The Influence of Realism on Congestion in Network Simulations*

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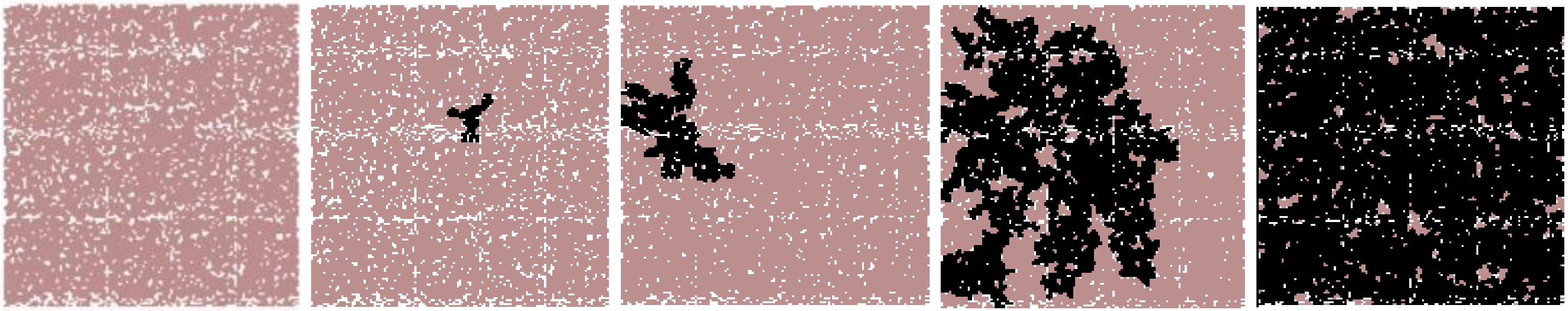
*For more details see: NIST Technical Note 1901
http://www.nist.gov/itl/antd/upload/TechNote1901-draft1.pdf

Total talk is 20 slides

- Motivation – 6 slides
- Research Questions and Approach – 2 slides
- Models – 5 slides
- Experiment Design – 1 slide
- Results – 5 slides
- Findings – 1 slide

Congestion Spreads across Networks in Space and Time

TIME



Empty 2D Lattice **Congestion Sporadic** **Congestion Persistent** **Congestion Spreading** **Congestion Widespread**

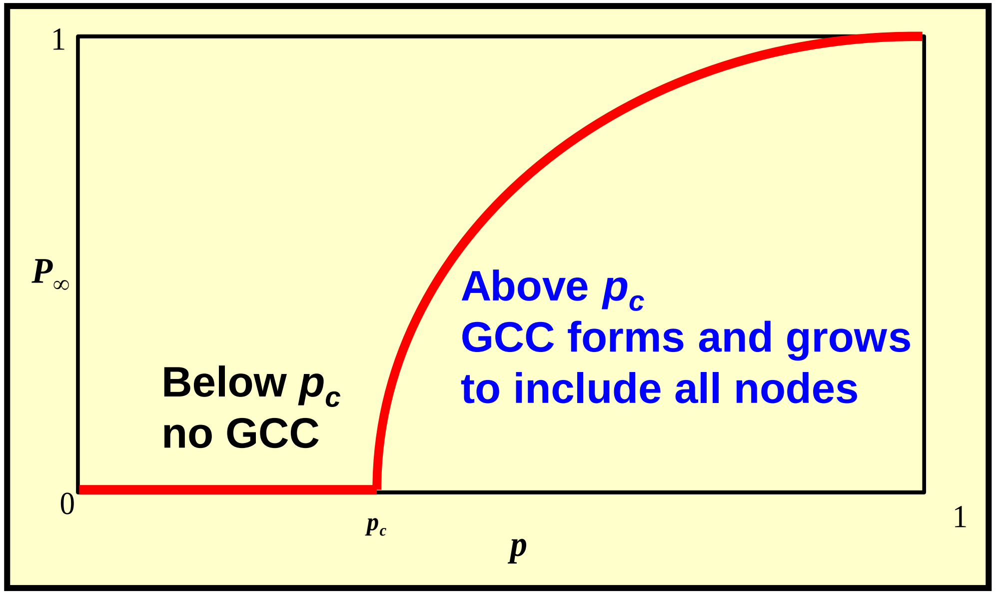
PACKET-INJECTION RATE

IMPLICATION: SHOULD BE POSSIBLE TO DETECT THE SPREADING PROCESS AND PROVIDE EARLY WARNING OF INCIPIENT CONGESTION COLLAPSE

2D lattice animation taken from “Percolation Theory Lecture Notes”, Dr. Kim Christensen, Imperial College London, October 9, 2002

Spreading Processes often Modeled as Percolation

Percolation → spread of some property in a lattice (or graph) leading to the formation of a *giant connected component* (GCC), as measured by P_∞, the proportion of nodes encompassed by the GCC



p is probability a node has property

p_c is known as the critical point

$p < p_c$ → no spread

$p = p_c$ → *percolation phase transition*

$p > p_c$ → spread occurs, and expands with increasing p

Near a critical point, the process exhibits signals, typically attributable to increasing, systemic correlation

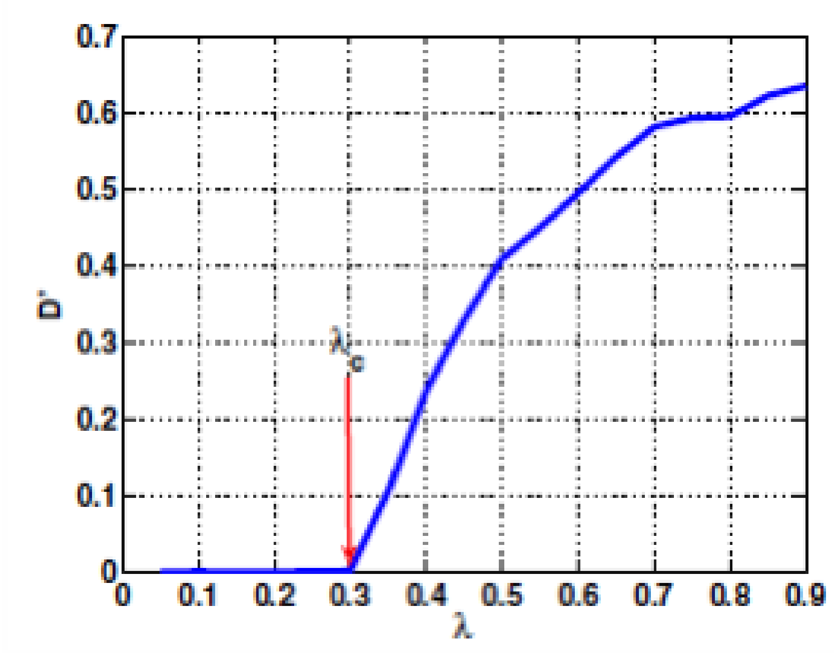
Academics Model Spreading Network Congestion as a Percolation Process

Year	Researchers	Location	Topology	Metrics	Precursor Signal
2001	**Sole & Valverde**	**Spain & USA (SFI)**	**2D Lattice**	**Packet Delay, Queue Length, Throughput**	**Self-similarity in log-log plot of power vs. freq.**
2002	**Woolf et al.**	**UK**	**2D Lattice**	**Packet Delay, Queue Length, Throughput**	**Long-Range Dependence (LRD) in time-series autocorrelation**
2004	**Arrowsmith et al.**	**UK**	**Triangular & Hexagonal Lattice**	**Packet Delay, Queue Length, Throughput**	**LRD shown with Hurst parameter increases from rescaled range statistical (R-S) analysis**
2005	**Mukherjee & Manna**	**India**	**2D Lattice**	**Packet Delay, Queue Length, Load per Node**	**Self-similarity in log-log plot of power vs. freq.**
2007	**Lawniczak et al.**	**Canada**	**2D Lattice**	**Packets in Flight**	**LRD shown with Hurst parameter increases from R-S analysis**
2007	**Tadic et al.**	**Slovenia, Austria, UK**	**Generated SF & UH**	**Packet Delay, Queue Length, Network Load**	**Systemic changes in network-load time series**
2009	**Sarkar et al.**	**USA**	**2D Lattice**	**Packet Delay, Queue Length**	**Order parameter becomes positive**
2009	**Wang et al.**	**China**	**Generated ER, WS, HK**	**Packets in Flight/Injected**	**Order parameter becomes positive**
2010	**Rykalova et al.**	**USA**	**1D Ring & 2D Lattice**	**Packet Delay, Queue Length, Network Load**	**Increasing amplitude fluctuation in metrics**

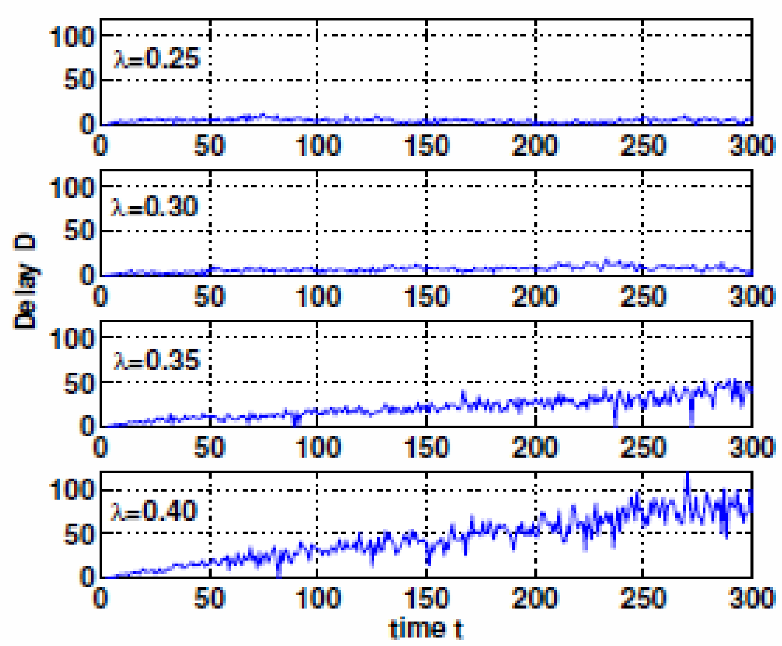
Topology Key: SF = Scale-Free UH = Uncorrelated Homogeneous ER = Erdos-Reyni Random
WS = Watts-Strogatz Small World HK = Holme-Kim variant of Preferential Attachment

Finding that Signals Appear Near a Critical Point in Abstract Network Models

Penn State Researchers (Sarkar, Mukherjee, Srivastav, and Ray 2009) find increasing transit delay as $p > p_c = 0.3$



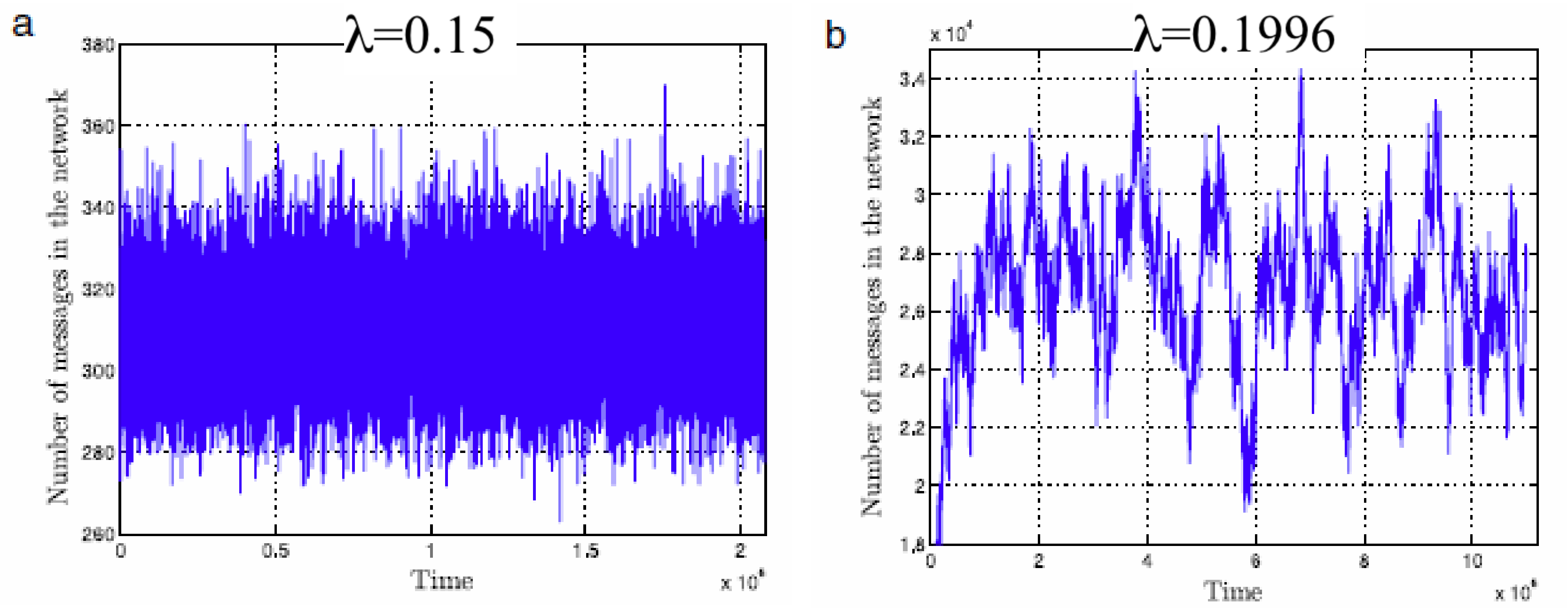
Aggregate Avg. Transit Delay (D^*) vs. Network Load (λ)



Sampled Avg. Transit Delays (D) for Four Network Loads (λ)

Increasing slope in time series of selected measured variables could signal crossing a critical point, allowing network managers to be alerted prior to network collapse

Boston University Researchers (Rykalova, Levitan, and Browe 2010) find increased correlation in time series of packets in transit as p nears $p_c = 0.2$



Packets fluctuate between 260 and 380

Packets fluctuate between 18,000 and 34,000

Increasing autocorrelation in time series could signal an approaching critical point, allowing network managers to be warned prior to network collapse

Abstract Models Lack Key Traits of Real Networks

Routers & Links

1. Human-engineered, tiered topologies, with propagation
2. Router buffer sizes finite
3. Router speeds varied to meet demands, limit losses

Computers

4. Injection from sources and receivers only at lowest tier
5. Distribution of sources and receivers non-uniform
6. Connection of sources/receivers with few varied speeds

Users

7. Duty cycle of sources exhibits cyclic behavior
8. Human sources exhibit limited patience
9. Sources transfer flows of various sizes

Protocols

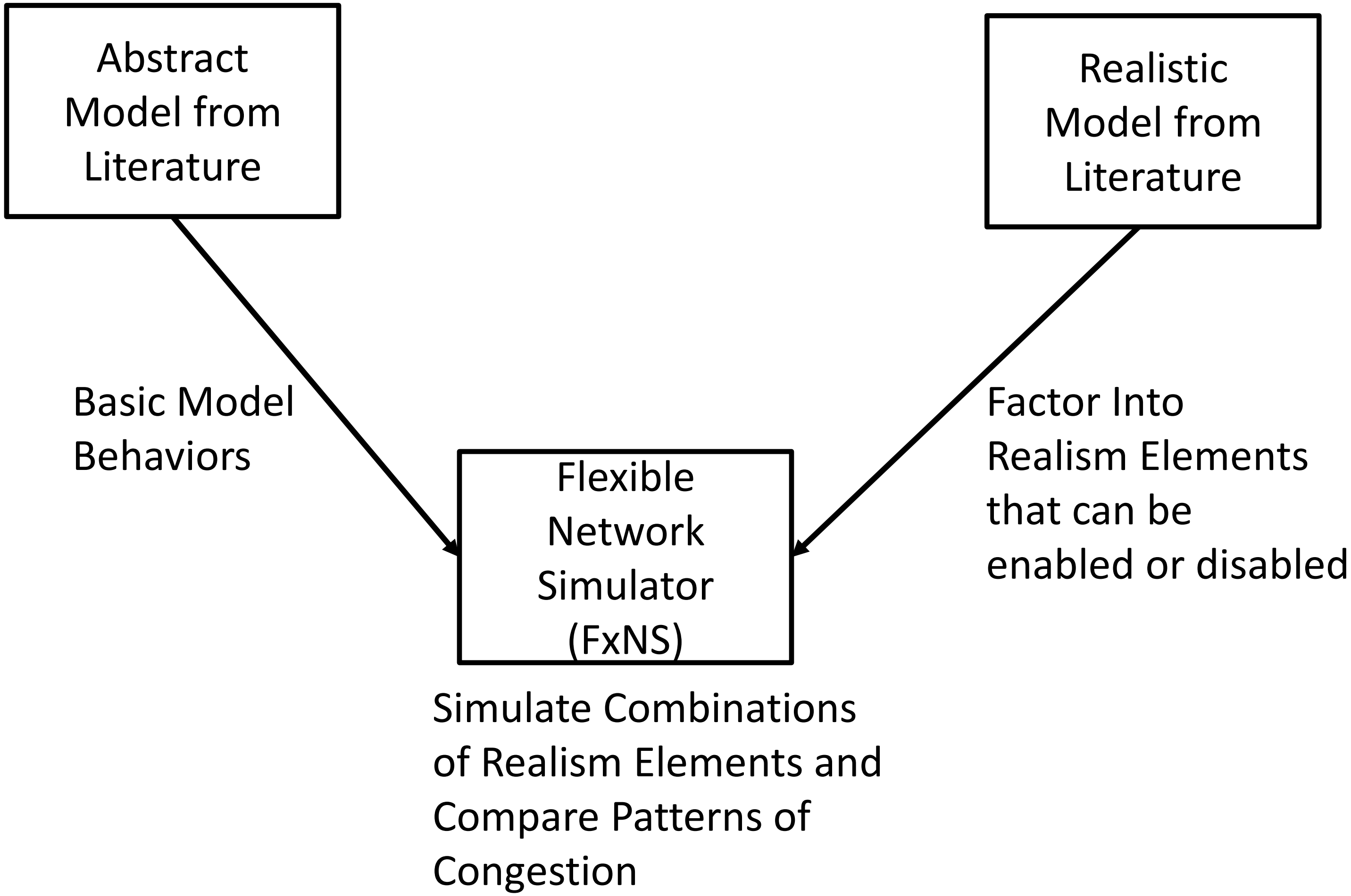
10. Flows use the Transmission Control Protocol (TCP) to modulate injection rate based on measured congestion

DOES LACK OF REALISM MATTER WHEN SIMULATATING NETWORK CONGESTION?

Specific Research Questions

- Does congestion spread in abstract models mirror spread in realistic models?
- Are some elements of realism essential to capture when modeling network congestion?
- Are some elements unnecessary?
- What measures of congestion can be compared, and how, across diverse network models?

Research Approach



Abstract Model from Literature

Realistic Model from Literature

Basic Model Behaviors

Factor Into Realism Elements that can be enabled or disabled

Flexible Network Simulator (FxNS)

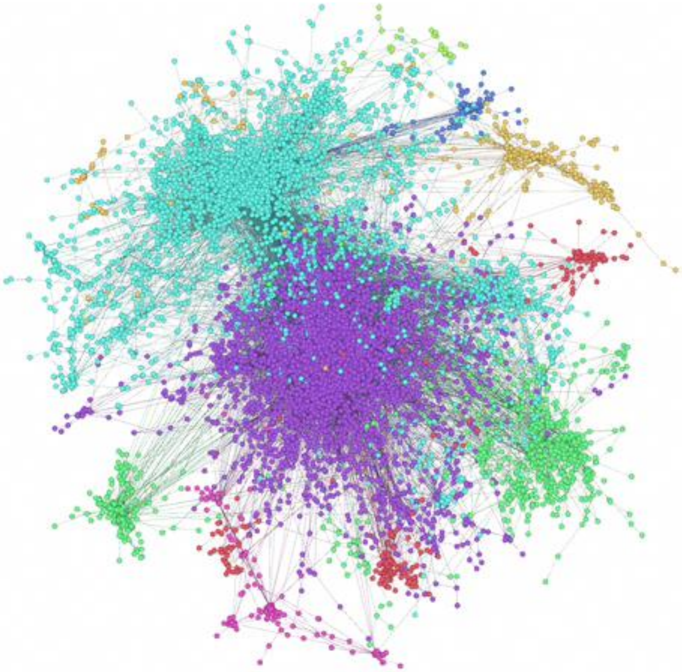
Simulate Combinations of Realism Elements and Compare Patterns of Congestion

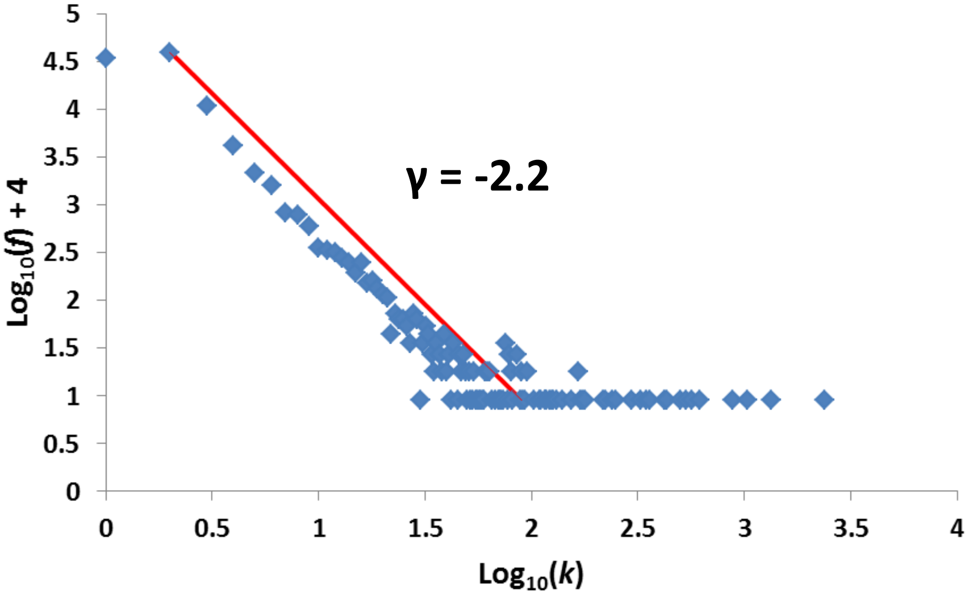
Models

- Abstract EGM Model→high abstraction
- Realistic MesoNet Model→high realism
- Flexible FxNS Model→combinations of realism from low to high

The Abstract (EGM) Model

P. **E**chenique, J. **G**omez-Gardenes, and Y. **M**oreno, “Dynamics of Jamming Transitions in Complex Networks”, *Europhysics Letters*, 71, 325 (2005)





Simulations based on 11,174-node scale-free graph, $P_k \sim k^{-\gamma}$ & γ=2.2, taken from a 2001 snapshot of the Internet Autonomous System (AS) topology collected by the Oregon Router Server (image courtesy Sandy Ressler)

Details of the EGM Model

Node Buffer Size: ∞ for EGM, all packets buffered, no packets dropped

Injection Rate: ***p*** packets injected at random nodes (uniform) at each time step

Destination Node: chose randomly (uniform) for each packet

Forwarding Rate: 1 packet per node at each time step

Routing Algorithm: If node is destination, remove packet; Otherwise select next-hop as neighboring node ***i*** with minimum δ_i

System Response: proportion ρ of injected packets queued in the network

Computing δ_i

h is a ***traffic awareness*** parameter, whose value 0 ... 1.

$$\delta_i = hd_i + (1-h)c_i,$$

where ***i*** is the index of a node's neighbor, d_i is minimum #hops to destination via neighbor ***i***, and c_i is the queue length of ***i***.

***h* = 1 is shortest path (in hops)**

Measuring ρ

$$\rho = \lim_{t\to\infty} \frac{A(t+\tau) - A(t)}{\tau p}$$

A = aggregate number of packets

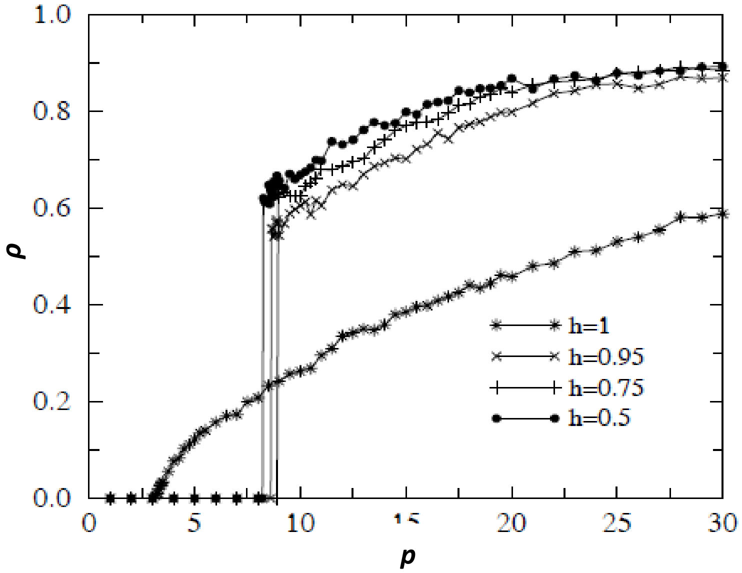
t = time

τ = measurement interval size

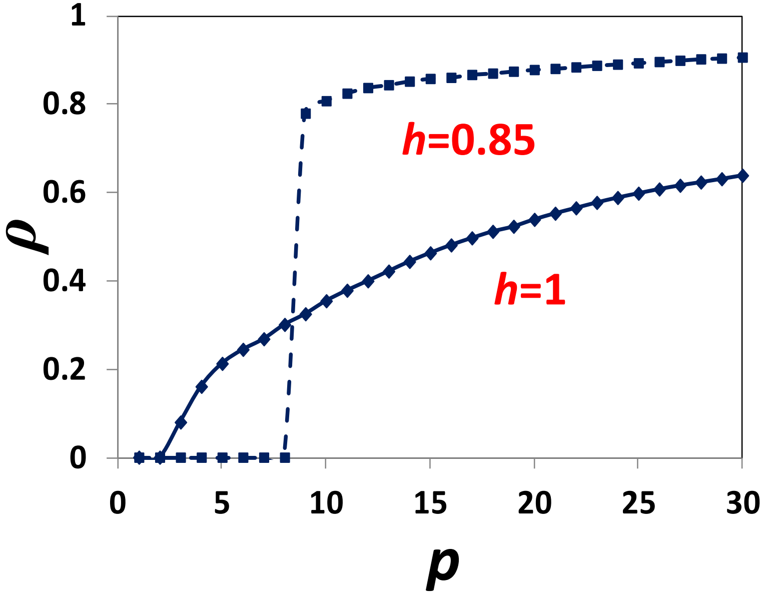
p = packet inject rate

Comparative Simulation Results

EGM Simulations



FxNS Simulations with
All Realism Elements Disabled



The Realistic (MesoNet) Model

K. Mills, E. Schwartz, and J. Yuan, "How to Model a TCP/IP Network using only 20 Parameters", WSC 2010, Dec. 5-8, Baltimore, MD.

Category	ID	Name	FxNS
Network	x1	topology	NC
	x2	propagation delay	DE
	x3	network speed	VS
	x4	buffer provisioning	PD
Sources & Sinks	x5	number sources/sinks	SR
	x6	source distribution	
	x7	sink distribution	
	x8	source/sink speed	VS
Users	x9	think time	*p*
	x10	patience	n/a
	x11	web object file sizes	FL
	x12	larger file sizes	n/a
	x13	localized congestion	
	x14	long-lived flows	
Congestion Control	x15	control algorithm	TCP
	x16	initial *cwnd*	
	x17	Initial *sst*	
Simulation Control	x18	measurement interval	fixed
	x19	simulation duration	fixed
	x20	startup pattern	*p*

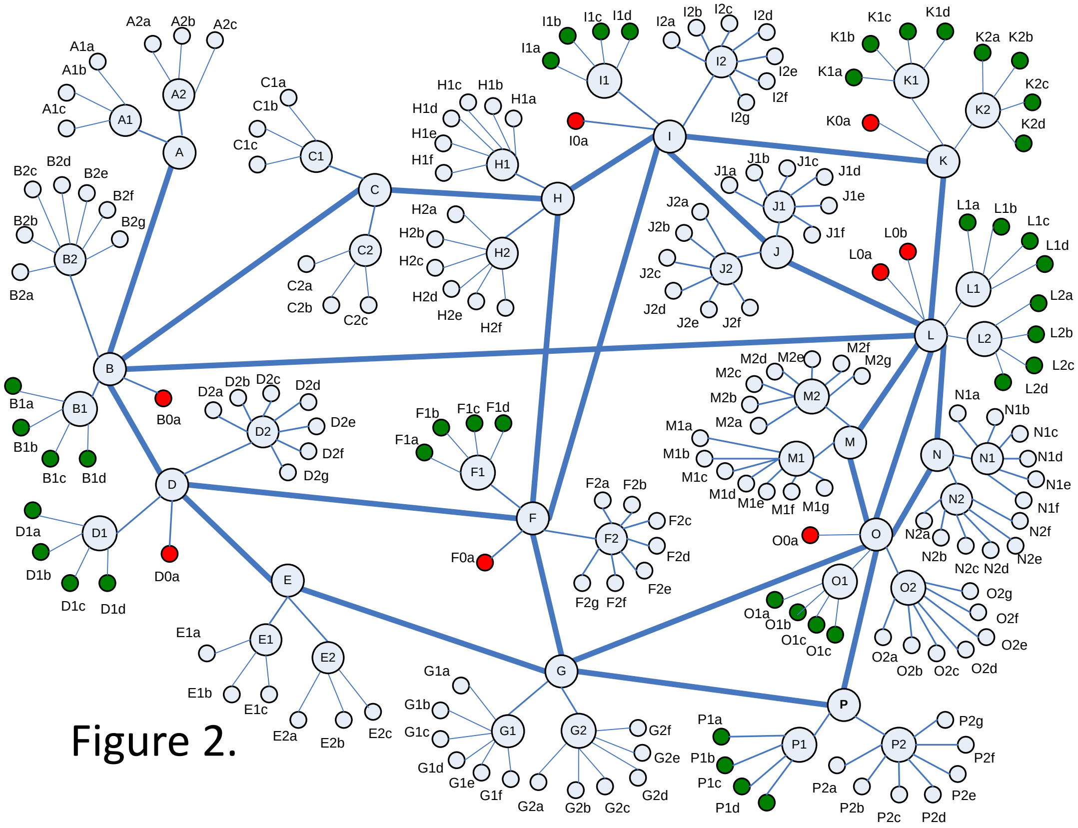


Figure 2.

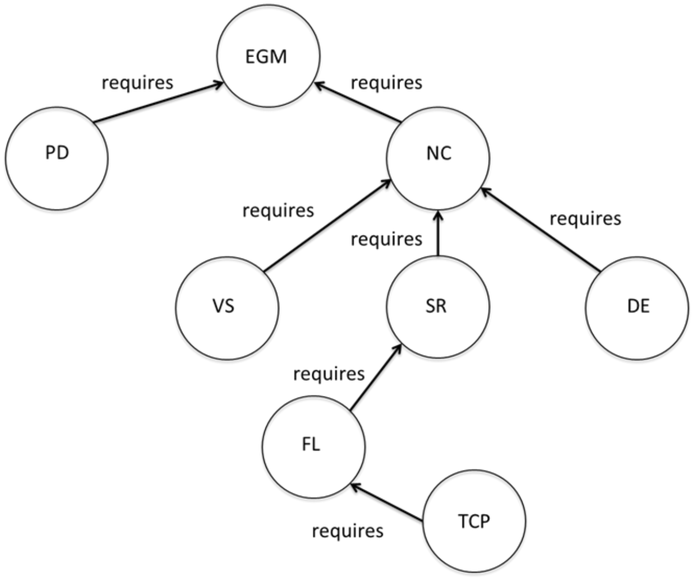
Comparisons of MesoNet Simulations vs. FxNS Simulations (all realism elements enabled) for eight MesoNet responses are available in **NIST TN 1901 – Appendix A**

FxNS Combinations

34 Valid FxNS Combinations

Seq	Cmb	TCP	FL	SR	DE	VS	NC	PD
1	c0	0	0	0	0	0	0	0
2	c1	0	0	0	0	0	0	1
3	c2	0	0	0	0	0	1	0
…								
32	c123	1	1	1	1	0	1	1
33	c126	1	1	1	1	1	1	0
34	c127	1	1	1	1	1	1	1

Dependencies among Realism Elements



Experiment Design

	Enabled	Disabled
PD	buffers = 250×router speed	buffers = ∞
NC	3-tier 218-node topology as in Fig. 2 with routers labeled as core, PoP, D-class, F-class or N-class	flat 218-node topology as in Fig. 2 but with routers unlabeled
VS	core 80 p/ts; PoP 10 p/ts; D-class 10 p/ts; F-class 2 p/ts; N-class 1 p/ts; fast source/sink 2 p/ts; normal source/sink 0.2 p/ts	all routers and sources/sinks 9 p/ts
DE	core links have propagation delays	no propagation delays
SR	51,588 sources & 206,352 sinks deployed uniformly below access routers	no sources or sinks deployed
FL	transfers are packet streams: sized randomly from Pareto distribution (mean 350, shape 1.5) - streams set up with TCP connection procedures	transfers are individual packets
TCP	packet transmission regulated by TCP congestion-control including slow-start (initial *cwnd* = 2 *sst* = $2^{30}/2$) and congestion avoidance	packet transmissions not regulated by congestion-control

FIXED PARAMETERS

- 218-Router Topology (Fig. 2)
- Routing (SPF propagation delay)
- Duration (200,000 ts per p)

VARIABLE PARAMETERS

- Packet-Injection Rate p (up to 2500)
- FxNS Combination

RESPONSES

- Congestion Spread $\chi=|G_\chi|/|G_N|$
- Connectivity Breakdown $\alpha=|G_\alpha|/|G_N|$
- Proportion of Packets Delivered π
- Scaled (0..1) Latency of Delivered Packets δ

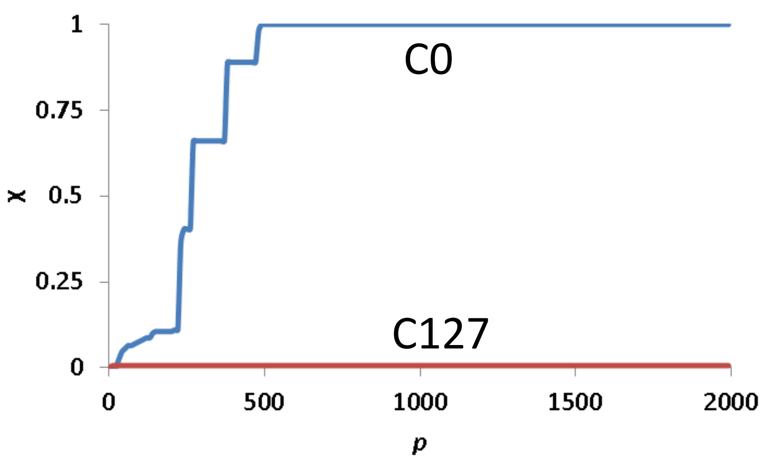
Only concepts in common among all 34 combinations: graph and packet

Results[1,2]

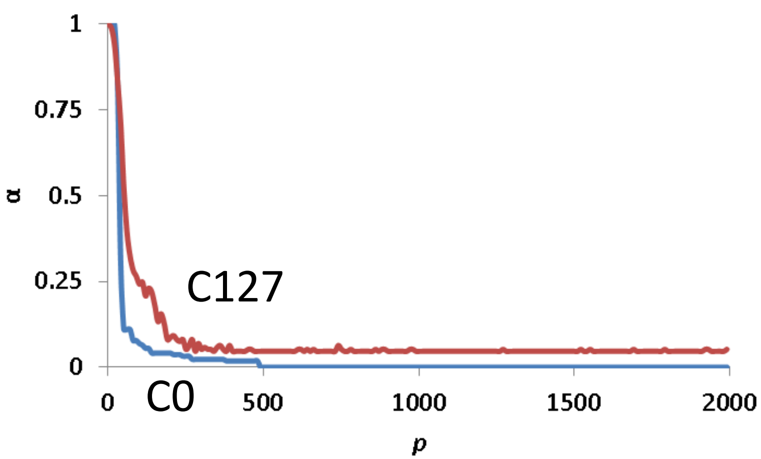
[1] 136 *xy*-plots (34 FxNS combinations × 4 responses) are available at: http://tinyurl.com/poylful

[2] Related FxNS simulation data can be explored interactively using a multidimensional visualization created by Phillip Gough of CSIRO: http://tinyurl.com/payglq6

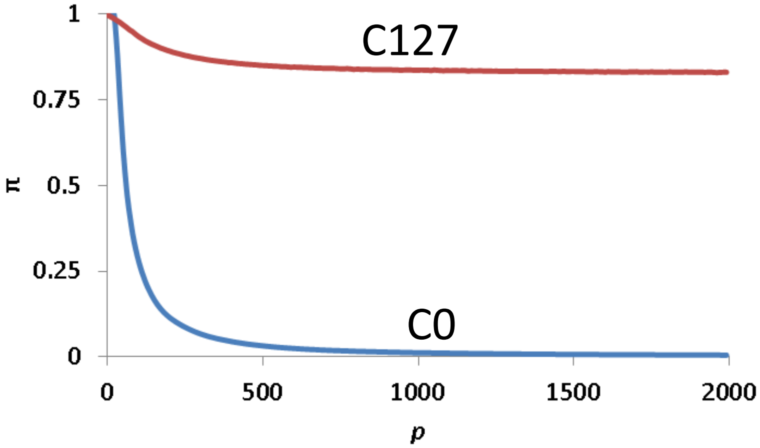
Results I – Abstract (C0) vs. Realistic (C127)



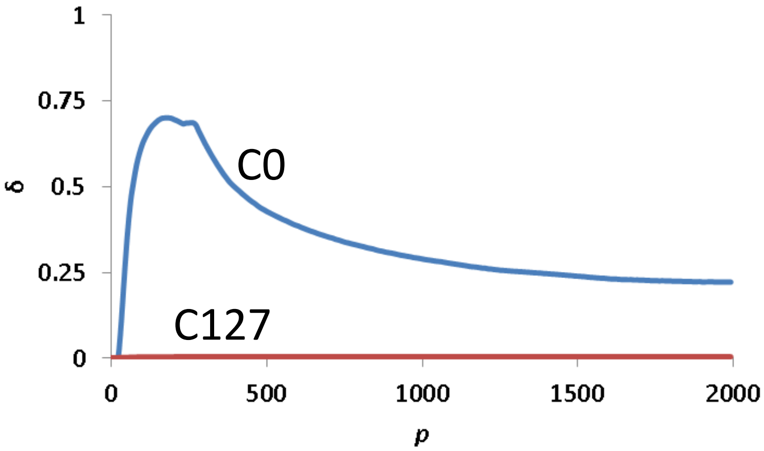
Congestion Spread (χ)



Connectivity Breakdown (α)



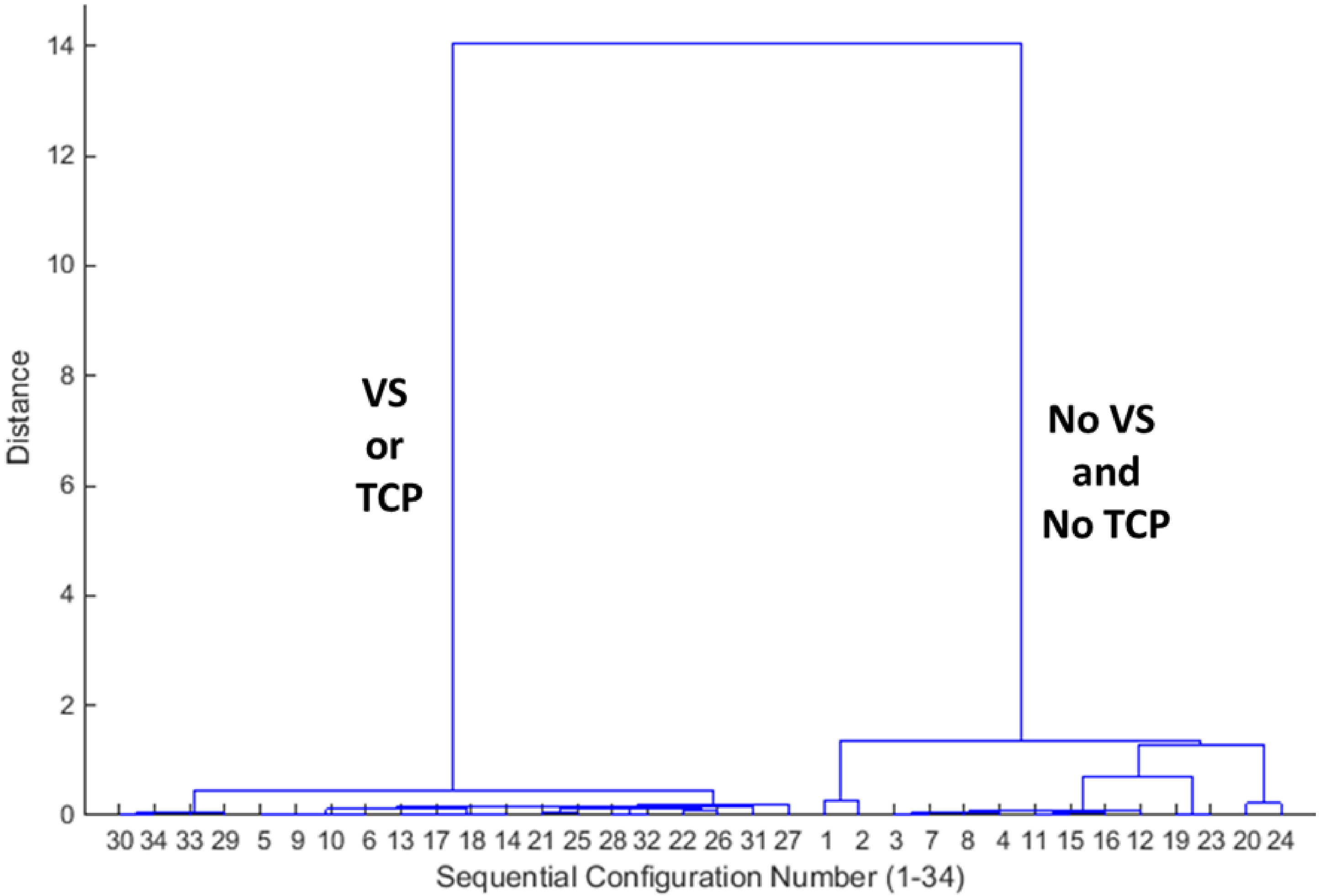
Packets Delivered (π)



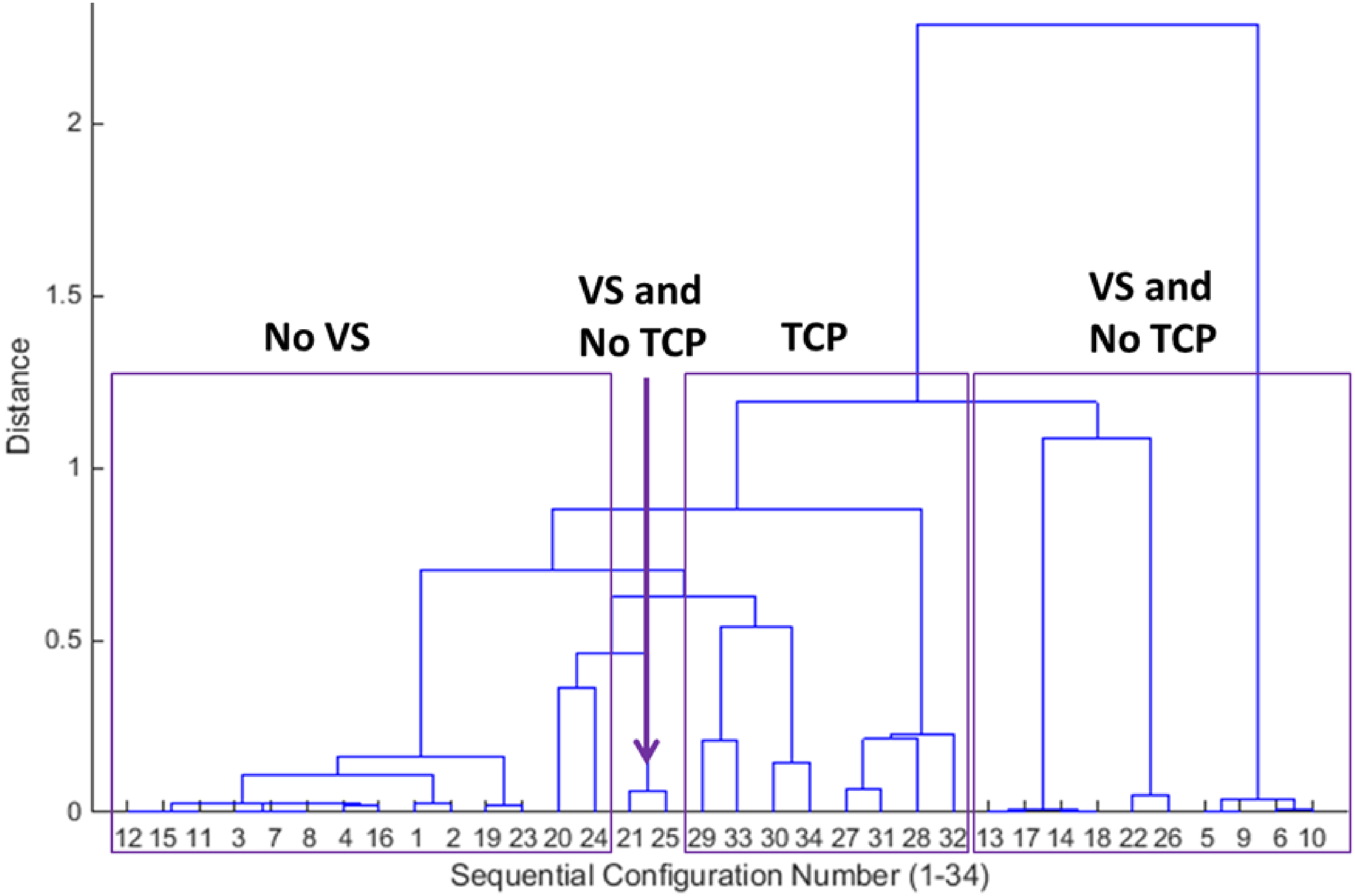
Packet Latency (δ)

Plots for all responses and all 34 combinations available: http://tinyurl.com/poylful

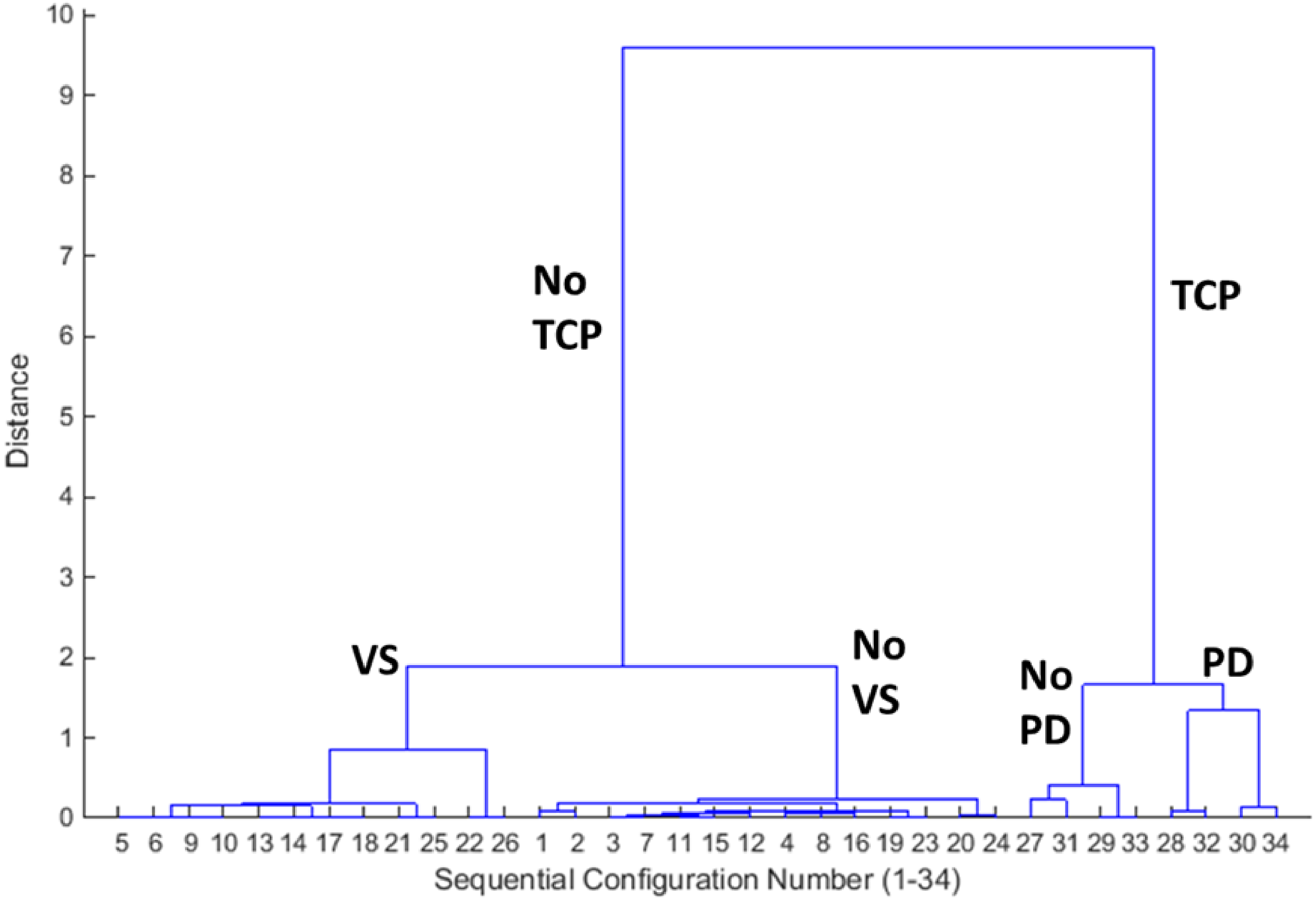
Results II – Congestion Spread χ All Combinations



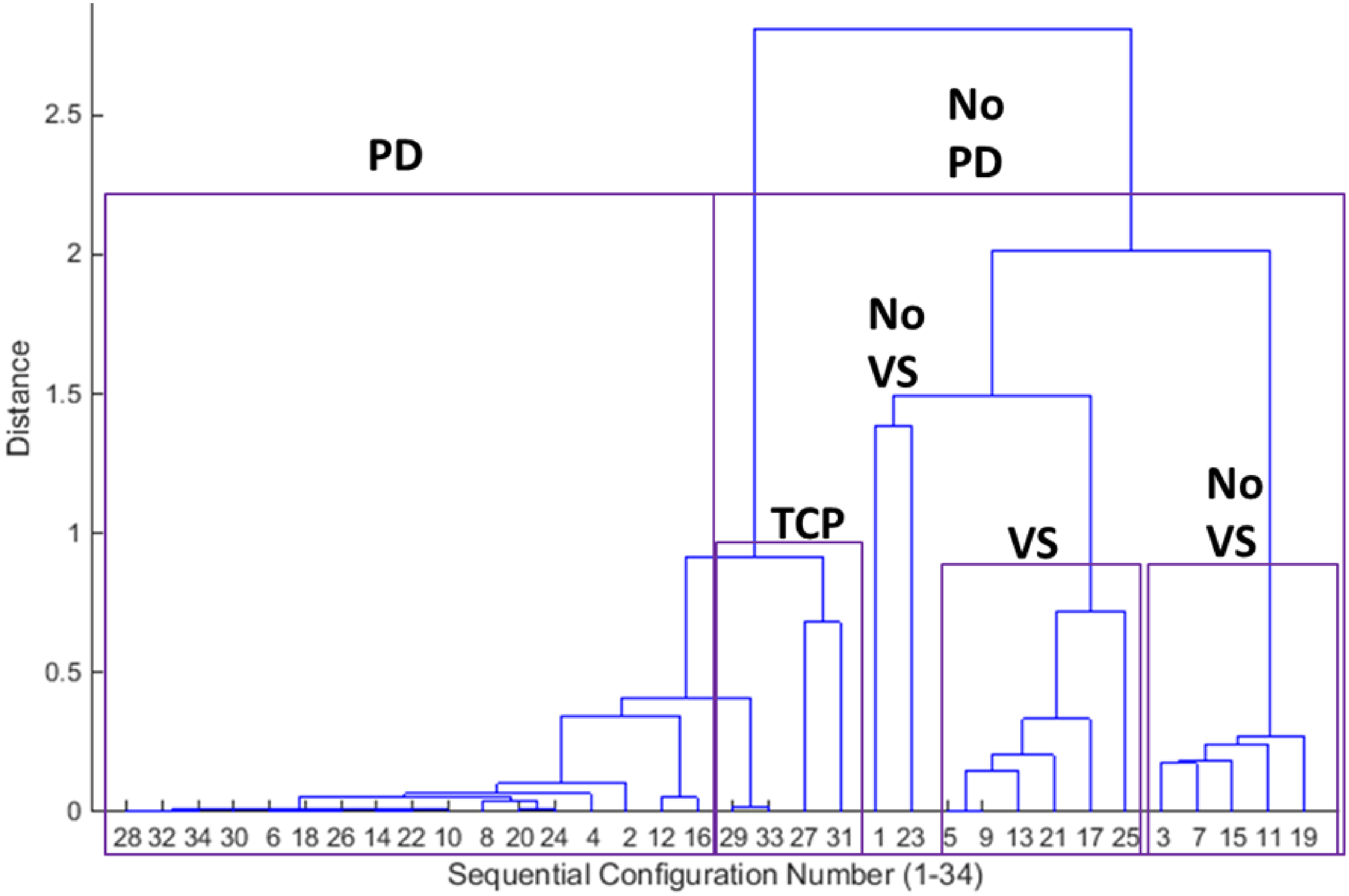
Results III – Connectivity Breakdown α All Combinations



Results IV – Packet Delivery π All Combinations



Results V – Scaled Packet Latency δ All Combinations



Findings

- Congestion spreads differently in abstract and realistic models
- Hierarchical Router Speeds and TCP very important to model
- Packet dropping important to model for accurate packet latencies
- Propagation delay not important to model in a continental US network, but would be important to model in topologies where propagation delays exceed queuing delays
- Congestion spread, connectivity breakdown and the effectiveness and efficiency of packet delivery can be measured using only two concepts: graphs and packets