DESIGNING MULTI-TIER WIRELESS MESH NETWORKS: CAPACITY-CONSTRAINED PLACEMENT OF MESH BACKBONE NODES

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Abstract

In this work we investigate the issue of automated design of Wireless Mesh Networks (WMN). The general scenario we envision is that of constructing WMNs with WLAN as clients and a mesh network to provide inter-WLAN as well as gateway connectivity. Our main aim in this work is to a) design capacity-constrained WMNs, b) build resilient WMNs with transient demands.

1 Introduction

The aim of this work is to present an approach for automated design of Wireless Mesh Networks (WMN). The design formulation takes demands at client nodes and designs a backbone mesh node topology to satisfy these demands. We also show the importance of using appropriate cost functions to compute a topology resilient to changes in demand constraints.

IEEE 802.11 based single-hop WLANs are now widely prevalent [1]. However adhoc deployment of such networks have the following issues : (i) They cannot adequately address QoS-constrained capacity requirements [5] and (ii) Provide cost-efficient backbone connectivity to the AP.

Removing wired connectivity to APs is an important goal in order to increase the cost savings accrued by avoiding the deployment of a wired backhaul connectivity. But additionally, a suitable technology is necessary to adequately replace the large bandwidth capability of wired networks.

Wireless Mesh Networks (WMN) are gaining popularity as a solution to provide a wireless backbone and address the capacity constraints of a single-hop wireless network [3]. In WMNs, mesh nodes acting as routers are placed in the network to provide the backbone connectivity to the gateways. The networks based on such a mesh backbone topology, allows multi-hop wireless access, support for self-forming and rapid reconfiguration of topologies.

For a single-hop network, the benefits are the absence of wired connectivity from the Access Points (AP) to the backbone and the use of multiple radios by the APs to communicate with the end-users and the backbone.

WMNs using IEEE 802.16 are also anticipated to significantly improve the performance of ad hoc networks, wireless personal area networks (WPAN), and wireless metropolitan area networks (WMAN) [3]. Hence it is important to have mechanisms to automate the design of such networks.

While the design of WMNs falls in the same class of network design problems as encountered in wired as well as cellular networks there is a significant difference in the node capabilities and the associated constraints and cost-functions. For example, the wireless nature of the links (including backbone links) gives rise to cost-functions not encountered in other networks, and also the use of multi-hop wireless transmission results in additional scheduling constraints.

We frame the network design problem for WMNs

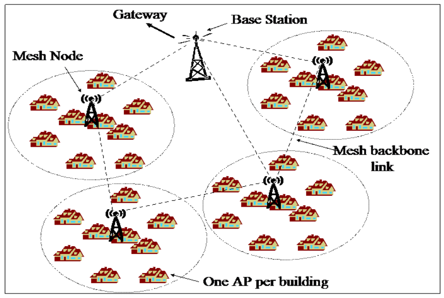

Figure 1: A typical mesh network scenario.

as an optimization problem to calculate both the WMN mesh backbone network topology as well as the optimal location of the mesh backbone nodes. We consider a typical urban scenario (as shown in figure 1) and present a design formulation for it using 802.16 as the enabling WMN technology [2], in sections [2, 3]. We have implemented the formulation in the CPLEX solver [6]. We find the optimal location of the 802.16 Mesh Subscriber Stations (MSS) and design the topology of the WMN backbone while keeping the traffic demands at each MSS satisfied.

Further more, we show the choice of a cost function significantly impacts the resulting topology. For example, a straight forward approach would be to calculate cost as a function of the distance between the nodes (similar to wired networks). However, we show that such a cost function gives rise to widely varying topologies with minor variations in the demands. We claim that the use of a transmission power-based cost function results in more resilient topologies.

2 Problem overview

We consider the following urban scenario (figure 1). Each building in the area in which a mesh network has to be established has an AP which provides the connectivity between the clients inside the building and mesh backbone. It does this by associating itself with the nearest mesh node (MSS in the 802.16 case). The mesh nodes can have multiple directional antennas in order to communicate with both the APs as well as other mesh nodes.

An AP therefore has two radio links, one providing internal connectivity and one providing the connection to the mesh backbone. The internal link is assumed to be an 802.11 device while the external link maybe an 802.16 link. Note that we are mainly concerned with the demand generated at each AP, hence the type of the internal link or the underlying sub-network topology is *irrelevant* to the problem as long as there is no overlap in the frequency allocated to the links (in order to avoid interference).

Now the problem is defined as follows. Given the demands at each AP and a set of potential mesh node locations, the problem is to find the optimal number of mesh node locations (from the given set) as well as the mesh topology to satisfy the demand constraints.

3 Design problem formulation

The optimal mesh node placement requirement makes this problem a mixed-integer linear programming (MILP) problem. The MILP formulation for this problem is given in algorithm 1.

3.1 Assumptions and definitions

The assumptions on node deployment scenarios for simplifying the model are :

- AP nodes are deployed over a given area with a uniform random distribution.
- Potential mesh node locations are given. These

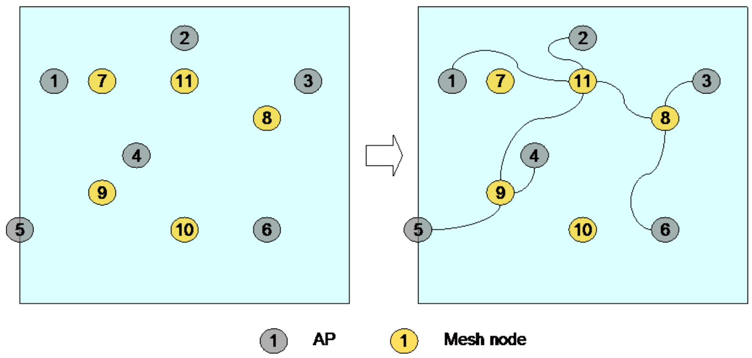

Figure 2: (a) 6 AP, 5 mesh node deployment scenario. (b) Output topology for a power-based cost function.

are deployed too with a uniform random distribution.

Now, the properties of the APs and mesh nodes are defined as :

- Access Points $w = (x, y, r, D)$. Where, the properties of node w are the co-ordinates (x, y), the transmission radius r and the demands D.
- Potential mesh nodes $v = (x', y', r', G)$. Where, the properties of a mesh node v are the coordinates (x', y'), the transmission radius r', and the number of links G. The mesh nodes merely act as relay nodes and hence have no traffic parameters.

3.2 Link costs and constraints

In order to facilitate the establishment of links between the APs and the mesh nodes as well as between the mesh nodes, we need to specify the cost function to be used. We precompute two such functions. One function calculates the cost based on the transmission distance between the nodes. The second function calculates the cost based on the power required for the transmission.

Now the constraints imposed on the network (algorithm 1) are :

- Demand volume flowing on each potential link should not exceed the link capacity (constraints 1, 5).
- Each AP demand in the network should be satisfied (constraints 2, 3, 4).
- The number of mesh links is bounded by G (constraint 6).

4 Implementation and results

We have implemented the formulation using the CPLEX solver. The parameters used in the formulation are given in table 1. The cost of establishment of a mesh node is 10000 while the cost of a link is a function of the transmission power.

For each network scenario, we varied the demands (11 artificially generated loads) to analyse topology changes and thus simulating anticipated future traffic patterns. It would be desirable that the changes brought about in the topology are minimal in nature.

Figure 2(a) presents an example scenario for a 6 AP nodes and 5 potential mesh nodes scenario. Using a cost function based on transmission distance and varying the load results in frequent topology changes (figure 3). These are abrupt changes in the output topology due to variations in parameters. For example, links at a node may be torn down and new links may be established at other nodes. Or, entirely new nodes among the potential mesh node locations

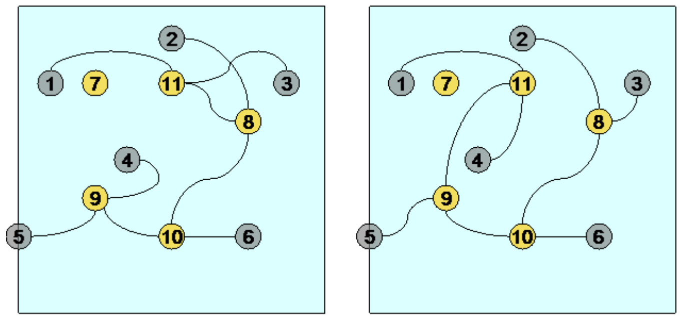

Figure 3: Output topologies for a distance-based cost function with change in demands.

might be switched on, while other nodes might be switched off. Our aim is to design a network which gracefully accepts change in parameters and hence we would like to minimise this cost of nodes and link changes.

Also, the solver took a significantly longer time to solve problems with the distance cost function. For example, for a 10 AP nodes and 8 mesh nodes scenario, the solver took an average of 6528.5 seconds. Similar timing for a power cost function was 69.92 seconds. So we present only the power cost-function results for various node deployment scenarios (table 2).

The use of a power cost function to establish a link proves to be a better estimate(figure 2(b)). Not only does this reduce the transmission power required, by forcing nodes to choose nearer nodes, it also reduces the volatility. The topology computed remains on an average invariant with change in demand (as can be seen from the average number of links in table 2).

We would like to note that the CPLEX solver's parameters needed to be tuned in order to reduce the solution time. We found that providing upper cutoff values for the objective speeds up the solver and also changing the emphasis parameter to feasibility instead of balancing feasibility and optimality can produce fast (but sub-optimal) solutions. We present only the optimal solutions found by the solver.

5 Conclusions

We have formulated a network design problem for deploying wireless mesh networks. We used the CPLEX solver to generate various topologies under varying loads. An important observation was the effect of cost functions on the resilience of the topology to changes in demands. As expected, the problem scales exponentially with even a small increase in node numbers due to the increase in search space required by the formulation. But the results (for problem sizes up to 12 AP and 8 mesh nodes) are encouraging. They provide us an insight to the issues faced in such design problems.

Further ongoing work on cost functions to correctly represent this phenomenon and computing topologies for large network scenarios is envisaged. We also plan to automate the design process by integrating it with the wireless infrastructure design tool proposed in [4]

References

[1] IEEE wireless LAN medium access control (MAC) and physical layer(PHY) specifications: R2003. 2003.

[2] IEEE standard for local and metropolitan area networks - part 16: Air interface for fixed broadband wireless access systems. 2004.

Algorithm 1: Mesh network design problem formulation

Indices:

$w = 1, 2, \ldots, W$: APs
$v = 1, 2, \ldots, V$: mesh nodes
$e = 1, 2, \ldots, E$: links
$f = 1, 2, \ldots, F$: directed access arcs (between AP & mesh nodes)
$t = 1, 2, \ldots, T$: directed transit arcs (between mesh nodes)

Constants:

$h_{ww'}$: volume of demand from AP w to w'
$H_w = \sum_{w'} h_{ww'}$: total demand outgoing from AP w
$\beta_{ev} = 1$ if link e is incident with mesh node v; 0, otherwise
$\beta_{fw} = -1$ if access arc f is incoming to AP w
$= 1$ if access arc f is outgoing from AP w
$= 0$ otherwise
$\beta_{fv} = -1$ if access arc f is incoming to mesh node v
$= 1$ if access arc f is outgoing from mesh node v
$= 0$ otherwise
$\beta_{tv} = -1$ if transit arc t is incoming to mesh node v
$= 1$ if transit arc t is outgoing from mesh node v
$= 0$ otherwise
$w_{ef} = 1$ if access arc f is realised on link e; 0, otherwise
$w_{et} = 1$ if transit arc t is realised on link e; 0, otherwise
κ_e : cost of installing link e
M_e : upper bound on the capacity of link e
φ_v : cost of installing mesh node v
G_v : upper bound on the number of radios of mesh node v

Variables:

x_{fw}: flow realising all demands originating at AP w on access arc f
x_{tw}: flow realising all demands originating at AP w on transit arc t
y_e: capacity of link e
$u_e = 1$ if link e is provided; 0, otherwise
$s_v = 1$ if mesh node v is installed; 0, otherwise

Objective function:

minimize $\boldsymbol{F} = \sum_e \kappa_e u_e + \sum_v \varphi_v s_v$

Constraints:

$\sum_t w_{et} \sum_w x_{fw} + \sum_f w_{ef} \sum_w x_{fw} \leq y_e$, $e = 1, 2, \ldots, E$ ***- (1)***
$\sum_f \beta_{fw} x_{fw} = H_w$, $w = 1, 2, \ldots, W$ ***- (2)***
$\sum_f \beta_{fw'} x_{fw} = -h_{ww'}$ ***- (3)***
$\sum_t \beta_{tv} x_{tw} + \sum_f \beta_{fv} x_{fw} = 0$ ***- (4)***
$y_e \leq M_e u_e$ ***- (5)***
$\sum_e \beta_{ev} u_e \leq G_v s_v$ ***- (6)***

Parameter	Value
Area	100mx100m
AP/Mesh Tx Range	70m
Max. Links (G)	4
Link capacity	10000 Mbps
Demand	1000 Mbps

Table 1: Design parameters.

AP	Mesh	Avg. time (s)	Optimal nodes (min,max)	Links (min,max,avg)
8	5	< 1	2, 3	8, 10, 9.82
10	7	50.93	3, 4	10, 13, 12.45
10	8	69.86	3, 4	10, 13, 12.45
12	7	178.12	3, 6	12, 16, 15.36
12	8	854.51	3, 5	12, 16, 15.45

Table 2: Results for various network scenarios using a power cost function.

[3] Ian Akyildiz, Xudong Wang, and Weilin Wang. Wireless mesh networks: a survey. *Computer Networks*, 2005.

[4] Raghuraman Rangarajan and Sridhar Iyer. Automatic topology generation for a class of wireless networks. *IEEE International Conference On Personal Wireless Communications*, 2005.

[5] Raghuraman Rangarajan, Sridhar Iyer, and Atanu Guchhait. Automated design of VoIP-enabled 802.11g WLANs. *OPNETWORK*, 2005.

[6] ILOG CPLEX Solver. www.cplex.com. 2004.