On the Packet Delay Distribution in Power-law Networks

Takahiro Hirayama*, Shinichi Nakamae**, Kenichi Anai***, and Masayuki Murata**
*Graduate School of Information Science and Technology, Osaka University, Japan.
**NTT Communication Science Laboratories, NTT Corporation, Japan.

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

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

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

Contributions of this work

- Traffic behavior in power-law topologies
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  - End-to-end flow control has large impacts to traffic behavior
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Network model

- 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
- Internet buffer
  - Each outgoing link has unlimited FIFO queuing buffer

*Ref. [12], Figure 6
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])

Betweenness centrality distribution
- Betweenness 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

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

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 ≤ P ≤ 1]
  - Within-module degree, \( W \)

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
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

The AT&T topology has a few inter-module packets and defines the within-module degree of node participation. Participation coefficient, $P_i$, is categorized into inter-module packets, where packets traverse through the inter-module links. The number of sessions is 250,000. Long-tail distribution is caused by flow-control between routers and end-host flow control in more evaluations of packet delay distribution on topologies that have flow-control perspective. For this purpose, we will conduct next topic is to consider the optimal design of topology from so that congestion does not occur on the inter-module links.

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