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Modularity Structure and Traffic Dynamics of ISP Router-level Topologies

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Research Background

- **The Internet is facing with ever-changing networking technologies and applications**
  - Adaptability to traffic fluctuation and various quality demands is required in the Internet
- **Understanding traffic dynamics of the Internet is important for designing future networks**
  - Flow control in the transport layer affects the traffic dynamics
  - However, it is not clear how the topological structure impacts on traffic dynamics

Investigating the relationships between traffic dynamics and topologies

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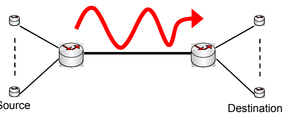
Flow Control and Statistical Properties of Traffic

- Internet traffic exhibits long-range dependence (LRD)
  - Traffic fluctuation appears to be independent of measurement time scale
- One of the reasons is flow control in the transport layer [4]
  - Because of flow control functionality of TCP: slow start, congestion avoidance
  - Stop-and-wait flow control causes LRD, too
  - However, previous studies deal with simple, and small topologies



[4] K. Fukuda, M. Takayasu, and H. Takayasu, "A cause of self- similarity in TCP traffic," International Journal of Communication Systems, vol. 18, pp. 603–617, Aug. 2005.

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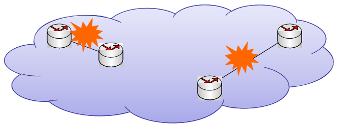
Investigation with Large-scale Topologies

- **Investigating with small-scale topologies is insufficient**
  - In large-scale topologies, competition of sessions occurs not only on the bottleneck link, but also on other links
  - Interactions between multiple competing sessions are difficult to examine



- **To reveal the traffic dynamics of real topologies, we discuss how end hosts affect each other in large-scale topologies**

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Research Purpose

- **Focusing on power-law characteristic of ISP topologies**
  - Power law: Probability $P(k)$ that a node has k links is proportional to $k^{-\gamma}$
  - Different topologies having the same degree distribution can exist
  - Difference in structure leads to difference in performance [7]

By comparing the statistical properties of traffic in various topologies, understanding characteristics of Internet traffic dynamics and its causal structure

[7] R. Fukumoto, S. Arakawa, T. Takine, and M. Murata, "Analyzing and modeling router-level Internet topology," Proceedings of the International Conference on Information Networking, pp.171–182, Jan. 2007.

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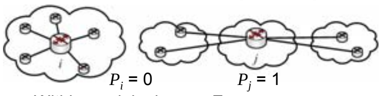
Network Topologies

- **Comparing two types of topologies having power-law characteristics**
  - To reveal the relationships between structures and traffic dynamics
  - Measured ISP (router-level) topologies
    - ISP: Internet Service Provider
  - Generated BA topologies
- **Two topologies having different structures**
  - 523 nodes and 1304 links
  - AT&T Topology: Measured router-level topology of AT&T
    - Measured by Rocketfuel [6]
  - BA (AT&T) Topology: Generated by BA model [5]

[5] A.L. Barabási and R. Albert, "Emergence of scaling in random networks," Science, vol.286, pp.509–512, Oct. 1999.
[6] N. Spring, R. Mahajan, D. Wetherall, and T. Anderson, "Measuring ISP topologies with Rocketfuel," IEEE/ACM Transactions on Networking, vol.12, pp.2–16, Feb. 2004.

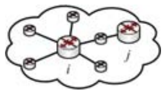
Comparison the structures of the 2 topologies

- **Classification of node functions***
  - Separating a topology into some modules [10]
  - Participation coefficient, P [$0 \le P \le 1$]

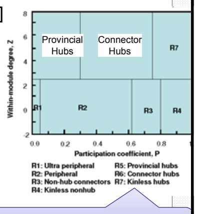


$P_i = 0$ $P_j = 1$

  - Within-module degree, Z



Z_i is large, and Z_j is small

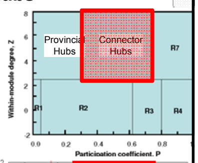


The functionality of the nodes is categorized by this figure

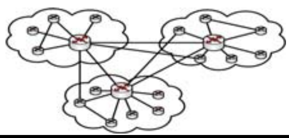
* Referenced from "R. Guimera and L. A. N. Amaral, "Functional cartography of complex metabolic networks," Nature, vol. 433, pp.895-900, 2005."
[10] M.E.J. Newman, "Modularity and community structure in networks," Proceedings of the National Academy of Sciences of the United States of America, pp.8577–8582, April 2006.

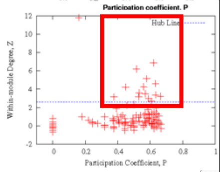
The property of structure of the BA topology

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



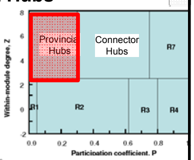
Congestions tend to occur near hub nodes and cause long delay

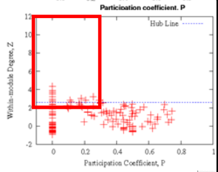


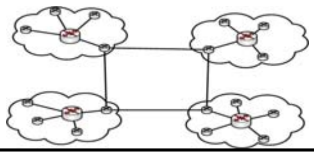


The property of structure of the AT&T topology

- **The AT&T topology has many "Provincial Hubs"**
  - Hub nodes have many links connecting to the nodes in the same module
  - Modules are connected by a few inter-module links (*high-modularity structure*)
- **Packets are first aggregated at hub nodes, and then forwarded via inter-module links**





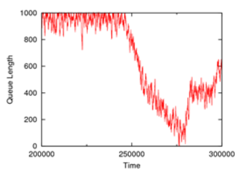


Simulation Evaluation

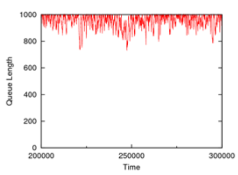
- **Network model**
  - Each link has the uniform link capacity and buffer size
  - Network load is defined by the number of sessions
    - The number of sessions is 100,000
  - Source and destination node pairs are selected randomly
  - Two flow control models
    - Stop and wait and TCP Reno model
- **Evaluation metric**
  - Queue length fluctuation

Evaluating Queue Length Fluctuation

- **Queue length fluctuation impacts on network throughput**
  - Drastic queue length fluctuation leads to non-constant queuing delay
- **Evaluating fluctuation with Hurst parameter (H)**
  - Index of Long-range Dependence ($0.5 < H < 1$)
  - Measurement Hurst parameters for each link with R/S plot method



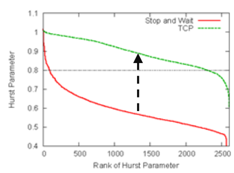
Ex. $H \fallingdotseq 1.0$



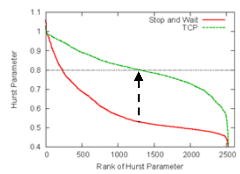
Ex. $H \fallingdotseq 0.5$

Topologies and Fluctuation

- **The number of highly fluctuating links increases by TCP**
  - Because of flow control functionality of TCP
- **In the AT&T topology, the number of highly fluctuating links is smaller than that in the BA topology**
  - Structure of the AT&T topology reduces highly fluctuating links



BA Topology



AT&T Topology

Evaluation of other ISP topologies

- **Each ISP topology has higher modularity value and reduces the number of fluctuating links**
  - Modularity is calculated using the method in [9]

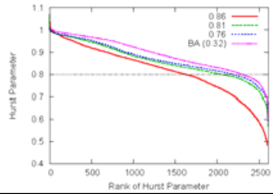
Topology	Nodes	Links	Modularity	Ratio of Fluctuating Links
AT&T	523	1304	0.89	0.11
BA AT&T			0.63	0.26
Sprint	467	1280	0.87	0.12
BA Sprint			0.68	0.26
Verio	817	1874	0.81	0.10
BA Verio			0.58	0.19
Telstra	296	594	0.96	0.14
BA Telstra			0.77	0.22

[9] M.E.J. Newman and M. Girvan, "Finding and evaluating community structure in networks," Physical Review E, vol.69, 026113, Feb. 2004

Correlation between Modularity and Fluctuation

- **Comparison between the three topologies having different modularity value (*Q*)**
  - Configured by changing the number of inter-module links
  - As the number of inter-module links increases, the modularity value decreases

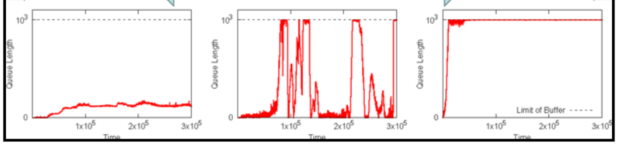
High-modularity structures prevent the appearance of highly fluctuating links



Relationships between link load and fluctuation

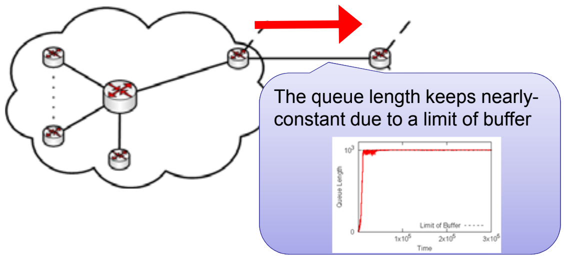
- **When a link load is low, the queue length does not fluctuate**
- **If the link load exceeds a certain level, the queue length is mostly constant due to a limit of buffer size in queue**
  - This phenomenon frequently occurs on the inter-module links
- **The queue length of the tributary links to the inter-module links fluctuates due to the dynamics of each TCP session**

Low ⟷ Number of passing sessions ⟷ High



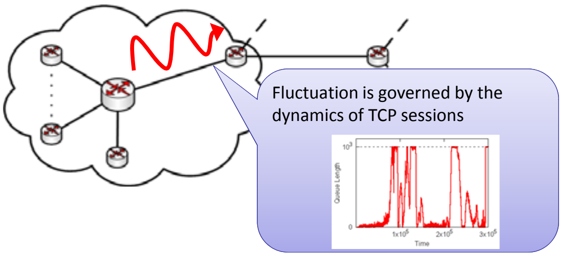
High-modularity Structure Prevents Fluctuation (1/2)

- **The large number of TCP sessions is aggregated at a few inter-module links**



High-modularity Structure Prevents Fluctuation (2/2)

- **Fluctuation occurs only around the connector nodes**
  - Connector-hub nodes rarely exist in high-modularity structure



Conclusion and Future Work

- **Investigating the interaction between the structures of topologies and flow control**
  - The functionality of TCP makes the queue length to fluctuate
- **The high-modularity structure of the ISP topologies reduces the ratio of highly fluctuating links**
  - As the modularity value decreases, the ratio of highly fluctuating links decreases
  - The modularity structure is essential to reduce fluctuation
- **Future work**
  - Developing a topology generation method that reproduces the modularity structure and apply it to performance evaluations