A conservation-law-based modular fluid-flow model for network congestion modeling

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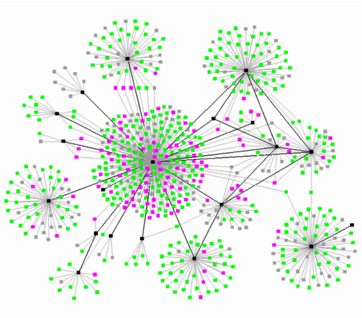
Introduction

Introduction

Congestion problem

- The users (green) communicate all together
- Packets accumulate at the servers (black)
- Large delays, data loss
- Congestion control



Why congestion modeling ?

- Understanding the process of congestion
- Simulation purpose
- Protocol validation/design

Congestion models

Time-domain

- Discrete-time models [Johari et al., 01], [Shorten et al., 06]
- Continuous-time models [Paganini et al., 05], [Vinnicombe, 00] → fluid-flow model.
- Hybrid models [Hespanha et al., 01]

Stochastic vs. Deterministic

- Stochastic [Misra et al., 00]
- Deterministic [Tang et al., 10]

Modular vs. monolithic

- Monolithic [Misra et al., 00], [Hollot et al., 01]
- Modular [Paganini et al., 05], [Liu et al., 07]

What properties a network model should have ?

1. Few universal concepts (quantities) related by laws.
2. Local description of the elements (modularity, scalability)
3. New models corresponding to new devices may be freely added without compromising existing ones (genericity).
4. Easy transcription of the network into a topologically identical diagram/model, and vice-versa.
5. Model predictions fit the reality.
6. Systematic way of analysis by hand calculations or simulators.

Modeling procedure

Core idea

- Information conservation law

Independent models

- Transmission channels
- Buffers/Queues
- Users

Properties of the model

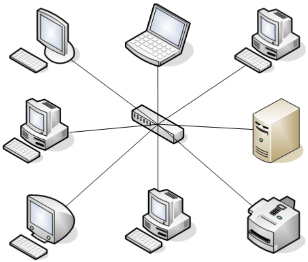
- Obtained model is explicit, modular and scalable
- Similar to electrical networks

Network congestion modeling

Fluid-flow models

Ingredients

- Flight-size: controlled variable
- Congestion window: reference
- Congestion measure: measurement
- Sending rate: control input



Rate/flow definition

- Quantity of information: N [bit] or [Pkt]
- Rate: ϕ [bit/s] or [Pkt/s]
- Quantity of information having passed through point x between t_0 and t:

$$N_x(t_0, t) := \int_{t_0}^{t} \phi(x, s) ds$$

Information conservation law

Observations

- If a packet is in transit in a network element, it must have entered it in the past.
- We can count the number of packets $P_E(t)$ in an element E at time t simply by counting the entering packets during a certain amount of time.

Conservation law statement

There exists $t_0(t) \leq t$ such that the following equality holds:

$$P_E(t) = \int_{t_0(t)}^{t} \phi(s)ds.$$

where $\phi(t)$ is the input flow of the element E.

Information conservation law - Example

Balance equation

$$P'_E(t) = \underbrace{\phi(t)}_{\text{input}} - \underbrace{\phi^o(t)}_{\text{output}} = \phi(t) - t_0(t)'\phi(t_0(t))$$

Output flow model

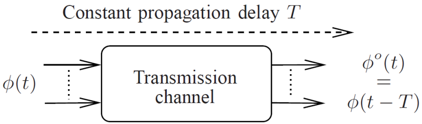
The output flow of element E, $\phi^o(t)$, is given by

$$\phi^o(t) := t_0(t)'\phi(t_0(t)).$$

Transmission Channel model

Assumptions

- Lossless
- Constant propagation delay $T > 0$



Stored information

$$P_E(t) = \int_{t-T}^{t} \phi(s)ds$$

I/O Relationship and output flow

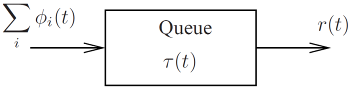
$$\begin{array}{rcl} P_E'(t) & = & \phi(t) - \phi(t-T) \\ \phi^o(t) & = & \phi(t-T) \end{array}$$

Basic queue model

$$
\begin{aligned}
\dot{q}(t) &= \sum_j \phi_j(t) - r(t) \\
r(t) &= \begin{cases} c & \text{if } q(t) > 0 \vee \sum_j \phi_j(t) > c \\ \sum_j \phi_j(t) & \text{otherwise} \end{cases}
\end{aligned}
$$

Buffer model

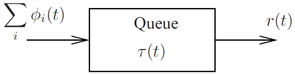
- Flow integrator
- Hybrid system
- Queueing delay $\tau(t) = q(t)/c$



Model inaccuracies

- Aggregate output flows $r(t)$!
- How to connect buffers to other buffers ?
- Does this model describe a FIFO queue ?

FIFO Buffer Model - Output flow separation (1)



Difficulties

- Integration destroys the information
- Indistinguishability of the output flows due to aggregation

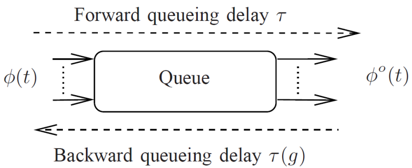
Solution

- Apply the conservation law !

$$\begin{aligned} q(t) &= c\tau(t) \\ &= \int_{g(t)}^{t} \phi(s)ds \end{aligned} \tag{1}$$

where $g(t) = t - \tau(g(t))$.

Internal FIFO Model - Output flow separation (2)

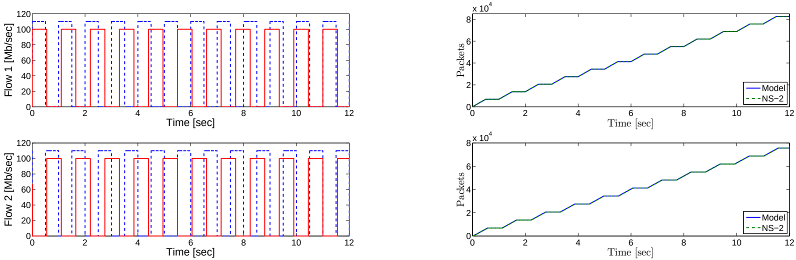


FIFO buffer model

$$\begin{aligned}
\dot{q}(t) &= \sum_j [\phi_j(t) - r_j(t)] \\
r_j(t) &= \begin{cases} \dfrac{\phi_j(g(t))c}{\sum_k \phi_k(g(t))} & \text{if } q(t) > 0 \\ \phi_j(t) & \text{otherwise} \end{cases} \\
g(t) &= t - q(g(t))/c
\end{aligned}$$

- Model proposed in [Ohta et al., 98], [Liu et al., 04], but no proof.
- Immediate consequence of the conservation law

Internal FIFO Model - Output flow separation (3)



- Single queue, two on/off input flows in phase opposition
- Exact matching with NS2

User protocol model

Description variables

- Window size w: desired flight-size
- Congestion measure μ, e.g. delays, packet loss
- Sending rate $\phi^o(t)$ and ACK flow $\phi(t)$

Continuous-time model of user protocol

$$\begin{array}{lrcl} \text{Protocol state :} & \dot{z}(t) & = & \mathcal{P}(z(t),\mu(t)) \\ \text{Window size :} & w(t) & = & \mathcal{W}(z(t),\mu(t)) \end{array}$$

Problem

Relate rates, flight-size and window size together...

$$\phi^o(t) = \mathcal{U}(w(t),\phi(t)) \ ?$$

Derivation of the model

Conservation law

- Flight-size (ACK-clocking [Jacobsson et al, 08]):

$$\begin{aligned} P_C(t+\mathrm{RTT}\{t\}) &= \int_t^{t+\mathrm{RTT}\{t\}} \phi^o(s)ds \\ P_C(t) &= \int_{B(t)}^t \phi^o(s)ds \end{aligned} \qquad (2)$$

Results

- ACK flow: $\phi(t) = B'(t)\phi^o(B(t))$ is the flow leaving the circuit.
- Sending rate: $\phi^o(t) = P_C'(t) + \phi(t)$ is the flow entering the circuit (self-clocking).
- Relation between flight-size and window-size obtained by a counter to the model.

Complete user model

Protocol Equations

$$\begin{aligned} \dot{z}(t) &= \mathcal{P}(z(t),\mu(t)) \\ w(t) &= \mathcal{W}(z(t),\mu(t)) \end{aligned}$$

Sending rate model

$$\begin{aligned} \phi^o(t) &= \begin{cases} \dot{w}_i(t)+\phi(t) & \text{if } \mathcal{T}_i(t) \\ 0 & \text{otherwise} \end{cases} \\ \dot{\pi}_i(t) &= \begin{cases} 0 & \text{if } \mathcal{T}_i(t) \\ \dot{w}_i(t)+\phi(t) & \text{otherwise.} \end{cases} \\ \mathcal{T}_i(t) &= ([\pi_i(t)=0] \wedge [\dot{w}_i(t)+\phi(t) \geq 0]) \end{aligned}$$

Model benefits

Structure

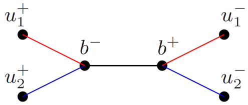
- Coherence of the blocks
- Modular and scalable representation

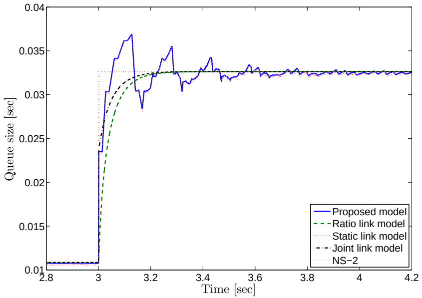
Theoretical implications

- Previous rate models are approximations of the conservation law (ACK-clocking model)
  - Ratio model $\phi^o(t) \simeq w(t)/\,\mathrm{RTT}\{t\}$ [Paganini et al., 02], [Vinnicombe, 00]
  - Joint model $\phi^o(t) \simeq w(t)/\,\mathrm{RTT}\{t\} + \dot{w}(t)$ [Jacobsson et al., 08]
- Static model $\phi^o(t) \simeq \dot{w}(t)$ [Wang et al., 05] is shown to be exact under some topology assumptions.
- Window-based ACK-clocking model $w(t) \simeq P_C(t)$ [Tang et al., 10] exact when the packet counter is always at 0.

Examples

Single buffer - Two Users

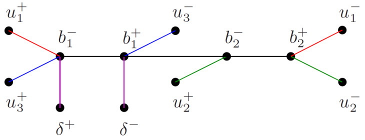


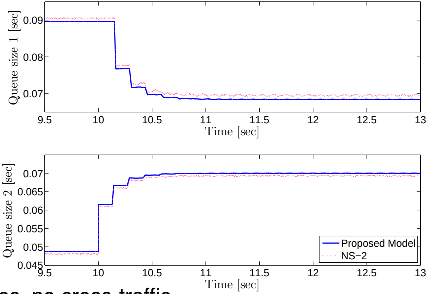


Scenario 1 [Tang et al., 10]

- $c = 100$Mb/s, $\rho = 1590$ bytes
- Propagation delays: $T_1 = 3.2$ms and $T_2 = 117$ms
- Initial congestion window sizes: $w_1^0 = 50$ and $w_2^0 = 550$ packets
- At 3s, w_1 is increased to 150 packets.

Two buffers - Three Users

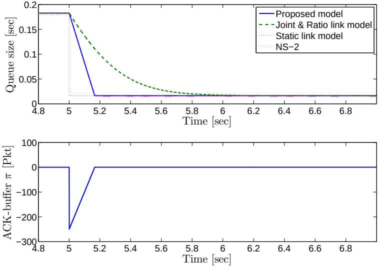




Scenario 2 [Tang et al., 10]

- $c_1 = 72$Mb/s, $c_2 = 180$Mb/s, $\rho = 1448$ bytes, no cross-traffic
- Propagation delays: $T_1 = 120$ms, $T_2 = 80$ms and $T_3 = 40$ms
- Initial congestion window sizes: $w_1^0 = 1600$, $w_2^0 = 1200$ and $w_3^0 = 5$ packets
- At 10s, w_2 is increased to 1400 packets.

Single-buffer/Single-user



Scenario 3 [Jacobsson, 08]

- $c = 12.5$Mb/s, $\rho = 1040$ bytes, no cross-traffic
- Propagation delay: $T = 150$ms
- Initial congestion window size: $w^0 = 500$ packets
- At 5s, w_1 is halved.

Conclusion

Conclusion

- Model obtained from few principles: 1 conservation law and 2 basic models
- Network component models expressed in terms of these variables:
  - Transmission channel
  - Queues
  - Users
- Describe quite well the reality for considered topologies
- Model is modular, scalable, topologically identical
- Suitable for building (graphical) simulators
- Provides insights on validity domains of flow models

Thank you for your attention