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

Hiroyuki Hisamatsu

Graduate School of Information Science and Technology
Osaka University, Japan

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)

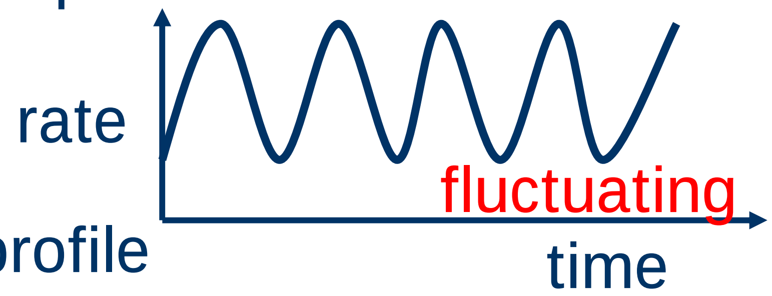
- Simple protocol for datagram transfer
- Doesn't have a congestion control mechanism
- We should implement some congestion control mechanism on application layer

TCP (Transmission Control Protocol)

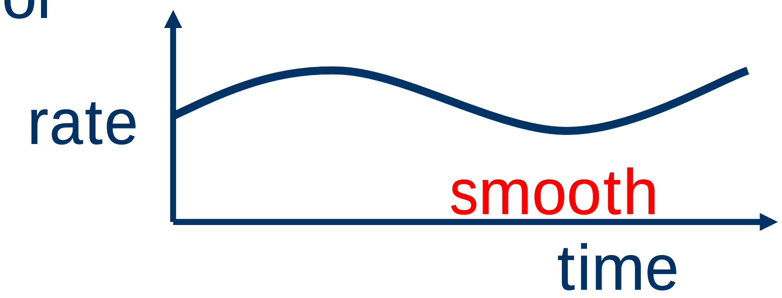
- Has a congestion control mechanism
  - Adjust its packet transmission rate
- Designed for data transfer applications
  - Can tolerate a certain amount of delays
- AIMD window flow control
- Packet transmission rate fluctuates
  - Serious problem for a real-time applications

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



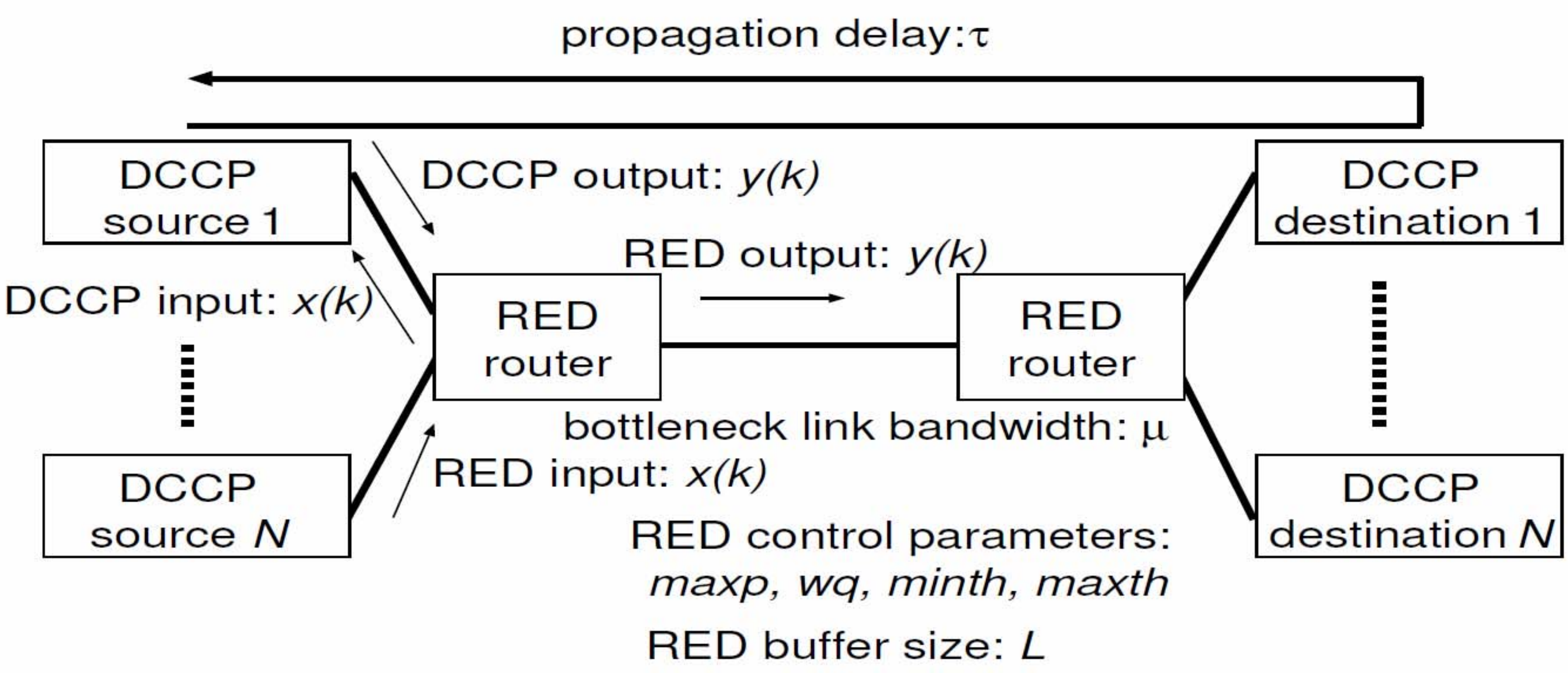
RED (Random Early Detection)

- 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
- Δ : time slot

$$
\begin{aligned}
y(k+1) &\simeq f(x(k), y(k), R) \\
&= y(k) + \Delta \frac{x(k)}{y(k)R^2} - \frac{2}{3}\Delta y(k) z(k) \{1 - p_{TO}(k)\} \\
&\quad - \left\{\frac{4}{3}y(k) - \frac{1}{R}\right\} \Delta z(k) p_{TO}(k)
\end{aligned}
$$

multiplicative decrease

additive increase

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
- Δ: time slot

packet loss event rate

$$
\begin{aligned}
y(k) &= g(x(k), y(k), R) \\
&= X\left(pe(k), R\right)
\end{aligned}
$$

$$pe(k) = h\left(1 - \frac{x(k)}{y(k - \frac{R}{\Delta})}\right)$$

$$X(pe(k), R) = \frac{1}{R\sqrt{\frac{2pe(k)}{3}} + t_{RTO}\left(3\sqrt{\frac{3pe(k)}{8}}pe(k)(1 + 32pe(k)^2)\right)}$$

Retransmission timer

Modeling RED Router

- x(k): input (packet arrival rate)
- y(k): output (packet departure rate)
- minth, maxth, maxp, wq: RED control parameters
- Δ : time slot

$$\begin{aligned} y(k) &= g(x(k), R) \\ &= min(x(k), \mu) \end{aligned}$$

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

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

$$p_b(k) = \begin{cases} 0 & \text{if } q(k) < min_{th} \\ \dfrac{max_p}{max_{th} - min_{th}}(\overline{q}(k) - min_{th}) & \\ & \text{if } min_{th} \leq \overline{q}(k) < max_{th} \\ 1 & \text{if } \overline{q}(k) \geq max_{th} \end{cases}$$

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:

$$y_D(k+1) = y_D(k) = y_D^*, x_D(k) = \frac{y_R^*}{N}$$

$$y_R(k+1) = y_R(k) = y_D^*, x_R(k) = N\, y_D^*$$

Transient State Analysis: DCCP with TFRC Congestion Control Profile (1/2)

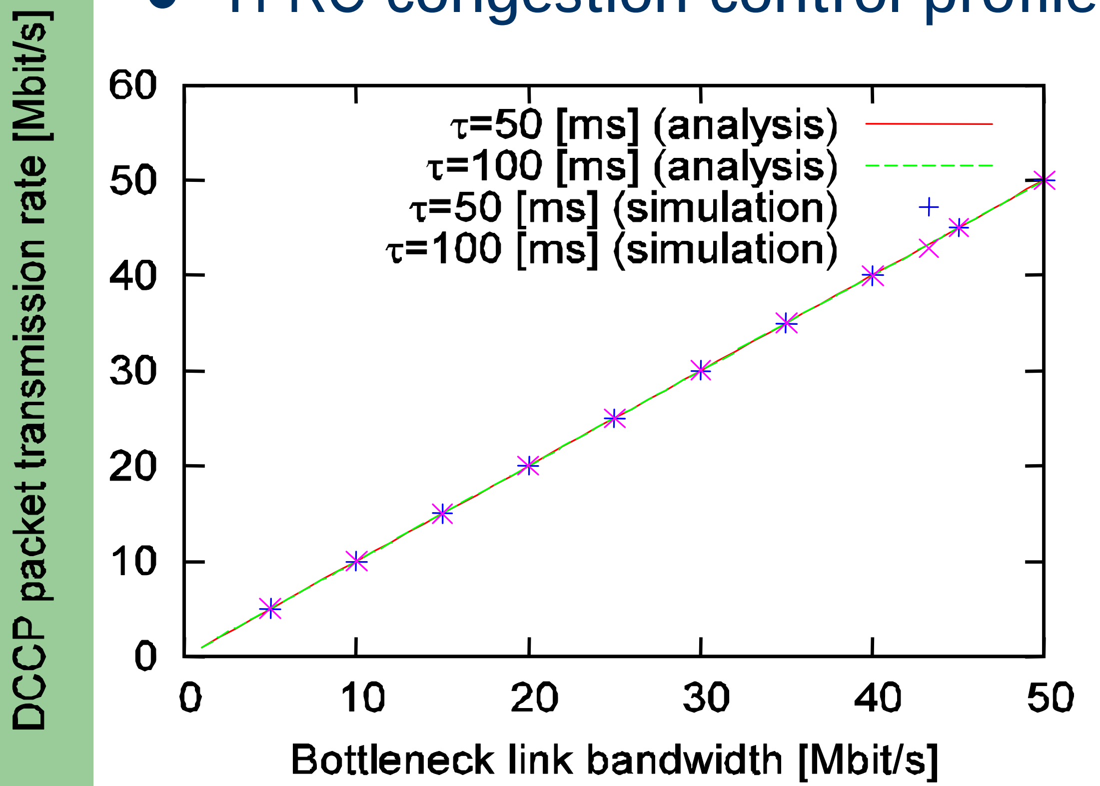
- Assume TFRC notifies its source host of feedback information every M slots
- Linearize models around equilibrium points
- Obtain the transition matrix from slot $\boldsymbol{k}$ to slot k+m $x(k+M) = \boldsymbol{A}\boldsymbol{B}^{M-1}x(k)$
  - $\boldsymbol{A}$: state transition matrix when DCCP source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

Transient State Analysis: DCCP with TFRC Congestion Control Profile (2/2)

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

Numerical Examples: DCCP Packet Transmission Rate

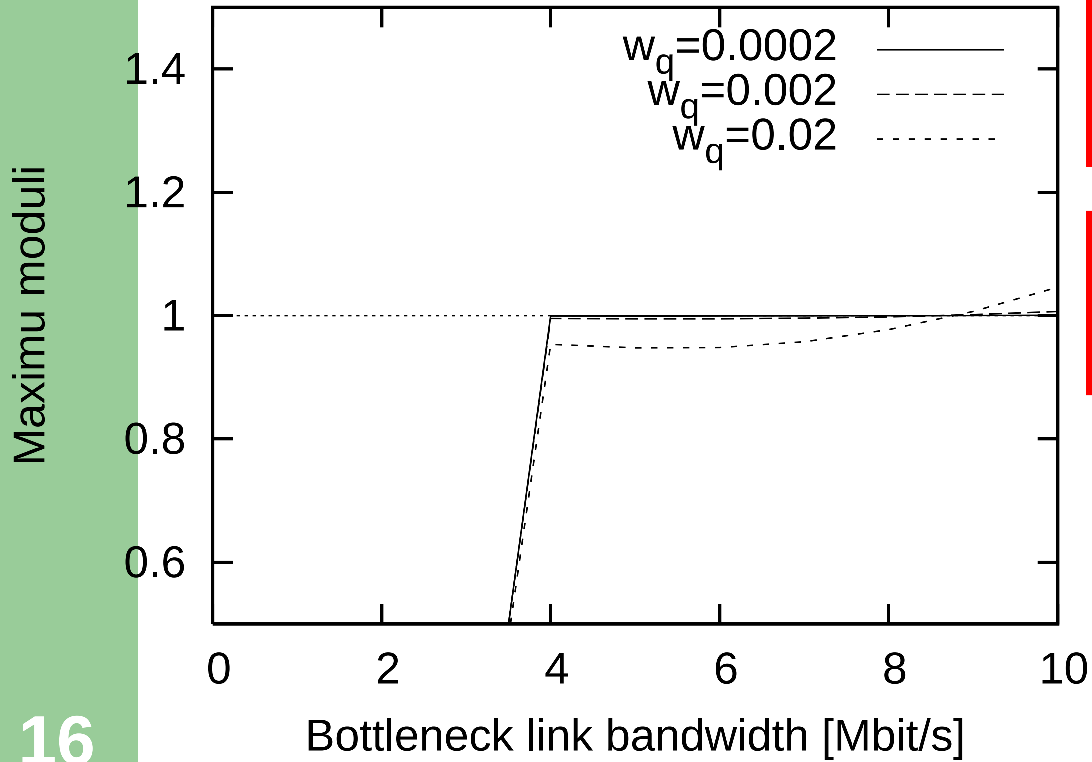
- TFRC congestion control profile



good agreement

Numerical Examples: Stability Region of DCCP/RED

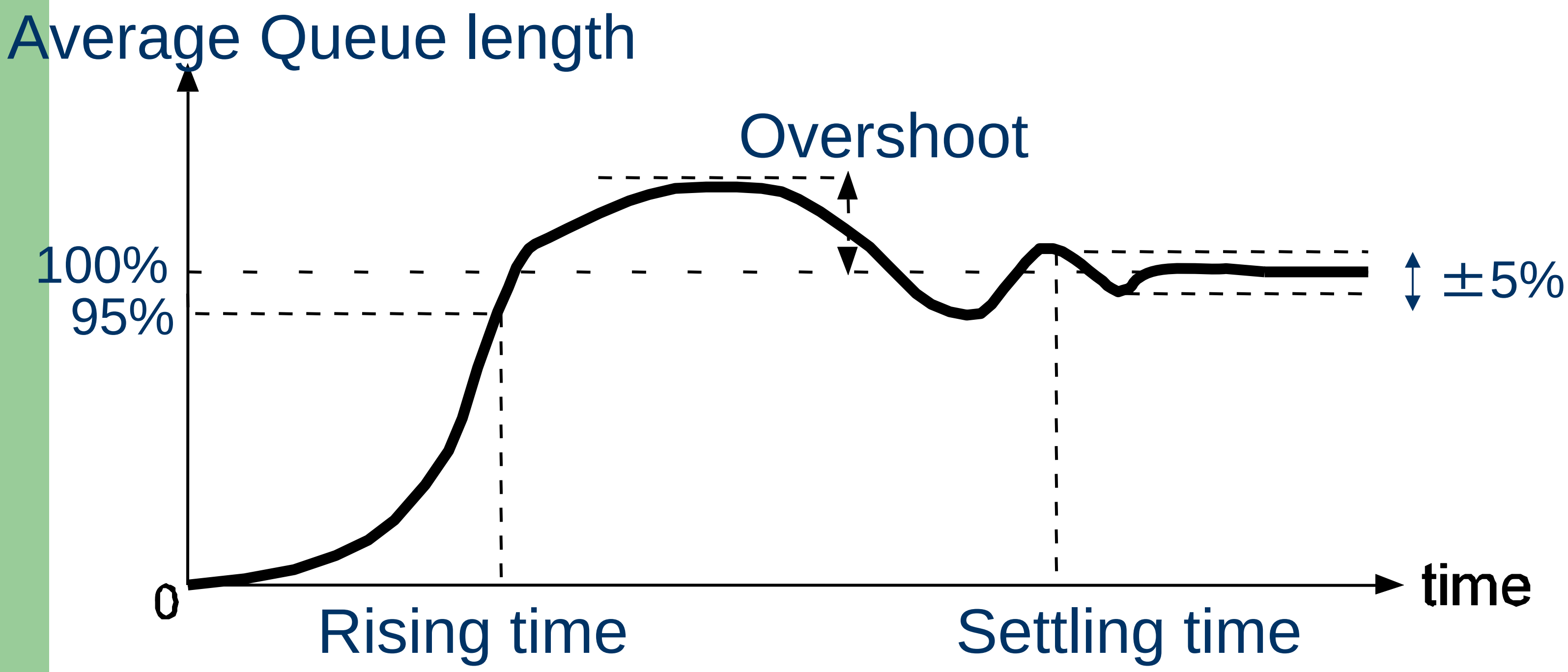
- TFRC congestion control profile



Bandwidth → large,
Maximum modulus → large

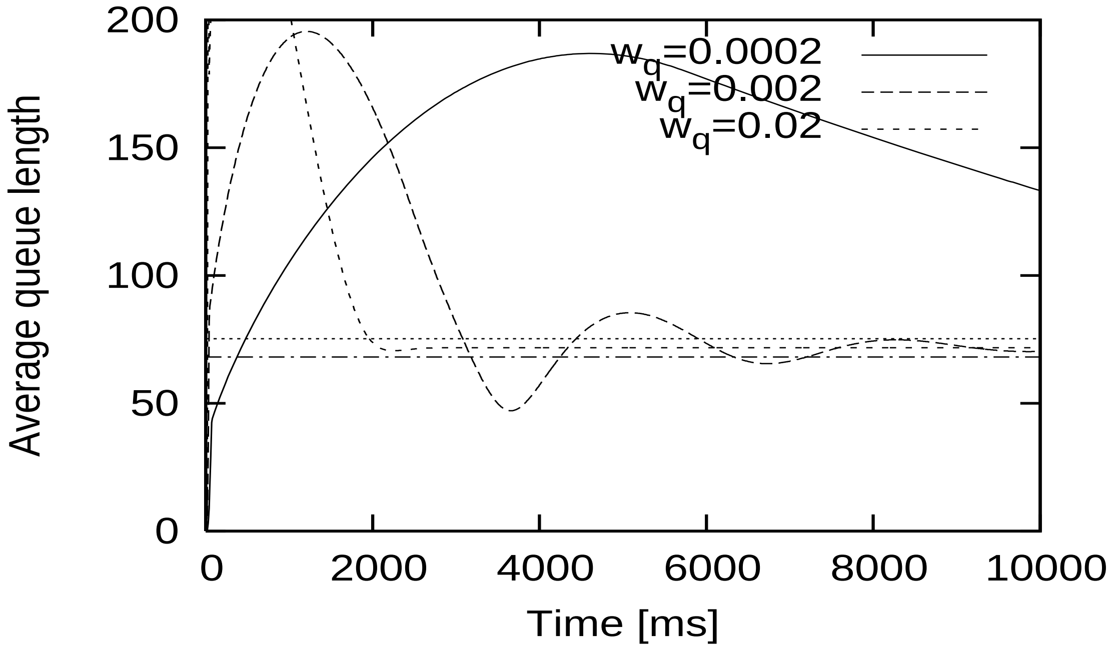
w_q → small,
Maximum modulus → large

Transient State Performance Indexes



Numerical Examples: DCCP/RED Transient State Performance

- TFRC congestion control profile



w_q → large, ramp-up time and settling time → small

Calculation Method of RED Average Queue Length

- Update average queue length for every packet receipt
  - Average: Exponential Weighted Moving Average

$$\overline{q} \leftarrow (1 - w_q)\,\overline{q} + w_q\, q$$

average queue length

EWMA weight

current queue length

- Determine packet loss probability by linear function of Queue Occupancy $\dfrac{\overline{q} - min_{th}}{max_{th} - min_{th}}$,

$$p_b = max_p \left(\frac{\overline{q} - min_{th}}{max_{th} - min_{th}} \right)$$

maxp,minth,maxth:
control parameter of RED

packet loss
probability

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

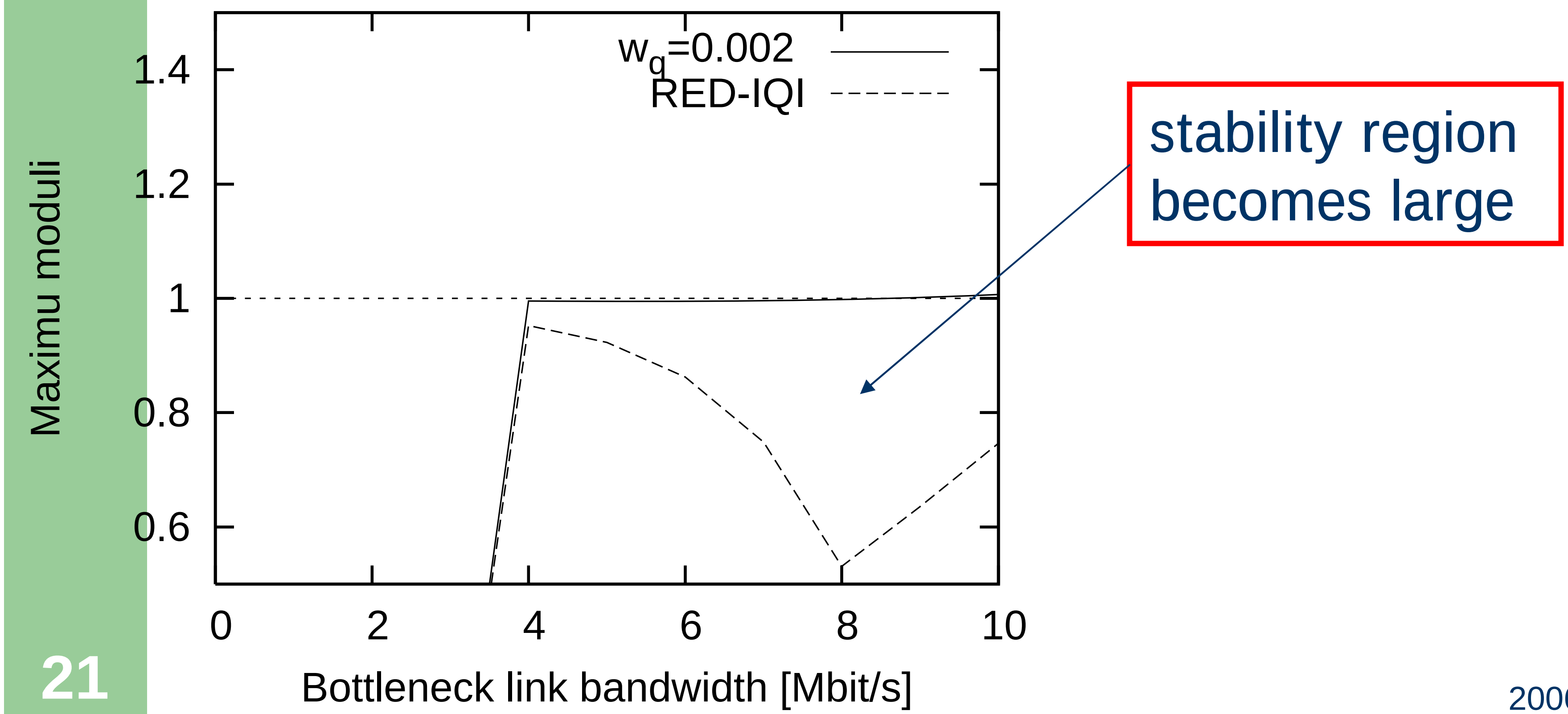
$$p_b = max_p F\left(\frac{\bar{q} - min_{th}}{max_{th} - min_{th}}\right)$$

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

$$(\phi \geq \frac{1}{2})$$

Numerical Examples: Stability Region of DCCP/RED

- TFRC congestion control profile



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