Steady state and transient state analyses of TCP and TCP-friendly rate control mechanism using a control theoretic approach

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Outline

• Introduction
  – New transport-layer communication protocols for real-time system applications

• Analytic model
  – TFRC, TCP, RED

• Steady state analysis
  – Derive TFRC goodput, TCP goodput

• Transient state analysis
  – Use a control theoretic approach

• Numerical examples

• Conclusion
Background

• Real-time applications
  – Have been widely deployed
  – Use either UDP or TCP

• Internet
  – Best effort network
  ➢ All network applications should have a mechanism for adapting to the congestion status of a network
UDP (User Datagram Protocol)

- Simple protocol for datagram transfer
- Doesn't have a congestion control mechanism
- We should implement some congestion control mechanism on application layer
TCP (Transmission Control Protocol)

- Has a congestion control mechanism
  - Adjust its packet transmission rate
- Designed for data transfer applications
  - Can tolerate a certain amount of delays
- AIMD window flow control
- Packet transmission rate fluctuates
  - Serious problem for a real-time applications
New transport-layer communication protocols

• TFRC, RAP, GAIMD
  – TCP-Friendly Rate Control
  – Rate Adaptation Protocol
  – General AIMD Congestion Control

• Have a congestion control mechanism

• Realize a fairness with competing TCP flows

• Change the packet transmission rate smoothly
Related work

• TFRC have been studied variously
• Steady state behavior
  – Fairness between TFRC and TCP
  – Validity of the rate control mechanism
• Transient state behavior
  – Smoothness of the throughput variation
  – Responding speed to the change of the network congestion status
• Most of these researches are based only on simulation experiments.
Objectives

- Model a network with TFRC and TCP connections
  - Multiple TFRC connections
  - Multiple TCP connections
  - Single RED (Random Early Detection) router
- Steady state analysis
  - Derive several performance measures
    - TFRC goodput, TCP goodput, packet loss probability
- Transient state analysis
  - Quantitatively show convergence speed
  - Using a control theoretic approach
Analytic model

\[ \tau_F [\text{ms}] \]

\[ \mu [\text{packet/ms}] \]

BufferSize = \( L [\text{packet}] \)

\[ \tau_C [\text{ms}] \]
Assumption

• All TCP connections operate in their congestion avoidance phase
• Maximum window size of TCP is sufficiently larger than the bandwidth-delay product of a network
• RED routers operate appropriately
  – Average queue length of RED router is kept between $min_{th}$ and $max_{th}$
**TFRC**

- **Destination host**
  - measures the *loss event rate* and feeds this information back to the source host
    - loss event: one or more lost packet from a window of data

- **Source host**
  - uses feedback messages to measure the round-trip time
  - Loss event rate and round-trip time are then fed into TFRC’s throughput equation
  - adjusts its transmission rate
Overview of model (1)

- Model TFRC, TCP, RED as discrete time systems with a time slot of $\Delta$
- TFRC

We derive packet loss event rate $p_e(k)$, as a function of packet loss probability and round-trip time.
Overview of model (2)

- **TCP**
  - packet loss probability \( p(k) \)
  - round-trip time \( R_C(k) \)

- **RED**
  - TCP window size \( w(k) \)
  - packet loss probability \( p(k+1) \)
  - TFRC transmission rate \( T(k) \)
  - TFRC & TCP round-trip time \( R_C(k+1) & R_F(k+1) \)

\[ q(k) \text{: current queue length} \]
\[ \bar{q}(k) \text{: average queue length} \]
Steady state analysis

- Obtain equilibrium values from models numerically
  - Equilibrium values: values in steady state
  - TCP window size $w^*$, round-trip time $R_f^*$
  - TFRC transmission rate $T^*$, round-trip time $R_c^*$
  - RED packet loss probability $p^*$
- Derive TFRC & TCP goodput
  - TFRC goodput: $T^* \times (1 - p^*)$
  - TCP goodput: $\frac{w^*}{R_f^*} \times (1 - p^*)$
Transient state analysis (1)

• Define state variables & state vector
  – State variables: $T(k), \cdots, T\left(k - \frac{R_f(k)}{\Delta}\right), w(k), \cdots, w\left(k - \frac{R_c(k)}{\Delta}\right), q(k), \cdots, q\left(k - \max\left(\frac{R_f(k)}{\Delta}, \frac{R_c(k)}{\Delta}\right)\right)$
  – State vector $x(k)$:
    • Differences between each state variables and its equilibrium values
      \[ x(k) = (T(k) - T^*, \cdots, w(k) - w^*, q(k) - q^*, \cdots, \overline{q}(k) - \overline{q}^*) \]
Transient state analysis (2)

• Assume TFRC notifies its source host of feedback information every $M$ slots
• Linearize models around equilibrium points
• Obtain the transition matrix from slot $k$ to slot $k+m$
  \[ x(k + M) = AB^{M-1}x(k) \]
  - $A$: state transition matrix when TFRC source receives feedback information
  - $B$: state transition matrix when TFRC source doesn’t receive feedback information
Transient state analysis (3)

- Eigen values of $AB^{M-1}$ determine transient state behavior
  - $s$: the maximum absolute eigen values of $AB^{M-1}$, maximum modulus
  - smaller $s$: better transient behavior
    - $s < 1$: stable
    - $s > 1$: unstable
Numerical example setting

- **Analysis & simulation**
  - TFRC & TCP packet size: 1000 [byte]
  - # of TFRC & TCP connections: 10, 10
  - Two-way propagation delays of TFRC & TCP are set to the equal value: $\tau_F = \tau_C = \tau[ms]$
  - RED parameters
    - $min_{th} = 0.25 \mu \tau$
    - $max_{th} = 1.25 \mu \tau$
    - $L = 2.5 \mu \tau$
    - $w_q = 0.002$
    - $max_p = 0.1$
  - $L$ : RED buffer size [packet]
  - $\mu$ : bottleneck link capacity [packet/ms]

- **Simulation**
  - Simulator: ns-2
  - Simulation time: 300 [s]
  - # of simulation: 10
Numerical example

Good agreement

\[ \tau = 50[\text{ms}] \text{ (analysis)} \]
\[ \tau = 100[\text{ms}] \text{ (analysis)} \]
\[ \tau = 50[\text{ms}] \text{ (simulation)} \]
\[ \tau = 100[\text{ms}] \text{ (simulation)} \]
Conclusion

- Analyze the steady state behavior of TFRC & TCP where TFRC & TCP coexist
- Model TFRC, TCP, RED as discrete time systems
- Derive TFRC & TCP goodput in steady state
  - Our analytic results show good agreement with simulation ones
- Analyze the transient state behavior of TFRC & TCP where TFRC & TCP coexist