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# Evaluating Predictors of Congestion Collapse in Communication Networks

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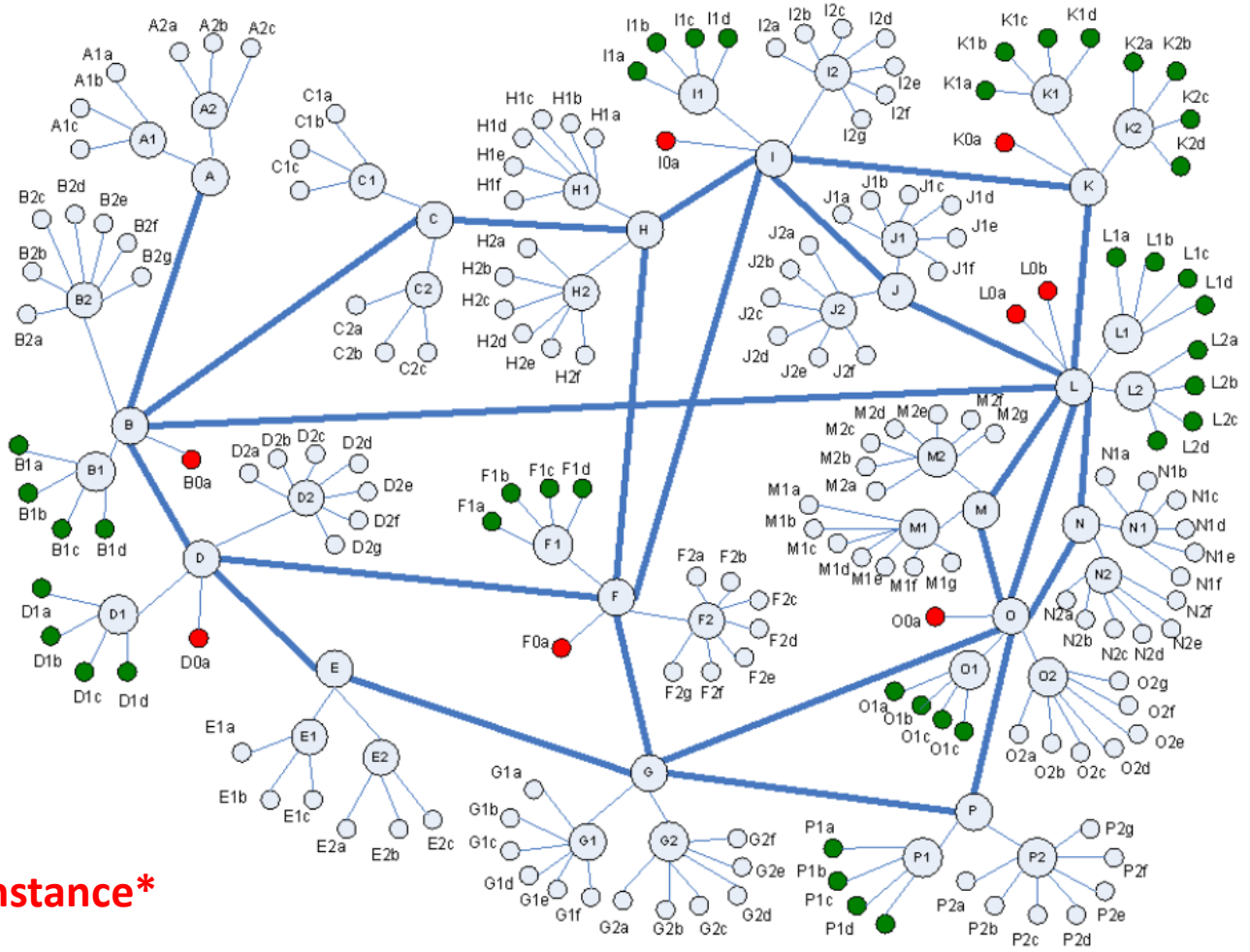
# Paper Contributions

- Proposes *5 run-time predictors* of congestion collapse
- Defines *simulation-based method* to evaluate predictors
- Applies method to characterize and *compare predictors*
- Shows *simulation realism affects predictor performance*

# Evaluated Congestion Predictors in Simulated Internet-Protocol Network

- 218 routers in 3 Tiers: 16 core, 32 PoP, and 170 edge
- Tier 4 (not shown): 257K sources/receivers
- Bush-Meyer buffer sizing
- TCP (or UDP) packet-injection procedures
- SPF routing - hops
- Tiered router speeds

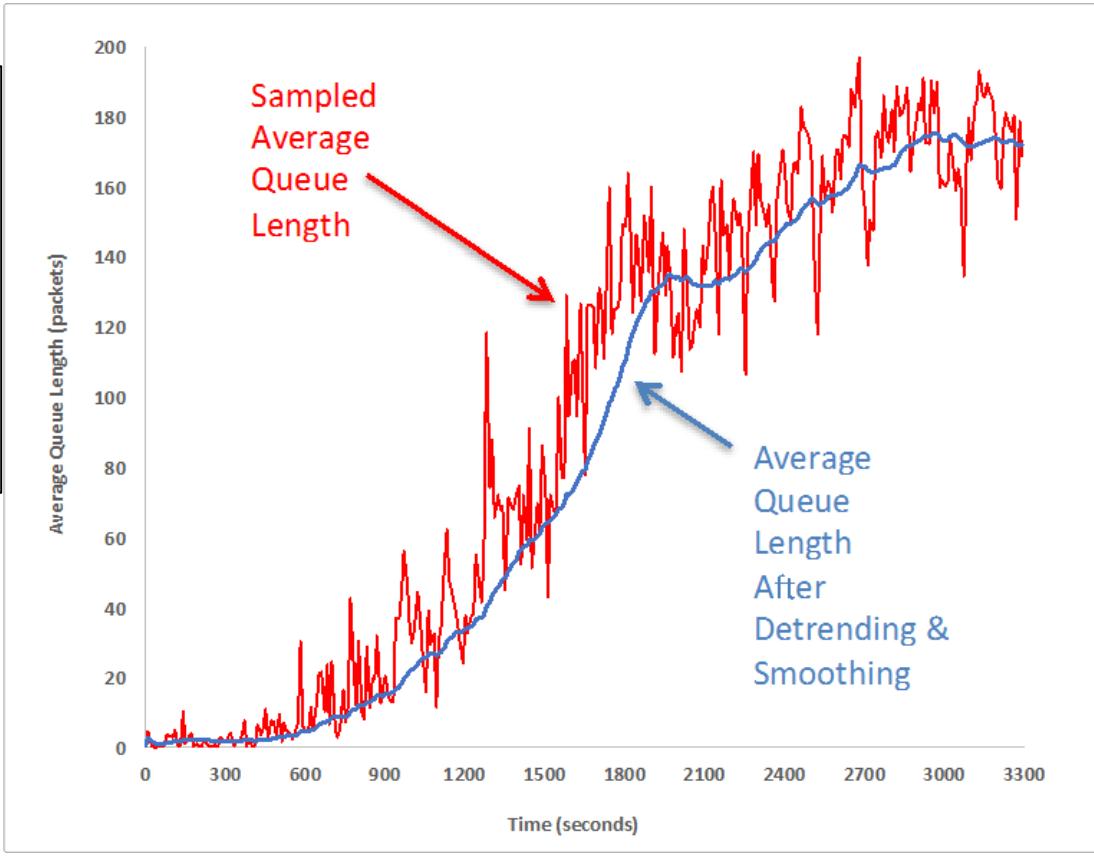
| Tier | Speed | |
|---|---|---|
| Core | 2*S* | |
| PoP | *S*/4 | |
| Edge: Normal | *S*/4/10 | gray |
| Edge: Fast | 2*S*/4/10 | green |
| Edge: Very Fast | *S*/4 | red |




***Each router runs predictor instance***

# Predictors Analyze Sampled, Smoothed Router Queue-Length Time Series

1. Queue sampled every 200 ms
2. Statistic (μ or v) computed over 50 samples (i.e., in each 10-s slot)
3. Queue under normal traffic subtracted
4. Samples smoothed using Nadaraya-Watson algorithm




***Predictors analyze** **sliding window, *W*, of size 300 s, i.e., 30 10-s slots, with a 10-s advance, over smoothed queue-length statistic time series***

# Predictor Definition

**GENERAL PROCEDURE FOR ANY PREDICTOR:**

$$\sum_{i=1}^{W} [\mathbf{P}(Q_i) \geq P_{Threshold}] \geq P_{AlertLimit}$$

**THREE PARAMETERS SPECIALIZE EACH PREDICTOR:**

(**P**, $P_{Threshold}$, $P_{AlertLimit}$) ➔ **P** ≡ *predictor-specific* Function

$P_{Threshold}$ ≡ *predictor-specific* Threshold

$P_{AlertLimit}$ ≡ *predictor-specific* Alert Limit

# Predictors

**Predictors require 11.9 us (TH) to 23.3 us (AC) per sliding window (i.e., every 10 s) on a 3.4 GHz processor**

**AC – autocorrelation** (α(1), 0.7, 21)

$$a(1) = \frac{\mathrm{E}[(Q_i - \mu(Q))(Q_{i-1} - \mu(Q))]}{\sigma^2(Q)}$$

MATLAB xcorr(), xcov(), or statistical autocorrelation function

**VR – variance** (ν, μ(ν)+|3σ(ν)| : *steady load*, 21)

$$\nu = \frac{\sum_{i=1}^{N} |Q_i - \mu(Q)|^2}{(N-1)}$$

Variance beyond $P_{Threshold}$ should occur by chance < 1% of the time (also tried μ(ν)+|σ(ν)|

**TH – threshold** ($Q_i$, 0.25($C$ - μ($Q$) : *steady load*), 1)
$C$ is buffer capacity and μ($Q$) is mean queue length under steady load

**GP – growth persistence** ($Q_i$ | $Q_i > Q_{i-1}$, 0.25($C$ - μ($Q$) : *steady load*), 21)

**GR – growth rate** ((estimated $Q_{j-1} + s_{j-1}$) + $s_j$, 0.25($C$ - μ($Q$) : *steady load*), 21))

$$s = \frac{\sum_{i=1}^{W} (i - (W+1)/2)(Q_i - \mu(Q))}{\sum_{i=1}^{W} (i - (W+1)/2)^2}$$

Predictor implementation costs in processor kilocycles/window; ↓= better; best cost in **bold:** TH cheapest; AC most expensive

| Predictor | Sample/ Detrend | Smooth | Compute Predictor | Decide Alert | Total↓ |
|---|---|---|---|---|---|
| AC | **0.98** | **25.86** | 51.90 | 0.41 | 79.14 |
| VR | 36.10 | 26.58 | 3.21 | **0.36** | 66.26 |
| TH | **0.98** | **25.86** | **0** | 13.61 | **40.45** |
| GP | **0.98** | **25.86** | **0** | 13.95 | 40.78 |
| GR | **0.98** | **25.86** | 1.19 | 12.93 | 40.95 |

# Experiment

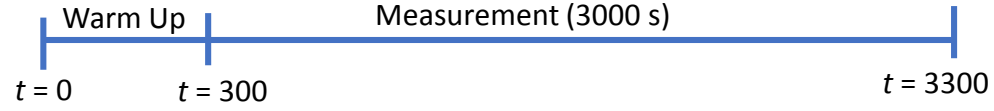
| Predictor | | Network Model | | Traffic Scenario |
|---|---|---|---|---|
| Autocorrelation | X | Realistic TCP | X | Increasing Load |
| Variance | | Realistic UDP | | |
| Threshold | | | | Steady Load |
| Growth | | Abstract | | |
| Growth Rate | | | | |

**Evaluate each predictor under 6 conditions**

Steady Load:= *p* is 10 packets/s throughout time

Increasing Load := *p* increases by 10 packet/s every 10 s after warm up

Time Line :=




Abstract Network Model :=

- flatten topology
- assign routers identical speeds
- remove sources & receivers
- infinite buffers
- packets injected at rate *p*, source routers chosen uniformly
- destination routers chosen uniformly
- SPF routing - hops

TCP & UDP sources inject flows (i.e., packet streams) with flow injection probability := $p/s \times f$, where *s* is # sources and *f* is mean flow size (350 packets here)

A := predictor alert; O := overload exception; *t* := time

**true positive** (*tp*) := $A_t < O_t$
**true negative** (*tn*) := ¬A ^ ¬O
**false positive** (*fp*) := A ^ ¬O
**false negative** (*fn*) := ¬A ^ O
**late positive** (*lp*) := $O_t < A_t$

## Performance Metrics

measured for each router; then averaged

**accuracy** := (*tp* + *tn*) / (*tp* + *tn* + *fp* + *fn* + *lp*)

**latency** := $O_t - A_t \mid tp$

**persistence** := $\frac{\int_{A_t}^{O_t} A}{(O_t - A_t)} \mid tp$

Each router raises overload exception, O, when queue length ≥ 70% *C*

# Successful Outcomes under Increasing Load

## True-Positive & True-Negative Rates

| | TPR ↑ | | | TNR ↑ | | | TPR + TNR | | |
|---|---|---|---|---|---|---|---|---|---|
| | TCP | UDP | ABS | TCP | UDP | ABS | TCP | UDP | ABS |
| AC | 0.913 | 0.963 | 0.131 | 0 | 0 | 0.805 | 0.913 | 0.963 | 0.936 |
| VR | 0.862 | 0.963 | 0.133 | 0 | 0 | 0 | 0.862 | 0.963 | 0.133 |
| TH | 0.723 | 0.75 | 0.128 | 0.254 | 0.25 | 0.859 | 0.977 | 1 | 0.986 |
| GP | 0.634 | 0.74 | 0 | 0.259 | 0.26 | 0.853 | 0.894 | 1 | 0.853 |
| GR | 0.686 | 0.75 | 0 | 0.254 | 0.25 | 0.853 | 0.94 | 1 | 0.853 |

- ~85% of routers in Abstract Network do not reach overload, as congestion spreads outward slowly from routers with high centrality (unrealistic)
- Threshold predictor performs best
- Variance predictor performs worst, no true negatives in Abstract Network

## Mean Warning Times & Persistence

| | Mean Latency (min) | | | Mean Persistence ↑ | | |
|---|---|---|---|---|---|---|
| | TCP | UDP | ABS | TCP | UDP | ABS |
| AC | 10.73 | 22.89 | 17.52 | 1 | 1 | 0.992 |
| VR | 10.48 | 21.72 | 24.33 | 0.994 | 1 | 0.991 |
| TH | 7.67 | 15.77 | 0.58 | 1 | 1 | 1 |
| GP | 4.61 | 11.86 | — | 0.972 | 0.99 | — |
| GR | 5.63 | 13.53 | — | 1 | 1 | — |

All predictors quite persistent

- Under realistic network models, average warning times from ~ 5 to 23 mins
- Variance and Autocorrelation gave most warning time because the other predictors transition more slowly to alerts (guarded by $0.25(C - \mu(Q)$ : *steady load*)
- TCP Network yielded least warning time because congestion-control procedures slow the rate of increasing congestion
- TCP Network warning time exceeded 15 mins for 12% (GP) to 23% (VR) of routers

# Erroneous Outcomes under Increasing Load

Error Rates ↓ is better

| | Error Rate (1 – Con) | | | Mean |
|---|---|---|---|---|
| | TCP | UDP | ABS | Error Rate |
| AC | 0.087 | 0.037 | 0.074 | 0.06 |
| VR | 0.138 | 0.037 | 0.867 | 0.347 |
| TH | 0.023 | 0 | 0.014 | 0.012 |
| GP | 0.106 | 0 | 0.147 | 0.084 |
| GR | 0.06 | 0 | 0.147 | 0.069 |

- Threshold predictor performs best (1.2% error)
- Variance predictor performance unacceptable
- Other predictor error rates okay (< 10% error)

Error Rates Decomposed: False-Positive Rate; False-Negative Rate; Late-Positive Rate

| | FPR ↓ | | | FNR ↓ | | | LPR↓ | | |
|---|---|---|---|---|---|---|---|---|---|
| | TCP | UDP | ABS | TCP | UDP | ABS | TCP | UDP | ABS |
| AC | 0.087 | 0.037 | 0.058 | 0 | 0 | 0 | 0 | 0 | 0.016 |
| VR | 0.12 | 0.037 | 0.85 | 0 | 0 | 0 | 0.018 | 0 | 0.017 |
| TH | 0.023 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.014 |
| GP | 0.023 | 0 | 0 | 0 | 0 | 0 | 0.083 | 0 | 0.147 |
| GR | 0.023 | 0 | 0 | 0 | 0 | 0 | 0.037 | 0 | 0.147 |

- No predictors made false negatives
- Autocorrelation and Variance predictors mainly false-positive errors
- Growth Persistence and Growth Rate predictors mainly late-positive errors
- False-positive rate (2.3%) for Threshold, Growth Persistence, and Growth Rate predictors encompassed 5 edge routers that had reached 64% of *C* and would have reached overload given more time

# False-Positive Rates under Steady Load

| | FPR ↓ | | |
|---|---|---|---|
| | **TCP** | **UDP** | **ABS** |
| **AC** | **0.995** | **0.927** | **0.064** |
| **VR** | **0.362** | **0.45** | **0.949** |
| **TH** | **0** | **0** | **0** |
| **GP** | **0** | **0** | **0** |
| **GR** | **0** | **0** | **0** |

- Three predictors gave no false positives
- For realistic network models, Autocorrelation predictor issued predominately false positives, as queue time series highly self-similar
- Variance predictor issued too many false positives in all network models
- Adding guard condition – $0.25(C - \mu(Q)$ : *steady load*) – to Autocorrelation and Variance predictors eliminated false positives, but at the cost of reduced warning times (results not shown)

# Predictor Accuracy across Load Scenarios

| | Accuracy ↑ | | |
|---|---|---|---|
| | TCP | UDP | ABS |
| AC | 0.459 | 0.518 | 0.936 |
| VR | 0.75 | 0.757 | 0.092 |
| TH | 0.989 | 1 | 0.993 |
| GP | 0.947 | 1 | 0.927 |
| GR | 0.97 | 1 | 0.993 |

- Three predictors perfectly accurate in UDP Network
- For TCP Network, Threshold predictor most accurate
- Threshold predictor gives 3-4 mins more warning time than Growth Persistence and Growth Rate predictors (which must await alerts in 21/30 slots)
- Autocorrelation and Variance predictors unreliable
- Threshold predictor most suited to investigate further in emulated and real networks
- Abstract Network models should not be used to evaluate congestion predictors

# Future Work

- Verify predictor results in emulated and real networks
- Explore parameter space of all predictors to determine relative influence of parameters and to select optimal parameter values
- Investigate predictor performance in more complex traffic scenarios, e.g., cycles of increasing and decreasing load
- Define and investigate additional predictors

For more research results, see:

https://www.nist.gov/programs-projects/measurement-science-complex-information-systems