Design of Multi-tier Wireless Mesh Networks

Raghuraman Rangarajan

Advisor
Prof. Sridhar Iyer

July 2009, IIT Bombay
Introduction

Issues in Wireless Network Design
Multi-tiered Wireless Network Design
Solution Approach

Stage 1: AP-Client Association
Capacity of WLANs
AP-assignment problem

Stage 2: WLAN Topology Design
Generic Framework
Topology Construction
\textsc{WIND}_{\text{wlan}} Tool

Stage 3: WMN Node Locationing and Topology Design
Mesh Network Design Problem
Problem Formulation
\textsc{WIND}_{\text{wmn}} Tool
Goal
Design wireless data networks
  ► mesh networks and wireless local area networks
  ► capacity constraints

Purpose
  ► Construct topology
  ► Position infrastructure nodes
  ► Provision bandwidth
Overview of Wireless Networks

Wireless data networks can be used as

- Infrastructure or peer-to-peer (802.11)
- Local (WLAN) or Backhaul networks (802.16, Mesh)

Wireless vs Wired

- Removes physical connectivity
- Allows user mobility
- Re-configuration of network incurs minimal cost
- Wired n/w have higher data rates
- Capacity provisioning important in wireless n/ws
Introduction
Issues in Wireless Network Design
Multi-tiered Wireless Network Design
Solution Approach

Stage 1: AP-Client Association
Capacity of WLANs
AP-assignment problem

Stage 2: WLAN Topology Design
Generic Framework
Topology Construction
WIND\textsubscript{wlan} Tool

Stage 3: WMN Node Locationing and Topology Design
Mesh Network Design Problem
Problem Formulation
WIND\textsubscript{wmn} Tool

Summary
Wireless Network Design I

Example Campus Network

Network elements

- User devices
- Last-hop access (APs)
- Backhaul network (Routers)
- Application services

Network elements

- User devices
- Last-hop access (APs)
- Backhaul network (Routers)
- Application services
Wireless Network Design II

Design problem

Construct network topology satisfying design constraints

Design constraints

- Coverage
- Capacity
- Application scenarios
- Heterogeneous technologies
- Cost

Outline

Introduction
Issues in Wireless Network Design
Multi-tier Wireless Design
Solution Approach

Stage 1: AP-assignment
Capacity of WLANs
AP-assignment problem

Stage 2: WLAN Topology
Generic Framework
Topology Construction
WIND_wlan Tool

Stage 3: WMN Topology Design
Mesh Network Design Problem
Problem Formulation
WIND_wmn Tool

Summary
Generic Design Problem

**Network design problem (NDP)**

*Given* client nodes and deployment layout  
*Construct* network topology  
*Subject to* constraints  
*While* minimizing network infrastructure cost
Wireless Network Design IV

Current approaches

- Site survey
- Simulations
- Test measurements
- Signal strength measurements
- RF planning

Drawbacks [Mclean, How to design a WLAN, 2003]

- Difficult to provision 802.11 DCF
- Suitable for small-sized networks
- Address only coverage issues

Need

Integrated Approach to Wireless Design
Wireless Network Design V

Design issues

- Provisioning 802.11 WLANs in heterogeneous application scenarios
- Capacity-constrained wireless network design
- Minimising network infrastructure cost
- Integrated design of local area and backhaul wireless networks
Outline

Introduction
- Issues in Wireless Network Design
- Multi-tiered Wireless Network Design
- Solution Approach

Stage 1: AP-Client Association
- Capacity of WLANs
- AP-assignment problem

Stage 2: WLAN Topology Design
- Generic Framework
- Topology Construction
- \textit{WIND}_{\text{wlan}} Tool

Stage 3: WMN Node Locationing and Topology Design
- Mesh Network Design Problem
- Problem Formulation
- \textit{WIND}_{\text{wmn}} Tool
Bottom-up Design Flowchart
Three design stages

Outline
Introduction
Issues in Wireless Network Design
Multi-tier Wireless Design
Solution Approach

Stage 1: AP-assignment
Capacity of WLANs
AP-assignment problem

Stage 2: WLAN Topology
Generic Framework
Topology Construction
WIND wlan Tool

Stage 3: WMN Topology Design
Mesh Network Design Problem
Problem Formulation
WIND wmn Tool

Summary
Stage 1: AP-assignment

Given client nodes

Compute APs required

Subject to capacity constraints

While minimizing |APs|
Problem formulation

Stage 2

WLAN topology design

*Given* client nodes, deployment layout

*Construct* WLAN topology

*Subject to* capacity constraints

*While* minimizing network infrastructure (APs)
Problem formulation

Stage 3

Mesh network design

*Given* deployment layout, AP nodes deployed and their characteristics

*Construct* backhaul topology

*Subject to* capacity constraints

*While* minimizing network infrastructure (mesh nodes and links)
Outline

Introduction
Issues in Wireless Network Design
Multi-tiered Wireless Network Design
Solution Approach

Stage 1: AP-Client Association
Capacity of WLANs
AP-assignment problem

Stage 2: WLAN Topology Design
Generic Framework
Topology Construction
WIND\textsubscript{wlan} Tool

Stage 3: WMN Node Locationing and Topology Design
Mesh Network Design Problem
Problem Formulation
WIND\textsubscript{wmn} Tool

Summary
Solution Approach

Stage 1

AP-assignment

- Analyse heterogeneous application deployments
- Prioritise applications to improve system utilisation
- Validate with simulation
Stage 2

WLAN topology design

- Framework for deploying WLANs from simple network input parameters
- Construct topology using AP-assignment solutions as input
- Validate with simulation
Solution Approach

Stage 3

Mesh network design

- Framework for deploying WMNs from simple network input parameters
- Optimisation problem for Node locationing and topology construction
- Minimise network deployment cost using node and link costs
Outline

Introduction
- Issues in Wireless Network Design
- Multi-tiered Wireless Network Design
- Solution Approach

Stage 1: AP-Client Association
- Capacity of WLANs
- AP-assignment problem

Stage 2: WLAN Topology Design
- Generic Framework
- Topology Construction
  \textit{WIND}_{\text{wlan}} Tool

Stage 3: WMN Node Locationing and Topology Design
- Mesh Network Design Problem
- Problem Formulation
  \textit{WIND}_{\text{wmn}} Tool

Summary
Associating Clients with APs

**AP-assignment**

*Given* client nodes

*Compute* APs required

*Subject to* capacity constraints

*While* minimizing |APs|
Capacity of WLANs

Aim

- Study **single** application scenario
  - Analyse 802.11 DCF mechanism
  - Realtime applications (voice and video codecs)
  - Theoretical vs Simulation results
- Capacity of system (in number of flows)
- Base case for analysis of heterogeneous deployments
System Setup

DCF schemes

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Data rate (in Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>802.11b</td>
<td>1, 5.5, 11</td>
</tr>
<tr>
<td>802.11g</td>
<td>1, 11, 54</td>
</tr>
</tbody>
</table>

Codec parameters

<table>
<thead>
<tr>
<th>Parameters / Codecs</th>
<th>G.711</th>
<th>G.723.1</th>
<th>G.729</th>
<th>GSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit rate (in kbps)</td>
<td>64</td>
<td>6.4</td>
<td>8</td>
<td>13.2</td>
</tr>
<tr>
<td>Framing interval (in ms)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Payload (in bytes)</td>
<td>160</td>
<td>24</td>
<td>20</td>
<td>33</td>
</tr>
</tbody>
</table>

MAC parameters and Stack overheads
Theoretical Calculation

Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>pkt</td>
<td>Packet size (at MAC, in bytes)</td>
</tr>
<tr>
<td>ACK</td>
<td>Size of ACK packet (14 bytes for 802.11)</td>
</tr>
<tr>
<td>$r$</td>
<td>Data rate (in Mbps)</td>
</tr>
<tr>
<td>DIFS</td>
<td>DIFS time (in $\mu S$)</td>
</tr>
<tr>
<td>SIFS</td>
<td>SIFS time (in $\mu S$)</td>
</tr>
<tr>
<td>slot</td>
<td>Slot time (in $\mu S$)</td>
</tr>
<tr>
<td>backoff</td>
<td>Backoff</td>
</tr>
<tr>
<td>PHY</td>
<td>PHY overhead (in $\mu S$)</td>
</tr>
</tbody>
</table>

Throughput ($T$)

$$T = \frac{\text{Payload}}{t_{\text{total}}} = \frac{\text{pkt} \times 8}{\text{DIFS} + \text{SIFS} + 2 \times \text{PHY} + \frac{\text{backoff}}{2} \times \text{slot} + t_{\text{pkt}} + t_{\text{ack}}}$$

Where,

$$t_{\text{pkt}} = \frac{(\text{pkt} + \text{MAC}) \times 8}{r}, \quad t_{\text{ack}} = \frac{\text{ACK} \times 8}{r}$$
Simulation Setup

Implementation details
- Opnet Modeler
- Voice scenarios modeled as application definition
- Number of flows increased until constraints failed

Constraints
- Throughput satisfaction
- Delay $\leq 75$ msec
Results: G.711 Codec

Theoretical vs Simulation

<table>
<thead>
<tr>
<th>Scheme</th>
<th>802.11b</th>
<th>802.11g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate (r)</td>
<td>1 5.5 11</td>
<td>1 11 54</td>
</tr>
<tr>
<td>Theoretical</td>
<td>3 8 10</td>
<td>4 25 39</td>
</tr>
<tr>
<td>Simulation</td>
<td>3 8 10</td>
<td>4 18 34</td>
</tr>
</tbody>
</table>
## Results: Voice Codecs

<table>
<thead>
<tr>
<th>Scheme</th>
<th>802.11b</th>
<th>802.11g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate (r)</td>
<td>1</td>
<td>5.5</td>
</tr>
<tr>
<td>G.711</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>G.723.1</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>G.729</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>GSM</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

**Table:** Maximum number of voice calls: theoretical results.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>802.11b</th>
<th>802.11g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate (r)</td>
<td>1</td>
<td>5.5</td>
</tr>
<tr>
<td>G.711</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>G.723.1</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>G.729</td>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>GSM</td>
<td>6</td>
<td>10</td>
</tr>
</tbody>
</table>

**Table:** Maximum number of voice calls: simulation results.
Observations

- Simulation results closely follow theoretical results
- Theoretical results form upper bound
- 802.11g vs 802.11b: Effect of shorter timings seen in 11 Mbps case
- Delay ≪ Delay constraint (Max delay ≤ 18 μS)
- Minimal variation in number of calls between codecs
- CSMA/CA mechanism is main limitation
- Results well known [Anurag Kumar, Comm Networking, 2005]
### Results: Video Capacity

<table>
<thead>
<tr>
<th>Scheme</th>
<th>802.11b</th>
<th>802.11g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate (r)</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>1 5.5 11</td>
<td>1</td>
<td>11 54</td>
</tr>
<tr>
<td>SQCIF 128x96, 30fps</td>
<td>4 13 16</td>
<td>5 34 59</td>
</tr>
<tr>
<td>QCIF 176x144, 15fps</td>
<td>3 13 20</td>
<td>3 31 83</td>
</tr>
<tr>
<td>CIF 352x286, 10fps</td>
<td>1 6 10</td>
<td>1 13 46</td>
</tr>
</tbody>
</table>

Table: Maximum number of video flows: theoretical results.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>802.11b</th>
<th>802.11g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate (r)</td>
<td>1</td>
<td>11 54</td>
</tr>
<tr>
<td>1 5.5 11</td>
<td>1</td>
<td>11 54</td>
</tr>
<tr>
<td>SQCIF 128x96, 30fps</td>
<td>4 13 16</td>
<td>5 29 76</td>
</tr>
<tr>
<td>QCIF 176x144, 15fps</td>
<td>3 13 20</td>
<td>3 27 94</td>
</tr>
<tr>
<td>CIF 352x286, 10fps</td>
<td>1 6 10</td>
<td>1 14 52</td>
</tr>
</tbody>
</table>

Table: Maximum number of video flows: simulation results.
Homogeneous applications can be provisioned in DCF

Realtime applications can be provided QoS guarantees - voice and video

AP bottleneck: Equal opportunity CSMA/CA leads to AP starvation

Heterogeneous deployment difficult
  ▶ Single FTP flow breaks delay constraint (G.711 max calls scenario)
  ▶ Extending DCF

802.11e standard for QoS provisioning
  ▶ Complex standard, difficult to implement
  ▶ Not widely adopted
  ▶ Wireless MultiMedia (WMM) uses parts of 802.11e

Homogeneous analysis forms base case for analysis of heterogeneous deployments
Outline

Introduction
Issues in Wireless Network Design
Multi-tiered Wireless Network Design
Solution Approach

Stage 1: AP-Client Association
Capacity of WLANs
AP-assignment problem

Stage 2: WLAN Topology Design
Generic Framework
Topology Construction
WIND_{wlan} Tool

Stage 3: WMN Node Locationing and Topology Design
Mesh Network Design Problem
Problem Formulation
WIND_{wmn} Tool
Problem Statement: Recap

AP-assignment

*Given* heterogeneous client nodes

*Compute* APs required

*Subject to* capacity constraints

*While* minimizing |APs|
Deploying Heterogeneous Applications I

Issues with homogeneous capacity analysis

- Network utilisation is not maximal (On average, number of flows less than maximum flows)
- Homogeneous capacity unrelated to heterogeneous capacity
- WLAN capacity usually evaluated as maximum capacity
Deploying Heterogeneous Applications II

Heterogeneous capacity analysis

- Capacity in terms of heterogeneous applications
- Analysis of realtime applications with non-realtime applications
- Example: VoIP and FTP deployment
Deploying Heterogeneous Applications III

Sub-optimal heterogeneous application deployment
Deploy restricted number of priority applications
- Implement priority mechanism
- Number of flows = $k$ (< $n$, where $n$ = homogeneous capacity)
Sub-optimal heterogeneous application deployment
Deploy additional non-prioritised applications

- Best effort service
- Applications can be of same class as priority applications

Use restricted number of flows to set ACL policies
Deploying Heterogeneous Applications V

Example Sub-optimal G.711 Calls

- 802.11b 11 Mbps, G.711 codec
- Theoretical capacity

\[ T = \frac{\text{Payload}}{t_{total}} = \frac{\text{pkt} \times 8}{\text{DIFS} + \text{SIFS} + 2 \times \text{PHY} + \frac{\text{backoff}}{2} \times \text{slot} + t_{\text{pkt}} + t_{\text{ack}}} \]

\[ = \frac{200 \times 8}{\text{DIFS} + \text{SIFS} + 2 \times \text{PHY} + \frac{31}{2} \times \text{slot} + 170.18 + 10.18} \]

\[ = \frac{1600}{934.36} = 1.712 \text{ Mbps} \]

- G.711 bandwidth \( b = 0.16 \text{ Kbps} \)
- Maximum theoretical calls = \( \lfloor T/b \rfloor = 10 \text{ calls} \)
Deploying Heterogeneous Applications VI

- Sub-optimal capacity

\[ \lfloor k \cdot \frac{T}{b} \rfloor = \lfloor 1.73k \cdot \frac{1}{16} \rfloor \]

- Example: 30% bandwidth reservation for voice calls

\[ \lfloor 1.73k \cdot \frac{1}{16} \rfloor = \lfloor 1.73 \cdot 0.3 \cdot \frac{1}{16} \rfloor = 3 \text{ calls} \]
Sub-optimal Capacity: G.711 deployment

<table>
<thead>
<tr>
<th>$k$</th>
<th>Number of calls: $\left\lceil \frac{kT}{b} \right\rceil$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>802.11b (in mbps)</td>
</tr>
<tr>
<td>2.5</td>
<td>11.390 10.818 10.818</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\frac{T}{b}$</th>
<th>1</th>
<th>0.9</th>
<th>0.8</th>
<th>0.7</th>
<th>0.6</th>
<th>0.5</th>
<th>0.4</th>
<th>0.3</th>
<th>0.2</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.6</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.7</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.8</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.9</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table: $k$ vs Number of voice calls for G.711 codec.
Sub-Optimal Application Deployment

Problem definition

Application classes

- **Alpha (α)**: Prioritised applications under ACL
- **Beta (β)**: Applications with normal priority
- **Gamma (γ)**: Applications of same class as Alpha running un-prioritised
Sub-Optimal Application Deployment

Problem definition

SOAP1

Given \( k \) Alpha flows \((|\alpha| = k)\)

Compute number of Beta flows \((|\beta|)\)

Subject to constraints \( R \)
Sub-Optimal Application Deployment
Implementation details

- Contention-window based service differentiation mechanism
- Impose ACL mechanism on $\alpha$ flows
- Add additional $\beta$ and/or $\gamma$ flows as best effort service
- Extension of DCF MAC in OPNET Modeler
- Constraints $R$:
  - $\alpha$: Throughput and delay constraints
  - $\beta, \gamma$: Throughput constraint

<table>
<thead>
<tr>
<th>Application</th>
<th>CWmin</th>
<th>CWmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>VoIP (priority)</td>
<td>15</td>
<td>31</td>
</tr>
<tr>
<td>FTP</td>
<td>31</td>
<td>1023</td>
</tr>
</tbody>
</table>

Table: Contention window parameters for SOAP.
Sub-Optimal Application Deployment

Simulation setup

- 802.11g mechanism
- G.711 codec
- Application classes

<table>
<thead>
<tr>
<th>Application class</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>VoIP - G.711</td>
</tr>
<tr>
<td>$\beta$</td>
<td>FTP - 250 &amp; 500 Kbps</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>VoIP - G.711</td>
</tr>
</tbody>
</table>

- Constraints $R$:
  - For all classes: Throughput satisfaction
  - $\alpha$: $\alpha_k < 75 ms$

Other simulation parameters
## Sub-Optimal Application Deployment

### Results

| $k$ | $|\alpha_k|$ | $\alpha_k$ delay (in s) | $|\beta_k|$ | $\beta_k$ throughput (in bps) | $\beta_k$ delay (in s) |
|-----|--------------|-------------------------|-------------|-------------------------------|------------------------|
| 1.0 | 18           | 0.086                   | 1           | 101247                        | 0.008                  |
| 0.9 | 16           | 0.070                   | 2           | 758230                        | 0.105                  |
| 0.8 | 14           | 0.073                   | 4           | 1481418                       | 0.013                  |
| 0.7 | 12           | 0.073                   | 5           | 2229776                       | 0.015                  |
| 0.6 | 10           | 0.072                   | 7           | 2969675                       | 0.015                  |
| 0.5 | 9            | 0.071                   | 9           | 3386316                       | 0.016                  |
| 0.4 | 7            | 0.038                   | 12          | 4293402                       | 0.022                  |
| 0.3 | 5            | 0.011                   | 15          | 5179227                       | 0.021                  |

*Other results*
Sub-Optimal Application Deployment

Observations

- \( \alpha = \text{G.711 voice codec and } \beta = \text{FTP 500 Kbps} \)
- At \( k = 0.4 \) effect of \( \beta \) on \( \alpha \) negligible
- System utilisation improves from 30% to 50%
- Table used to set ACL - operating point of AP
Stage Summary

- Theoretical and simulation study of homogeneous and heterogeneous deployments
- Joint deployment of realtime and non-realtime applications
- Application prioritisation for sub-optimal application deployment
- System utilisation improvement \( \sim 75\% \) over normal DCF (with SOAP1)
- Access control limit mechanism for AP management

SOAP improves system utilisation
WLAN topology design problem

Given client nodes & deployment area,
Construct WLAN topology,
Subject to capacity constraints,
While minimizing nw infrastructure (num of APs).
Outline

Introduction
issues in Wireless Network Design
Multi-tiered Wireless Network Design
Solution Approach

Stage 1: AP-Client Association
Capacity of WLANs
AP-assignment problem

Stage 2: WLAN Topology Design
Generic Framework
Topology Construction
WIND_{wlan} Tool

Stage 3: WMN Node Locationing and Topology Design
Mesh Network Design Problem
Problem Formulation
WIND_{wmn} Tool
Generic Framework

Advantages

- Allows planning for capacity at design stage
- Automate design process
- Eases validation with simulation
Outline

Introduction
Issues in Wireless Network Design
Multi-tiered Wireless Network Design
Solution Approach

Stage 1: AP-Client Association
Capacity of WLANs
AP-assignment problem

Stage 2: WLAN Topology Design
Generic Framework
Topology Construction
WIND\textsubscript{wlan} Tool

Stage 3: WMN Node Locationing and Topology Design
Mesh Network Design Problem
Problem Formulation
WIND\textsubscript{wmn} Tool

Summary
Example I

Office layout: (a) floor plan, (b) corresponding deployment layout
Example II
Topology construction
Outline

Introduction
Issues in Wireless Network Design
Multi-tiered Wireless Network Design
Solution Approach

Stage 1: AP-Client Association
Capacity of WLANs
AP-assignment problem

Stage 2: WLAN Topology Design
Generic Framework
Topology Construction
\texttt{WIND\_wlan} Tool

Stage 3: WMN Node Locationing and Topology Design
Mesh Network Design Problem
Problem Formulation
\texttt{WIND\_wmn} Tool
Composite Unit I

Definition
Virtual network element constructed for aggregating nodes, or branch of network, and their properties

\[ CU = (CU' \mid NU)^+ \]

Where,
\( CU = \) Composite Unit
\( NU = \) Node Unit (any network element)
Design of Wireless Mesh Networks

Outline
Introduction
Issues in Wireless Network Design
Multi-tier Wireless Design
Solution Approach
Stage 1: AP-assignment
Capacity of WLANs
AP-assignment problem
Stage 2: WLAN Topology
Generic Framework
Topology Construction
WIND\_wlan Tool
Stage 3: WMN Topology Design
Mesh Network Design Problem
Problem Formulation
WIND\_wmn Tool
Summary

Composite Unit II
Class definition

```cpp
class CU {

private:

    int id;
    string name;

    double outLoadTotal;
    double inLoadTotal;

    LinkList* linkList;
    ASList* asList;
    CUList* childList;

public:

    void print(int tab);
    CU(NodeType* nt); // NU constructor
    CU(); // CU constructor

    ASList* getASList();
    LinkType* getBestLink();
    void addChild(CU* cu);
    void rstChildProperty(LinkType*);
    void setProperty();
    void resetLinks(LinkType*);
    void resetTraffic();

    LinkList* getUnusedLinks();
    ASList* getUnfulfilledTraffic();

};
```
Wireless Infrastructure Network Deployment Tool (WIND)

- Implemented using C++
- Input and output descriptions correspond with OPNET Modeler XML formats (for validation)

Pseudo code for WIND
Validation I

Deployment layout

Example parameters

- 5 PDAs running a VoIP call (Load 100 Kbps)
- 5 Workstations running FTP client (Load 1000 Kbps)
Validation II
Constructed topology

Simulation results

- Average VoIP throughput ~ 100 Kbps
- Average FTP throughput ~ 1000 Kbps
Stage summary

- Framework for deploying WLANs from simple network input parameters
- Inputs and Outputs modeled on simulator formats for integration
- Validation with simulation

Topology construction tool for WLANs
Example Campus Mesh Network

- Each building represents a WLAN
- APs connected to mesh with AP-mesh links
- Mesh nodes provide routes to gateway (through mesh links)
- AP-mesh forms a two-tier architecture
Mesh Network Design Problem

Mesh network design problem

*Given* deployment layout, AP nodes and their characteristics

*Construct* backhaul topology,

*Subject to* demand constraints

*While* minimizing network infrastructure (mesh nodes and links)

**Constraints**

- **Capacity**: Satisfy demand placed by APs (& their underlying networks)
- **Cost**: Minimise mesh nodes and links
- **Connectivity**: Connect all APs
Example Deployment: 6 APs, 5 Mesh Nodes

Deployment details

- Potential mesh nodes = 5
- Transmission range AP = 1.5 and mesh = 2
- Upper bound on mesh links (G) = 4
- Demands (100 Kbps) = < 1 – 2 >, < 2 – 5 >, < 2 – 6 >, < 3 – 4 >, < 3 – 6 >, < 4 – 6 > & < 5 – 2 >
Outline

Introduction
- Issues in Wireless Network Design
- Multi-tiered Wireless Network Design
- Solution Approach

Stage 1: AP-Client Association
- Capacity of WLANs
- AP-assignment problem

Stage 2: WLAN Topology Design
- Generic Framework
- Topology Construction
- WIND_{wlan} Tool

Stage 3: WMN Node Locationing and Topology Design
- Mesh Network Design Problem
- Problem Formulation
- WIND_{wmn} Tool

Summary
Network Model

Requirements
- Determine potential links (Mesh and Mesh-AP)
- Node and link costs
- Objective function
- Constraints
Computing Potential Links

- **Distance-based**: Compute distance between nodes and compare with transmit radius of AP
  
  **Example**:
  
  Given \( AP = (x, y, r, \ldots) \), \( Mesh = (x', y', r', \ldots) \)
  
  Potential link condition:
  
  \[
  \sqrt{(x - x')^2 + (y - y')^2} < r
  \]

- **Power-based**: Compute distance between nodes using transmit power

- Calculating potential links using channel conditions
Node and Link Costs

- $\varphi_v$: cost of installing mesh node $v$.
- $\kappa_e$: cost of installing link $e$.

Cost of link

- Cost of hardware ($\sigma_e$)
- Cost of power requirements (determined by transmit power)
  - Fixed power: $\kappa_e = \sigma_e + \text{ceil} \left( \frac{r_e^2}{\rho_e} \right)$
    Where,
    - $r_e$ is transmit radius of node in link $e$
    - $\rho_e$ is a cost factor
  - Variable power: $\kappa_e = \sigma_e + \text{ceil} \left( \frac{tx\_dist_e^2}{\rho_e} \right)$
    Where,
    - $tx\_dist_e$ is transmission distance
    - $\rho_e$ is a cost factor
Objective Function

Minimize

\[ F = \sum_{e} \kappa_e u_e + \sum_{v} \phi_v s_v \]

Where,

- \( u_e \) = binary variable specifying whether link \( e \) is ON/OFF
- \( s_v \) = binary variable specifying whether node \( v \) is ON/OFF
Demand constraints

- Total demand flowing on each link not to exceed link capacity (1,5)
- Each demand has path from source AP to destination (2,3,4)
- Upper bound on number of demands per AP

Link constraint

- Upper bound on the number of links per node - G (6)
Comments

- Modeling of nodes and links as binary variables
- Mixed-Integer Linear Programming problem (MILP)
- Finds node location and topology
- Routing algorithm computes all pairs shortest path
Outline

Introduction
   Issues in Wireless Network Design
   Multi-tiered Wireless Network Design
   Solution Approach

Stage 1: AP-Client Association
   Capacity of WLANs
   AP-assignment problem

Stage 2: WLAN Topology Design
   Generic Framework
   Topology Construction
   WIND\textsubscript{wlan} Tool

Stage 3: WMN Node Locationing and Topology Design
   Mesh Network Design Problem
   Problem Formulation
   WIND\textsubscript{wmn} Tool
Extending WIND

WIND\textsubscript{wmn} tool overview

Outline

Introduction
Issues in Wireless Network Design
Multi-tier Wireless Design
Solution Approach

Stage 1: AP-assignment
Capacity of WLANs
AP-assignment problem

Stage 2: WLAN Topology
Generic Framework
Topology Construction
WIND\textsubscript{wmn} Tool

Stage 3: WMN Topology Design
Mesh Network Design Problem
Problem Formulation
WIND\textsubscript{wmn} Tool

Summary

- Input parameter details
- Module details
Implementation Details

- Implemented using PERL and ILOG OPL
- CPLEX solver used for MILP formulation
**Experiment Details**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>100mx100m</td>
</tr>
<tr>
<td>AP/Mesh Tx Range</td>
<td>70m</td>
</tr>
<tr>
<td>Mesh node cost $\varphi$</td>
<td>1000</td>
</tr>
<tr>
<td>Mesh link cost factor $\rho$</td>
<td>10</td>
</tr>
<tr>
<td>Max. Links $G$</td>
<td>4</td>
</tr>
<tr>
<td>Link capacity</td>
<td>10 Mbps</td>
</tr>
<tr>
<td>Demand</td>
<td>1 Mbps</td>
</tr>
</tbody>
</table>

- Mesh and AP nodes deployed randomly
- 11 artificially generated loads for each network scenario
## Results

<table>
<thead>
<tr>
<th>AP</th>
<th>Potential mesh</th>
<th>Exec time (s)</th>
<th>Mesh nodes (min,max)</th>
<th>Links (min,max,avg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>5</td>
<td>&lt; 1</td>
<td>2, 3</td>
<td>8, 10, 10</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>50.93</td>
<td>3, 4</td>
<td>10, 13, 12</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>69.86</td>
<td>3, 4</td>
<td>10, 13, 12</td>
</tr>
<tr>
<td>12</td>
<td>7</td>
<td>178.12</td>
<td>3, 6</td>
<td>12, 16, 15</td>
</tr>
<tr>
<td>12</td>
<td>8</td>
<td>854.51</td>
<td>3, 5</td>
<td>12, 16, 15</td>
</tr>
</tbody>
</table>

▲ Average number of links: avg = ceil(average of all scenarios)
Stage Summary

- Framework for deploying WMNs from simple network input parameters
- Node locationing and topology construction
- Minimise network deployment cost using node and link costs

Node locationing and topology construction tool for WMNs
Summary

Contributions

- Provisioning 802.11 WLANs in homogeneous and heterogeneous scenarios.
- Capacity-constrained design of wireless networks.
- WIND tool for design of local area and backhaul wireless networks.

Possible extensions

- Include coverage as constraint in design problem
- Scheduling and routing issues in WMN design
- Use of tool in other areas: Sensor networks (lifetime constraint), Sparse networks (reachability)
Appendix

Publications

Capacity of WLANs

WLAN Design

Mesh Network Design
Publications


▶ Automated design of VoIP-enabled 802.11g WLANs. *OPNETWORK*, 2005. Joint work with: Sridhar Iyer and Atanu Guchhait.


MAC Parameters and Stack Overheads

802.11 DCF MAC parameters

<table>
<thead>
<tr>
<th>Parameter (in $\mu S$)</th>
<th>802.11b</th>
<th>802.11g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot time</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td>SIFS</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>DIFS ($= SIFS + 2 \times$ Slot time)</td>
<td>50</td>
<td>28</td>
</tr>
<tr>
<td>PHY preamble</td>
<td>192</td>
<td>20</td>
</tr>
<tr>
<td>Signal extension</td>
<td>-</td>
<td>6</td>
</tr>
</tbody>
</table>

Table: 802.11 b and g MAC parameters: timing, preamble transmission time and signal extension.

Stack overheads

<table>
<thead>
<tr>
<th>Overhead</th>
<th>Value (in bytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTP</td>
<td>12</td>
</tr>
<tr>
<td>UDP</td>
<td>8</td>
</tr>
<tr>
<td>IP</td>
<td>20</td>
</tr>
<tr>
<td>MAC</td>
<td>34</td>
</tr>
</tbody>
</table>

Table: RTP, UDP, IP and MAC stack overheads.
Voice Capacity: Maximum Calls I

Figure: Maximum G.723.1 voice calls: theoretical vs simulation results.
Voice Capacity: Maximum Calls II

Figure: Maximum G.729 voice calls: theoretical vs simulation results.
Voice Capacity: Maximum Calls III

Figure: Maximum GSM voice calls: theoretical vs simulation results.
**Voice Capacity: Maximum Calls IV**

![Figure: Delay for voice schemes in 802.11b/g.](image)

Figure: Delay for voice schemes in 802.11b/g.
## Voice Capacity: Detailed Calculations

<table>
<thead>
<tr>
<th>Scheme</th>
<th>802.11b</th>
<th></th>
<th>802.11g</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>1</td>
<td>5.5</td>
<td>11</td>
</tr>
<tr>
<td>( \text{pkt} ) (in bytes)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G.711</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>G.723.1</td>
<td>64</td>
<td>64</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>G.729</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>GSM</td>
<td>73</td>
<td>73</td>
<td>73</td>
<td>73</td>
</tr>
<tr>
<td>DIFS</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>28</td>
</tr>
<tr>
<td>SIFS</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>PHY</td>
<td>192</td>
<td>192</td>
<td>192</td>
<td>20</td>
</tr>
<tr>
<td>backoff slot</td>
<td>31</td>
<td>31</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>t_{\text{pkt}} (in ( \mu s ))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G.711</td>
<td>1872</td>
<td>340.364</td>
<td>170.182</td>
<td>1872</td>
</tr>
<tr>
<td>G.723.1</td>
<td>784</td>
<td>142.546</td>
<td>71.273</td>
<td>784</td>
</tr>
<tr>
<td>G.729</td>
<td>752</td>
<td>136.727</td>
<td>68.364</td>
<td>752</td>
</tr>
<tr>
<td>GSM</td>
<td>856</td>
<td>155.636</td>
<td>77.818</td>
<td>856</td>
</tr>
<tr>
<td>t_{\text{ack}} (in ( \mu s ))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G.711</td>
<td>112</td>
<td>20.364</td>
<td>10.182</td>
<td>112</td>
</tr>
<tr>
<td>G.723.1</td>
<td>20</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>G.729</td>
<td>20</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>GSM</td>
<td>20</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Throughput (T) (in Mbps)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G.711</td>
<td>0.584</td>
<td>1.435</td>
<td>1.712</td>
<td>0.727</td>
</tr>
<tr>
<td>G.723.1</td>
<td>0.310</td>
<td>0.558</td>
<td>0.613</td>
<td>0.460</td>
</tr>
<tr>
<td>G.729</td>
<td>0.297</td>
<td>0.527</td>
<td>0.577</td>
<td>0.444</td>
</tr>
<tr>
<td>GSM</td>
<td>0.339</td>
<td>0.628</td>
<td>0.694</td>
<td>0.493</td>
</tr>
<tr>
<td>Bandwidth (b) (in Mbps)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G.711</td>
<td>0.160</td>
<td>0.160</td>
<td>0.160</td>
<td>0.160</td>
</tr>
<tr>
<td>G.723.1</td>
<td>0.051</td>
<td>0.051</td>
<td>0.051</td>
<td>0.051</td>
</tr>
<tr>
<td>G.729</td>
<td>0.048</td>
<td>0.048</td>
<td>0.048</td>
<td>0.048</td>
</tr>
<tr>
<td>GSM</td>
<td>0.058</td>
<td>0.058</td>
<td>0.058</td>
<td>0.058</td>
</tr>
<tr>
<td>Number of calls</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G.711</td>
<td>3</td>
<td>8</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>G.723.1</td>
<td>6</td>
<td>10</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>G.729</td>
<td>6</td>
<td>10</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>GSM</td>
<td>5</td>
<td>10</td>
<td>11</td>
<td>8</td>
</tr>
</tbody>
</table>

Table: Number of voice calls: voice capacity calculations.
Voice Capacity: 39 Call Scenario
Simulation: 802.11g - G.711 codec

- Maximum 39 voice calls
- Packet drop $\leq 20\%$
- Delay bounded

Figure: Load and throughput for G.711, 54 mbps 802.11g - 39 call scenario.
Video Capacity: Theoretical Calculation

Throughput equation: Extension for large payloads

- Maximum MAC payload size = 2304 bytes
- Large packets are fragmented
- Depending on codec, video packets may be fragmented

\[
T_{frag} = \frac{\text{Payload}}{\frac{\text{backoff}}{2} \times \text{slot} + t_{frag} \times \text{frag}_\text{num}}
\]

Where,

\[
t_{frag} = \text{DIFS} + \text{SIFS} + 2 \times \text{PHY} + t_{pk}_\text{frag} + t_{ack}
\]

\[
t_{pk}_\text{frag} = \frac{(pk_{frag} + \text{MAC}) \times 8}{r}
\]

\[
\text{frag}_\text{num} = \lceil pkt/pk_{frag} \rceil
\]
Figure: Maximum CIF video flows: theoretical vs simulation results.
Figure: Maximum QCIF video flows: theoretical vs simulation results.
Video Capacity: Maximum Calls III

Figure: Maximum SQCIF video flows: theoretical vs simulation results.
Video Capacity: Maximum Calls IV

Figure: Delay for video schemes in 802.11b/g.
Video Capacity: Observations

- Large packet size affects maximum number of flows
- Maximum number of flows varies with codec (unlike Voice codecs)
- Efficient use of channel due to large packet size

Go back
## Video Capacity: Detailed Calculations

<table>
<thead>
<tr>
<th>Scheme</th>
<th>802.11b</th>
<th>802.11g</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>5.5</td>
</tr>
<tr>
<td>Data rate (r)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pkt (in bytes) SQCIF</td>
<td>304</td>
<td>304</td>
</tr>
<tr>
<td>(in bytes) QCIF</td>
<td>1112</td>
<td>1112</td>
</tr>
<tr>
<td>CIF</td>
<td>3256</td>
<td>3256</td>
</tr>
<tr>
<td>frag_size</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>fragments per pkt SQCIF</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>QCIF</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CIF</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>DIFS</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>SIFS</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>PHY</td>
<td>192</td>
<td>192</td>
</tr>
<tr>
<td>backoff fragments per pkt SQCIF</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>QCIF</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CIF</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>slot PHY</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>$t_{pkt}$ (in $\mu$s) SQCIF</td>
<td>2704</td>
<td>491.636</td>
</tr>
<tr>
<td>QCIF</td>
<td>9168</td>
<td>1666.909</td>
</tr>
<tr>
<td>CIF</td>
<td>12000</td>
<td>2181.818</td>
</tr>
<tr>
<td>$t_{ack}$ (in $\mu$s)</td>
<td>1.978</td>
<td>0.36</td>
</tr>
<tr>
<td>Throughput (T) SQCIF</td>
<td>0.681</td>
<td>1.921</td>
</tr>
<tr>
<td>(in Mbps) QCIF</td>
<td>0.887</td>
<td>3.644</td>
</tr>
<tr>
<td>(in Mbps) CIF</td>
<td>0.686</td>
<td>3.281</td>
</tr>
<tr>
<td>Bandwidth (b) SQCIF</td>
<td>0.146</td>
<td>0.146</td>
</tr>
<tr>
<td>(in Mbps) QCIF</td>
<td>0.267</td>
<td>0.267</td>
</tr>
<tr>
<td>(in Mbps) CIF</td>
<td>0.521</td>
<td>0.521</td>
</tr>
<tr>
<td>Number of calls SQCIF</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>QCIF</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>CIF</td>
<td>1</td>
<td>6</td>
</tr>
</tbody>
</table>

Table: Number of video flows: video capacity calculations.
Extending DCF to provide guarantees I

Figure: Contention window for ACL scheme - VoIP + FTP flows.

Extended DCF

▶ Simple scheme to differentiate traffic flows
▶ Prioritise realtime time applications
▶ Additional flows of best effort service
Extending DCF to provide guarantees II

<table>
<thead>
<tr>
<th>Application</th>
<th>CWmin</th>
<th>CWmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>VoIP (priority)</td>
<td>15</td>
<td>31</td>
</tr>
<tr>
<td>FTP</td>
<td>31</td>
<td>1023</td>
</tr>
</tbody>
</table>

Table: Contention window parameters for SOAP.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Command mix (get/total)</td>
<td>50%</td>
</tr>
<tr>
<td>Inter-request time (s)</td>
<td>exponential(60)</td>
</tr>
<tr>
<td>File size (bytes)</td>
<td>constant(125000)</td>
</tr>
<tr>
<td>Fragmentation size (bytes)</td>
<td>1500</td>
</tr>
<tr>
<td>Type of service</td>
<td>Best Effort (AC_BE)</td>
</tr>
</tbody>
</table>

Table: FTP simulation parameters.
Extending DCF to provide guarantees III

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Load (in bps)</th>
<th>Throughput (in bps)</th>
<th>Delay (in sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCF</td>
<td>81265</td>
<td>73712</td>
<td>0.009</td>
</tr>
<tr>
<td>Extended DCF</td>
<td>89575</td>
<td>85612</td>
<td>0.019</td>
</tr>
</tbody>
</table>

Table: Comparison of VoIP plus FTP performance DCF.

Observations

- FTP flows in extended DCF = 4
- VoIP delay in extended DCF ≤ 0.062s
- VoIP delay in DCF ≥ 0.1s
### Sub-optimal Capacity: Voice Codecs

| $k$ | $\frac{T}{b}$ | $\begin{array}{c|c|c|c} 
802.11b \\
(in \text{ mbps})
\end{array}$ | $\begin{array}{c|c|c} 
802.11g \\
(in \text{ mbps})
\end{array}$ |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.5</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>1</td>
<td>6.494</td>
<td>11.15</td>
<td>12.115</td>
</tr>
<tr>
<td>0.9</td>
<td>5.5</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>0.8</td>
<td>5</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>0.7</td>
<td>4</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>0.6</td>
<td>3</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>0.5</td>
<td>3</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>0.4</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>0.3</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>0.2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>0.1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table:** $k$ vs Number of voice calls for G.723.1 codec.
Sub-optimal Capacity: Voice Codecs

<table>
<thead>
<tr>
<th>$k$ (\downarrow)</th>
<th><strong>Number of calls:</strong> (\lfloor k \frac{T}{b} \rfloor)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>802.11b</strong> (in mbps)</td>
</tr>
<tr>
<td>1</td>
<td>5.5</td>
</tr>
<tr>
<td>$\frac{T}{b} \rightarrow$</td>
<td>6.631</td>
</tr>
<tr>
<td>1.0</td>
<td>6</td>
</tr>
<tr>
<td>0.9</td>
<td>5</td>
</tr>
<tr>
<td>0.8</td>
<td>5</td>
</tr>
<tr>
<td>0.7</td>
<td>4</td>
</tr>
<tr>
<td>0.6</td>
<td>3</td>
</tr>
<tr>
<td>0.5</td>
<td>3</td>
</tr>
<tr>
<td>0.4</td>
<td>2</td>
</tr>
<tr>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>0.1</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table:** $k$ vs Number of voice calls for G.729 codec.
## Sub-optimal Capacity: Voice Codecs

### Table: $k$ vs Number of voice calls for GSM codec.

<table>
<thead>
<tr>
<th>$k$</th>
<th>802.11b (in mbps)</th>
<th>802.11g (in mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 5.5 11</td>
<td>1 11 54</td>
</tr>
<tr>
<td>$\frac{T}{b}$ →</td>
<td>6.204 10.989 12.019</td>
<td>9.298 33.841 42.847</td>
</tr>
<tr>
<td>1.0</td>
<td>6 10 12</td>
<td>9 33 42</td>
</tr>
<tr>
<td>0.9</td>
<td>5 9 10</td>
<td>8 30 38</td>
</tr>
<tr>
<td>0.8</td>
<td>4 8 9</td>
<td>7 27 34</td>
</tr>
<tr>
<td>0.7</td>
<td>4 7 8</td>
<td>6 23 29</td>
</tr>
<tr>
<td>0.6</td>
<td>3 6 7</td>
<td>5 20 25</td>
</tr>
<tr>
<td>0.5</td>
<td>3 5 6</td>
<td>4 16 21</td>
</tr>
<tr>
<td>0.4</td>
<td>2 4 4</td>
<td>3 13 17</td>
</tr>
<tr>
<td>0.3</td>
<td>1 3 3</td>
<td>2 10 12</td>
</tr>
<tr>
<td>0.2</td>
<td>1 2 2</td>
<td>1 6 8</td>
</tr>
<tr>
<td>0.1</td>
<td>0 1 1</td>
<td>0 3 4</td>
</tr>
</tbody>
</table>
Sub-Optimal Application Deployment

Problem definition

SOAP 2

Given $k$ Alpha flows ($|\alpha| = k$)

Compute number of Beta flows ($|\beta|$) & Gamma flows ($|\gamma|$)

Subject to constraints $R$
## Other Simulation Parameters

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Command mix (get/total)</td>
<td>100%</td>
</tr>
<tr>
<td>Inter-request time (s)</td>
<td>exp(1)</td>
</tr>
<tr>
<td>File size (bytes)</td>
<td>FTP 250 - cons(31250)</td>
</tr>
<tr>
<td></td>
<td>FTP 500 - cons(62500)</td>
</tr>
<tr>
<td>Fragmentation size (bytes)</td>
<td>1500</td>
</tr>
<tr>
<td>Type of service</td>
<td>Best Effort (AC_BE)</td>
</tr>
</tbody>
</table>

**Table:** SOAP simulation parameters for FTP - Average load 250 and 500 kbps.
### SOAP1 Results I

| $k$ | $|\alpha_k|$ | $\alpha_k$ delay (in s) | $|\beta_k|$ | $\beta_k$ throughput (in bps) | $\beta_k$ delay (in s) |
|-----|-------------|------------------------|-------------|-----------------------------|------------------------|
| 1.0 | 18          | 0.086                  | 1           | 63672                       | 0.007                  |
| 0.9 | 16          | 0.067                  | 3           | 713658                      | 0.010                  |
| 0.8 | 14          | 0.074                  | 7           | 1447647                     | 0.012                  |
| 0.7 | 12          | 0.075                  | 10          | 2181612                     | 0.013                  |
| 0.6 | 10          | 0.071                  | 13          | 2920485                     | 0.015                  |
| 0.5 | 9           | 0.071                  | 16          | 3306418                     | 0.017                  |
| 0.4 | 7           | 0.027                  | 20          | 4134720                     | 0.023                  |
| 0.3 | 5           | 0.009                  | 24          | 5002889                     | 0.021                  |

**Table:** SOAP1 results for FTP 250 Kbps with G.711 codec on 11 Mbps 802.11g.
Figure: SOAP1 FTP 250 Kbps: $k$ vs Number of $\alpha_k$ and $\beta_k$ flows.
## SOAP2 Results I

| $|\beta_k|$ | $|\gamma_k|$ | $\gamma_k$ delay | $\alpha_k$ delay |
|-----------|-------------|------------------|------------------|
| 7 to 3    | 0           | -                | -                |
| 2         | 2           | 0.033            | 0.074            |
| 1         | 4           | 0.337            | 0.012            |

**Table:** SOAP2 results for $k = 0.8$ ($|\alpha_{0.8}| = 14$), FTP 250 Kbps with G.711 codec on 11 Mbps 802.11g. $\alpha_k$ and $\gamma_k$ delays are in seconds.
Algorithm 1: Pseudo-code for WIND\textsubscript{wlan}

\begin{verbatim}
input : ib: info base, ip: input parameters
cuList ← NULL
// G\textsubscript{DL}: Deployment layout
forall v ∈ V(ip.G\textsubscript{DL}) do
    // af: affinity factor
    deployedList ← ∪\textsubscript{i} (v.af\textsubscript{i} * ip.num\textsubscript{NU\textsubscript{i}}) . NU\textsubscript{i}
end
cuList ← computeCU(cuList, ib)
printTopology(cuList)
\end{verbatim}
Algorithm: ComputeCU()

\textbf{input} : cuList, ib: info base
\textbf{if} sizeof(cuList) = 1 \textbf{then} return cuList
newCULList ← NULL
L ← linktypes\_present(cuList)
forall \( lt \in L \) do
  \( \text{cuList}_{lt} \leftarrow \text{cuList}_{lt} + \{ \text{cuList}[i], \text{cuList}[i].\text{linktype} = lt \} \)
while \( \text{cuList}_{lt} \) NOTEMPTY do
  \( \text{cuList}' = \text{lt}.\text{maxNodes}(\text{cuList}_{lt}) \)
  // Average load
  \( t \leftarrow \sum_{j} \frac{\text{cuList}'[j].\text{total}\_\text{load}}{\text{sizeOf(\text{cuList}')}} \)
  \text{new cu'}
  \text{cu'.child(cuList')}
  \text{cuList}_{lt}.\text{remove(\text{cuList}')}
  \text{newcu}_{\text{relay}} = \text{findRelayNode}(lt, t)
  \text{cu'.child(newcu}_{\text{relay}})
  for \( \text{cu} \in \text{cuList}' \) do \text{cu.resetProperty()}
  \text{cu}_{\text{relay}.\text{resetProperty()}}
  \text{cu'.setProperty()}
  \text{newCULList.add(cu')}
end
end
\textbf{return} computeCU(newCULList, ib)

Algorithm 2: Psuedo-code for computeCU()
Information Base and Affinity Factor

<table>
<thead>
<tr>
<th>NU</th>
<th>Traffic out</th>
<th>Traffic in</th>
<th>Addr src</th>
<th>Addr destn</th>
<th>Link</th>
<th>AS-Link Map</th>
<th>Mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td>NU_{PDA}</td>
<td>10000</td>
<td>100000</td>
<td>&lt; N_{PDA} &gt;</td>
<td>&lt; N_{S} &gt;</td>
<td>1</td>
<td>1</td>
<td>Yes</td>
</tr>
<tr>
<td>NU_{WS}</td>
<td>10000</td>
<td>1000000</td>
<td>&lt; N_{WS} &gt;</td>
<td>&lt; N_{S} &gt;</td>
<td>1</td>
<td>1</td>
<td>Yes</td>
</tr>
<tr>
<td>NU_{S}</td>
<td>10^6</td>
<td>10000</td>
<td>&lt; N_{S} &gt;</td>
<td>Undefined</td>
<td>2</td>
<td>2</td>
<td>No</td>
</tr>
<tr>
<td>NU_{Relay}</td>
<td>5 \times 10^5</td>
<td>5 \times 10^5</td>
<td>Undefined</td>
<td>Undefined</td>
<td>1,2</td>
<td>2</td>
<td>No</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Table: Example information base. Traffic_{out}, Traffic_{in} are in bits per second. Link type 1 represents a 802.11 10 Mbps wireless link and type 2 represents a 10 Mbps Ethernet link.

<table>
<thead>
<tr>
<th>Node type ↓, Vertex →</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>NU_{PDA}</td>
<td>0.6</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>NU_{WS}</td>
<td>0.6</td>
<td>0.0</td>
<td>0.4</td>
</tr>
<tr>
<td>NU_{S}</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Table: Affinity factors.
Potential Links: Including Channel Conditions

\[
(\psi_{rcv})_{dB} = (\psi_{xmt})_{dB} - 10\eta \log_{10}(d/d_0) - \xi
\]

Where,

- \((\psi_{rcv})_{dB}\) & \((\psi_{xmt})_{dB}\) are received and transmit powers
- \(d\) is transmit distance
- \(d_0\) is reference distance
- \(\eta\) is path loss exponent
- \(\xi\) is shadowing component
# Mesh Topology Design Formulation

**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 $F = \sum_e \kappa_e u_e + \sum_v \varphi_v s_v$

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

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
\( \kappa_e \): cost of installing link \( e \)
\( M_e \): upper bound on the capacity of link \( e \)
\( \varphi_v \): cost of installing mesh node \( v \)
\( G_v \): upper bound on the number of radios of mesh node \( v \)
Mesh Topology Design Formulation

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 \( F = \sum_e \kappa_e u_e + \sum_v \varphi_v s_v \)

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

cost_min $\leftarrow$ COSTMIN
forall ON/OFF combination of mesh_nodes do
  // on mesh nodes which have been switched ON
 forall ON/OFF combination of links &
  num_of_mesh_links < max_links do
    forall demands do
      if demand < remaining_link_capacity() then
        cost $\leftarrow$ cost_of_shortest_path() if cost <
        cost_min then cost_min $\leftarrow$ cost
        adjust_link_capacity()
      end
    end
  end
end

Algorithm 3: Psuedo-code for mesh routing.
Input Parameters

1. Network elements: Number of AP and potential mesh nodes
2. Network element properties: Properties of nodes and their associated links
3. Network scenario strategy: Properties of deployment layout and node distribution
4. Traffic demands: User generated traffic demands for each AP
5. Link cost functions: Cost functions for fixed and variable transmit powers
6. Optimizer parameters and heuristics: Heuristics and initial settings for the optimiser
WIND\textsubscript{wmn} Modules I

- Network scenario generator: Created based on deployment layout parameters and number of nodes. Creates locations of AP nodes and potential mesh nodes.
- Link constructor: Uses heuristics to generate list of potential links.
- Optimization preprocessor: Constructs inputs for optimiser and demand matrix for the constraint verifier.
WIND\textsubscript{wmn} Modules II

- Optimizer: External optimizer invoked to solve MILP problem
- Constraint verifier: Verifies capacity constraints imposed on scenario by comparing optimizer output with demand matrix
- Topology generator: Constructs corresponding capacity-constrained topology
- Simulator: External simulator invoked to validate topology generated