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Advanced Network Architecture Research Group
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On the Packet Delay Distribution in Power-law Networks

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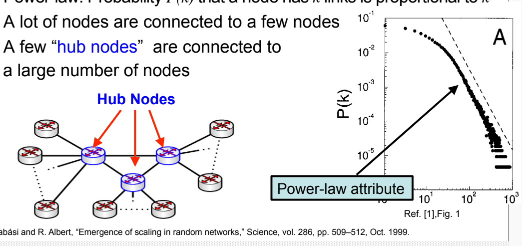
Power-law in the Internet

- The degree distribution of the Internet topology follows a power-law
  - Power-law: Probability $P(k)$ that a node has k links is proportional to $k^{-\gamma}$
  - A lot of nodes are connected to a few nodes
  - A few "hub nodes" are connected to a large number of nodes



Ref. [1],Fig. 1

[1] A.-L. Barabási and R. Albert, "Emergence of scaling in random networks," Science, vol. 286, pp. 509–512, Oct. 1999.

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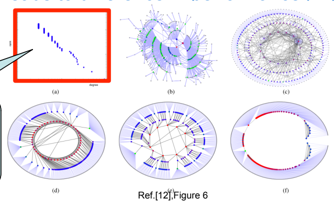
Relationship between topologies and performance

- Structures of topologies are defined not only by degree distribution, but also by other factors
- Difference in structure leads to difference in performance [12]



These topologies have the same degree distribution. However, they have different structures.

Ref.[12],Figure 6

[12] L. Li, D. Alderson, W. Willinger, and J. Doyle, "A first-principles approach to under- standing the Internet's router-level topology," in ACM SIGCOMM Computer Communication Review, vol. 34, pp. 3–14, Oct. 2004.

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Research purpose

- Difference in structure leads to difference in performance
  - The power-law degree distribution is not enough to discuss performance of networks
- We focus on the relationships between structure of topology and packet-level behavior
  - each of nodes has end-to-end flow control functionality
- Goal
  - Investigation of the optimal structure for efficient packet forwarding
  - Proposal of a new topology design method with this achievement

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Contributions of this work

- Traffic behavior in power-law topologies
  - Many researches are discussed in flow-level, but end-to-end flow control is not concerned
  - End-to-end flow control has large impacts to traffic behavior
  - Traffic behavior in BA topologies with end-to-end flow control is discussed, but structures of topologies are not concerned
- Reveals the relationships between structures of topologies and traffic behavior with end-to-end flow control

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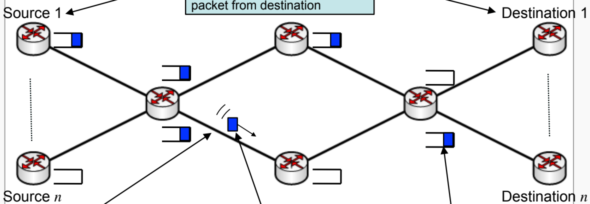
Network model

Stop-and-wait flow control
Source node stops to sending a packet till it receives ACK packet from destination



Uniform link capacity
Each outgoing link transfers 1 packet per 1 time unit

Shortest path routing
If multiple shortest paths are found, the next node is selected randomly

Unlimited buffer
Each outgoing link has unlimited FIFO queuing buffer

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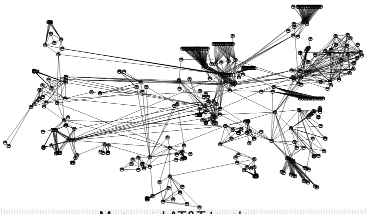
Network topologies

- 2 topologies having different structures
  - The number of nodes and links is the same
  - AT&T Topology･･･Measured router-level topology of AT&T
  - BA（AT&T）Topology･･･Generated by BA model [1]



Measured AT&T topology

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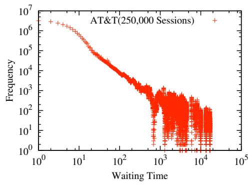
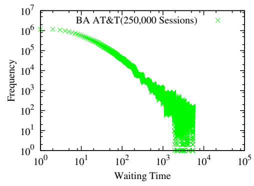
Waiting time distribution

- Waiting time is the time from when a packet is stored in a buffer to when a packet is delivered to next node
- These 2 waiting time distributions are similar, in spite of different structures
  - They exhibit long-tail characteristics



AT&T topology



BA topology

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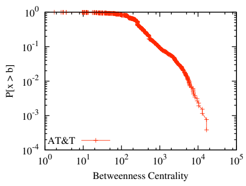
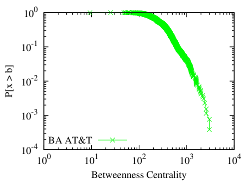
Betweenness centrality distribution

- Betweeness centrality is the number of node pairs that pass through a link
  - The number of packets that pass through the link is proportional to the betweenness centrality of the link
- Similar waiting time distributions are caused by betweenness centrality distributions



AT&T topology



BA topology

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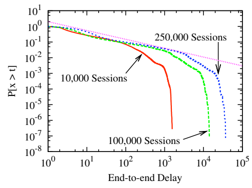
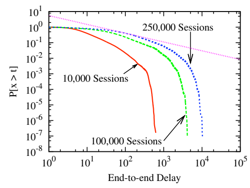
End-to-end packet delay distribution

- In spite of the similar waiting time distributions, packet delay distributions are much different
  - In the AT&T topology, packet delay distribution has long-tail
- Difference in structure leads to different packet delay distributions



AT&T topology



BA topology

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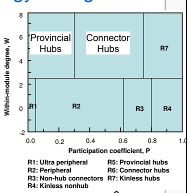
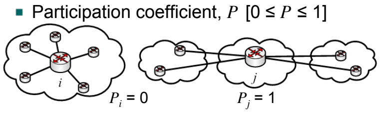
Comparison the structures of the 2 topologies

- Why the delay distribution of the AT&T topology is long-tailed?
  - Comparing the structures of the 2 topologies
- Classification of the roles of the nodes [17]
  - Separating a topology into some modules
  - Participation coefficient, P $[0 \le P \le 1]$

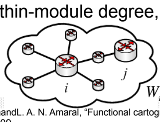


The roles of the nodes categorized by this figure



$P_i = 0$ $P_j = 1$

- Within-module degree, W



W_i is large, and W_j is small

[17] R. GuimeraandL. A. N. Amaral, "Functional cartography of complex metabolic networks," Nature, vol. 433, p. 895, 2005.

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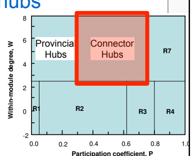
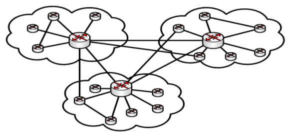
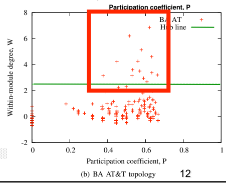
The property of the structure of the BA topology

- The BA topology has many "Connector hubs"
  - Hub nodes have many links connecting to other modules
- Hub nodes transfer a large amount of packets between modules







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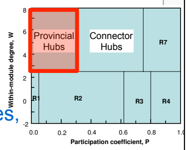
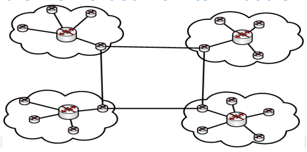
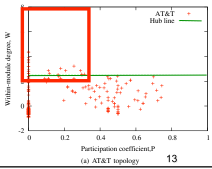
The property of the structure of the AT&T topology

- The AT&T topology has many “Provincial Hubs”
  - Hub nodes have many links connecting to the nodes in the same module
  - The AT&T topology has a few inter-module links
- First, packets are aggregated at hub nodes, and then forwarded via inter-module links







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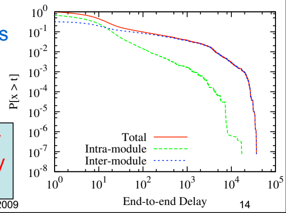
Effects of structure of router-level topology

- Separating the packet delay distribution of the AT&T topology into intra-module packets and inter-module packets
  - The number of sessions is 250,000
  - Inter-module packets traverse through the inter-module links the rest is inter-module packets
- The packet delay distribution of inter-module packets exhibits a long-tail characteristic
  - Inter-module links in the AT&T topology tend to be congested

The structure of the AT&T topology lead to this long-tailed packet delay distribution



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Conclusions and future works

- Investigation of traffic behavior in power-law networks with end-host flow control (stop & wait protocol)
  - 2 topologies have different structures
  - 2 topologies have the similar waiting time distribution
- The structure of the AT&T topology makes the packet delay distribution long-tailed
  - “Connector hubs” and a few inter-module links
- Future works
  - Evaluations on topologies that have heterogeneous link capacity
  - Evaluations with more complex flow control like TCP
  - Evaluations of combination of flow control between routers and end-host flow control