Performance Challenges in Wireless Mesh Networks

Pasi Lassila

Networking Laboratory

Helsinki University of Technology

Email: Pasi.Lassila@tkk.fi

Outline

Mesh networks from a network performance evaluation point of view

- Mesh network architecture

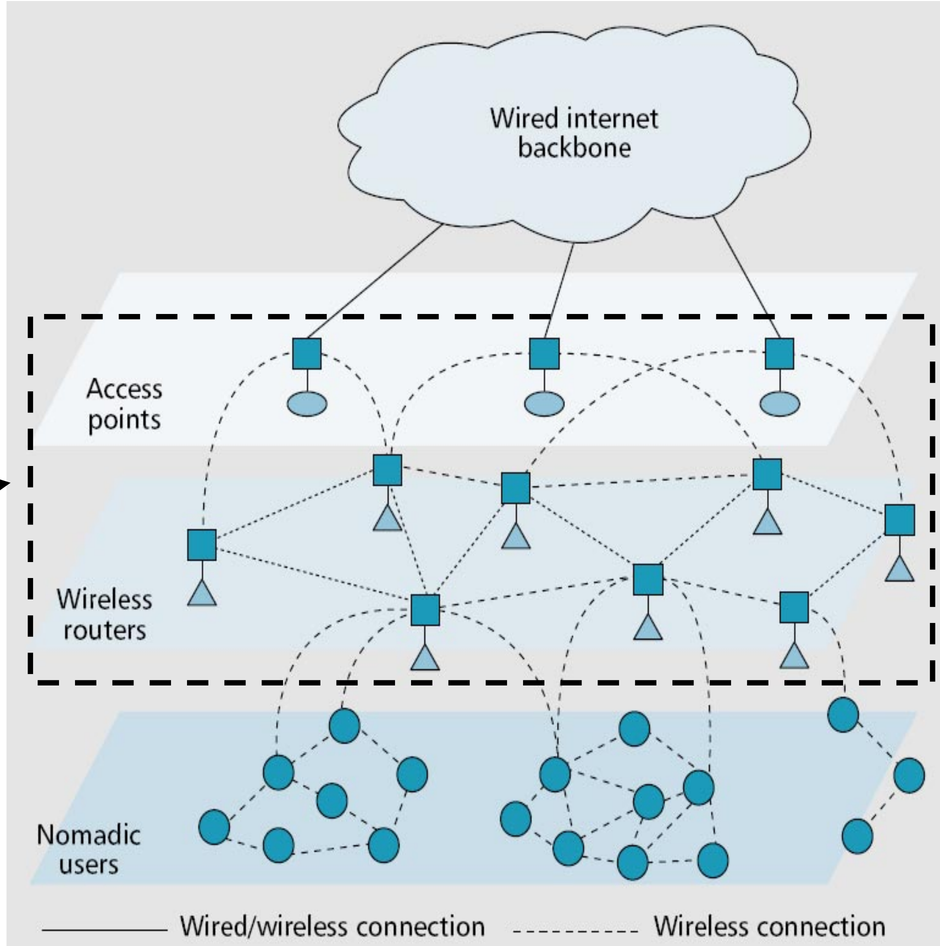
- Performance challenges
  - Analytical approach
  - Towards protocols
  - Standardization (802.11 and 802.16)

- User perceived performance of data traffic
  - Flow level modeling
  - Some simple examples

Mesh network architecture (1)

- Network consists of
  - Access points
  - Wireless routers
  - Clients (may be mobile)

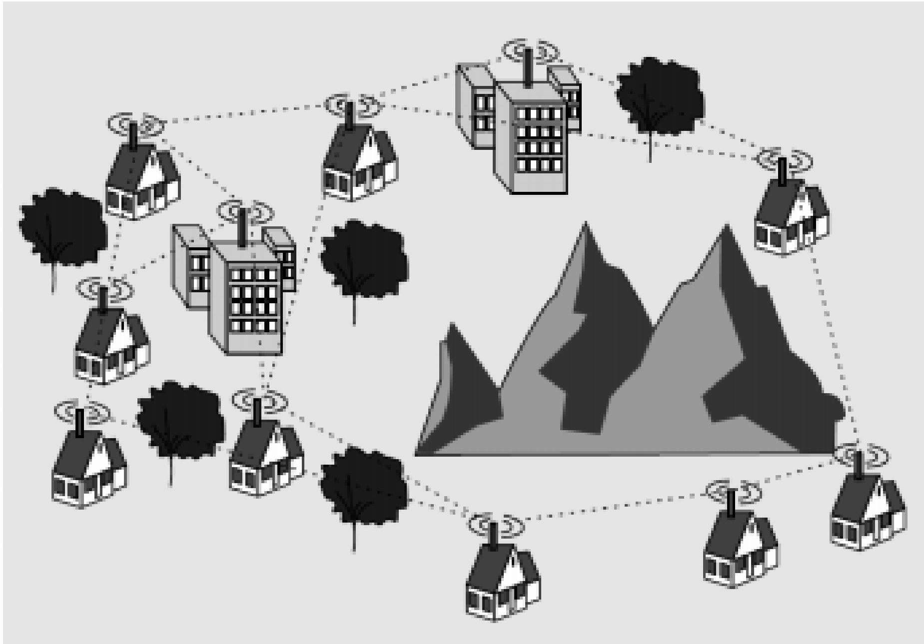
- Mesh backhaul network
  - Wireless multihop network with stationary nodes
  - Today's talk mostly focuses on this part



From R. Bruno et al., "Mesh networks: commodity multihop ad hoc networks", IEEE Communications Magazine, Mar 2003.

Mesh network architecture (2)

- Applications
  - IP access networks
  - Backhaul networks in 4G cellular networks
  - Municipal emergency networks



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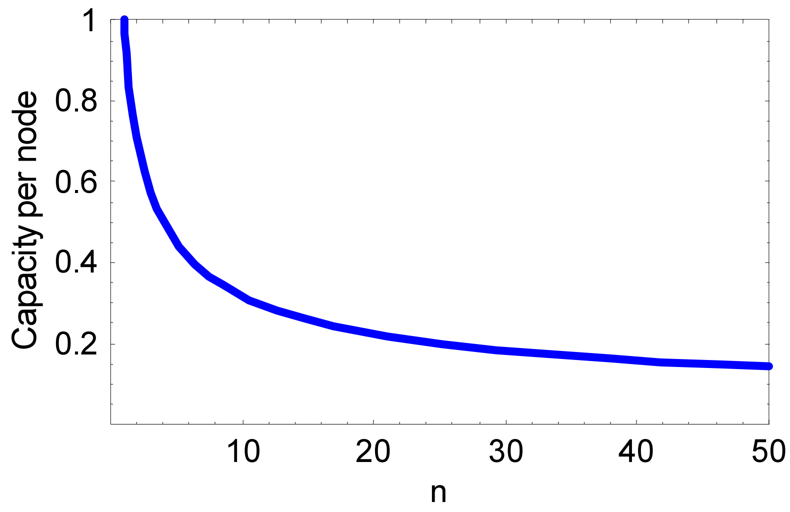
- Standardization
  - Many 802 working groups are developing standards to support mesh networking
  - 802.11, 802.15, 802.16,…

Mesh network performance challenges (1)

– In MANETs node mobility is a fundamental problem for scalability
  - Frequent mobility results in routing info explosion

– In mesh networks, challenge is to achieve efficient radio resource usage
  - In single channel wireless multihop networks capacity per node scales as $\Theta(1/\sqrt{n})$
  - Due to interference and half duplex radios



Mesh network performance challenges (2)

- For a given MAC, to mitigate interference one can use
  - Multiple orthogonal channels and multiple radio interfaces
  - Directional antennas
- Main mechanisms at link/network layers being affected are
  - Scheduling
  - Routing
- Problem: maximize performance and maintain fairness
  - Analytical modeling to understand fundamental tradeoffs
  - Protocols can be developed to approximate the “optimal” performance

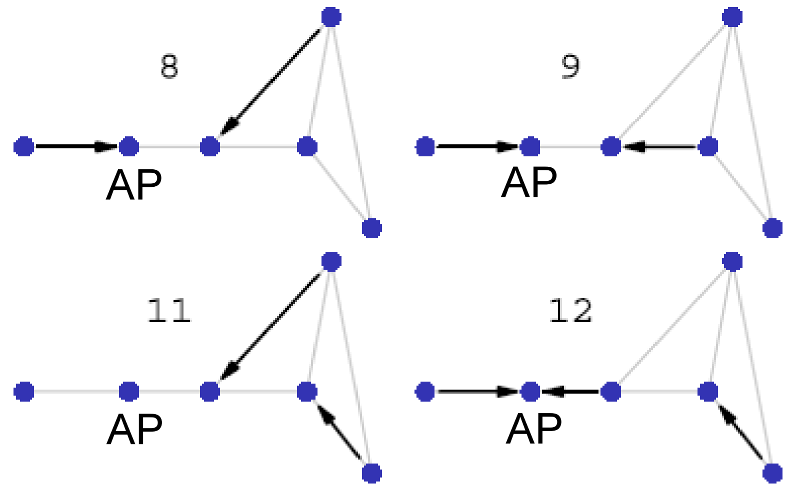
Analytical approach example (1)

– Routing/scheduling in multi-radio/multi-channel systems

– Cross layer modeling
  - Scheduling and interference modeled by STDMA
  - Channel assignment affects set of possible modes
  - Multipath routing

– Modeling framework
  - Multi-commodity flow optimization problem
  - Maximize throughput subject to a fairness constraint
  - Huge (I)LP problems

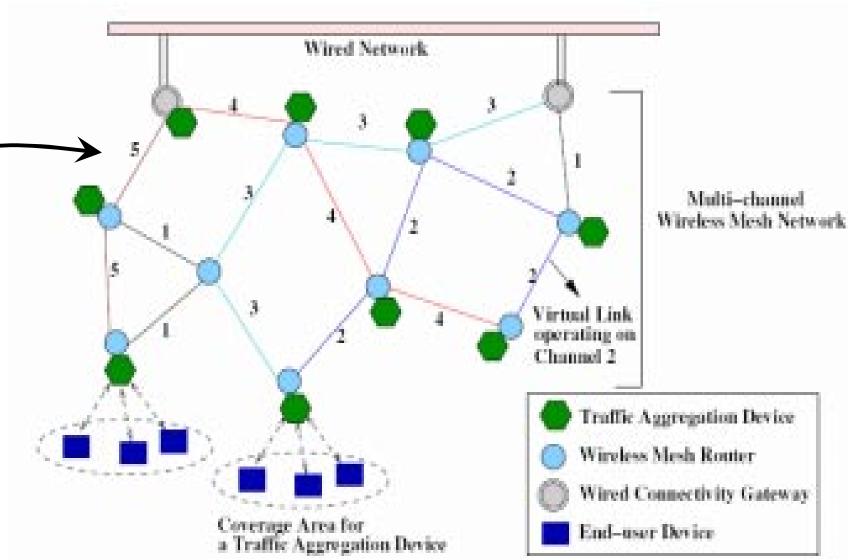
STDMA example



- Single channel network
- Each node has 1 radio, except AP has 2
- Transmission mode is a set of links that may operate simultaneously

Analytical approach example (2)

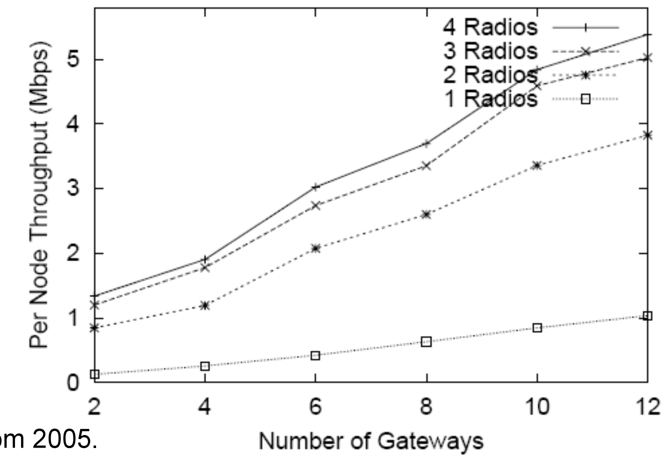
- Problem decomposition
  - Solve channel assignment first
  - Then solve routing/scheduling optimization problem



- Both subproblems difficult
  - Heuristic solutions and approximation algorithms

• 2 radios/node $\Rightarrow$ coloring problem

- Result
  - Only few interfaces needed[1]
  - Similar results from asymptotic analysis also available[2]



[1]A. Alicherry et al., "Joint Channel Assignment and Routing for Throughput Optimization in Multi-radio Wireless Mesh Networks", ACM MobiCom 2005.
[2]P. Kyasanur and N. Vaidya, "Capacity of Multi-Channel Wireless Networks", ACM MobiCom 2005.

Towards protocols: multi-channel 802.11 networks

- Analytical studies based on centralized solutions
  - 802.16 supports this but not 802.11

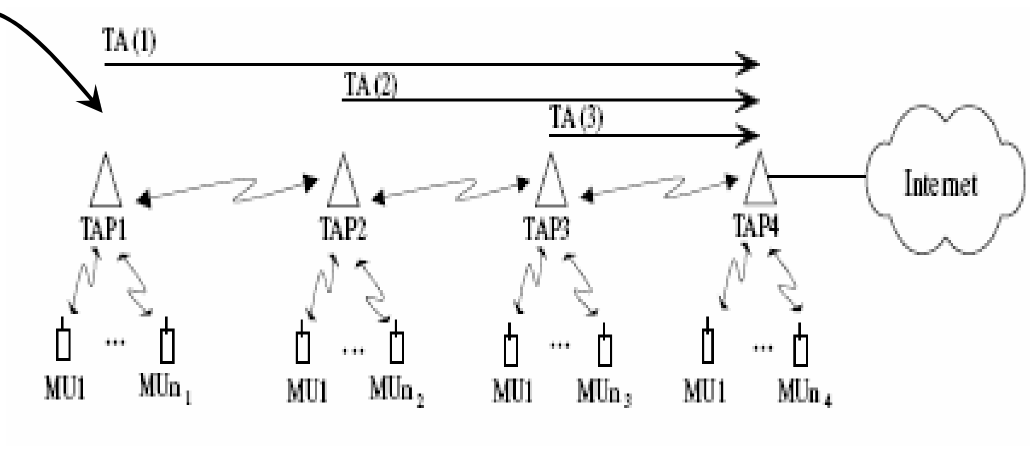
- Routing
  - Distributed proactive routing
  - Routing metric is critical for finding high performance paths
  - Link metric examples: ETX and ETT
  - Typically single (shortest) path routing

- Channel assignment
  - Centralized approach is possible (topology control)
  - Distributed solution ⇒ multichannel MAC
  - Single radio: frame is divided in control and data part (TDM)
  - Multiple radios: common control channel

Towards protocols: fairness

- Fairness solved in 802.16 by STDMA and centralized scheduling
  - Distributed solution for 802.11 difficult

- 802.11 poses fairness problems at two levels
  - Local unfairness due to hidden nodes and 802.11 backoff
  - End-to-end unfairness at flow level
  - Solving e2e unfairness
    - Fair queuing module
    - Mechanism to compute/distribute flow weights



Standardization

- 802.11s
  - Multichannel MAC based on random access (CSMA/CA)
  - Routing at layer 2
    - New routing metric, combines proactive/reactive routing
  - Challenges: fairness?
- 802.16
  - (S)TDMA based system
    - Allows time slot allocation at fine time granularity
    - OFDMA alows resource allocation in time and frequency
  - Mesh mode support exists
    - Both centralized and distributed scheduling supported
  - Challenges
    - Scheduling algorithms beyond the scope of standardization
    - Joint routing/scheduling in mesh mode

User level performance

- We consider data traffic
  - Also called elastic traffic

- User perceived performance is manifested at the flow level
  - flows = file transfers
  - performance = per-flow throughput (bps) or flow transfer delay (s)

- Dynamic traffic
  - Randomly arriving flows and flows have random sizes
  - Flows traverse the network and share the bandwidth with other flows
  - Realized by TCP in IP networks

Balanced Fairness (BF)

- Fair bandwidth sharing according to Balanced Fairness (BF)
  - Originally introduced by Bonald and Proutière[1] in fixed networks
  - Significantly facilitates computation
  - Minimal traffic assumptions (performance depends on traffic load)
  - Approximates well other sharing schemes (max-min, proportional fairness)

- BF extended recently to wireless multihop networks[2]
  - Assumes network operates according to STDMA
  - Scheduling works at a fast time scale compared with flow arrivals $\Rightarrow$ time scale decomposition
  - Parameterization of link layer (schedule) and bandwidth allocation can be optimized jointly
  - Inherently cross layer analysis

[1]T. Bonald and A. Proutière, “Insensitive bandwidth sharing in data networks”, Queuing Systems, 2003.
[2]A. Penttinen et al., “Performance analysis in multi-hop radio networks with balanced fair resource sharing”, Telecommunication Systems, 2006

Simple scheduling example[1]

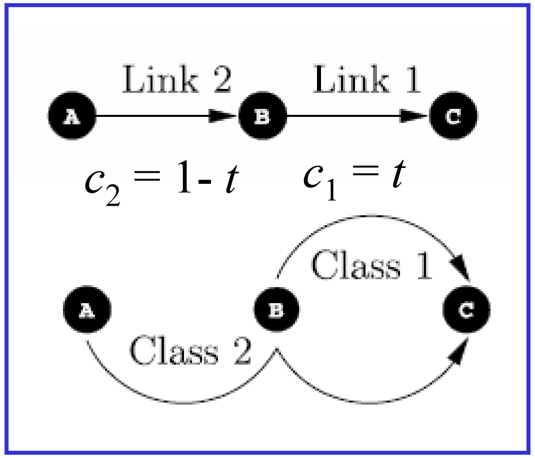
- Toy network
  - Link 1 and 2 can not operate simultaneously
  - Link 1 is as good as Link 2
- Scheduling alternatives
  - Optimize at flow-level

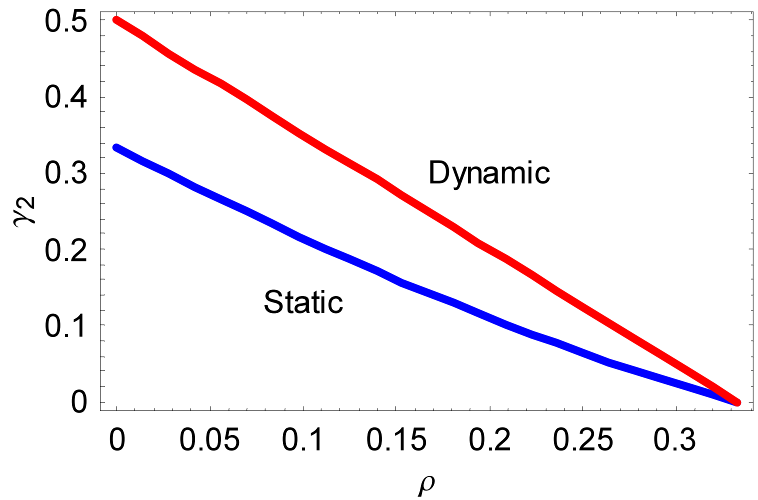
$$\gamma_2 = \frac{1-\rho_1}{1+1/\sigma} - \rho_2$$

  - Decompose: fix schedule τ by an auxiliary optimization problem

$$\gamma_2(\tau) = \left(\frac{1}{(1-\tau)-\rho_2} + \frac{1}{\tau-(\rho_1+\rho_2)} - \frac{1}{\tau-\rho_1} \right)^{-1}$$

  - Layered approach where scheduling is not aware of flow-level

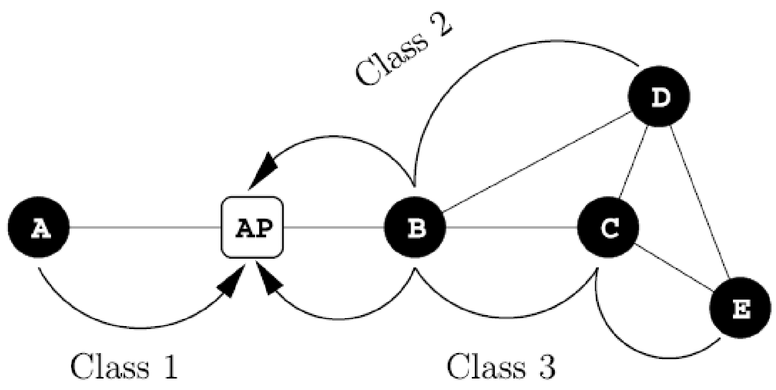


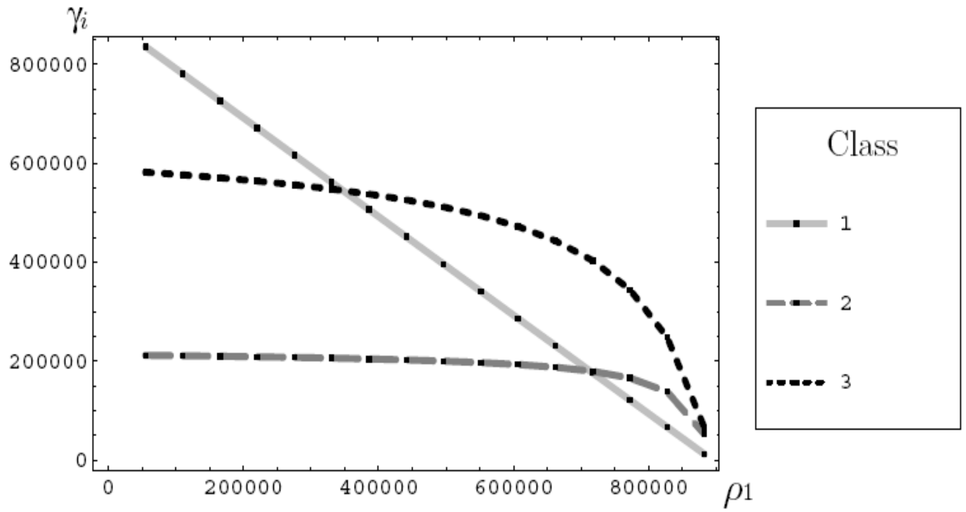


[1]A. Penttinen et al., “Performance analysis in multi-hop radio networks with balanced fair resource sharing”, Telecommunication Systems, 2006

Larger wireless network[1]

- Interference model
  - AP has 2 radios
  - Other nodes have one radio
- Link capacities
  - Shannon capacities
  - Depend on distance and interference from others
- Performance as a function of ρ_1 when ρ_2 and ρ_3 are fixed





[1]A. Penttinen et al., "Performance analysis in multi-hop radio networks with balanced fair resource sharing", Telecommunication Systems, 2006

Conclusions

- In mesh networks challenge is in efficient utilization of radio resources
- In 802.11 networks
  - Centralized algorithms can sometimes be used (channel assignment)
  - Distributed solutions needed for routing (+ good metric) and fairness
- In 802.16 networks
  - Centralized algorithms can be used to realize scheduling/routing
  - Algorithmic problems for large networks
  - OFDMA adds frequency as a new dimension in scheduling
- User level performance
  - BF provides an efficient computational tool for data traffic performance evaluation
  - New scenarios: routing/scheduling in a multihop wireless network
    - Computationally intensive ⇒ new computational tools needed