Dimensioning of Wireless Mesh Networks with Flow-Level QoS Requirements

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Introduction

- Dimensioning problem
  - Given the network (nodes, links, routing) and the traffic demands
  - Determine link capacities such that a given criterion is fulfilled
  - Relation to QoS: criterion must be a meaningful performance metric for users
- Background
  - Dimensioning of wireline IP access networks for data traffic
  - Based on applying recent flow-level network models of data traffic
- Scope of this work
  - Extend ideas from earlier work to Wireless Mesh Networks (WMNs)
  - Main point: include impact of wireless interference in the modeling

Flow-level modeling and dimensioning (1)

- "Good old" circuit switched networks
  - QoS determined by blocking probability
  - Dimensioning based on classical Erlang formula (insensitivity!)
- Other approaches to dimensioning IP networks
  - Bertsekas-Gallager square root method: based on packet level QoS
  - Multi-commodity flow optimization (e.g., Pioro et al): easy to apply, but ignores the stochastic (dynamic) nature of traffic
- What is QoS in IP networks?
  - No established QoS metric has been defined
  - Majority of Internet traffic is elastic (controlled by TCP)
  - Users experience QoS at the flow level (e.g., as file transfer delay)
  - Natural choice for the QoS metric is the flow throughput

Flow-level modeling and dimensioning (2)

- We apply flow-level models based on balanced fairness (BF)
  - Flow-level performance depends on random flow arrivals, random file lengths and how the flows share the capacity
  - BF is an idealized fair bandwidth sharing scheme for which performance can be computed efficiently, at least approximately
  - BF approximates max-min fairness and proportional fairness, for which performance can not be easily evaluated
  - The models are robust, i.e., performance only depends on the load

$\Rightarrow$ **BF is used as a computationally efficient tool that allows robust dimensioning based on flow-level throughput**

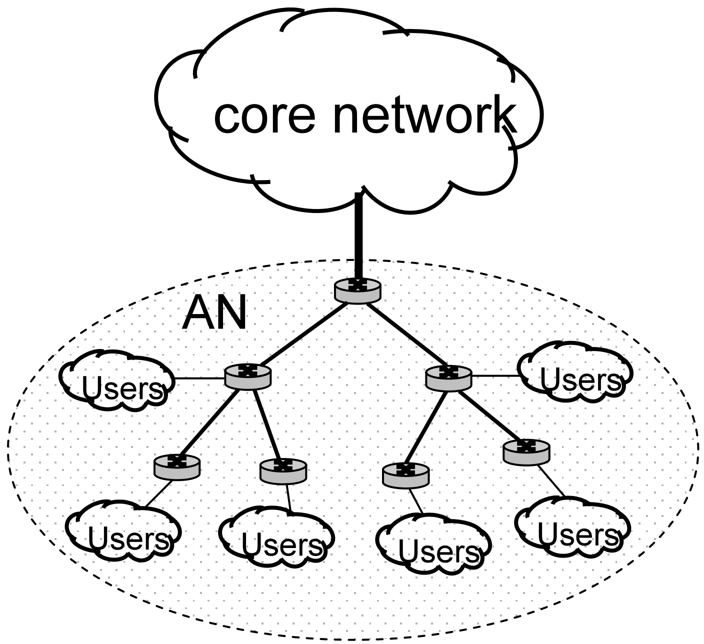
- Practical use of the results:
  - Approximate answers to “how much capacity is needed?”
  - Provides “educated guesses”

Where is dimensioning at flow-level required?

- On a given link, flow throughput ≈ $C - \rho$ (available capacity)

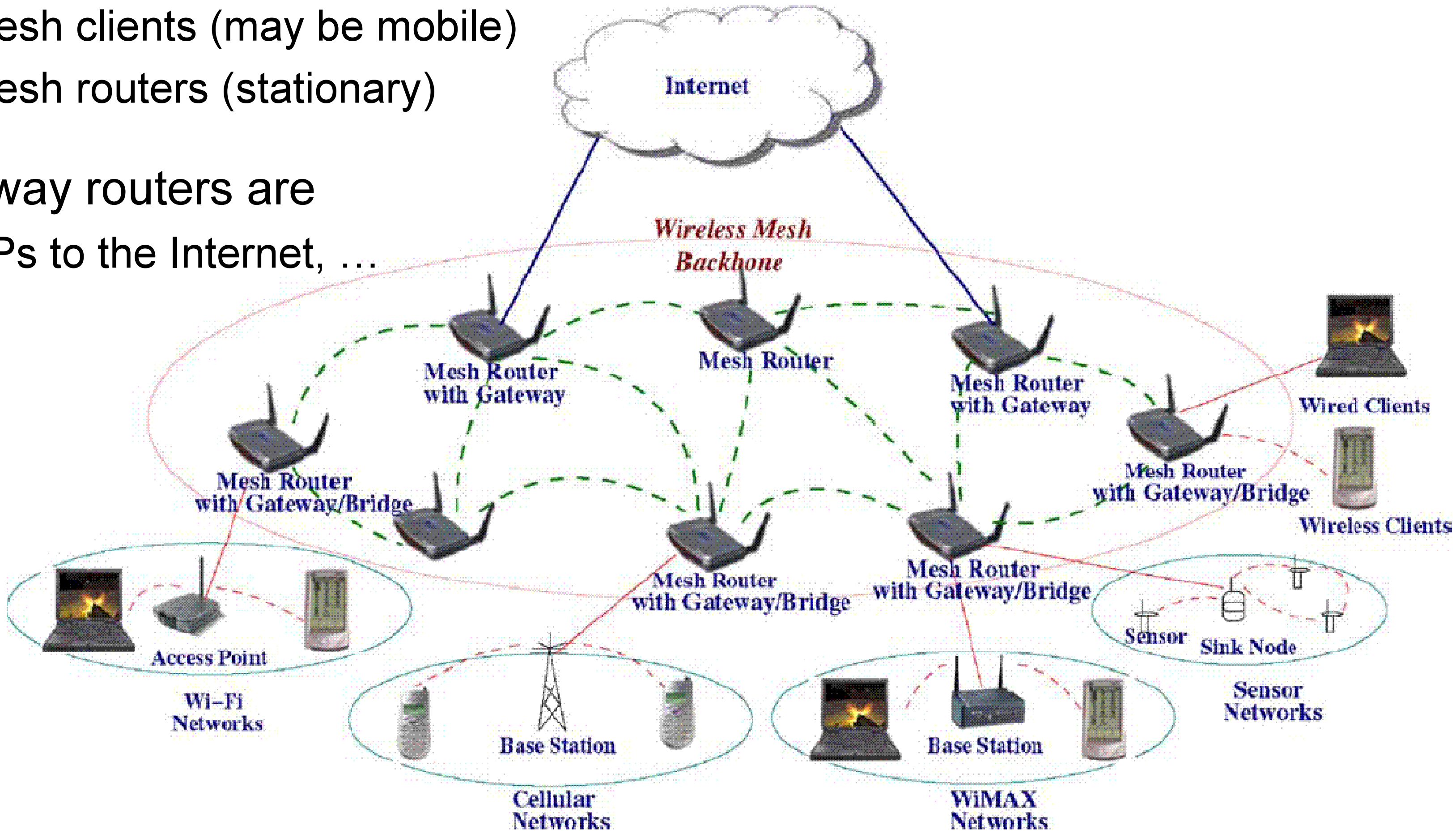
- Core network links are “transparent”
  - Even with modest over-provisioning, $C - \rho$ is so huge that core does not affect e2e delays

- In access networks (ANs) throughput criterion is closer to offered load
  - More detailed dimensioning is needed



Backbone WMN (Wireless Mesh Network)

- WMN consists of
  - mesh clients (may be mobile)
  - mesh routers (stationary)
- Gateway routers are
  - APs to the Internet, …

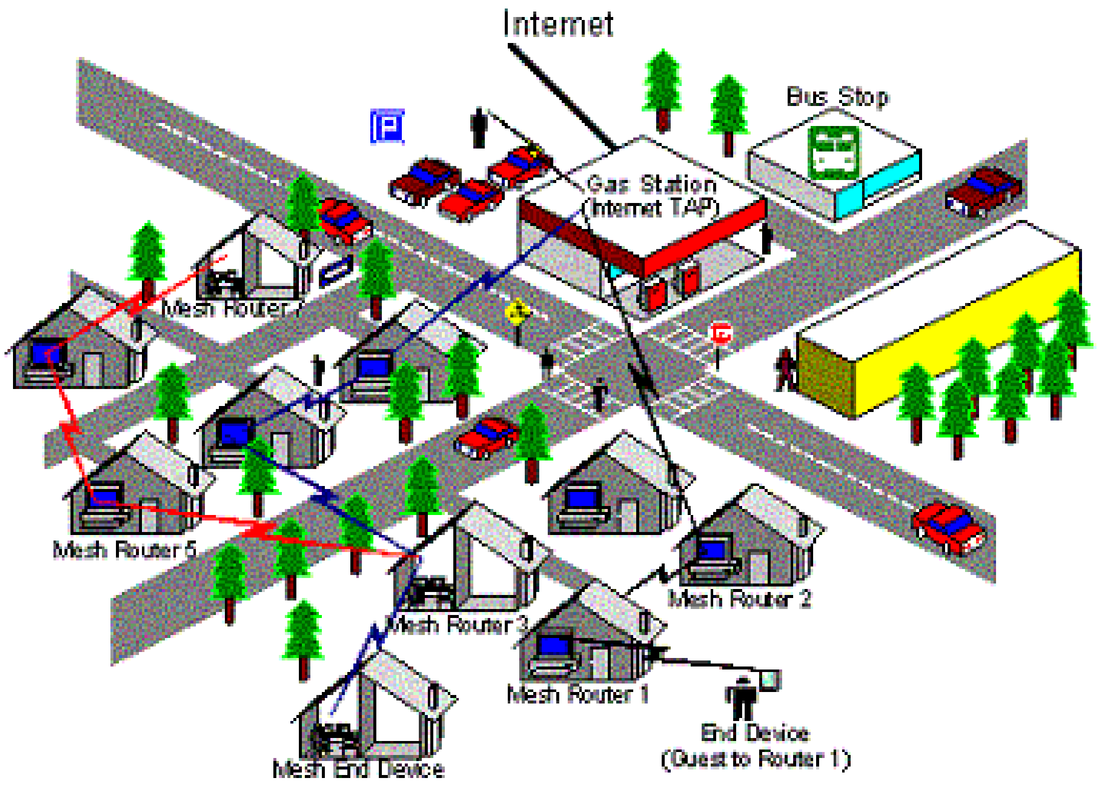


I. Akyildiz et al., "Wireless mesh networks: a survey", *Computer Networks*, 2005.

Practical (existing) example of WMN

- Community/neighborhood networks providing wireless access to Internet

- Companies:
  - Legacy vendors:
    - Motorola
    - Cisco
    - Nortel
    - Microsoft
  - New start-ups:
    - Tropos Networks
    - Mesh Dynamics
    - …



http://research.microsoft.com/mesh/

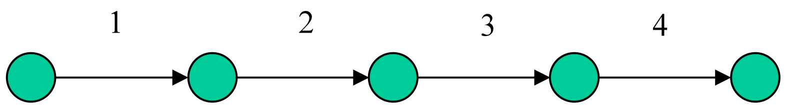
Network model and assumptions (1)

- Network consists of nodes connected by uni-directional links
  - Set of links denoted by $\mathbf{L} = \{1,\ldots,L\}$
- Routing is fixed and traffic matrix is given
  - There are K classes of flows, i.e., K routes
  - $\mathbf{R}_i$ = set of links on the route of class i
  - $\mathbf{F}_l$ = set of classes that use link l
  - The offered load in each class is ρ_k (bit/s)
  - R_l = offered load on link l, $R_l = \sum_{i \in \mathbf{F}_l} \rho_i$
- MAC layer model
  - We assume that MAC layer operates according to STDMA
  - Allows to incorporate wireless interference effects in flow level models
  - Approximates performance of other MAC schemes (e.g., based on CSMA)

Network model and assumptions (2)

- STDMA operation
  - Network characterized by a schedule **P** and a set of transmission modes **S** = $\{S_1,\ldots,S_M\}$
  - Each transmission mode is a vector $S_i = [s_{i1},\ldots,s_{iL}]$, where $s_{il} = 1$ if link l is used in mode i and 0 otherwise
  - Whether link l is used or not depends on the interference model
    - Allows very versatile modeling of interference!
  - Schedule **P** = $[p_1,\ldots,p_M]$, where p_m defines the proportion of time that transmission mode m is used

- Example
  - Node can only send or receive (1 transmitter)



$$S = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \end{bmatrix}$$

Network model and assumptions (3)

- Interference model in this study
  - Each node has a single transmitter with nominal capacity *B* (bit/s)
  - All nodes have the same radio (i.e., the same *B*)
  - Each node has a fixed transmission range (constant power)
  - Within this range the link capacity is constant, i.e., *B*
  - Interference occurs if receiver hears more than one transmission within its transmission range
  - This type of binary interference can also be modeled using so called clique constraints

- Impact of interference on link capacities
  - Schedule **P** determines effective bandwidth of link *l*

$$C_l = B \sum_{m=1}^{M} s_{ml}\, p_m$$

- Dimensioning task: Find minimum *B* such that performance is sufficient

Dimensioning for sufficient capacity

- Determine *B* according to stability limit subject to interference constraints
  - Capacity is "just enough"
- Non-linear problem can be converted to an equivalent LP-problem
  - Let $q_m = B\,p_m \quad \Rightarrow \quad \sum_{m=1}^{M} q_m = B$

Non-linear problem		LP problem
$\min_{B,\mathbf{P}} \quad B$		$\min_{\mathbf{Q}} \quad \sum_{m=1}^{M} q_m$
s.t. $\quad R_l \le B \sum_{m=1}^{M} s_{ml}\, p_m \quad ,\forall l$	$\Rightarrow$	s.t. $\quad R_l \le \sum_{m=1}^{M} s_{ml}\, q_m \quad ,\forall l$
$p_m \ge 0 \quad ,\forall m$		$q_m \ge 0 \quad ,\forall m$
$\sum_{m=1}^{M} p_m = 1$		

Dimensioning with flow-level QoS requirements

- Joint optimization of MAC layer performance and flow-level performance
  - Minimum throughput requirement for each class, denoted by $\gamma_k^{\min}$
  - Class-k throughput $\gamma_k(\mathbf{C})$ depends on capacity vector $\mathbf{C} = [C_1,\ldots,C_L]$

$$\text{SF-bound for throughput}: \frac{1}{\gamma_k(\mathbf{C})} = \sum_{l \in R_k} \frac{1}{C_l - R_l}$$

  - Let $d_l = \sum_{m=1}^{M} s_{ml}\, p_m$ and $D(\mathbf{P}) = [d_1,\ldots,d_M] \Rightarrow \gamma(\mathbf{C}) = \gamma(B \cdot D(\mathbf{P}))$

$$\begin{aligned} \min \quad & B \\ \text{s.t.} \quad & \gamma_k(B \cdot D(\mathbf{P})) \ge \gamma_k^{\min} \quad, \forall k \\ & p_m \ge 0 \quad, \forall m \\ & \sum_{m=1}^{M} p_m = 1 \end{aligned} \quad \Longrightarrow \quad \begin{aligned} \min \quad & \sum_{m=1}^{M} q_m \\ \text{s.t.} \quad & \gamma_k(\mathbf{Q}) \ge \gamma_k^{\min} \quad, \forall k \\ & q_m \ge 0 \quad, \forall m \end{aligned}$$

Simplified flow-level dimensioning method

- Layered approach
  - Fix schedule according to capacity limit LP-problem
  - Using that schedule, determine minimum *B* that satisfies QoS requirements

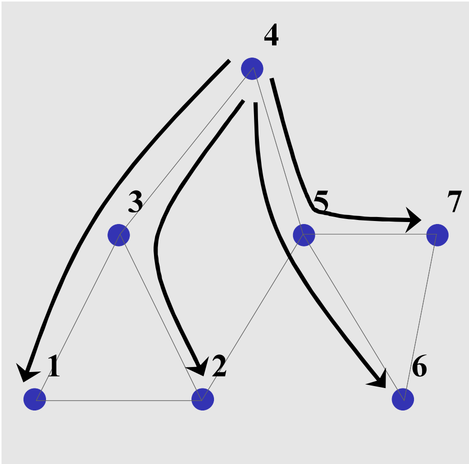
- More detailed
  - Step 1: Solve LP-problem for optimal schedule at MAC layer
    - Denote the result by **P***
  - Step 2: Find sufficient B such that throughput for all classes $\geq \gamma_k^{\min}$

$$B = \max b_k$$
$$b_k = \left\{ B : \gamma_k\left(B \cdot D\left(\mathbf{P}^*\right)\right) = \gamma_k^{\min} \right\}, \forall k$$

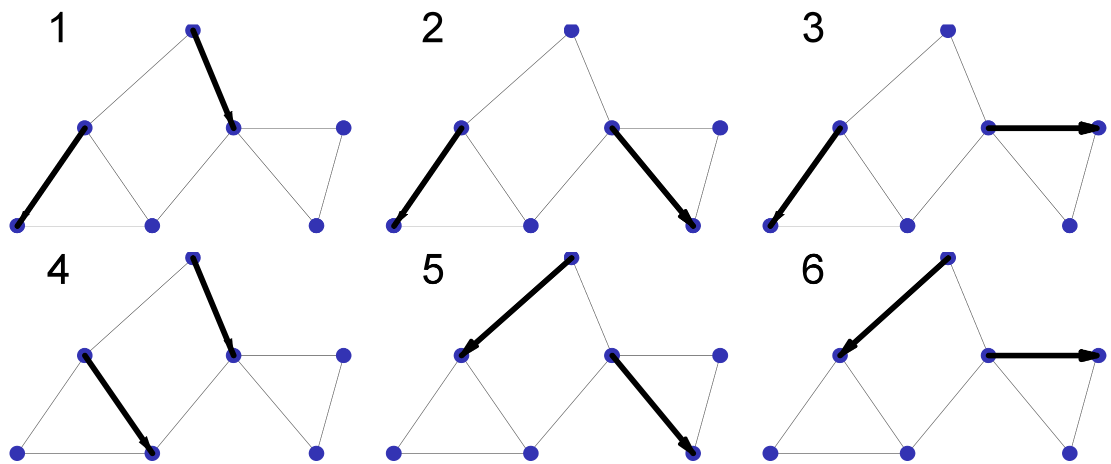
- Overestimates the required *B*

Numerical example

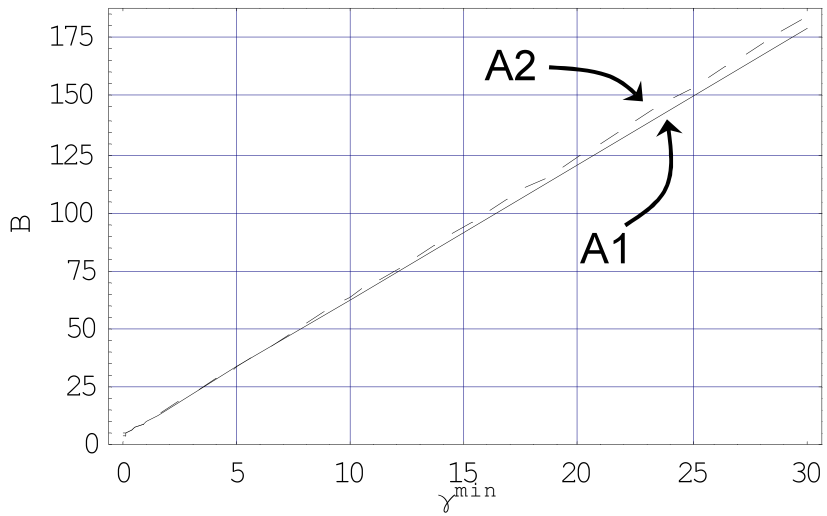
Network, links and routing



Transmission modes



- Load vector: ρ_k = [1 1 1 1]
- Dimensioning based on capacity :
  - B* = 4
  - P* = [0.25, 0, 0, 0.25, 0.25, 0.25]
- Flow-level dimensioning
  - A1 = full optimization
  - A2 = layered optimization



Conclusions

- Dimensioning approach for wireless multihop networks
  - Includes interference modeling via an STDMA assumption of the MAC layer
  - Dimensioning can be based on flow level QoS requirements (per flow throughput)
  - Problem:
    - Number of transmission modes M grows exponentially with number of links L, in the worst case $M = 2^L$
    - Solving the non-linear program for large instances is computationally demanding
    - Efficient solution methods need to be developed

- Extensions and challenges
  - Is the interference model realistic enough? Most likely not, but what are the most relevant aspects to change?
  - Routing is now fixed, but it could be included in the optimization. I
  - Assumes now that node location are given, but this could also be subject to optimization (optimal dimensioning and topology design)
  - However, all this is at the expense of increased computational cost