Layering, dynamics, optimization & control in software defined networks

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joint work with John Doyle (Caltech) and Kevin Tang (Cornell)
Distributed optimal control & software defined networks

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Control theory

Using feedback to mitigate the effects of dynamic uncertainty on a system

“open loop”

disturbances

plant

set-point
Control theory

feedback to close the loop

Controller

measurements

control action

Actuators

Sensors

disturbances

set-point

plant
A familiar example: TCP

\[ \max \sum_s U(x_s) \]

s.t. \[ Rx \leq c \]

Feedback: AIMD based on drops, RTT, queue length, etc. Guarantees: converge to NUM optimizing transmission rates

Only steady state guarantees
Stabilizing controllers

Controller #1

Controller #2
Optimal control theory

minimize \textbf{worst-case} amplify

minimize $u$ maximize $w \in W$

$f(\Delta x, u, w)$

error control action disturbance

Bounded energy

$W = A(t)$

Bounded magnitude

$W =$
Optimal control theory

minimize \[ \text{Expected Value} \begin{bmatrix} f(\Delta x, u, w) \end{bmatrix} \]

average

amplification

white noise
Centralized control

Can lead to poor performance for large-scale systems

One system
One controller

Global access to measurements
Global control of inputs

Controller

Sensors
Plant
Actuators

measurements
control inputs
Distributed control
Distributed control

convex!

if control packets get priority
Distributed optimal control in WANs
WAN distributed optimal control

nominal flows

\{ f^*_\ell \} 

TE solved using nominal demands

\[ D_{s,d}(t) = D_{s,d} + \omega(t) \]

real traffic fluctuates around nominal rates

High Frequency Traffic Control

\[
\min \lim_{n \to \infty} \sum_{\ell} \mathbb{E}[\Delta f_\ell(n)]^2 + \lambda_l \mathbb{E}[b_\ell(n)]^2
\]

egress buffer control
Generalizes FIFO/Smoothing

\[
\text{minimize } \lim_{n \to \infty} \sum_l \mathbb{E}[\Delta f_l(n)]^2 + \lambda_l \mathbb{E}[b_l(n)]^2
\]

egress buffer control
Controller architectures

High Frequency Traffic Control

\[
\text{minimize } \lim_{n \to \infty} \sum_{l} E[\Delta f_l(n)]^2 + \lambda_l E[b_l(n)]^2
\]

egress buffer control

Globally Optimal Delay Free (GOD-F)

0 delay comms
Controller architectures

High Frequency Traffic Control

\[
\min_{\Delta u_l(n)} \lim_{n \to \infty} \sum_l E[\Delta f_l(n)]^2 + \lambda_l E[b_l(n)]^2
\]

egress buffer control

Centralized

Diagram showing network with various cities and data nodes.
Controller architectures

High Frequency Traffic Control

\[
\text{minimize } \lim_{n \to \infty} \sum_l \mathbb{E}[\Delta f_l(n)]^2 + \lambda_l \mathbb{E}[b_l(n)]^2
\]

rate deviation queue length
egress buffer control

Distributed
new theory
ctrl packets get priority = convex!
Controller architectures

High Frequency Traffic Control

\[ \lim_{n \to \infty} \sum_l \mathbb{E}[\Delta f_l(n)]^2 + \lambda_l \mathbb{E}[b_l(n)]^2 \]

Decentralized (myopic)

non-convex
use best guess
WAN reflex layer

Max link utilization

<table>
<thead>
<tr>
<th></th>
<th>Centralized</th>
<th>Distributed</th>
<th>Decentralized</th>
<th>FIFO (standard)</th>
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</thead>
<tbody>
<tr>
<td>Demand fluctuation std. dev.</td>
<td></td>
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<tr>
<td>$\sigma = 5$</td>
<td>![Centralized](5 link utilization)</td>
<td>![Distributed](8 link utilization)</td>
<td>![Decentralized](9 link utilization)</td>
<td>![FIFO](10 link utilization)</td>
</tr>
<tr>
<td>$\sigma = 10$</td>
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<td>![Distributed](8 link utilization)</td>
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</tbody>
</table>

Theory & experiments are consistent!

N. Wu, A. Tang, J.C. Doyle, ..., N. Matni, in preparation
A theory of network architecture

Can we understand & automate:

- deciding where to put functionality?
- layering and inter/intra-layer protocol design?
- choosing centralized, distributed or decentralized implementations?

Must model **dynamics** & **delay**
Select references:


- N. Matni, A. Tang & J. C. Doyle, A case study in network architecture tradeoffs, ACM Symposium on SDN Research (SOSR), 2015

High-frequency traffic control preprint available upon request.