On the design of Wireless Mesh Networks

Edoardo Amaldi, Antonio Capone, Matteo Cesana, Federico Malucelli

Dipartimento di Elettronica e Informazione

Politecnico di Milano, 20133 Milano, Italy

Email: {last-name}@elet.polimi.it, Telephone: +39-02-2399-3567, Fax: +39-02-2399-3412

Keywords: Wireless mesh networks, coverage, connectivity, network design, location, routing

1. Wireless Mesh Network planning

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. Wireless mesh networking seems to be one of the most promising solution for the provision of wireless connectivity in a flexible and cost effective way, see e.g. [1].

Wireless Mesh Networks (WMNs) are composed of a mix of fixed and mobile nodes interconnected via wireless links to form a multihop ad hoc network. They contain three types of network devices: *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. The structure of a WMN is illustrated in Figure 1.

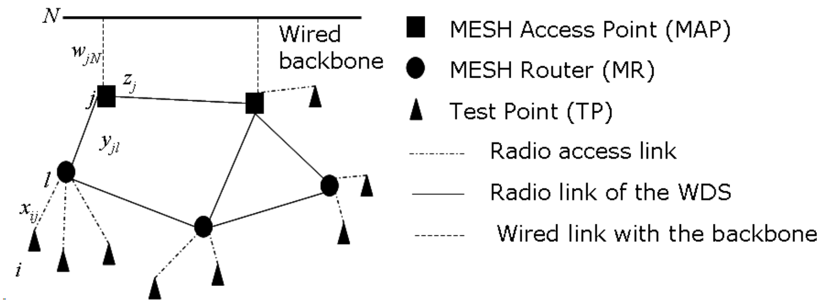


Figure 1: WMN structure.

The problem of planning WMNs differs from that of planning other wireless access networks, such as second generation cellular systems or WLANs. In the latter cases, network planning involves selecting the locations in which to install the base stations or access points, 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 [2].

In the case of WMNs, each candidate site can host either MAPs or MRs, which have different installation costs. Roughly speaking, MAPs are more expensive than MRs since they must be directly connected to the wired backbone and might be more powerful than MRs in terms of both processing and transmission capabilities. Moreover, the traffic to/from the wired backbone has to be routed on a path connecting the MR to one 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.

Thus WMN design involves deciding where to install the network nodes (out of a set of candidate sites), which type of node to select (MAP or MR) and which channel to assign them, while taking into account users coverage, wireless connectivity between MRs and MAPs, and traffic flows. In the resulting network design problem we must simultaneously consider the radio coverage of users, like in classical radio planning for wireless access networks, and the traffic routing, like in the design of wired networks.

Due to the lack of space, we just mention that most of the previous work deals with protocol optimization (see e.g. [3]) or with routing and channel assignment for a fixed topology (see e.g. [4, 5]). To the best of our knowledge, the main attempt to address the problem of locating WMN devices appears in [6]. But the models do not consider the coverage part of the problem and focus only on the optimization of routing and connectivity among mesh nodes considering an approximated interference model.

2. Mixed integer programming model

Let $S = \{1, \ldots, m\}$ denote the set of *Candidate Sites* (CSs) where network devices can be installed, and $I = \{1, \ldots, n\}$ the set of *Test Points* (TPs) representing the users in the service area. A special node N represents the wired backbone network. The cost for 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 installation cost for a MAP in CS j is thus equal to $c_j + p_j$.

The traffic generated by TP i is given by the parameter d_i, $i \in I$. The capacity of the wireless link between CSs j and l is denoted by u_{jl}, with $j, l \in S$, while the capacity of the radio access interface of CS j is denoted by v_j, $j \in S$. For each TP $i \in I$, we can determine an ordered sequence $S_i = \{j_1^{(i)}, j_2^{(i)}, \ldots, j_{L_i}^{(i)}\}$ of indices of the CSs from which TP i could be covered, where the CSs are ordered according to non increasing received signal strength.

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

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

and L the set of possible radio links defining the wireless connectivity parameters, $L = \{(j, l)\}$ if a wireless link can be established between positions j and l, with $j, l \in S$.

As to the decision variables, we consider the TP assignment variables

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

for each pair $i \in I, j \in S$, the installation variables

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

for each $j \in S$, the wired backbone connection variables

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

for each $j \in S$ (if $z_j = 1$, w_{jN} indicates whether j is connected to the wired network N, i.e., whether it is a MAP or a MR), and the wireless connection variables

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

for each pair $j, l \in S$.

We also consider the continuous variables f_{jl}, for $(j, l) \in L$, to represent the traffic flow routed on link (j, l). The special variable f_{jN} denotes the traffic flow on the wired link between MAP j and the backbone network.

The WMN design problem can then be formulated as follows:

$$
\begin{array}{llll}
\min & \sum_{j\in S}(c_j z_j + p_j w_{jN}) & & (1)\\
s.t. & \sum_{j\in S} x_{ij} = 1 & \forall i \in I & (2)\\
& x_{ij} \le a_{ij} z_j & \forall i \in I, \forall j \in S & (3)\\
& \sum_{i\in I} d_i x_{ij} + \sum_{l\in S}(f_{lj} - f_{jl}) - f_{jN} = 0 & \forall j \in S & (4)\\
& f_{lj} + f_{jl} \le u_{jl} y_{jl} & \forall (j,l) \in L & (5)\\
& \sum_{i\in I} d_i x_{ij} \le v_j & \forall j \in S & (6)\\
& f_{jN} \le M w_{jN} & \forall j \in S & (7)\\
& y_{jl} \le z_j & \forall (j,l) \in L & (8)\\
& y_{jl} \le z_l & \forall (j,l) \in L & (9)\\
& y_{j_\ell^{(i)}} + \sum_{h=\ell+1}^{L_i} x_{ij_h^{(i)}} \le 1 & \ell = 1,\dots,L_i - 1, i \in I & (10)\\
& x_{ij},\ z_j,\ y_{jl},\ w_{jN} \in \{0,1\} & i \in I, j,l \in S & (11)
\end{array}
$$

The objective function (1) accounts for the total network cost, including installation costs c_j and the costs related to the connection of MAP to the wired backbone p_j. If for any practical reason only a MR (and not a MAP) can be installed in a given CS j, the corresponding variable w_{jN} is set to zero.

Constraints (2) assign each TP to exactly a single MR or MAP, while constraints (3) are coherence constraints making sure that a TP i can be assigned to CS j only if a device (MAP or MR) is installed in j and if i belongs to the coverage set of j. Constraints (4) define the flow balance in node j. 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. Constraints (5) impose that the total flow on the link between device j and l does not exceed the capacity of the link itself (u_{jl}), provided that the wireless link does exist ($(j,l) \in L$). Constraints (6) 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, while constraints (7) force the flow between device j and 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 (8) and (9) define the existence of a wireless link between CS j and CS, namely they 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. The constraints expressed by (10) define the assignment of a TP to the best CS in which a MAP or MR is installed according to a proper sorting criteria (such as the received signal strength), while constraints (11) force the decision variables of the model to assume binary values only.

The above model, which considers fixed transmission rates for both the wireless access interface and for the wireless distribution system, is referred to as *Fixed Rate Model* (FRM). Since in real wireless systems the capacity of a given wireless link depends on the distance between transmitter and receiver, the FRM can be easily extended to account for transmission rate adaptation.

As to the wireless distribution system, the rate adaptation to the distance can be accounted for directly in the variables u_{jl}, which can be calculated in the new model as a function of the propagation conditions between CS j and CS l. No other modification to the model formulation is required. Rate adaptation in the wireless access network can be accounted for by slightly modifying constraints (6).

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.

Using such definitions, the FRM can be extended to the case of rate adaptation in the wireless access part of the network by substituting constraints (6) with the following new constraints:

$$\sum_{k \in R_j} \frac{\sum_{i \in I_j^k} d_i x_{ij}}{v_j^k} \leq 1 \qquad \forall j \in S \tag{12}$$

The new model including constraints (12) is referred to as *Rate Adaptation Model* (RAM).

Both the FRM and the RAM do not consider the effect of the interference on the access capacity and on the capacity of wireless links connecting mesh nodes. These models can be adopted with wireless technologies, like IEEE 802.16 mesh mode and IEEE 802.11 multi-radio mesh networks, that allow to limit the impact of interference by partitioning radio resources among wireless links using different frequencies or sub-carriers. However, when radio resources are limited, we must take into account interference effect. We focus here on the case of IEEE 802.11 and assume that all MAPs and MRs share the same radio channel for the access part and use another shared channel for the backbone links.

Since now the access capacity is shared by all mesh nodes, we can take into account interference quite easily modifying constraints (12) and considering not only the TPs assigned to the node in CS j but all TPs in the coverage range:

$$z_j \sum_{k \in R_j} \frac{\sum_{i \in I_j^k} d_i}{v_j^k} \leq 1 \qquad \forall j \in S \tag{13}$$

In fact, since transmissions between MAPs or MRs and MCs occur on the same channel and the CSMA/CA (Carrier Sense Multiple Access Collision Avoidance) protocol is adopted to regulate channel access, a single transmission at a time is allowed in the coverage range [7]. Since constraints (13) include a single decision variable z_j each, they can be easily managed during a pre-processing phase in which variables z_j are set to zero when constraint is not satisfied installing a MAP or MR in j. Therefore, the effect of constraints (13) is just a reduction of the number of CSs actually available.

The interference limiting effect on the wireless link capacities is more difficult to account for, since it depends on the network topology and the multiple access protocol. Considering the *protocol interference model* proposed in [8], sets of links that cannot be active simultaneously can be defined. These sets depend on the specific multiple access protocol considered. In the case of CSMA/CA, adopted by IEEE 802.11, each set C_{jl} considers a link (j, l) and includes all links that are one and two hops away in the mesh-network graph (links connecting j and l to their neighbors and their neighbors to the neighbors of their neighbors). We can consequently associate to each set a constraint on the flows crossing its links:

$$y_{jl} \sum_{(k,h) \in C_{jl}} \frac{f_{kh}}{u_{kh}} \leq 1 \qquad \forall j, l \in S \tag{14}$$

Replacing constraints (5) with (14) and (6) with (13) a so-called *Interference Aware Model* (IAM). Note that the nonlinear constraints (14) can be easily linearized.

By introducing additional binary variables z_j^q for each CS j and channel q, we obtain an overall model which takes into account also the assignment of multiple channels. The reader is referred to the full version of the paper for the details.

3. Some computational results

Interestingly, in spite of the considerable size of the three above formulations, medium-to-large-scale instances can be solved to optimality with a state-of-the-art MIP code. Due to lack of space, we just report a few typical computational results obtained with Cplex 8.2 on a workstation with 1.2GHz AMD Athlon processor and 1024Mb of RAM.

For the sake of testing, we have developed a generator of synthetic WMN topologies. Besides the numbers m of CSs and n of TPs (MCs), the input parameters include: the dimension D ([m]) of the square area to be covered, the coverage range R_A ([m]) of the wireless access part of the network (MC-MR), the coverage range R_B ([m]) of the wireless backbone links (MRs, MRs), the uniform traffic demand of the MCs $d = d_i$, for all $i \in I$, and the ratio β between the installation cost of a MR and of a MAP ($c_j/(c_j + p_j)$).

Our standard settings are: $D = 1000$, $n = 100$, $R_A = 100$, $R_B = 250$, $\beta = 1/10$, $v_j = 54$ Mb/s for all $j \in S$, $u_{jl} = 54$ Mb/s for all $j, l \in S$, and $M = 128$ Mb/s. 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, while the connectivity among MRs and between MRs and MAPs is assumed to be a circular region with radius R_B. The positions of the m CSs and n TPs are randomly generated according to the above parameters, and the network topology is guaranteed to be feasible (all TPs can be covered).

Table 1: Solutions of the FRM for different numbers of CSs m.

	$d = 600Kb/s$				
	MAP	**MR**	**Links**	**# Hops**	**Time (s)**
m=30	2.10	23.40	21.30	3.10	1.31
m=40	1.40	23.50	22.10	3.43	6.18
m=50	1.10	23.90	22.80	3.67	67.28
	$d = 2Mb/s$				
	MAP	**MR**	**Links**	**# Hops**	**Time (s)**
m=30	3.00	23.40	20.60	2.39	2.79
m=40	2.40	23.50	21.70	2.64	24.20
m=50	2.10	23.90	22.30	2.73	149.07
	$d = 3Mb/s$				
	MAP	**MR**	**Links**	**# Hops**	**Time (s)**
m=30	3.80	23.30	20.20	2.15	10.63
m=40	3.30	23.20	20.70	2.21	178.20
m=50	3.10	23.70	21.50	2.28	1,286.70

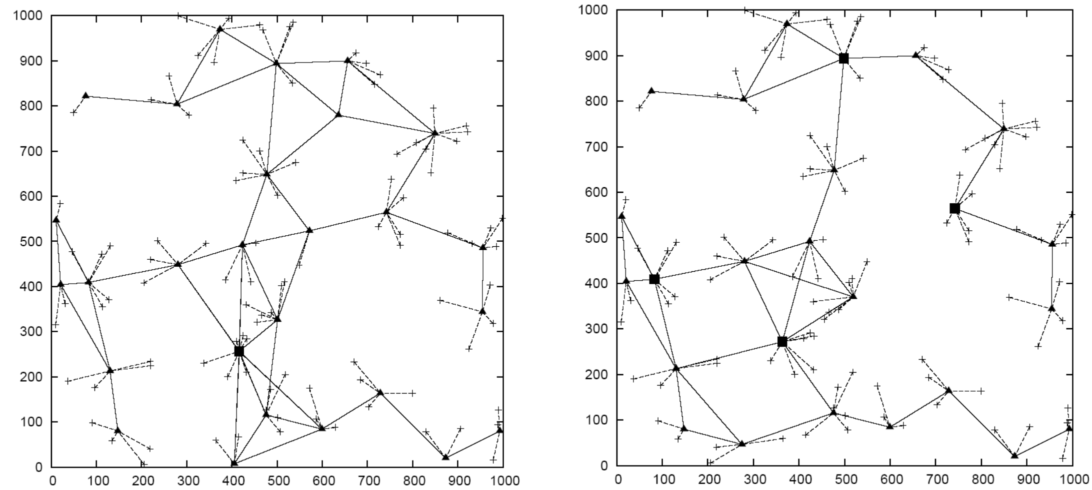
Table 2: Solutions of the FRM for different installation cost ratio β. Number of CSs $m = 30$ and MAP capacity $M = 128Mb/s$.

	$d = 600Kb/s$			
β	**MAP**	**MR**	**Links**	**# Hops**
1/10	2.10	23.40	21.30	3.22
1/7	2.40	24.00	21.60	3.22
1/5	2.40	24.30	22.70	3.22
1/3	2.40	24.30	21.60	3.22
1/2	2.80	23.60	20.80	2.95
	$d = 2Mb/s$			
β	**MAP**	**MR**	**Links**	**# Hops**
1/10	3.00	23.40	20.60	2.39
1/7	3.30	24.00	20.90	2.30
1/5	3.30	24.00	20.90	2.30
1/3	3.30	24.00	20.90	2.30
1/2	3.70	23.60	20.00	2.20

Table 1 summarizes the solution characteristics of the FRM when the number of CSs varies. The values correspond to averages on 10 instances. For each couple (m, d), we report the number of installed MRs and MAPs, the number of wireless links of the WDS, the average number of wireless hops between a generic TP and the nearest MAP, and the computing time. Table 2 reports the same performance metrics of Table 1when considering $m = 30$ positions for the candidate sites and varying the installation cost parameter β .

An increase in the traffic demands leads to an increase in the WDS dimension which is used to convey the traffic, both in terms of the number of installed devices (MAPs and MRs) and of the wireless links composing the WDS. For a given traffic level, increasing the number of CSs to 50 increases the probability that a MC is connected to a MAP through a multi-hop wireless path, so that the model tends to install less MAPs and more MRs. Conversely, if the number of CSs (30) is lower, more MAPs are installed since not all the MCs can be connected to the installed MAPs through multi-hop wireless paths. In other words, for higher values of m the solution space is larger and the model favors solutions providing connectivity with a lower impact on the network cost, i.e., networks containing more MRs than MAPs.

The number of installed MAPs and MRs clearly depends on the installation cost ratio between a simple wireless router and a mesh access point. Figure 2 illustrates this effect by showing the network layout in the case of traffic demand $d = 3$ Mb/s and infinite capacity of MAPs when varying the installation costs. Notice that an increase in the value of β leads to a network with multiple MAPs. On the other hand, if the installation cost of MAPs is twice that 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. Tha same trend is observed in the averaged results of Table 2 in the case of finite MAP capacity.



(a) $\beta = 1/2$

(b) $\beta = 10/11$

Figure 2: Example of WMNs obtained with the FRM for varying installation cost ratio β and very large MAPs capacity.

Due to lack of space we cannot compare the computational results obtained with the RAM and IAM models and report those of the overall model with channel assignment. Let us just mention that more than 75% of the instances with $m = 50$ CSs, $n = 200$ TPs and three channels we considered could be solved to optimality in a few hours of computing time. For larger instances we are developing efficient heuristics.

References

[1] I.F. Akyildiz, X. Wang, I. Kiyon, *A Survey on Wireless Mesh Networks*, IEEE Com. Mag., Sept. 2005, Vol. 43, No. 9, Pages S23– S30.

[2] E. Amaldi, A. Capone, F. Malucelli, C. Mannino, *Optimization Problems and Models for Planning Cellular Networks*, in Handbook of Optimization in Telecommunications, Springer, 2006.

[3] A. Raniwala, T. Chiueh, *Architecture and Algorithms for an IEEE 802.11-Based Multi-Channel Wireless Mesh Network*, IEEE INFOCOM 2005, Vol. 3, Pages 2223–2234.

[4] A.K Das, H.M.K. Alazemi, R. Vijayakumar, S. Roy, *Optimization models for fixed channel assignment in wireless mesh networks with multiple radios*, IEEE SECON 2005, Pages 463–474.

[5] M. Alicherry, R. Bhatia, L. E. Li, *Multi-radio, multi-channel communication: Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks*, ACM MOBICOM 2005, Pages 58–72.

[6] R Chandra, L. Qiu, K Jain, M Mahdian, *Optimizing the placement of integration points in multi-hop wireless networks*, Proceedings of the 12th IEEE ICNP, 2004, Pages 271-282.

[7] E. Amaldi, A. Capone, M. Cesana, F. Malucelli, *Optimizing WLAN Radio Coverage*, IEEE ICC 2004, Vol. 1, Pages 180–184.

[8] P. Gupta and P.R Kumar, *The capacity of wireless networks*, IEEE Trans. on Information Theory, March 2000, Vol. 46, No. 2, Pages 388–404.