Fluid-Based Analysis of a Network with DCCP Connections and RED Routers

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Background

- Real-time applications
  - Have been widely deployed
  - Use either UDP or TCP
- Internet: best effort network
  - Network applications should have a congestion control mechanism
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
DCCP (Datagram Congestion Control Protocol)

- Transport-layer protocols for real-time applications
- Can choose congestion control mechanism
  - TCP-like congestion control profile
    - AIMD window control
  - TFRC congestion control profile
    - TCP-friendly rate control
RED (Random Early Detection)

- Representative AQM mechanism
  - Probabilistically discards an arriving packet
- High throughput can be achieved
- Average queue length can be kept small
  - Decrease the end-to-end transmission delay
- AQM mechanisms is effective for real-time applications
Objective

- Analyze steady state performance of DCCP/RED
  - Derive packet transmission rate, packet loss probability
- Analyze transient state performance of DCCP/RED
  - Investigate parameter region where DCCP/RED operate stably
  - Evaluate transient state performance of DCCP/RED
    - ramp-up time, overshoot, settling time
Analytic Model
Modeling DCCP with TCP-like Congestion Control Profile

- $x(k)$: input (arrival rate of ACK packets)
- $y(k)$: output (transmission rate of data packets)
- $R$: round-trip time
- $\Delta$: time slot

$$y(k+1) \simeq f(x(k), y(k), R)$$

$$= y(k) + \Delta \frac{x(k)}{y(k)R^2} - \frac{2}{3} \Delta y(k)z(k) \{1 - p_{TO}(k)\} - \left\{ \frac{4}{3} y(k) - \frac{1}{R} \right\} \Delta z(k)p_{TO}(k)$$

- additive increase
- multiplicative decrease
- TCP timeout
Modeling DCCP with TFRC Congestion Control Profile

- \( x(k) \): input (arrival rate of ACK packets)
- \( y(k) \): output (transmission rate of data packets)
- \( R \): round-trip time
- \( \Delta \): time slot

\[
\begin{align*}
y(k) &= g(x(k), y(k), R) \\
     &= X(pe(k), R) \\
X(pe(k), R) &= \frac{1}{R \sqrt{\frac{2pe(k)}{3}} + t_{RTO} \left(3 \sqrt{\frac{3pe(k)}{8}} pe(k) (1 + 32pe(k)^2)\right)}
\end{align*}
\]
Modeling RED Router

- $x(k)$: input (packet arrival rate)
- $y(k)$: output (packet departure rate)
- $\text{minth}$, $\text{maxth}$, $\text{maxp}$, $w_q$: RED control parameters
- $\Delta$: time slot

$$y(k) = g(x(k), R) = \min(x(k), \mu)$$

$$q(k + 1) = \min[\max\{q(k) + N x(k) \Delta, 0\}, L]$$

$$\bar{q}(k + 1) \simeq \bar{q}(k) + N x(k) \Delta w_q(q(k) - \bar{q}(k))$$

$$p_b(k) = \begin{cases} 
0 & \text{if } q(k) < \text{minth} \\
\frac{\text{maxp}}{\text{maxth} - \text{minth}}(\bar{q}(k) - \text{minth}) & \text{if } \text{minth} \leq \bar{q}(k) < \text{maxth} \\
1 & \text{if } \bar{q}(k) \geq \text{maxth}
\end{cases}$$

average queue length

current queue length

packet loss probability
Steady State Analysis

- $y^*_D, y^*_R$: Output of DCCP and RED in steady state
- $y_D(k), y_R(k)$: Output of DCCP and RED at time slot $k$
- $x_D(k), x_R(k)$: Input of DCCP and RED at time slot $k$
- $N$: number of DCCP connections
- Obtain $y^*_D, y^*_R$ by solving equations:

\[
\begin{align*}
  y_D(k + 1) &= y_D(k) = y^*_D, \quad x_D(k) = \frac{y^*_R}{N} \\
  y_R(k + 1) &= y_R(k) = y^*_D, \quad x_R(k) = N \cdot y^*_D
\end{align*}
\]
Transient State Analysis: DCCP with TFRC Congestion Control Profile (1/2)

- 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 $k+m$: $x(k + M) = A B^{M-1} x(k)$
  - $A$: state transition matrix when DCCP source host receives feedback information
  - $B$: state transition matrix when DCCP source host doesn’t receive feedback information
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 Examples: DCCP Packet Transmission Rate

- TFRC congestion control profile

![Graph showing the relationship between DCCP packet transmission rate and bottleneck link bandwidth. The graph includes lines for different values of delay ($\tau$) and indicates good agreement between analysis and simulation results.]
Numerical Examples: Stability Region of DCCP/RED

- TFRC congestion control profile

Bandwidth $\rightarrow$ large,
Maximum modulus $\rightarrow$ large

$w_q \rightarrow$ small,
Maximum modulus $\rightarrow$ large
Transient State Performance Indexes

- Average Queue length
- Overshoot
- Rising time
- Settling time

- 95%
- 100%
- ±5%
Numerical Examples: DCCP/RED Transient State Performance

- TFRC congestion control profile

\[ w_q \rightarrow \text{large, ramp-up time and settling time} \rightarrow \text{small} \]
Calculation Method of RED Average Queue Length

- Update average queue length for every packet receipt
  - Average: Exponential Weighted Moving Average
    \[ \bar{q} \leftarrow (1 - w_q) \bar{q} + w_q q \]
    \( \bar{q} \) - average queue length
    \( w_q \) - EWMA weight
    \( q \) - current queue length

- Determine packet loss probability by linear function of Queue Occupancy
  \[ p_b = \max_p \left( \frac{\bar{q} - \text{min}_\text{th}}{\text{max}_\text{th} - \text{min}_\text{th}} \right) \]
  \( p_b \) - packet loss probability
  \( \text{max}_p, \text{min}_\text{th}, \text{max}_\text{th} \): control parameter of RED
RED-IQI: RED with Immediate Queue Information

- Change calculation method of average queue length
  \[ w_q = 1 \]
  - Feedback delay of DCCP/RED-IQI becomes small

- Change function that determines packet loss probability

\[
p_b = \max_p F \left( \frac{\bar{q} - \min_{th}}{\max_{th} - \min_{th}} \right)
\]

where

\[
F(x) = \left(1 - \sqrt{1 - x^2}\right)^\phi
\]

with \( \phi \geq \frac{1}{2} \)
Numerical Examples: Stability Region of DCCP/RED

- TFRC congestion control profile

\[ w_q = 0.002 \]

Stability region becomes large
Conclusion

- Investigate parameter region where DCCP/RED operate stably
- Evaluate transient state performance of DCCP/RED
  - Stability and transient state performance degrade, when weight of EWMA is small
- Propose RED-IQI and Evaluate it
  - RED-IQI improves stability and transient state performance of DCCP/RED-IQI