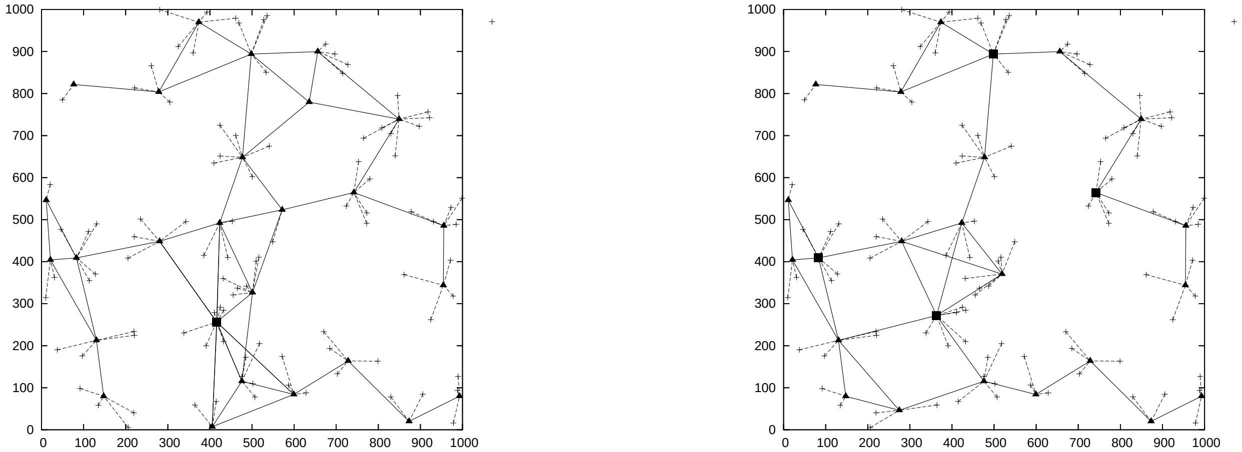
Two main results come from the observation of the two tables: first, the very same effect of traffic increase observed in figures 3 and 4 is evident also on averaged results, in fact the number of installed MAPs and MRs increases when increasing the traffic demands. In other words, the model reacts to an increase in the traffic demands by increasing the dimensions of the WDS which is used to convoy the traffic, both in terms of installed MRs and in terms of wireless links composing the WDS.

Second, for a given traffic value, increasing the number of CS to 50 augments the probability for a MC to be connected to a MAP through a multi hop wireless path, therefore the model tends to install less MAPs and more MRs. On the other side, if the number of CS is lower (30), the model installs more MAPs since not all the MCs can be connected to the installed MAPs through multi hop wireless paths. In other words, with high m the solution space is bigger and the model favors those solutions providing connectivity which have a lower impact on the network cost, i.e., those installing more MRs than MAPs.

The aforementioned discussion highlights one possible drawback of the proposed models which ensure each MC to be connected to one MAP at least without taking into account the quality of such connection in terms of number of wireless hops to the destination and interference. We assume the problem of routing decoupled with the problem of network planning, and we suppose that an optimal routing allocation can be easily designed on top of the planned network.

Effect of the Cost Parameter The number of installed MAPs and MRs intuitively depends on the installation cost ratio between a simple wireless router and a mesh access point. Such difference is mainly due to the fact that MAPs need to be connected to the wired backbone whilst MRs need power supply only. Qualitatively, if the cost for installing a MAP is much higher than the one spent for installing a MR, the proposed model tends to install very few MAP and multiple MRs. On the other hand, if the cost ratio tends to one the model will install MAPs only.

Figure 5 captures this effect by showing the planned network layout in the case of traffic demand $d = 3Mb/s$ and infinite capacity of MAPs when varying the installation costs. As clear from the figure, augmenting the value of the parameter β leads to a planned network with multiple MAPs installed. On the other hand, if the installation cost of MAPs is twice higher as the one of MRs the incidence of the MAPs installation cost on the overall network cost becomes relevant and consequently the model tends to install a lower number of MAPs, resorting to multiple hops path to service the MCs traffic.



(a) $\beta = 1/10$

(b) $\beta = 10/11$

Figure 5: Sample WMNs planned by the FRM when varying the installation cost ratio β. Standard setting of the topological parameters.

Table 4 reports the quality of the solutions when varying the parameter β for both the case of finite ($M = 128Kb/s$) and infinite ($M \rightarrow \inf$) capacity of the MAPs when using the standard setting of the configuration parameters. The results reported in the table confirms the same behavior observed in the singular planning instance of Figure 5. In fact, as the parameter β increases, the number of installed MAPs tends to increase, whereas the installed MRs decrease.

4.2 Rate Adaptation Model

In real wireless networks, the capacity of a given wireless link depends on the distance between transmitter and receiver. The RAM endorses this fact by defining three capacity regions around

Table 4: Quality of the solutions provided by the FRM when varying the installation cost ratio β. Standard setting of the topological parameters.

	$M \rightarrow \inf$			$M = 128Mb/s$		
β	**MAP**	**MR**	**Links**	**MAP**	**MR**	**Links**
1/10	1.1	31	35.5	3.1	29	30.4
1/2	1.8	29.2	31.3	3.4	29.4	31
2/3	2.5	28.3	29.1	4	28.3	29.3
10/11	4	28.1	28.5	4.6	28.1	28.6

a MR (and MAP) and assigning the link between MC and MR (or MAP) an increasing capacity when getting nearer to the MR (or MAP) location. Table 5 reports the rate adaptation scheme adopted in the RAM, which emulates the real life performance of a IEEE 802.11g transmission [].

The behavior of the RAM is similar to the one of the FRM in terms of sensitivity to the model parameters. Table 6 summarizes the characteristics of the solutions of the RAM when varying the number of candidate sites in the case of infinite capacity of the MAPs ($M \rightarrow \inf$) when considering two points of traffic intensities $d = 200Kb/s$ and $d = 600Kb/s$. The results reported in the table are averaged on 10 instances of WMNs. The traffic offered by the MCs is lower with respect to the one used to test the FRM to avoid problems due to unfeasible solutions.

Table 5: Rate Adaptation scheme.

Range Distance	**Link Capacity**
$0m \leq r \leq 30m$	36Mb/s
$30m < r \leq 60m$	18Mb/s
$60m < r \leq 100m$	2Mb/s
$r > 100m$	0Mb/s

As for the FRM, if the capacity of the $MAPs$ is not limited, the number of installed MRs increases when increasing the traffic demands, whilst the number of the MAPs remains almost constant.

The results obtained in the case of limited MAPs' capacity, not reported here for the sake of brevity, highlight a behavior of the RAM very similar to the one already observed for the FRM in the same configuration.

Table 6: Quality of the solutions provided by the RAM with two types of traffic demands with infinite capacity of the MAPs ($M \rightarrow \inf$). Standard setting of the topological parameters.

	d=200Kb/s				**d=600Kb/s**			
	MAP	**MR**	**Links**	**Time (s)**	**MAP**	**MR**	**Links**	**Time (s)**
m=30	2.3	23.1	17.6	0.85	2.7	24.9	21.8	0.65
m=40	1.4	27.3	25.5	3.26	1.4	28.4	30.6	5.43
m=50	1.1	28.7	29.7	11.95	1.1	31.8	38.9	6.65

5 Conclusion and Discussion

Wireless Mesh Networking is widely recognized to be a promising and cost effective solution for providing wireless connectivity to mobile users eventually competing with wired broadband access technologies. Such success is mainly due to the high flexibility of the mesh networking paradigm which has many potentials in terms of self configuration and installation cost viability.

The intrinsic flexibility both in the network architecture and in the implemented protocols calls for effective tools for the optimization of the network configuration. Within this field, the most of the ongoing research effort is devoted to studying novel approaches to the problems of MAC design, channel scheduling and routing optimization in WMNs.

On the other hand, in this paper we addressed the issue of WMNs planning in terms of deciding types (either MAP or MR) and positions of the network devices to be deployed. To this end, we proposed an optimization model based on mathematical programming whose objective function is the minimization of the overall network installation cost while taking into account the coverage of the end users, the wireless connectivity in the wireless distribution system and the management of the traffic flows.

In order to test the quality of the solutions provided by the model, we generated synthetic instances of WMNs and solved them using AMPPL/CPLEX varying several network parameters like the traffic demands, the number of candidate sites and the installation costs for MRs and MAPs. The numerical results we gathered show that the model is able to capture the effect on the network configuration of all these parameters, providing a promising framework for the planning of WMNs.

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