WIND: A Tool for Capacity-constrained Design of Resilient Multi-tier Wireless Mesh Networks

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I. Introduction

In this work we present a tool for the automated design of Wireless Mesh Networks (WMN). The general scenario we envision is that of constructing WMNs with WLAN networks as clients (tier 1) and a mesh network (tier 2) 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.

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 [2]. 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 WiMAX are also anticipated to significantly improve the performance of ad hoc networks, wireless personal area networks (WPAN), and wireless metropolitan area networks (WMAN) [2]. 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 (link creation cost). For example, the wireless nature of the links (including backbone links between mesh nodes) give rise to cost-functions not encountered in other networks, and also the use of multi-hop wireless transmission results in additional scheduling constraints.

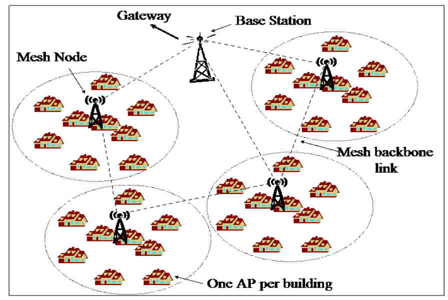

Fig. 1. A typical mesh network scenario.

The design of such a multi-tier network also has to consider the time-varying demands of the clients or the addition of new client nodes. In order to do so the design methodology has to build resilient networks to withstand these transient demands. We look at the WMN design problem as a special case of the traditional network design problem for optimal node location and topology construction [3]. With WiMAX as the enabling WMN technology and WLAN as the underlying first-tier network to be connected, we investigate various urban and rural deployment scenarios. Our aim is to use the tool to compare and classify the different scenarios vis-a-vis their cost of deployment.

We have formulated the core WMN design as an mixed-integer linear programming problem. The Wireless Infrastructure Deployment tool (WIND), uses an MILP solver (CPLEX) to generate topologies with varying parameters (the number of demands, demand volumes, number of links etc.).

An important aim was to observe the effect of changing the parameters on the resilience of the topology. Abrupt changes in the output topology due to variations in parameters results in links at a node being torn down and new links established at other nodes. Or, entirely new nodes among the potential mesh node locations may be switched on, while other nodes may be switched off. A resilient topology can be defined as one that gracefully accepts change in parameters and hence minimises the cost attached with node and link changes. We observed that the use of a transmission power based heuristic for link creation (Links are established in the network based on the cost of providing that link.) proves to be a better estimate than one based on transmission distance. Not only does this reduce the power required, by forcing nodes to establish links with nearer nodes, it also reduces the volatility.

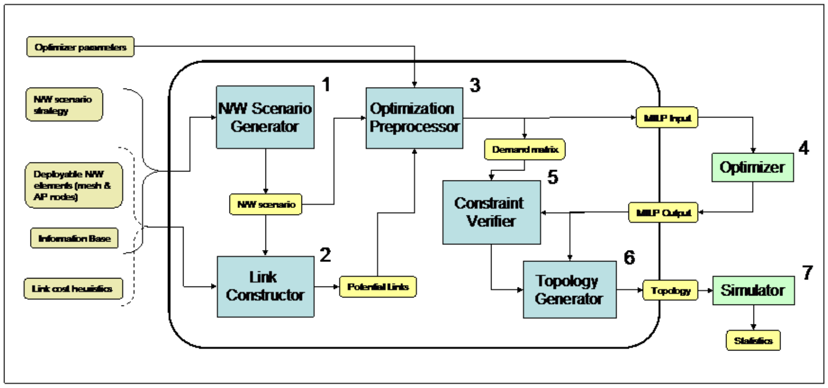

Fig. 2. WIND overview.

Initial results show that the computed topology changes infrequently with change in demands and hence showing resilience.

II. A Typical Urban Deployment Scenario

The following scenario presents the problem in an urban setting. We consider an area where the mesh network is going to be deployed. Each building in the area has an AP which provides the connectivity between the clients inside the building and the mesh backbone. It does this by associating itself with the nearest mesh node (based on some cost function). The mesh nodes can have multiple directional antennas (links) in order to communicate with both the APs as well as other mesh nodes.

An AP therefore has at least 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 a mesh (i.e. WiMAX) 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). Also note that the demands at the AP (which is the root node of the underlying sub-network) is generated as one of the outputs of the WIND topology construction process.

We assume that the AP nodes have demands associated with them and are deployed over a given area with a uniform random distribution. Also, the potential mesh node locations are given and these are deployed too with a uniform random distribution.

Also, to facilitate the establishment of links between the APs and the mesh nodes as well as between the mesh nodes, we need to specify a heuristic to establish the link costs. The tool precomputes 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 problem for this scenario 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. The constraints placed on the problem are :

- Link capacity constraint: Demand volume flowing on each potential link (of each node) should not exceed the capacity of the link.
- Demand satisfaction: Each AP demand in the network should be satisfied.
- Link bounds: There is an user-defined upper bound on the number of mesh links.

III. WIND overview

WIND (figure 2) takes in the following inputs:

1) AP nodes: number, co-ordinates, link properties (transmission radius) and the demands.
2) Potential mesh nodes: number, co-ordinates, link properties (transmission radius).
3) Link cost heuristics: used by WIND to construct the potential links (mesh-mesh links as well as mesh-AP links).
4) Node deployment strategy used (i.e. the node distribution)

The modules in WIND are:

- N/W Scenario generator: Creates the n/w scenario (or set of node placements).
- Link constructor: Uses heuristics to generate the list of potential links using node and link properties. It calculates the feasibility of each mesh-mesh and mesh-AP link based on transmission distance or transmission power-based heuristics. Also generates the cost of establishment of each link.
- Optimization preprocessor: Uses the n/w scenario and the list of potential links to construct the optimizer input. It also generates the list of demands present in the network as a demand matrix to be used by the constraint verifier.
- Constraint verifier: Verifies the capacity constraints imposed on the scenario by comparing the optimizer output with the demand matrix.

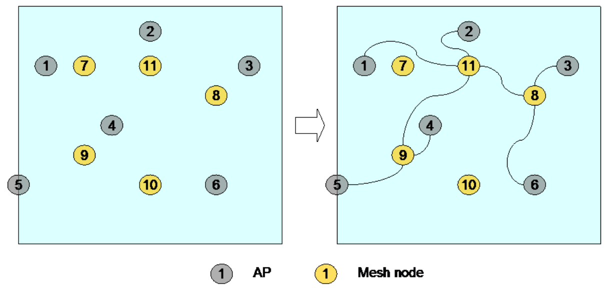

Fig. 3. (a) 6 AP, 5 mesh node deployment scenario. (b) Output topology for a power-based cost function (Note: Topology remains the same with change in demands.

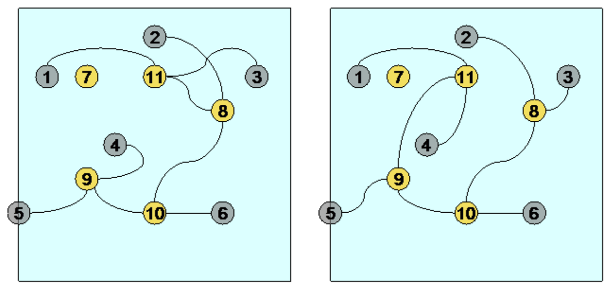

Fig. 4. Output topologies for a distance-based cost function with change in demands.

- Topology generator: The constraints being satisfied, the corresponding topology is generated from the optimizer output files and the capacity-constraints are validated by simulation.

IV. Preliminary results and ongoing work

Figure 3(a), presents the scenario for 6 AP nodes and 5 potential mesh nodes. The area of deployment is a *normalised* 4x4 square. The AP nodes have a transmission radius of 1.5. The mesh nodes have a transmission radius of 2 and maximum possible links $G = 4$. There are 7 demands (each of 10 KBytes/sec) between the nodes: $< 1-2 >, < 2-5 >, < 2-6 >, < 3-4 >, < 3-6 >, < 4-6 >$ and $< 5-2 >$. The cost of establishment of a mesh node is 100 while the cost of a link is a function of the transmission power. We see that the solver manages to fully connect the network using just 3 of the 5 potential mesh nodes.

The problem as expected scales exponentially with even a small increase in node numbers due to the increase in search space required by the formulation. But the initial results for small problem sizes (6 APs, 5 potential mesh nodes) are encouraging. They provide us an insight to the issues faced in such design problems.

We varied parameters (the number of demands, demand volumes, number of links allowed etc.) 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.

But this is not the case when we use transmission distance as the link creation cost (figure 4). Using such a cost and varying parameters results in frequent topology changes. 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 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.

The use of a link creation cost based on transmission power proves to be a better estimate(figure 3(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 changes infrequently with change in demand.

We are currently working on improving the heuristics to correctly capture the resilience phenomenon. Also, we are looking into using heuristics to reduce the MILP search space in order to compute topologies for real life network scenarios and validating the capacity constraints using simulations.

References

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