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Exploiting Link Rate Diversity for High-Performance Wireless Meshes

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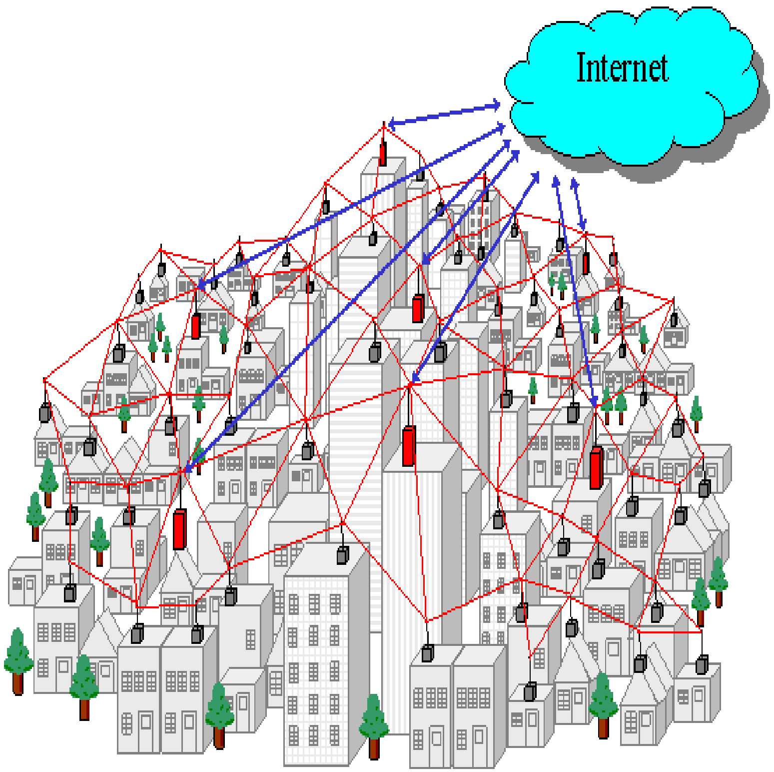
- How to make wireless multi-hop (mesh) networks suitable for latency-sensitive, multimedia traffic
  - Exploit rate and channel diversity for broadcast/multicast traffic

Wireless Mesh: Residential/Community Multi-Hop Connectivity

- **Possible emergence of fixed wireless networks**
  - Cellular-like, static architecture
  - Multi-hop wireless path to wireline gateway.
    - Mesh nodes form the backbone, with a subset having broadband wide-area connectivity.
    - Mobile devices attach to mesh (AP) nodes.
  - IEEE 802.11s standardization.

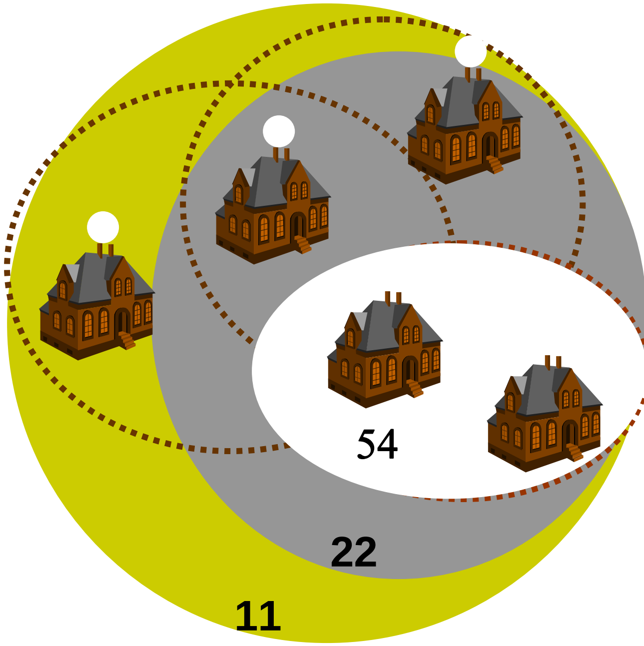
- **Significant government interest as a digital pervasive information infrastructure..**
  - Mesh deployments in Garland (TX), Portland (OR), Auckland (NZ), Philadelphia, Taiwan

- **Significant vendor interest as a low-OPEX broadband alternative to homes.**
  - Startups: Firetide, Tropos, MeshDynamics
  - Router/Chipset Vendors: Intel and Motorola (MeshConnex)
  - Consumer (Gateway Devices): Microsoft Mesh Networking Toolkit



Rate-Channel Diversity and Implications

- **Problem: Data throughput rates are still very low → makes wireless uncompetitive for even standard enterprise applications**
  - Interference among nodes on different paths
  - Interference among packets on the same flow on different links.
  - Asymptotic capacity degrades as 1/sqrt(N) for arbitrary flows.
- **Emergence of high-speed and variable rate WLANs.**
  - 802.11a/b provide up to (2, …, 22, 54) Mbps
  - Higher speeds (108 Mbps++) under standardization.
  - Larger bit-rate→ smaller coverage area
- **Emergence of multiple radios (NICs) on a single node.**
  - Radio tuned to orthogonal channels→ permits larger concurrent reuse.
    - 3/12 non-overlapped channels for 802.11b/a
  - Radio channels reconfigurable in software.
    - Typical channel switching time 180-200 ms with commodity cards.
  - 5-6 fold increase in capacity over single-channel mode has been reported.

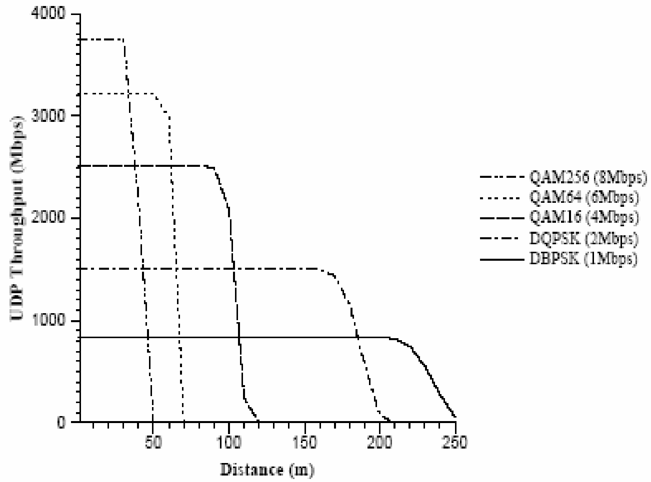


Exploiting Rate-Diversity for Low-Latency Broadcast Traffic

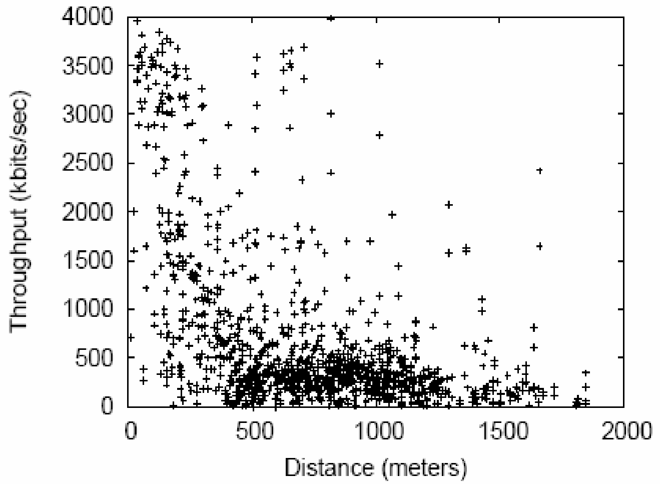
- **Major trend in mesh-architecture is used of multiple-radios, multiple-channels.**
  - Bulk of research on **unicast** traffic (Channel Assignment [Raniwala,2005], Interference&Robustness [Bicket,2005], Routing Metrics [Draves,2004])

- **Our research focuses on** multicast **(broadcast) traffic over wireless mesh architectures.**
  - Natural interplay between wireless broadcast medium and routing protocols.

- Current research: How to efficiently distribute broadcast data using rate and channel-diverse mesh links?
  - Important for various latency-sensitive multicast traffic (VoD, MMOGs)
  - Sensor feeds (broadcast dissemination of audio/video sensors and “presence”)
  - Community sports events



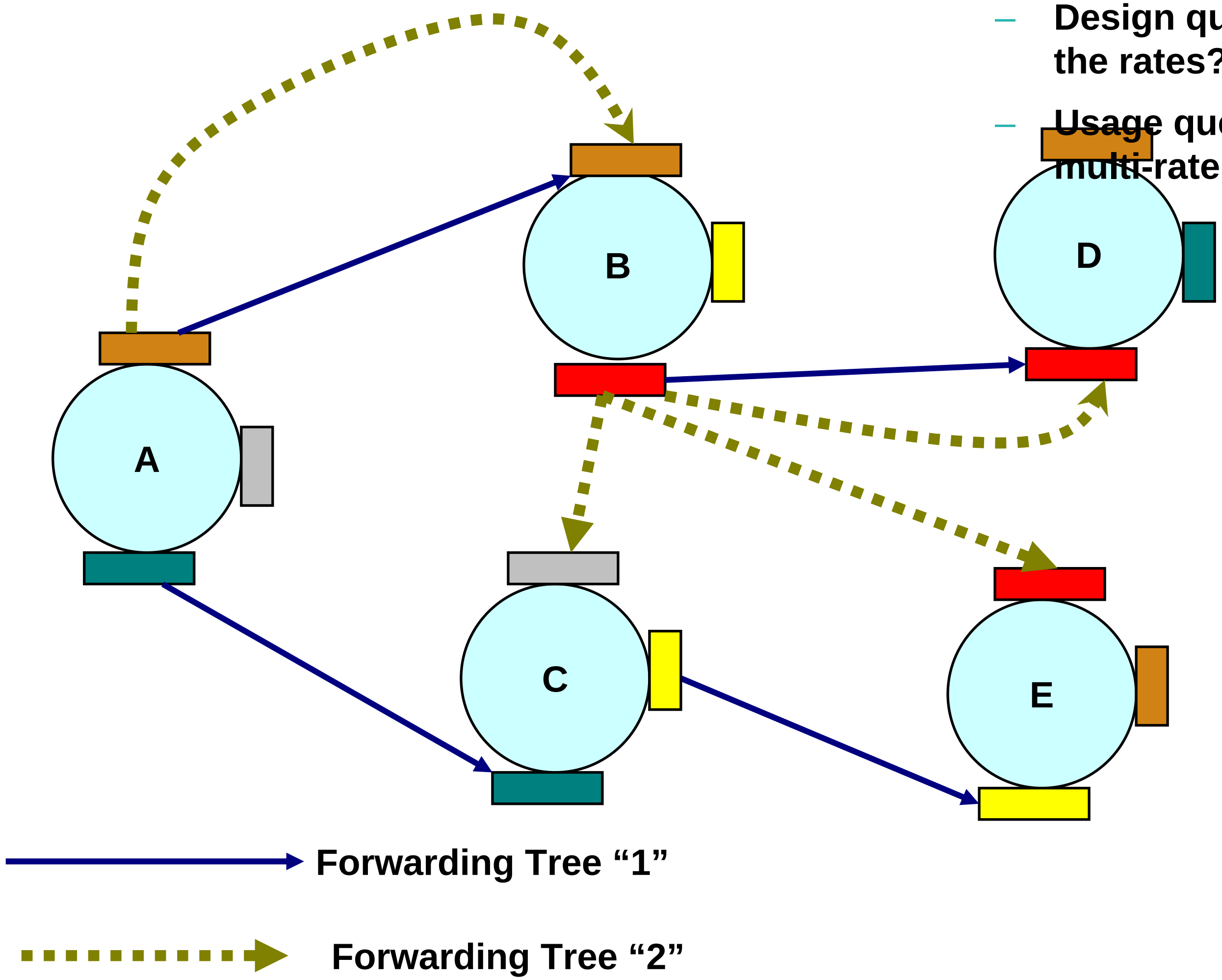
Theoretical UDP rate-distance variation for 802.11 (Holland, 2000)



Observed real-life rate/distance diversity (Roofnet, 2005)

Multicast Forwarding in Multi-Channel, Multi-Rate Mesh

- **Fundamental questions**
  - **Should we use multi-rate multicast?**
  - **Design questions e.g. How to choose the rates? Etc.**
  - **Usage questions e.g. How do we exploit multi-rate multicast?**

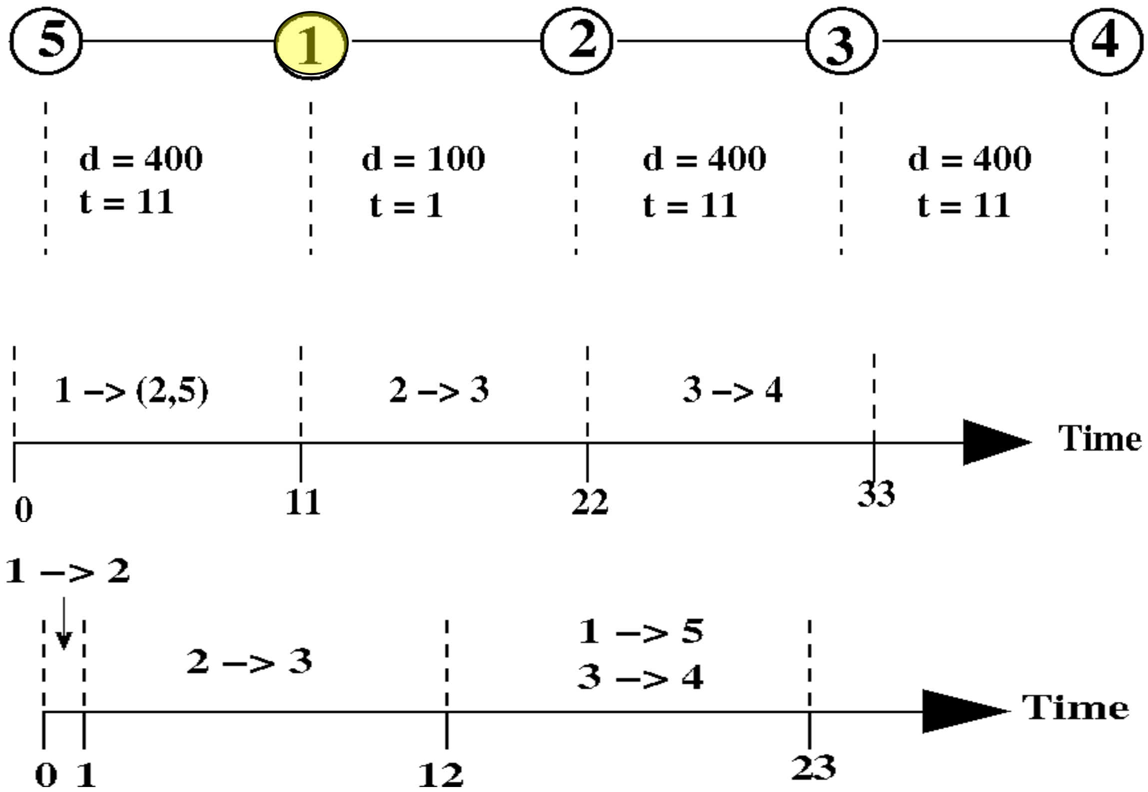


- **Minimum network broadcast latency that exploits**
  - Multi-rate
  - Wireless multicast advantage (WMA)
- **Metric:** broadcast latency $\Rightarrow$ **time till all nodes receive packet.**

Talk Themes

- **Single-channel, single-radio WMN**
- **Multi-channel, multi-radio WMN**
- **Increasing throughput via rate diversity in (SRSC) WMN**
- **Impact of link reliability in wireless multicasting**

Multi-Rate: Canonical Example



Broadcast latency = 33,
ρ= 1 pkt/33 time units

Broadcast latency = 23,
ρ= 1 pkt/23 time units

- **Multi-rate multicast ~= single-rate multicast**
- **A new degree-of-freedom**
  - Multicasting the same packet more than once but at different rates to a different subset of neighbors

(SRSC) Minimum Latency Broadcast: Three Step Heuristic

1. Topology construction: Compute a broadcast (spanning) tree
   - Non-leaf nodes broadcast to child nodes at the maximum of individual link rates.
   - Take multi-rate and WMA into account.
2. Multicast grouping: **At each node of tree, decide number and destination of local multicasts.**
   - Work backward from leaves to root
3. Transmission scheduling: **For defined set of transmissions, establish the optimal transmission order.**
   - Precedence constraints from broadcast tree
   - Conflict graph from radio interference

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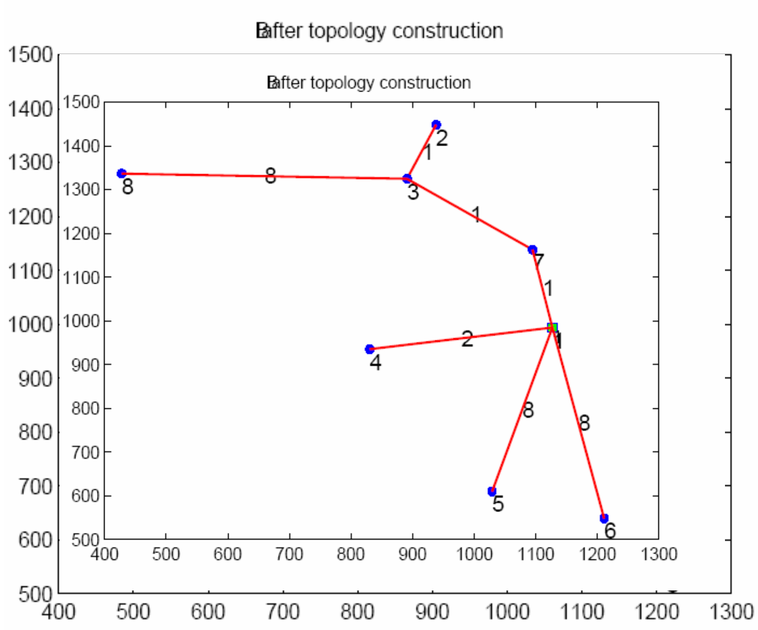


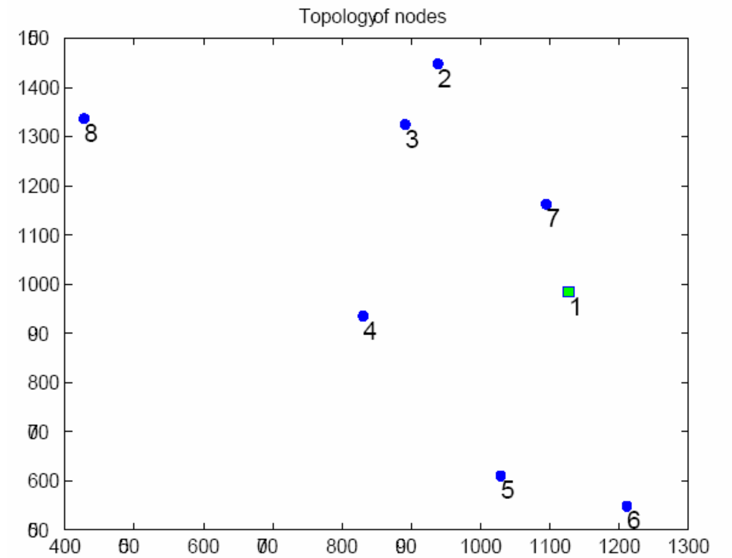
(SRSC) WCDS: Heuristic for Rate-Aware Broadcasting

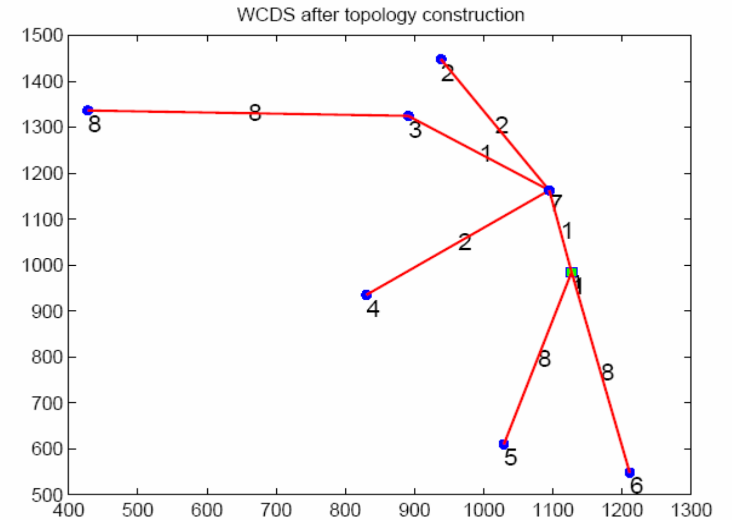
- **Add one (node,rate) pair every iteration**
  - Current estimate of WCDS is D
  - $C = \Cup \{x \in D\} N(x,r_x)$
    - Nodes in C are said to be covered
  - Find $x \in D$ and rate r_x such that

    $|N(x,r_x)\backslash C| * r_x$ **is maximized**

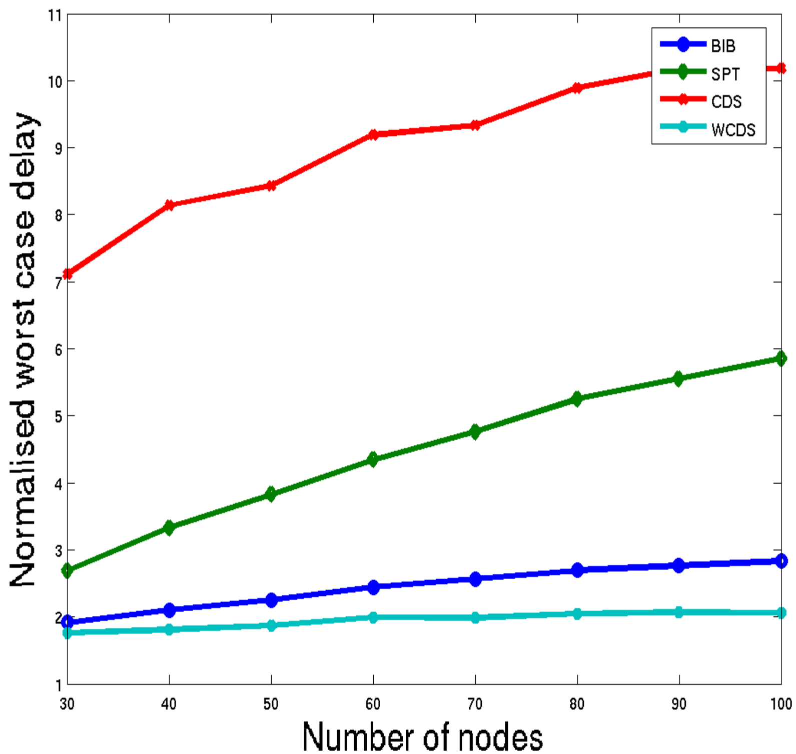
- Basic Intuition: Maximize the product of the rate and the number of not-yet-covered nodes

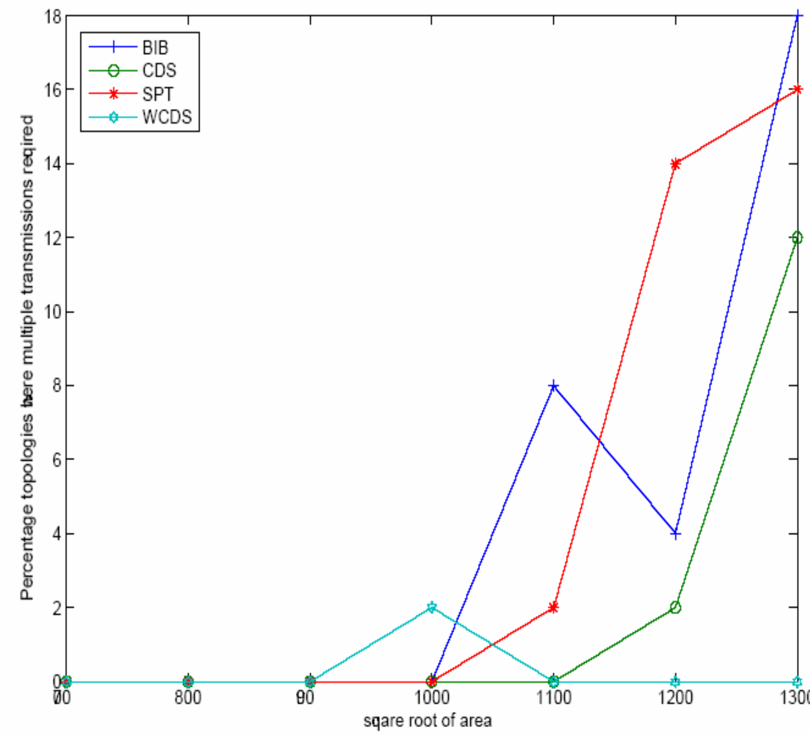
- **Tied into later result:** Efficiency of a rate for broadcast is measured by Rate x Coverage area





(SRSC) Main Results





Rate-aware heuristic results in 1/6th minimum latency delay (X6 throughput)

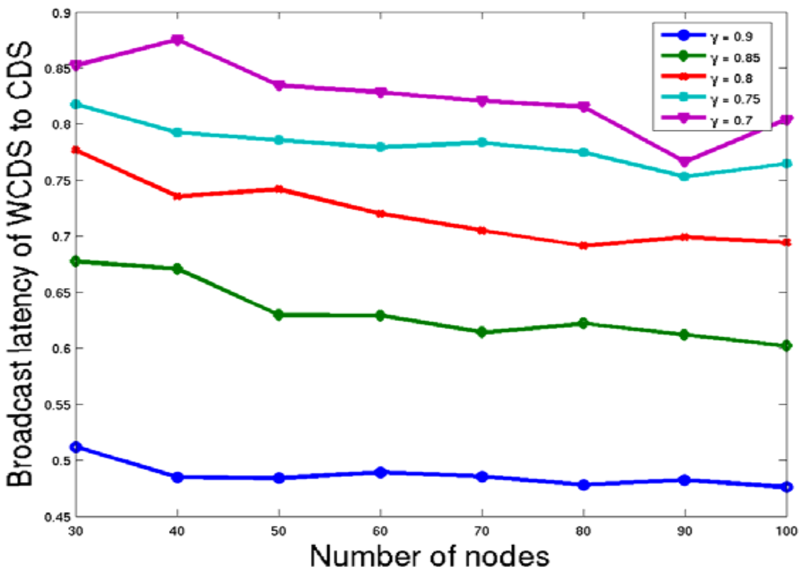
Number of additional transmissions per node NOT of much use-~10% reduction in latency in ~10% of topologies

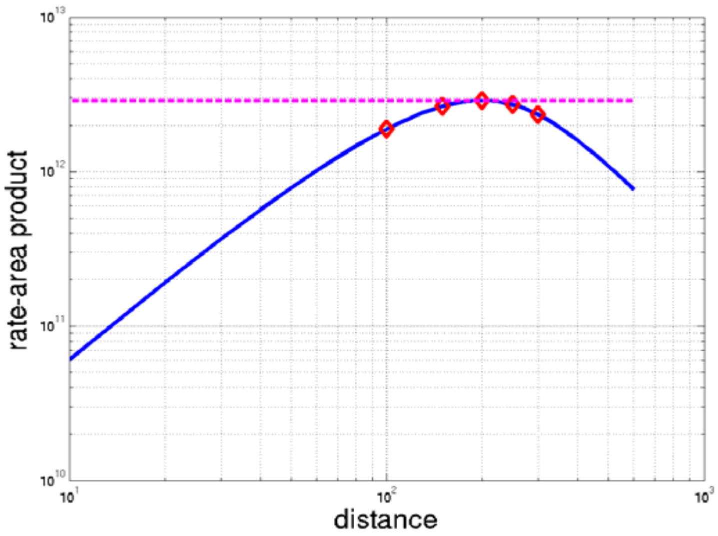
Minimum Latency Delay: Theory and Future

Broadcast area A = πd^2
Packet size = p
Covers A in time p/r

Rate	Range
r	d
ρ*r	0.5*d

Needs 4 broadcasts to cover A
Time required = 4*p / (ρ*r)





Result: Simulations support conjecture that rate of increase of transmission rate* decrease in area determines utility of rate.

Result: Shannon limit suggests that a limited set of multiple rates will always be useful.

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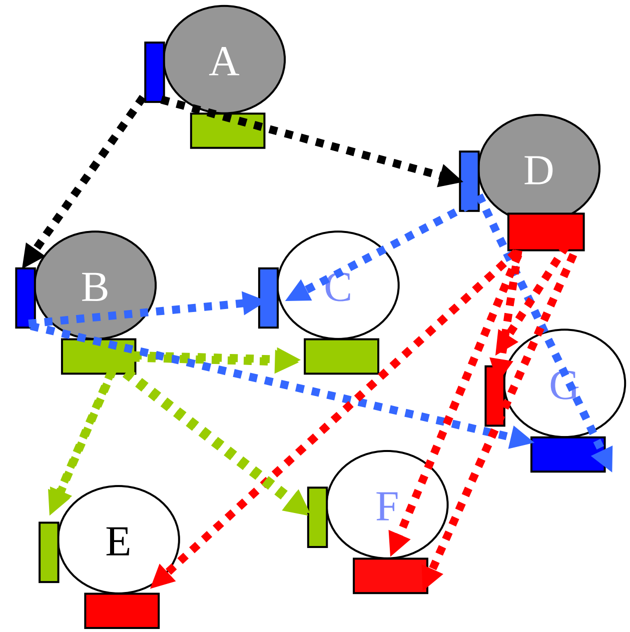
(MRMC) MWT: Multi-Radio Version of WCDS

- **Add one (node,rate, channel) tuple for every iteration**
  - Current estimate of WCDS is D
  - C = $\mathbb{U}\{x \in D\}\ N(x, r_x, c_x)$
    - Nodes in C are said to be covered
  - Find $x \in D$ and rate $r_{x,}$ channel c_x such that

    $|N(x, r_{x,} C_x) \backslash C| * r_x$ is maximized
  - In case of tie, choose the Cx that is least used in the x's "conflict graph"



- Basic Intuition: Maximize the product of the rate and the number of not-yet-covered nodes
  - **Additionally, investigate the choice of multiple channels in each node.**

$$\mathrm{MAX}(\ r^{B}_{G}*3,\ r^{B}_{B}*2,\ r^{D}_{B}*2,\ r^{D}_{R}*2,\ r^{\bar{D}}_{R}*3)$$

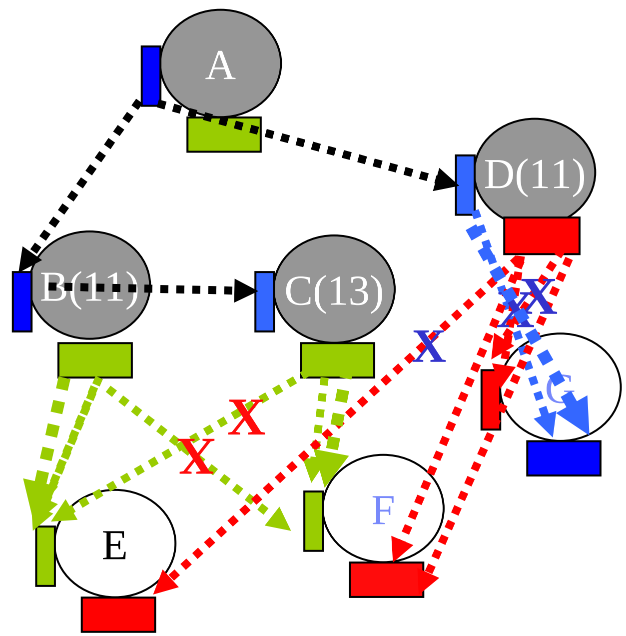
- **Caveat: Does NOT consider the possibility of multiple concurrent transmissions by a single node.**

(MRMC) PAMT: Parallelized, Approximate-Shortest Multi-Channel Tree

- **Add one (node,rate, channel) tuple for every iteration**
  - Current estimate of WCDS is D
  - C = $\mathbb{U}\{x \in D\}\ N(x,r_x, c_x)$
    - Nodes in C are said to be covered
- **Find x $\in$ D and rate r_x, channel c_x such that**

  $|N(x,r_x,C_x)\backslash C| * r_x$ is maximized

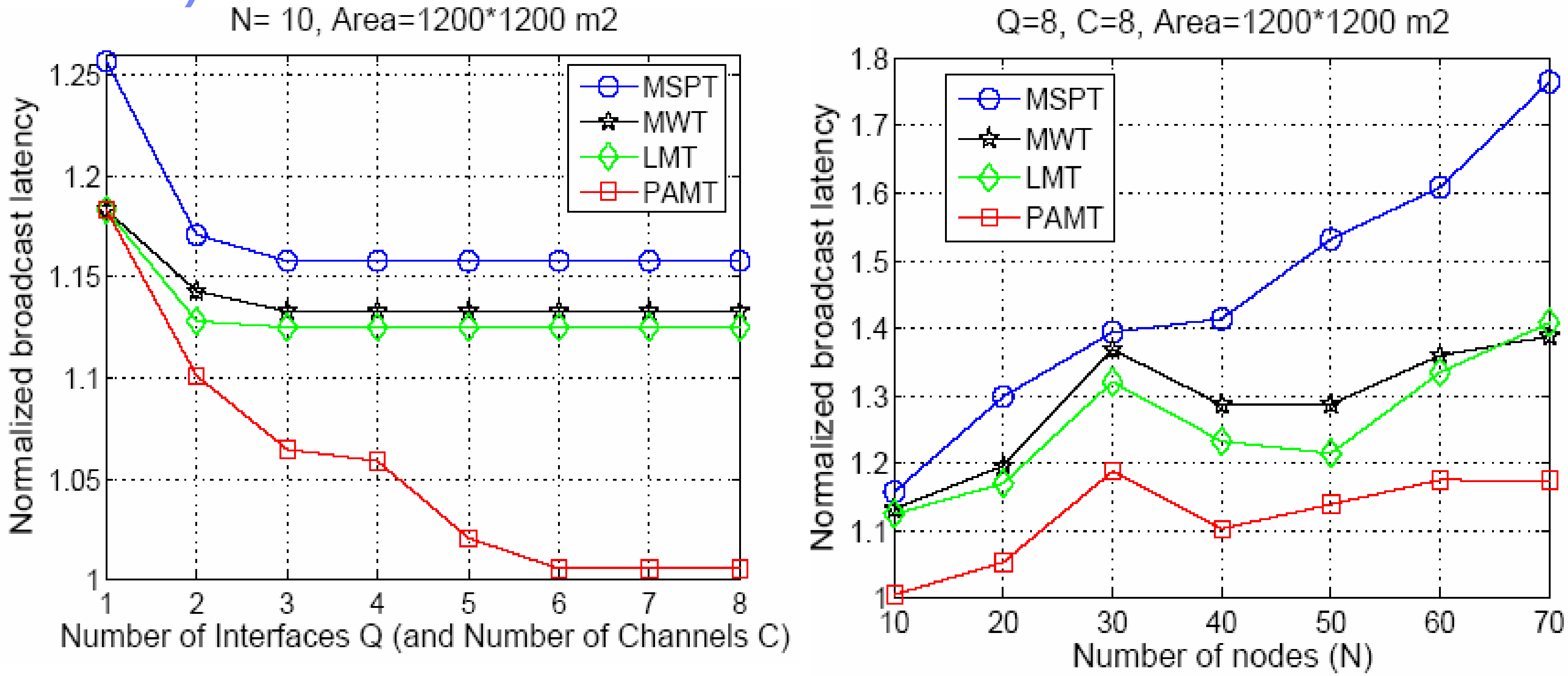
- **Each node x $\in$ D associated with latency value lat(x) = latency of path from S to x.**
  - Avoid counting in $N(x,r_x, C_x)$ nodes that can be reached by another channel $\mathbf{C^2_y}$ **(for all y $\in$ D)** with a latency (*lat(y)+ 1/r_y*) smaller than ***lat(x)+ 1/ r_x.***



- Basic Intuition: Do not count nodes that can be reached at lower latency by an idle interface (on any node already in the set).
  - **Behavior mimics a shortest path tree, subject to WBA and interface availability.**

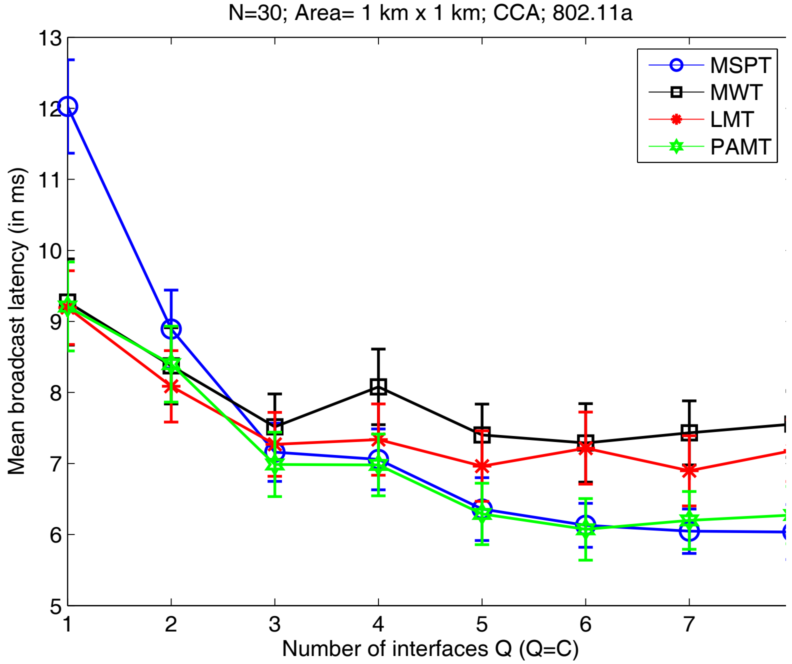
$$MAX(r_G^B(11)*1,\ \bar{r}_G^B(54)*1, r_G^C(22)*1,\ r_B^D(54)*1,\ r_R^D(11)*1,\ \bar{r}_R^D(2)*1)$$

(MRMC) Performance Results #1

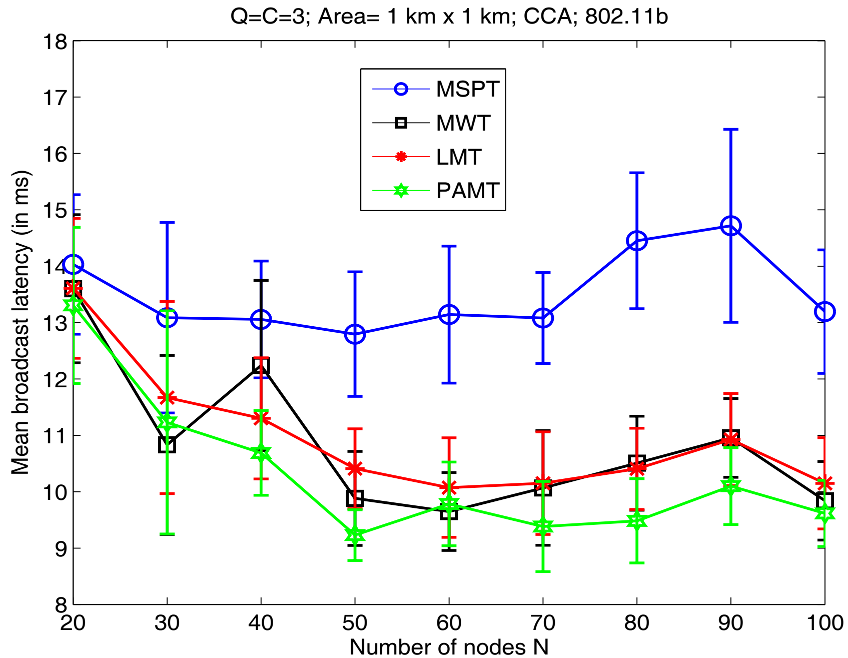


- **PAMT provides the best performance by exploiting Concurrency, Wireless Broadcast Advantage and Path Latency**
- **Relatively small number of radios (2/3) per node provide significant improvement in performance (within 10-20%) of infinite channel, infinite radio case)**
- **Overall normalized latency increases with node density (due to contention effects)**

(MRMC) Performance Results #2: (8011.a/b)



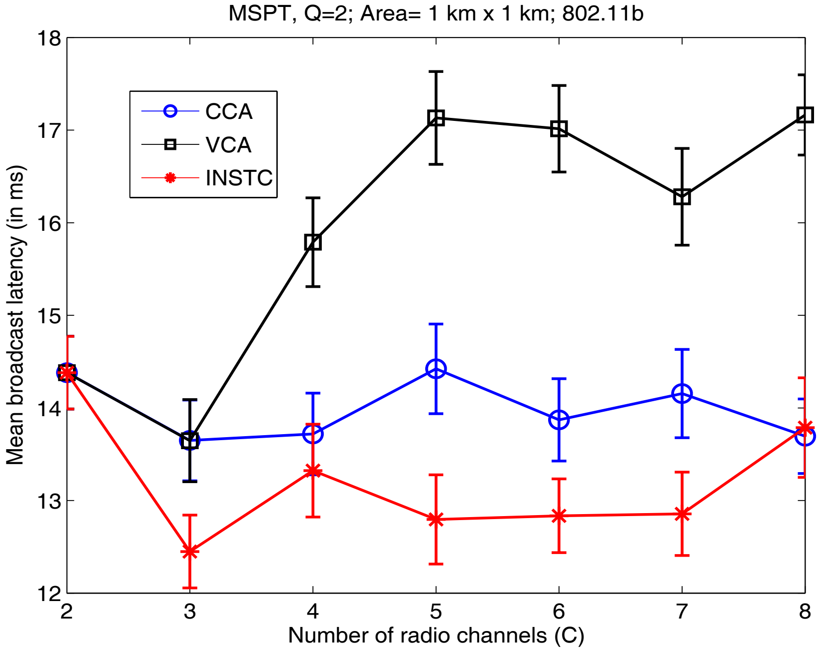
802.11a latency vs. Q

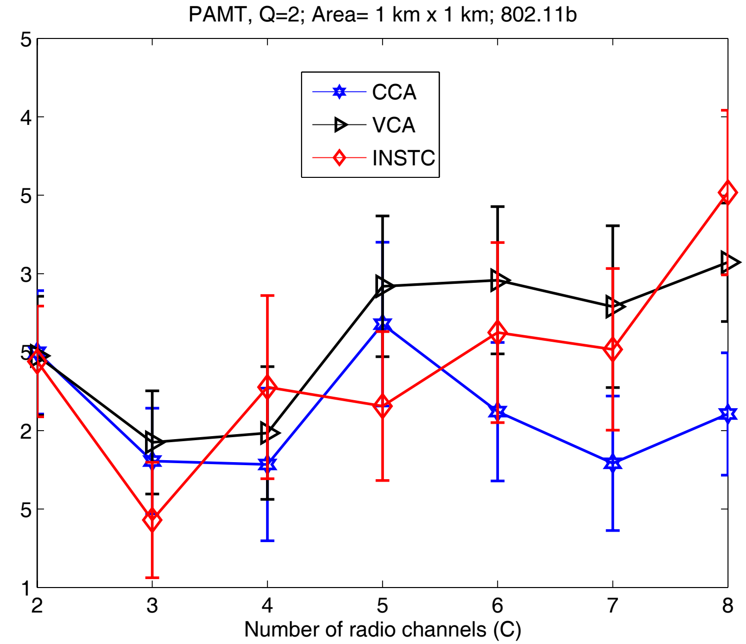


802.11b latency vs. N

- **PAMT can reduce the broadcast latency down to ~8-10 msecs (802.11a) and ~10-12 msecs (802.11b) with Q=3 interfaces.**
- **MSPT performance is pretty decent if we have a large number of radios and channels.**
- **Overall latency increases with node density (due to contention effects)**

(MRMC) Performance Results #3





- **Performance depends on the channel allocation strategy. Two competing objectives:**
  - **High connectivity (lower network depth, prevent disconnection and bottlenecks)**
  - **Low interference (reduce contention on link to avoid MAC delays)**
- **For PAMT, CCA results in the lowest latency; for MSPT, INSTC results in lowest latency.**
  - **Algorithms that exploit trx. Parallelism do better under greater connectivity.**
- **Channel assignment designed for unicast traffic is counterproductive to broadcast traffic.**

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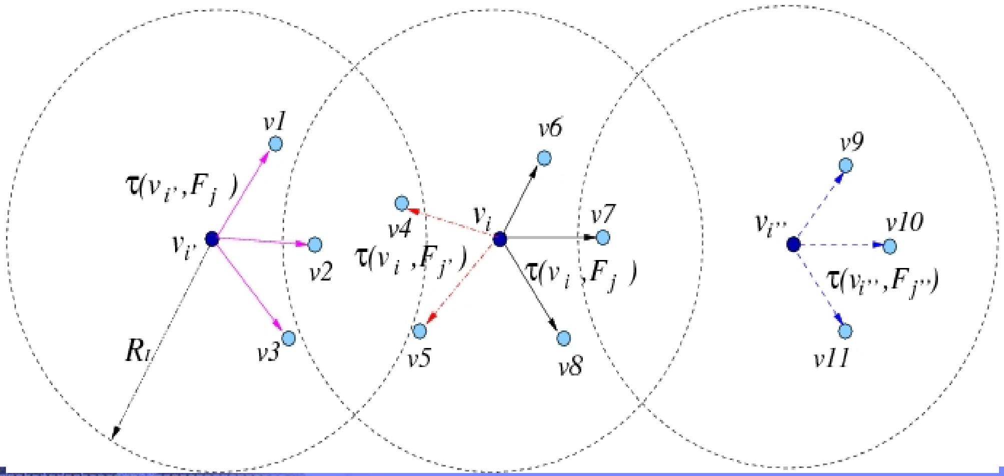
QoS-Aware Multicasting: Improving Network "Capacity"

- **Multiple point-to-multipoint flows in a mesh**
  - Goal: Increase the capacity (cumulative throughput) of admitted flows, without incurring excessive latency.

- **Challenges with even a centralized routing algorithm:**
  - Interference between multicast transmissions is not symmetric.
  - "Interference ring" transmissions change with change of receiver subset.
    - Particular challenge for multicast trees built "receiver-to-source".
  - In reality, no "link-interference graph", only "transmission interference graph".



Different Metrics for Broadcast Selection

- **WCMA: (same as WCDS)**

$$f_{WCMA}(\tau(v_i, F_j)) = |N(v_i, F_j)| \times \rho(v_i, F_j)$$

- **MRA: Maximum RTTF**

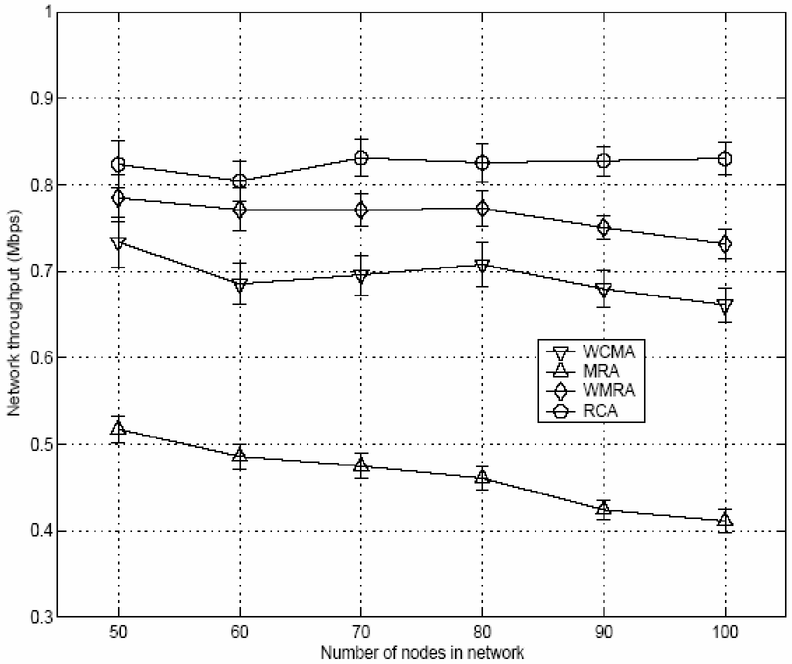
$$f_{MRA}(\tau(v_i, F_j)) = RTTF(\tau(v_i, F_j)|\rho(v_i, F_j))$$

- **WMRA: max rate*RTTF**

$$f_{MRA}(\tau(v_i, F_j)) = \rho(v_i, F_j) \times RTTF(\tau(v_i, F_j)|\rho(v_i, F_j))$$

- **RTTF-Aware Coverage:**

$$f_{RCA}(\tau(v_i, F_j)) = |N(v_i, F_j)| \times \rho(v_i, F_j) \times RTTF(\tau(v_i, F_j)|\rho(v_i, F_j))$$



• Result: RCA outperforms other algorithms in total capacity achieved (no. of 0.1 Mbps flows admitted)

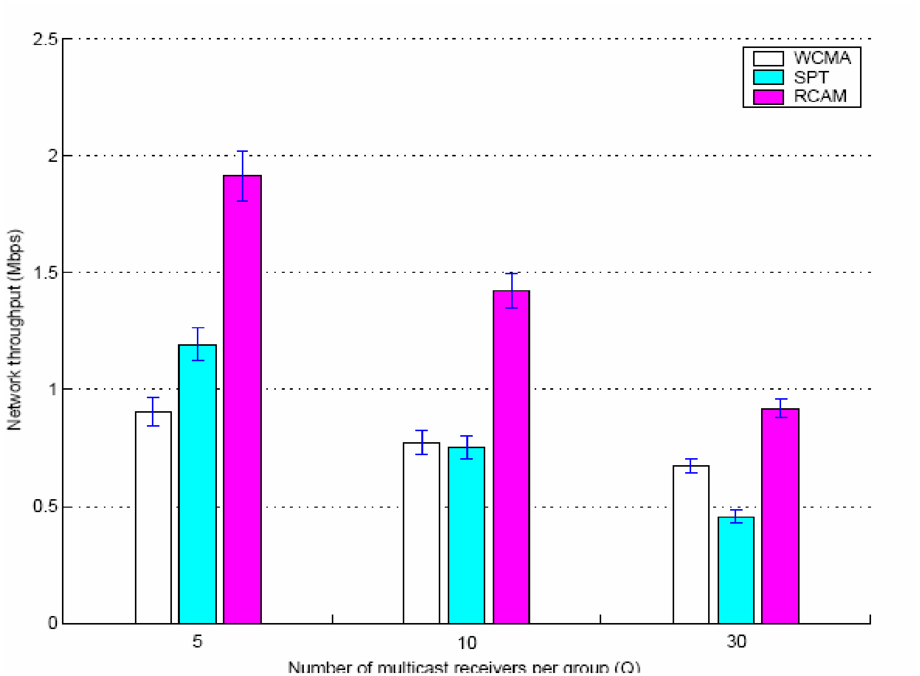
  • Results not spectacular for broadcast as ‘no routing around hotspot’.

QoS-Aware Multicasting: RCAM and Performance

- RCAM is a receiver-driven multicast tree formation algorithm.
  - *Basic idea: Each receiver computes least cost path to source and grafts at first ancestor already on the multicast tree.*

- Key difference is in the computation of cost:
  - **WBA:** $c(v_a,v_b)=0$ if v_a is already on multicast tree and can reach v_b.
  - **Incorporate rate diversity and contention:**

$$c(v_a, v_b) = \frac{1}{\rho(v_a, v_b)} \times \frac{1}{1 - \max_{d(v_a,v_l) \leq \kappa \times d(\rho_1)} CTTF(v_l)}$$



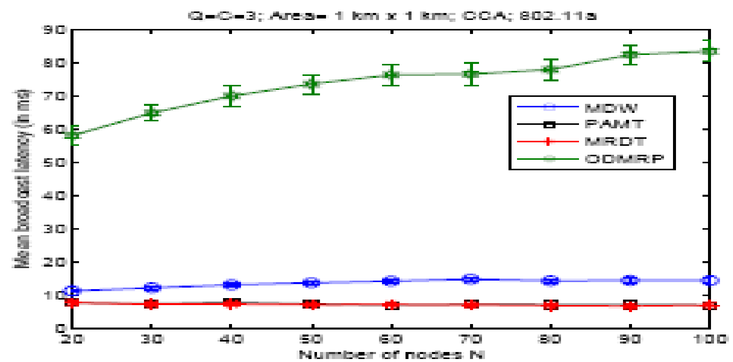
400 nodes in 1.5kmX1.5km; L=0.1 Mbps, 802.11a

Result: RCAM increases the total feasible multicast load of the network by ~70-90% by considering both load and route diversity.

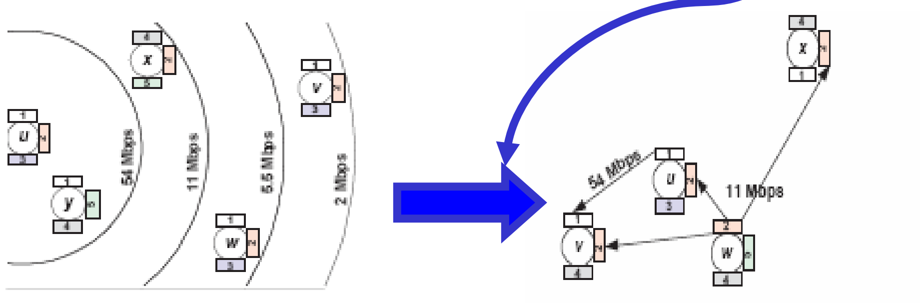
Performance of Distributed Multicasting Algorithms

- MRDT is a distributed version of the rate/channel aware broadcasting tree algorithm. It has 4 steps:
  - Form a CDS (no rate/channel diversity).
  - Decide 'nodes' that a marked nodes must 'cover'—(u→v→w vs. u→w).
  - Rate maximization: shift nodes to other nodes/ interfaces if it increases overall RAP value
  - RCAM is a receiver-driven multicast tree formation algorithm.
  - Build a source-routed spanning tree over the resulting CDS (eliminates many trx).

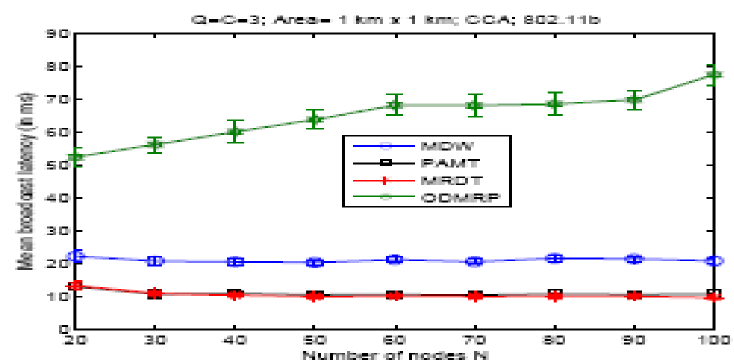
Protocol	Type	Interface and channel diversity	Rate diversity
MRDT	distributed	✓	✓
PAMT [9]	centralized	✓	✓
MDW [18]	distributed	×	✓
ODMRP [17]	distributed	×	×



(a) 802.11a with changing N



1. Before Local-Rate-Maximization at u . After External-Rate-Maximization at u



(b) 802.11b with changing N

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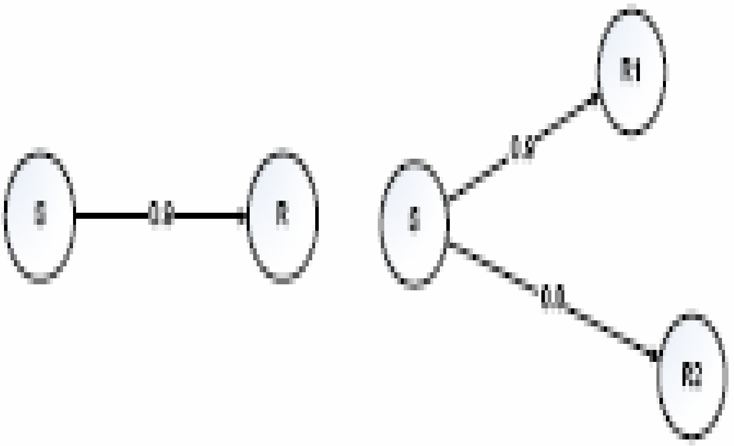
Reliability for Link-Layer Multicast

- **Big drawback of basic tree algorithms: packet loss rate increases with tree depth (no MAC-layer reliability).**
- **Two alternatives:**
  - Provide link-layer reliability by retransmissions.
  - Provide reliability through redundant transmissions (forest/mesh)
- **Question: what's the cost of retransmission-based reliability?**

EMT: Expected Multicast Transmissions (analogue of ETX)



ETX=1.1; EMT= 1.34

PROD: Probabilistically Reliable Delivery

- EMT can be calcuated as a function of link reliability $f_{i,j}$ and N_i (# of children)

$$f_{i,j} = 1 - d_{i,j}^{F} * d_{i,j}^{R}$$

- EMT is given by:

$$\mathrm{EMT}_i = \sum_{c=1}^{|N_i|} (-1)^{c-1} \sum_{S \in \Upsilon(N_i,\, c)} \frac{1}{1 - \prod_{j \in S} f_{i,j}} \, .$$

- PROD is receiver-driven multicast
  - Node x join node on tree with smallest ‘incremental EMT cost’

$$c(x,v) = EMT(v, child \cup x) - EMT(v, child)$$

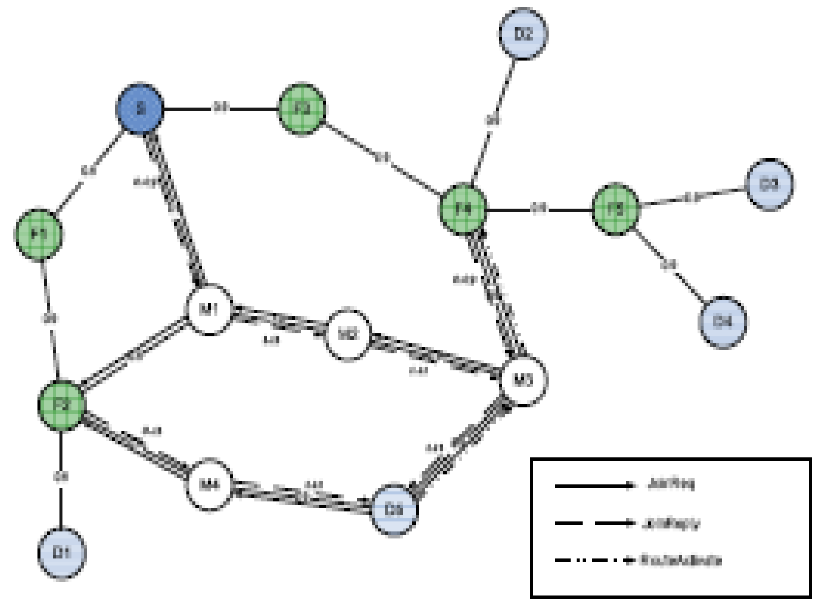
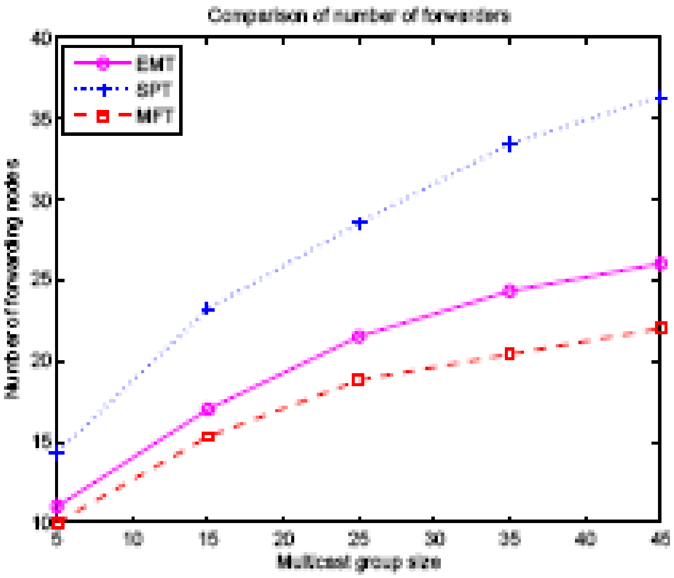


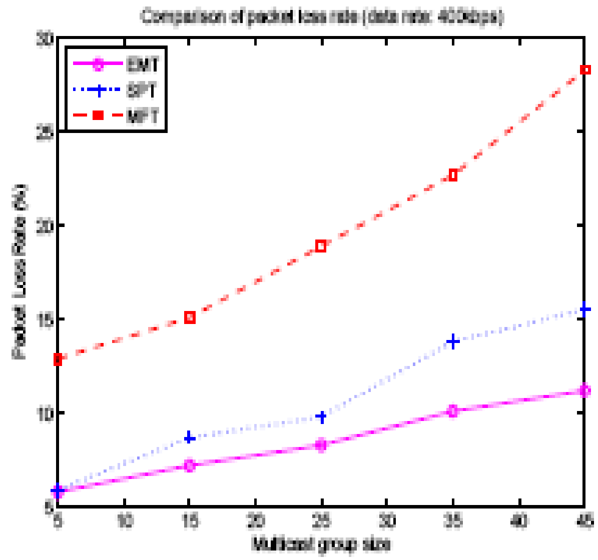
Fig. 3. Protocol Example

PROD: Performance Results

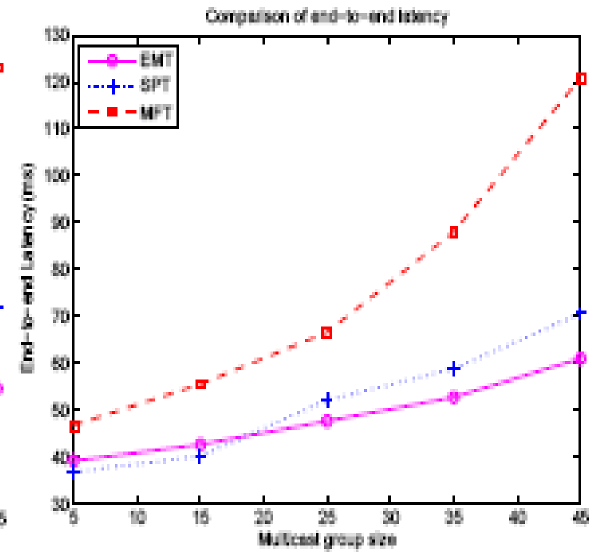
• (max. retries=5; MAC layer=BMM instead of 802.11) • 50 mesh nodes in 1.5km^2 area



Number of fwding nodes



Avg. packet loss rate



Avg. packet latency

• PROD decreases packet loss rates by ~30% and end-to-end latency for reliable delivery by ~15%. (Probabilistic as max. retries=5; MAC layer=BMM instead of 802.11

• Reliable delivery latency ~70-80 msecs, compared to 10-20 msecs for best-effort multicasting

Insights and Open Questions

- **Rate-diversity for link-layer broadcasts is critical for low latency and higher throughput.**
  - Such latency is critical consideration for broadcast/multicast data applications.

- **A limited number or radios/node and multiple channels offers significant benefits.**
  - PAMT algorithm adapts to the number of radio interfaces and channels
  - Use of 2 or 3 radios per node can bring the broadcast latency to within 20% of the ideal (infinite radio) case; with 1 radio we incur ~100% overhead.
  - Building a multicast tree that combines WBA with rate diversity can increase the network's multicast capacity by ~70-90%

- **Ongoing work to address:**
  - Robustness vs. delay sensitivity: How to provide resilience against link-losses while keeping broadcast latency low.
    - Is mesh vs. link-layer reliability the right approach?
  - How do the algorithms change when new physical layer technologies (e.g., cooperative diversity) become available?

Acknowledgements

- **Work on "High Performance Data Broadcasting in Wireless Meshes" performed jointly with Prof. C. Chou, J. Qadir, M. Liu and X. Zhao, Univ. of New South Wales, Australia under an Australian Research Council Grant.**
  - http://www.cse.unsw.edu.au/~aiolos/publication.html
  - Representative Publications:
    - J. Qadir, C. T. Chou, A. Misra and J. Lim, Localized Minimum-Latency Broadcasting in Multi-radio Multi-rate Wireless Mesh Networks, to appear, IEEE WoWMoM, June 2008.
    - X. Zhao, C. T. Chou, J. Guo, S. Jha, A. Misra, Probabilistically Reliable On-Demand Multicast in Wireless Mesh Networks, to appear, IEEE WoWMoM, June 2008.
    - M. Liu, C. T. Chou and A. Misra, *Maximizing Broadcast and Multicast Traffic Load through Link-Rate Diversity in Wireless Mesh Networks*, to appear as "Extended Paper", IEEE WoWMoM 2007, June 2007.
    - C. Chou, A. Misra and J. Qadir, *Low Latency Broadcast in Multi-rate Wireless Mesh Networks*, IEEE JSAC, special issue on "Multi-Hop Wireless Mesh Networks", November 2006.
    - J. Qadir, A. Misra and C. Chou, *Minimum Latency Broadcasting in Multi-Radio Multi-Channel Multi-Rate Wireless Meshes,* IEEE Sensor, Mesh and Ad-Hoc Communication Network Conference (SECON), September 2006.


Thank
You