Fall 2015-Performance Evaluation of Network Systems Course (CNA04)

TCP and Modeling TCP Performance: A Review & Survey

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Computer Communications Lab.

1:30pm-3:00pm
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Outline

1. Introduction
   - TCP
   - Performance Study of TCP/IP
2. TCP Congestion Control Review
   - Congestion indications & reactions
   - TCP variants classification
3. TCP Modeling
   - *Renewal Theory Models*
   - Fixed-point Methods
   - Control Theoretic Models
4. Summary & Recommended Refs

Introduction: TCP

- *Transmission Control Protocol (TCP) is the predominant transport protocol used by IP technology to support popular Internet services*
- TCP applications & services
  - Most popular Internet applications use TCP
    - E-mail, WWW, file transfer, remote login, etc.

Introduction: TCP

- Motivation for Performance Study of TCP
  - Originally, TCP worked well in wired network
  - Nowadays, in heterogeneous networks: TCP algorithms & parameters that are suitable for one environment are not always suitable for other environments
  - Must acquire a solid foundation & understanding TCP performance through such networks

Introduction: Performance Study of TCP

- Tools & techniques

	Scopes
Measurement	- Help users to reveal potential bottlenecks - Detect inadequate parameters settings - Test components reliability
Network simulation	- Provides a convenient way to predict the performance when the proposed network is not available for measurement - Allows the evaluation of performance under a wide variety of workload & network - Can incorporate more details than analytical modeling; results can be produced that are closer to reality
Analytical modeling	*- TCP connections operating across the Internet is a huge control system. We need mathematical models to capture a system of this magnitude* *- Convenience methods for design & optimization protocols*

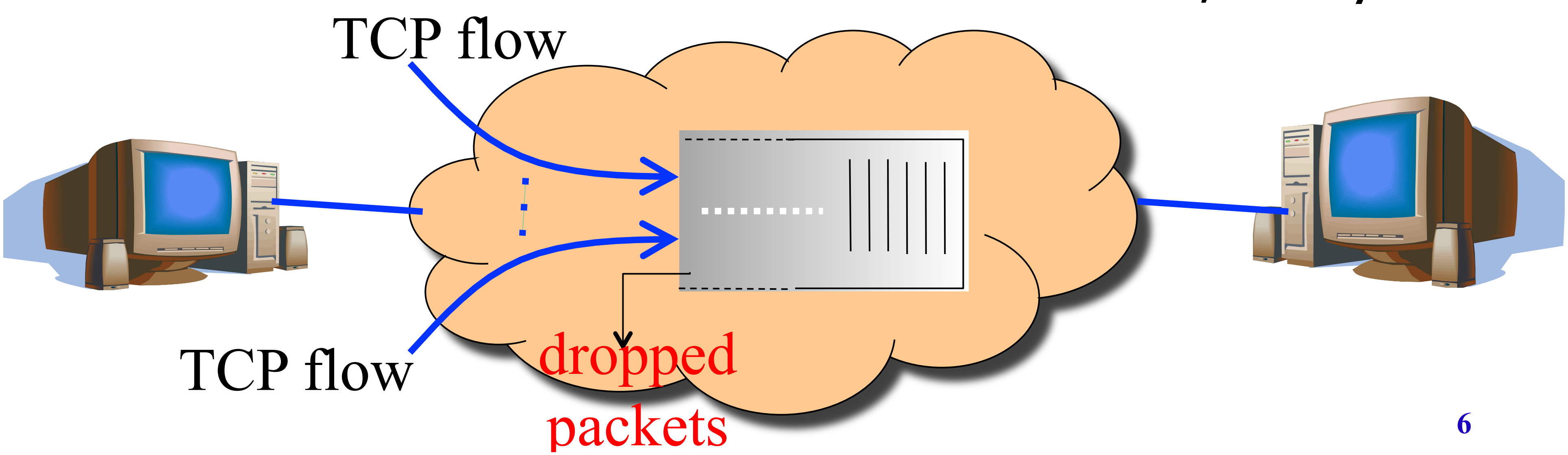
Full survey: M. Hassan and R. Jain. High Performance TCP/IP Networking: Concepts, Issues, and Solutions. Book 2003.

Introduction: Performance Study of TCP

- Main focus of this lecture
  - TCP analytical modeling
  - Objectives
    - Gain an understanding of the basic TCP operations, focusing on “Congestion Control”
    - Understand the fundamental relationship between network parameters and TCP performance
    - Apply a rage of “Mathematical Models” to predict TCP performance

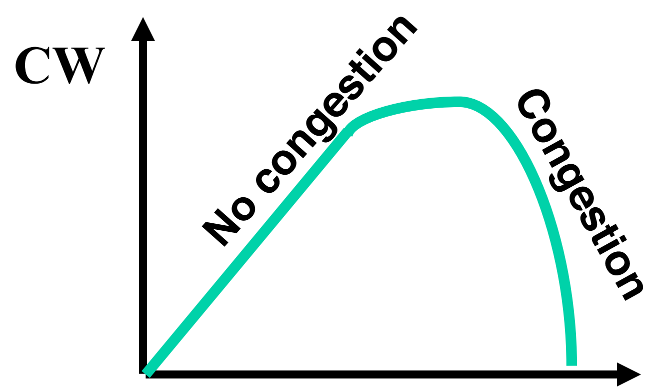
TCP Congestion Control Review

- What is congestion?
  - Load is higher than capacity
- What do IP routers do?
  - Drop the excess packets
- Why is this bad?
  - Wasted bandwidth for retransmissions; delay



TCP Congestion Control Review

- Congestion control
  - Keep senders from overloading the network
- Congestion window
  - Maximum data (bytes, packets) can be transmitted
- Upon *not detecting* congestion
  - *Increase* the window size
  - And see if the packets are successfully delivered
- Upon *detecting* congestion
  - *Decrease* the window size

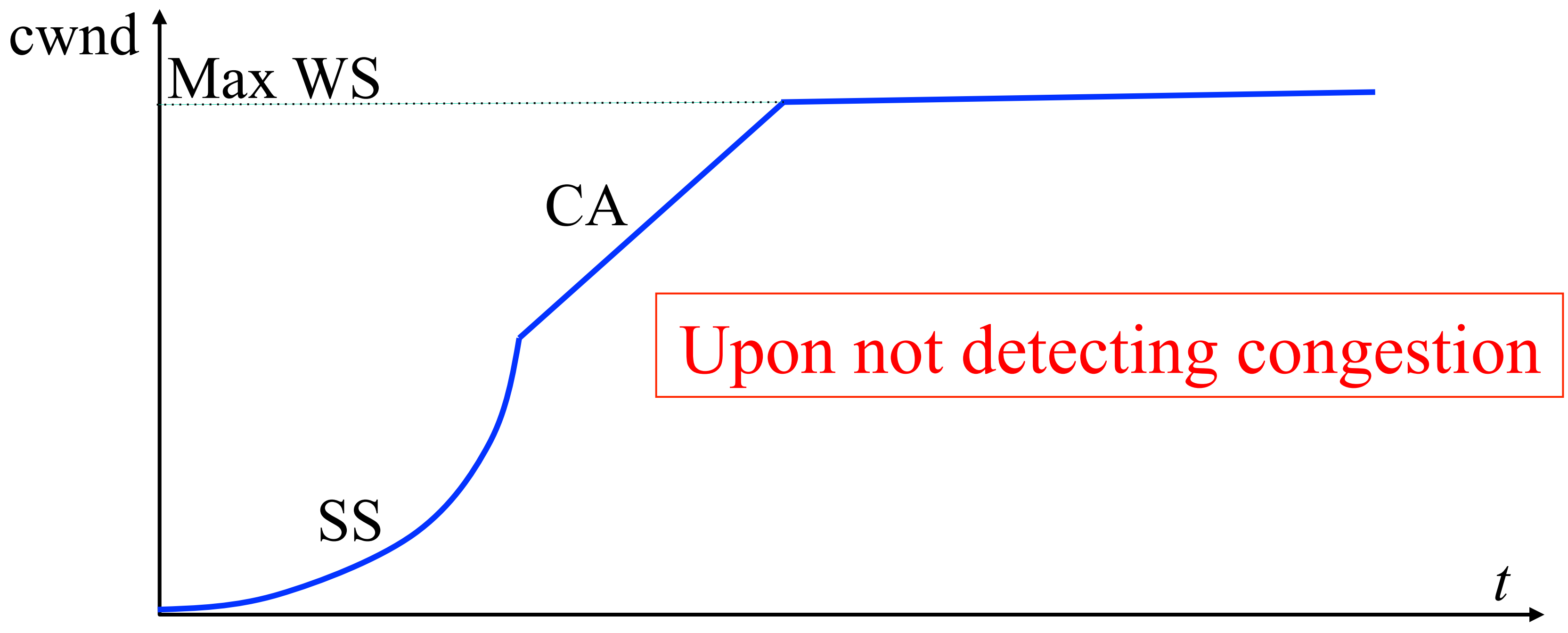


TCP Congestion Control Review

- Slow-start (SS) phase
  - Initially, CW is 1 Max Segment Size (MSS)
  - So, initial sending rate is MSS/RTT (slow rate)
  - Increases the rate exponentially
    - $cwnd=2*cwnd_{preivous}$
  - Until cwnd reaches SS threshold (ssthresh)
    - Switch to the next phase

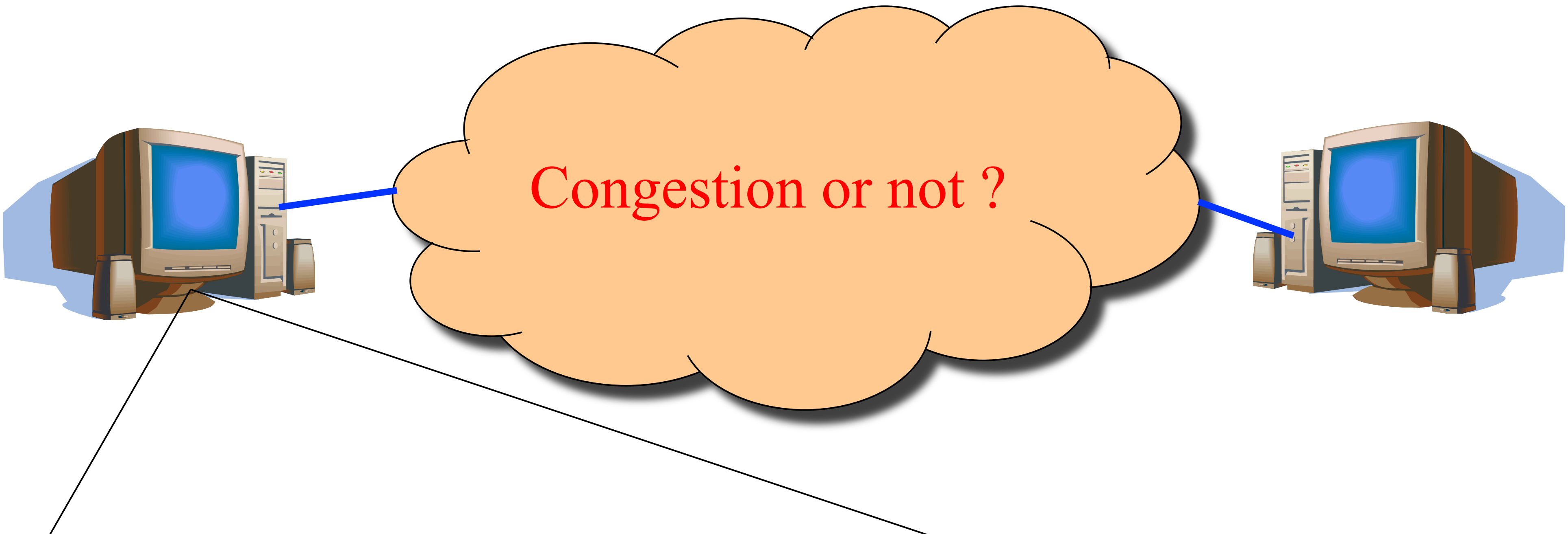
TCP Congestion Control Review

- Congestion Avoidance (CA) phase
  - Increases the rate linearly
    - $cwnd=1+cwnd_{preivous}$
  - Until cwnd reaches Maximum CW
    - Keep CW constant



TCP Congestion Control Review

- Congestion indications

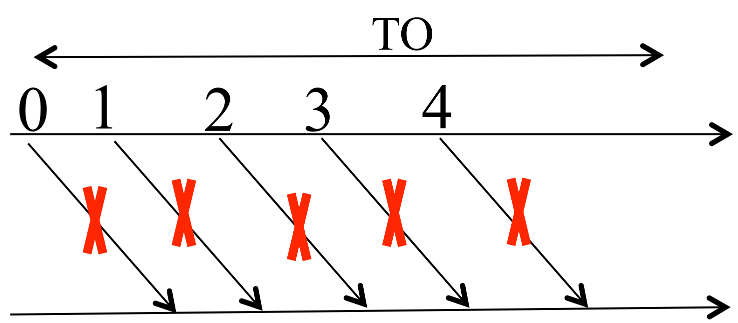


What does the TCP sender see?

– Packet losses
– Round-trip delay

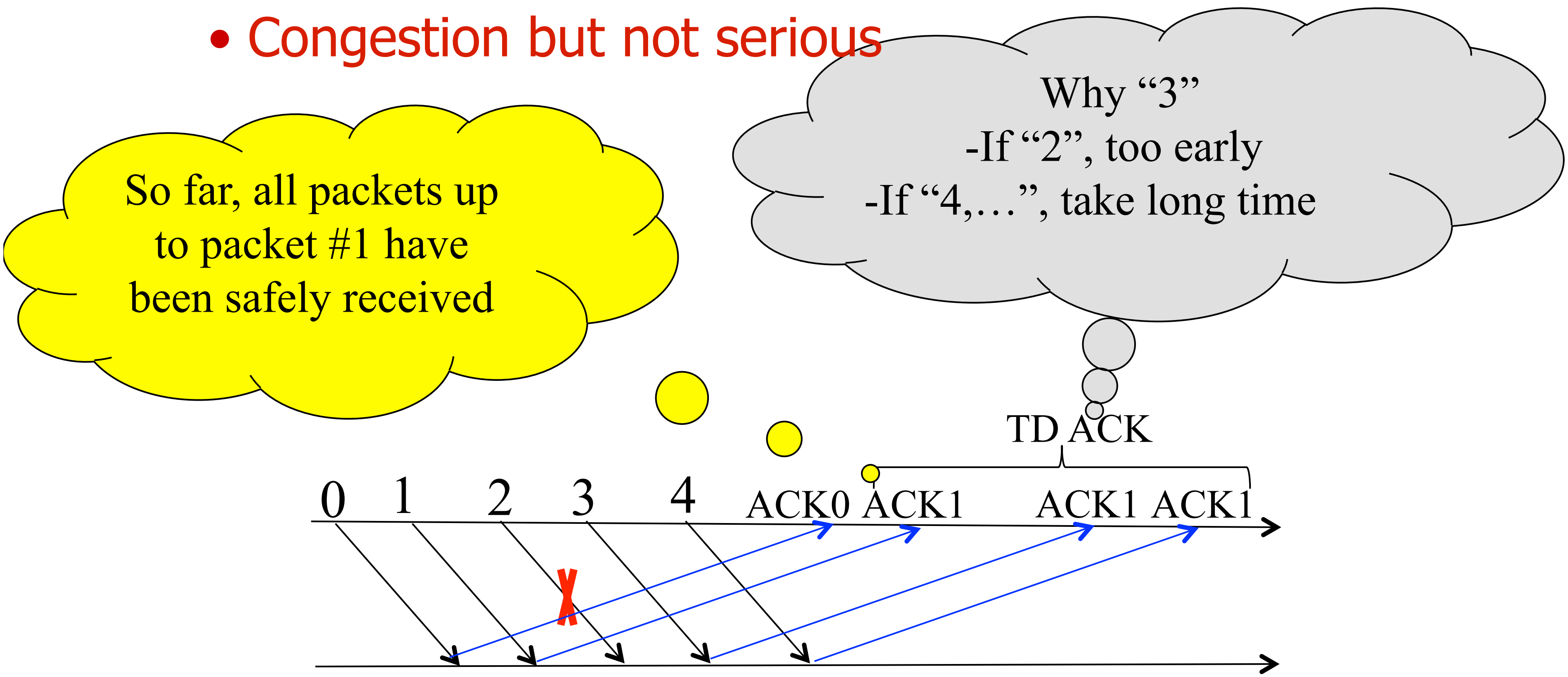
TCP Congestion Control Review

- Congestion indications
  - Timeout
    - Packet *n* is lost and detected via a timeout
      - E.g., because all packets in flight were lost
    - Serious congestion



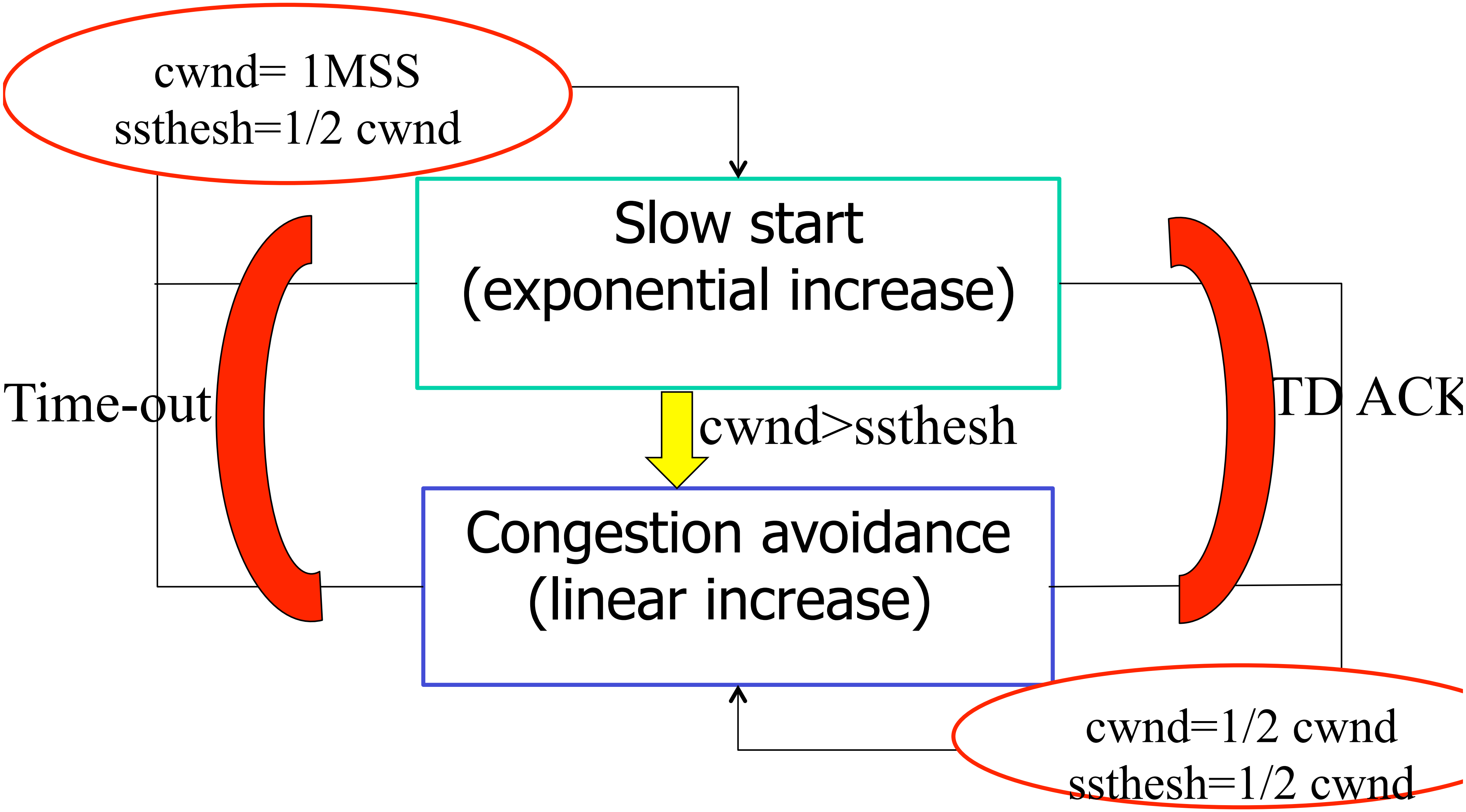
TCP Congestion Control Review

- Congestion indications
  - Triple duplicate ACK
    - Packet *n* is lost, but packets *n*+1, *n*+2, etc. arrive
      - Receiver sends duplicate acknowledgments
    - Congestion but not serious



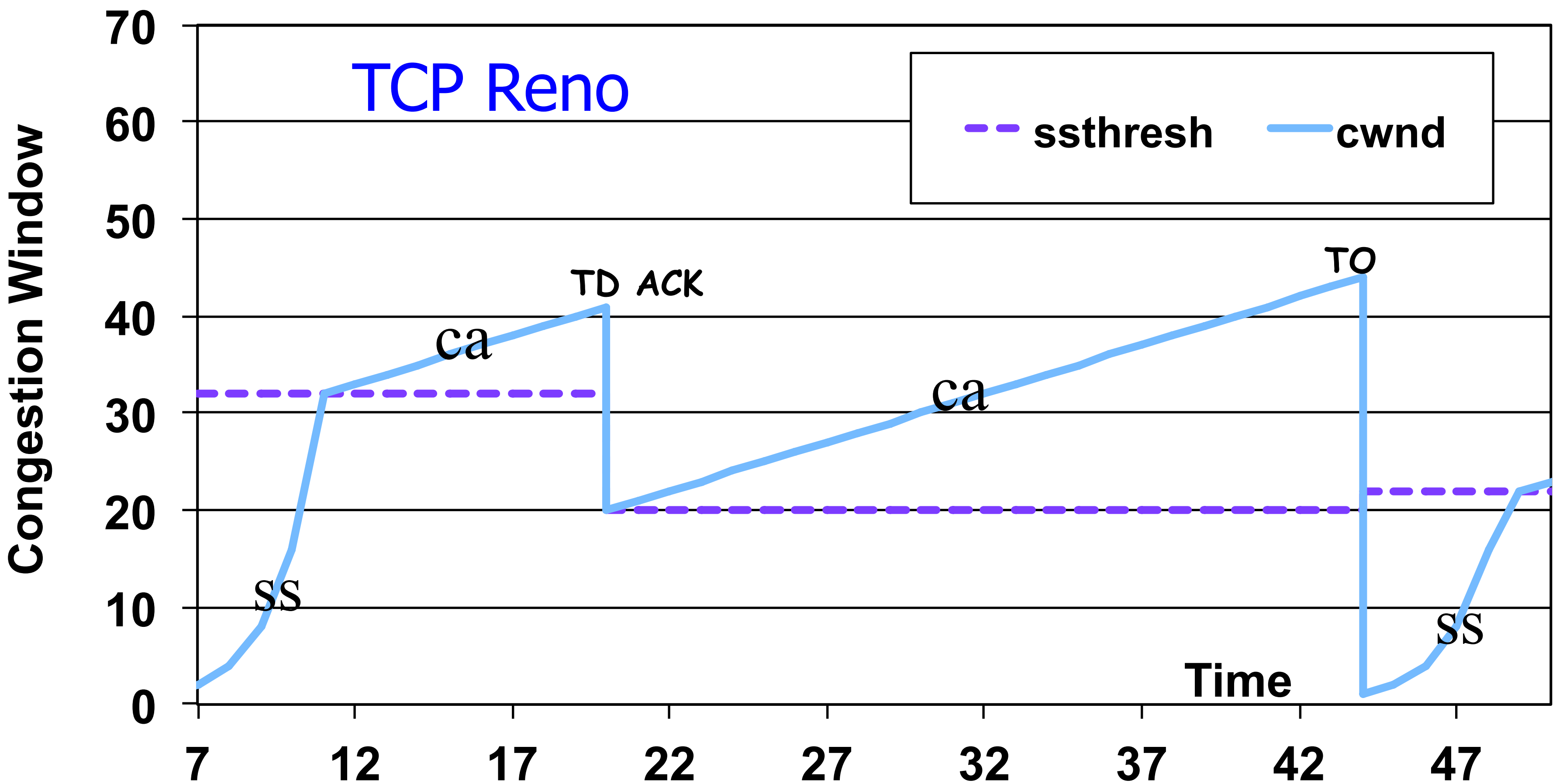
TCP Congestion Control Review

- Congestion reactions



TCP Congestion Control Review

- Congestion reactions
  - Congestion window trace



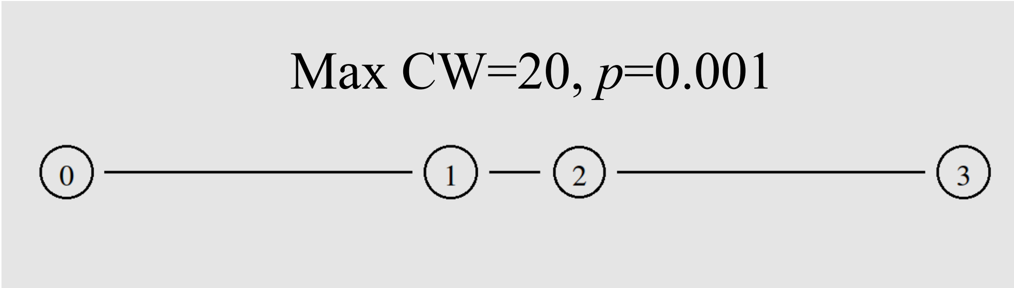
TCP Congestion Control Review

- TCP variants comparison

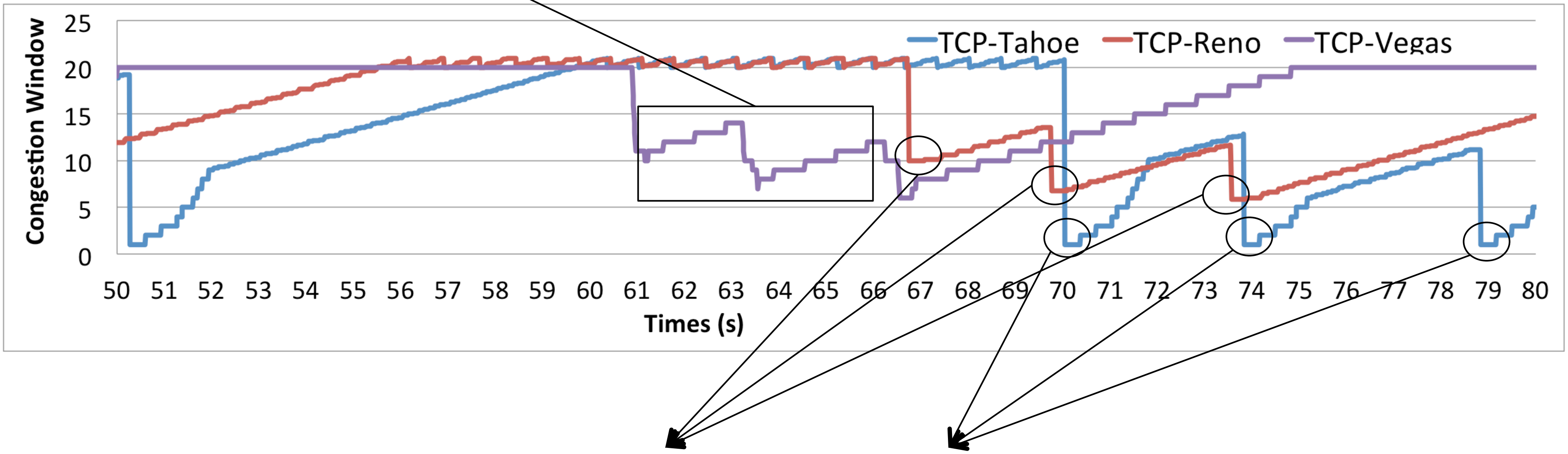
	Congestion indications	Congestion reactions
Tahoe	Packet losses	Only TO for congestion indication Reduce window to one & go to SS phase
Reno NewReno SACK	Packet losses	- Time-out: Reduce window to one & go to SS phase - TD ACK: Reduce window by a half & go to CA phase
Vegas	Packet losses & RTT delays	Time-out and TD ACK: similar to Reno/NewReno/SACK Keep adjusting RTT delays: Diff=f(W,RTT) CA phase - Diff<anpha: cwnd++ - Diff>beta: cwnd-- - anpha<=Diff<=beta: cwnd=cwnd SS phase - Diff>gamma: go to CA phase Expected = cwnd/BaseRTT; Actual = cwnd/RTT Diff= (Expected-Actual)*BaseRTT Typically, gamma=(anpha+beta)/2; anpha=2; 2<=beta<=4

TCP Congestion Control Review

- TCP variants comparison
  - Congestion window trace



Not linear increase

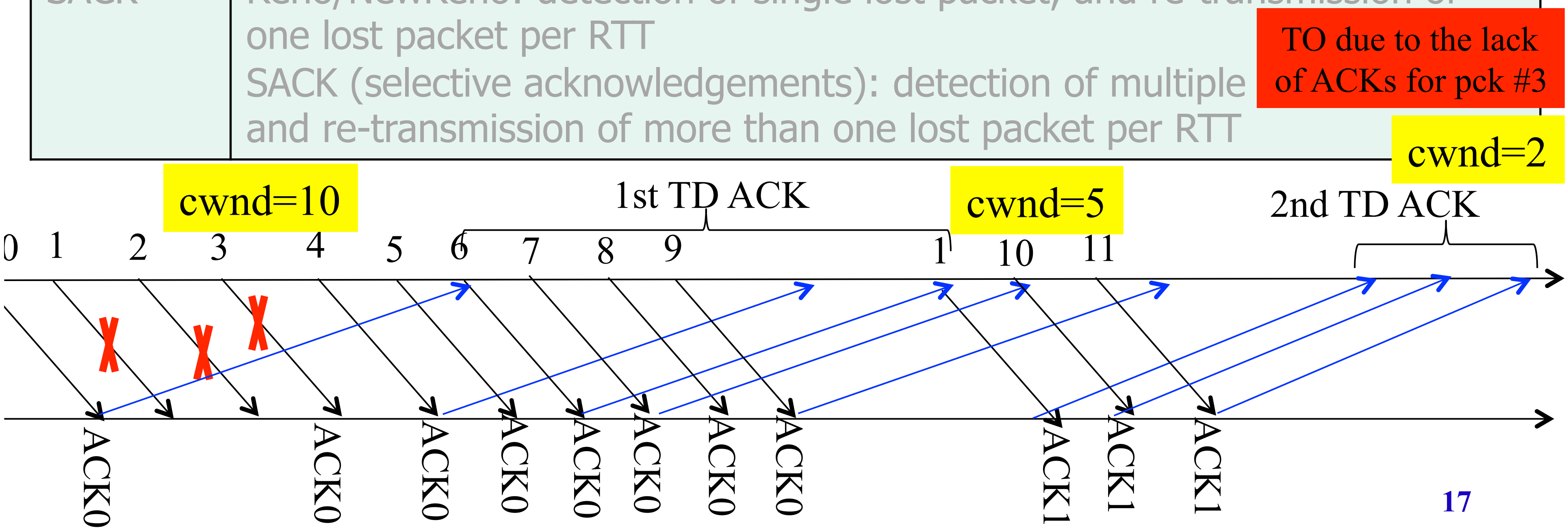


TD ACK Timeout

TCP Congestion Control Review

- TCP variants comparison

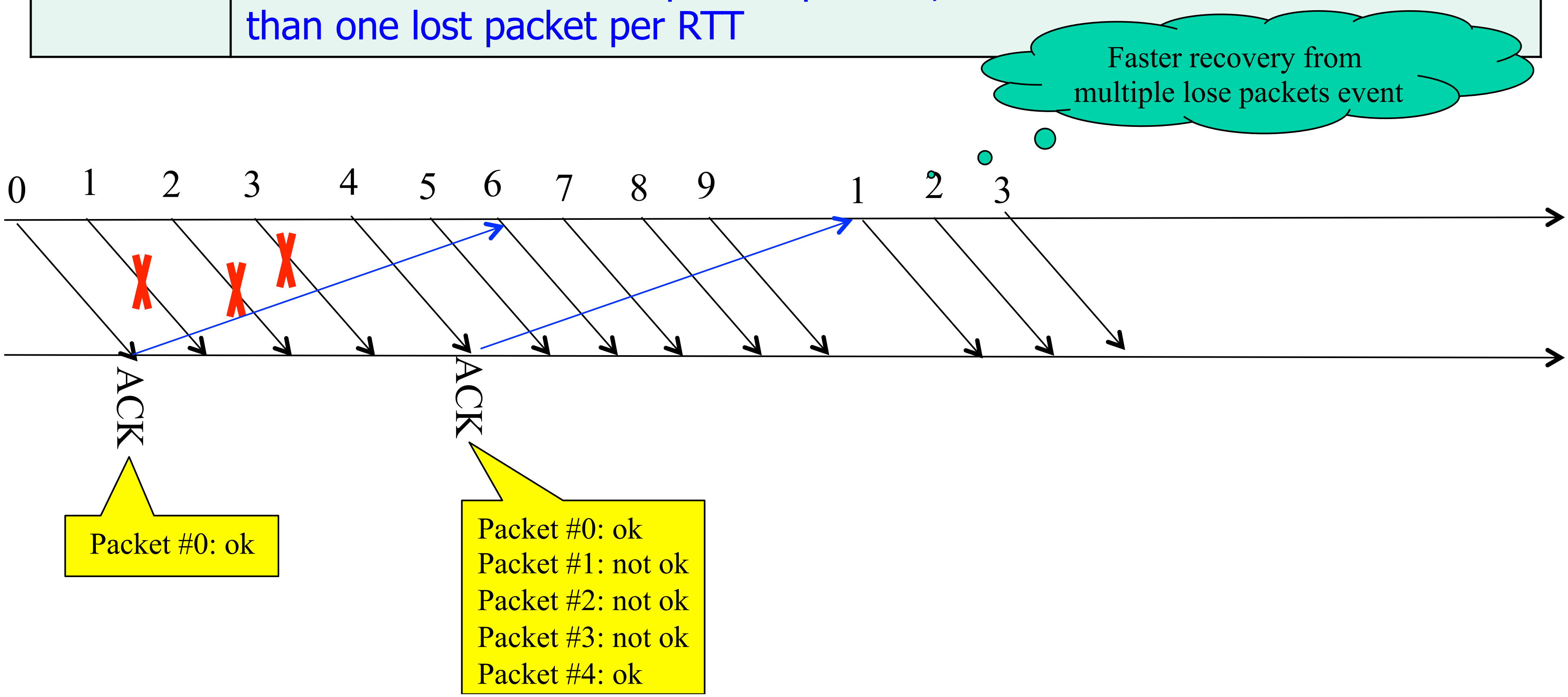
	Response to multiple packet losses
Reno	Problem with "multiple packet losses in one window" With *n* packet losses, cwnd->cwnd/2, cwnd/4,…, cwnd/(2^*n*) Reducing cwnd multiple times. When cwnd is too small, TO may happen due to the lack of ACKs
NewReno	With *n* packet losses within a trans window, Reducing cwnd one time
SACK	Reno/NewReno: detection of single lost packet, and re-transmission of one lost packet per RTT SACK (selective acknowledgements): detection of multiple and re-transmission of more than one lost packet per RTT



TCP Congestion Control Review

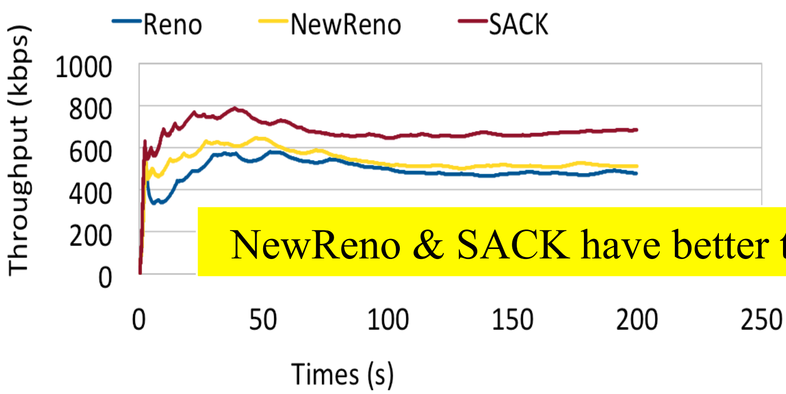
- TCP variants comparison

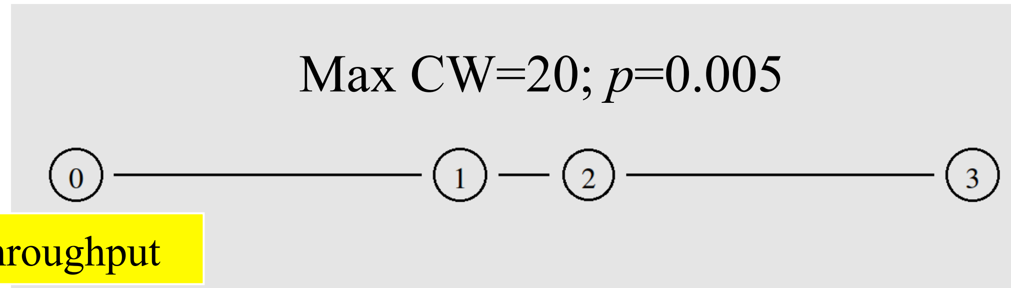
	Response to multiple packet losses
SACK	Reno/NewReno: detection of single lost packet, and re-transmission of one lost packet per RTT SACK: detection of multiple lost packets, and re-transmission of more than one lost packet per RTT



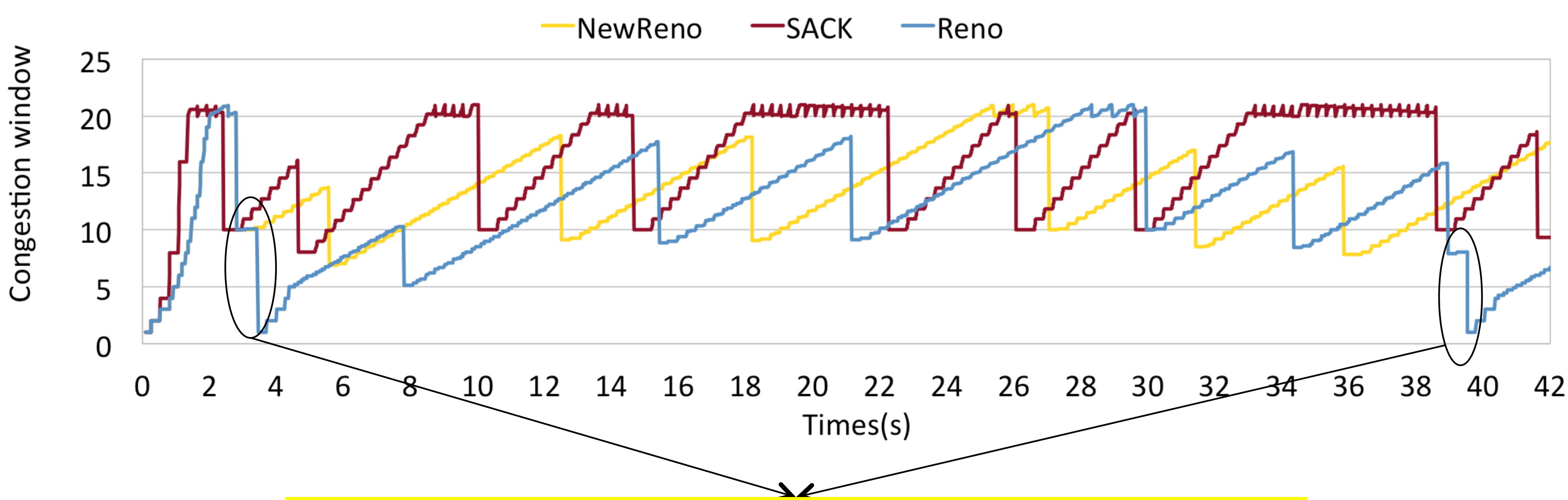
TCP Congestion Control Review

- TCP variants comparison





NewReno & SACK have better throughput



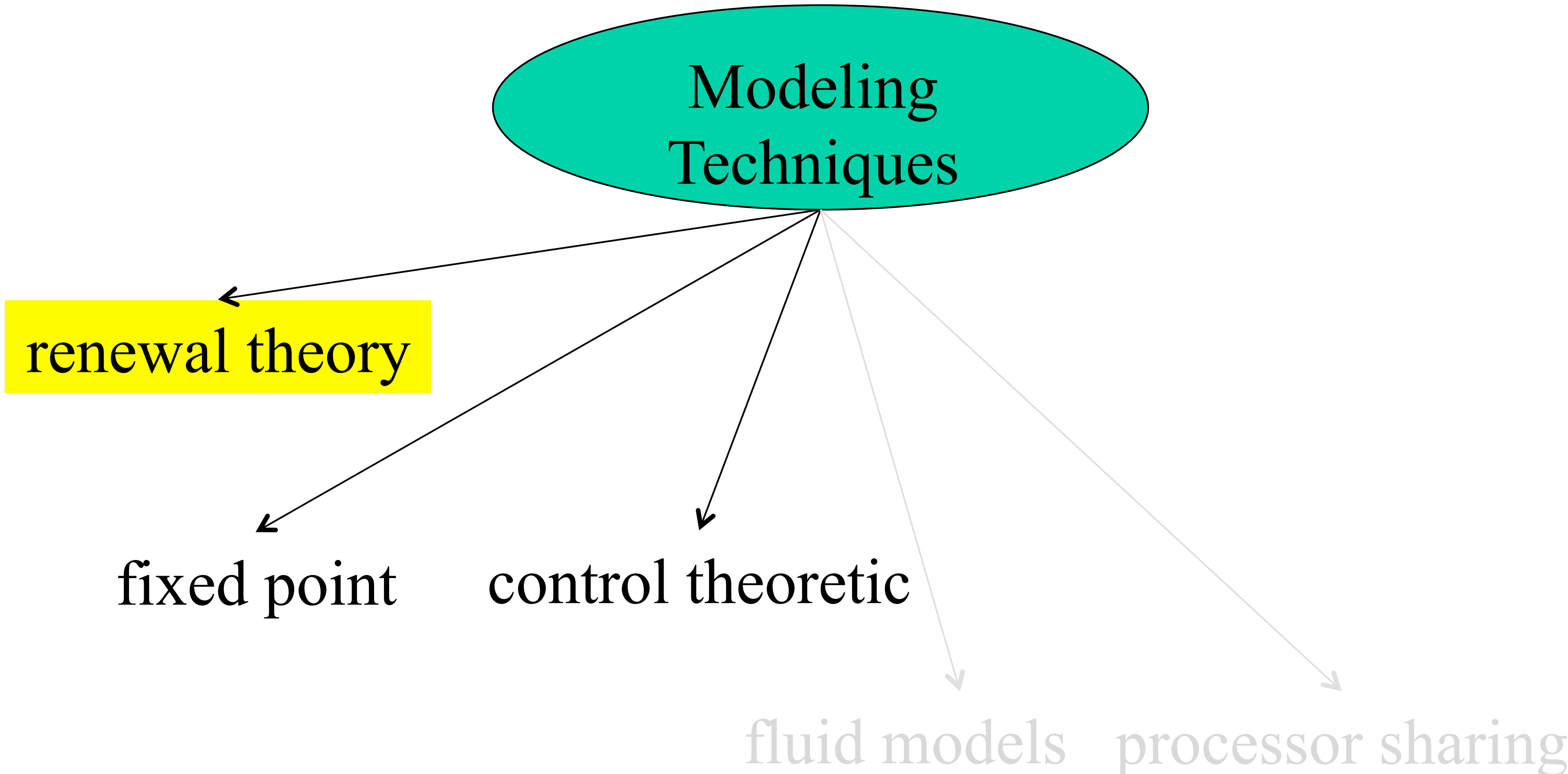
Reducing cwnd multiple times, even leading to TO

TCP Modeling

- Objectives
  - Understand the fundamental relationship between network parameters and TCP performance

    (Throughput, delay,…)<->(packet loss, round-trip time, topology,…)
  - Apply a rage of mathematical models to predict TCP performance

TCP Modeling



Full survey: Ols'en, J.. Stochastic Modeling and Simulation of the TCP Protocol. Ph.D thesis 2003.

TCP Modeling: Renewal Theory Models

- Scope
  - study window evolution in terms of cycles
  - Cycle: period between two consecutive loss events
- The steady state TCP throughput

$$Th = \frac{Avg\ number\ of\ packets\ sent\ per\ cycle}{Avg\ duration\ of\ a\ cycle}$$

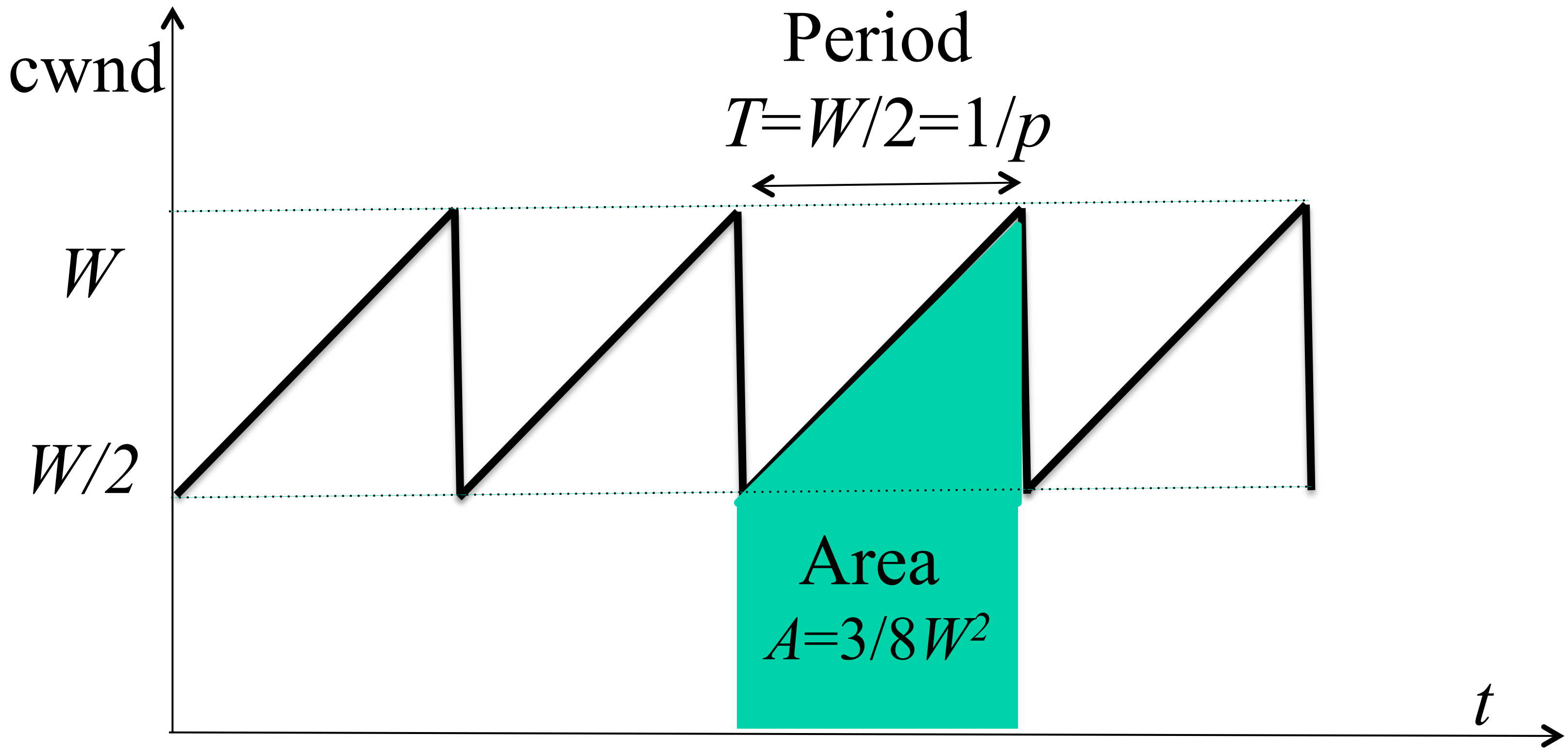
TCP Modeling: Renewal Theory Models

Periodic Model

- The simplest model for TCP throughput
- Assumptions
  - Infinitely long TCP flow
  - Bernoulli losses: packets are lost with a fixed probability p, independently of others
  - Consider periodic TD ACK losses

TCP Modeling: Renewal Theory Models

Periodic Model



$$Th = \frac{A}{L} = \frac{3/8W^2}{RTT \times W/2} = \frac{1}{RTT\sqrt{(2/3)p}}$$

Qualitatively show: throughput is inversely proportional to *RTT* & *p*

TCP Modeling: Renewal Theory Models

Detailed Packet Loss Model

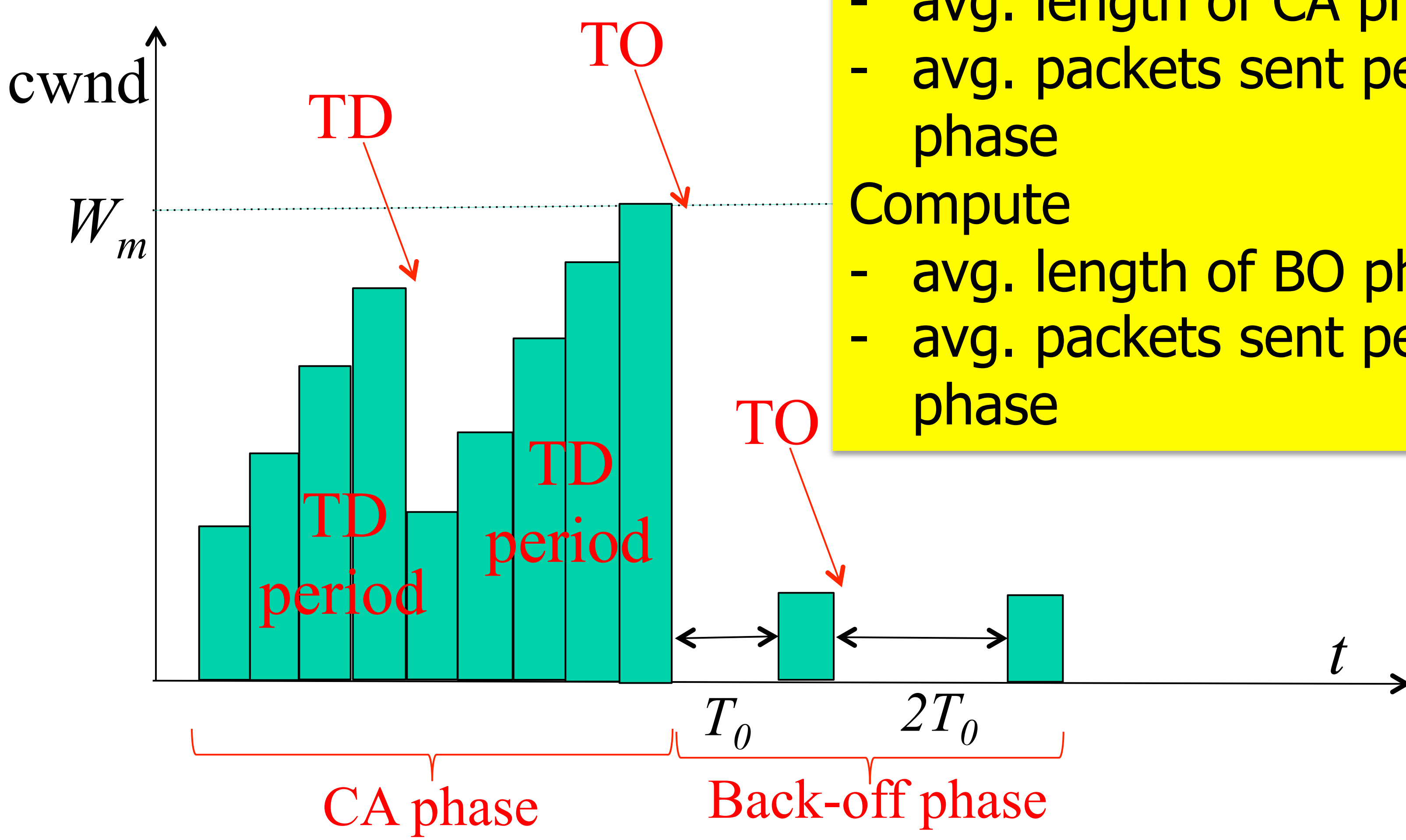
- Consider
  - Time-out and TD ACK losses
  - Correlated losses: packets are lost with a fixed probability *p*, independently of others; until first packet lost, remaining window packets are lost
  - Maximum CW (W_m)

TCP Modeling: Renewal Theory Models

Detailed Packet Loss Model

Compute
- avg. length of CA phase
- avg. packets sent per CA phase

Compute
- avg. length of BO phase
- avg. packets sent per BO phase



TCP Modeling: Renewal Theory Models

Detailed Packet Loss Model

$$Th = \frac{E[A^{CA}] + E[A^{BO}]}{E[L^{CA}] + E[L^{BO}]} = \frac{E[A^{TD}]E[n^{TD}] + E[A^{BO}]}{E[L^{TD}]E[n^{TD}] + E[L^{BO}]}$$

$$E[.] = f(p, RTT, T_0)$$

Ex:

- The number of TOs in a BO phase has a geometric distribution: $P(R = k) = p^{k-1}(1 - p)$

$$\rightarrow E[A^{BO}] = \sum_{k=1}^{\infty} kP(R = k) = 1/p$$

TCP Modeling: Renewal Theory Models

Detailed Packet Loss Model

Ex:

-The duration of a sequence with k TOs is

$$L_k = \begin{cases} (2^k - 1)T_0, k \le 6 \\ [63 + 64(k-6)]T_0, k > 6 \end{cases}$$

Maximum back-off counter

$$\rightarrow E[L^{BO}] = \sum_{k=1}^{\infty} L_k P(R = k) = T_0 \frac{1 + p + 2p^2 + 4p^3 + 8p^4 + 16p^5 + 32p^6}{1 - p}$$

And so on, see (*) for full derivations

*Jitendra Padhye, Victor Firoiu, Don Towsley, and Jim Kurose.
Modeling TCP throughput: a simple model and its empirical validation.

TCP Modeling: Renewal Theory Models

Detailed Packet Loss Model

$$Th \approx \min\left(\frac{W_m}{RTT}, \frac{1}{RTT\sqrt{\frac{2p}{3}} + T_0 \min(1, 3\sqrt{\frac{3p}{8}})p(1-32p^2)} \right)$$

Maximum CW

TD losses

Time-out

TCP Modeling: Renewal Theory Models

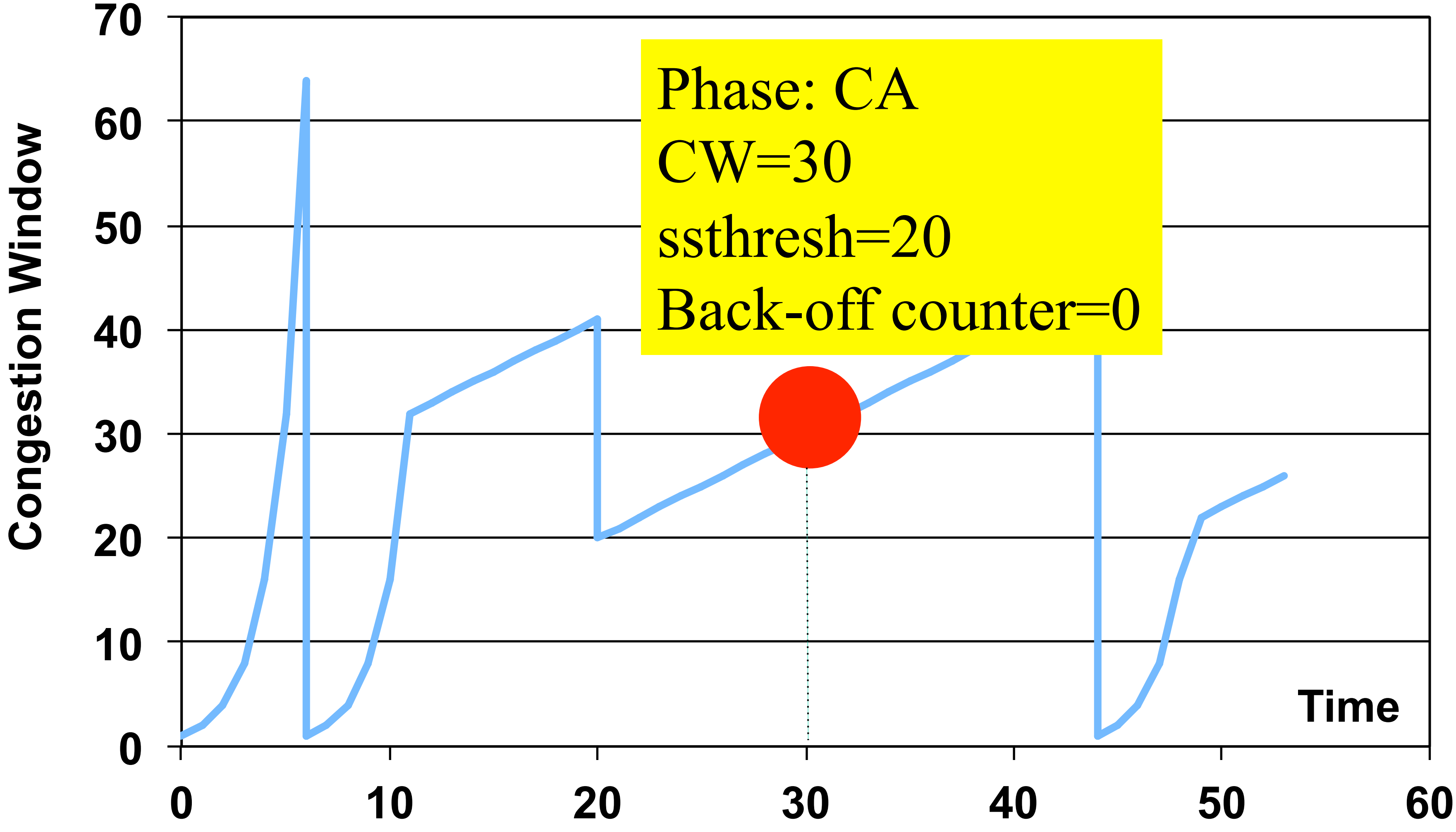
Markov Chain Model

- Chain keeps track of TCP operation through
  - Phases: CA, SS, BO, TO
  - Parameters, e.g., window size, ssthresh and back-off counter.
- Allows more “careful” models

TCP Modeling: Renewal Theory Models

Markov Chain Model

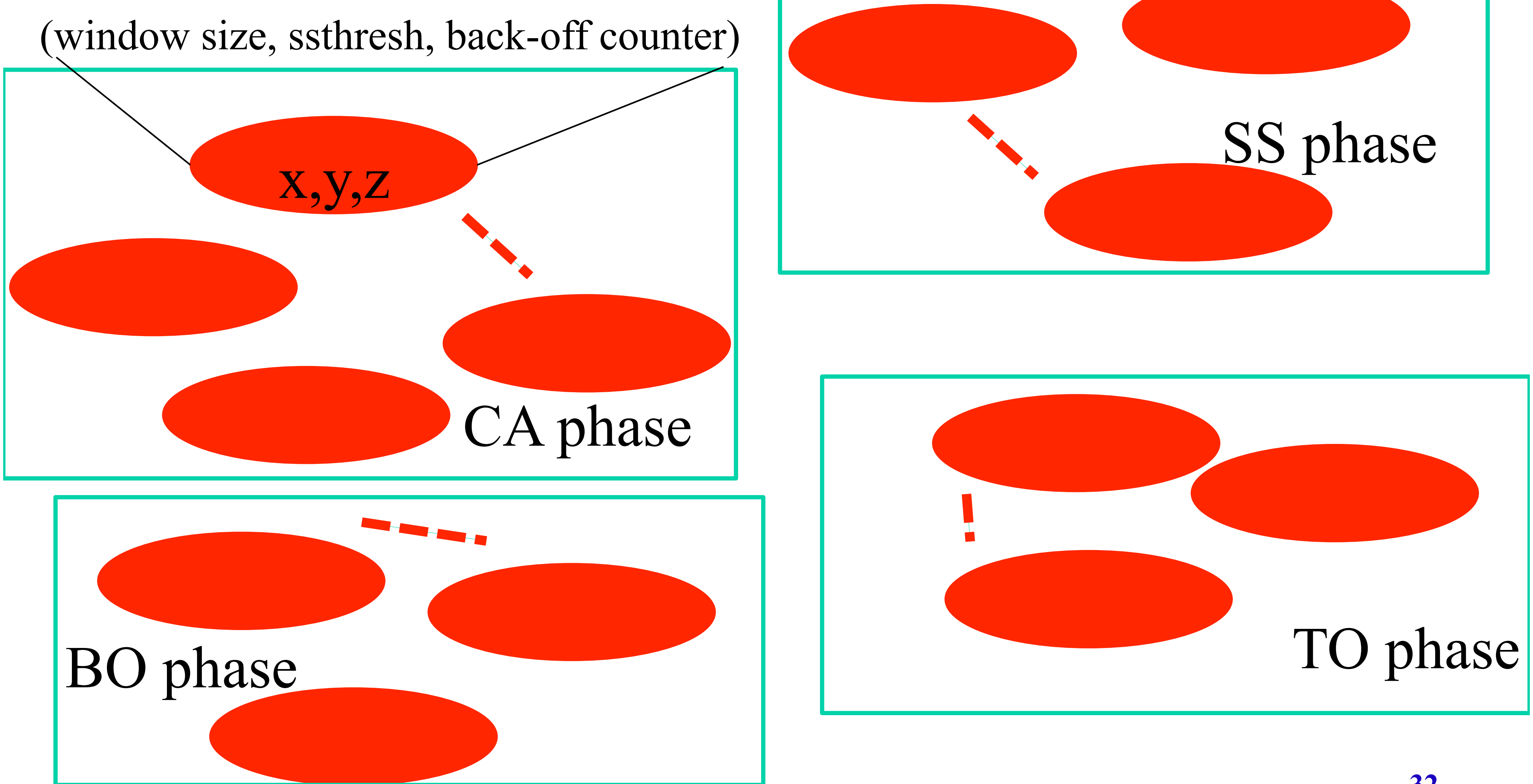
- Observe TCP operation at a cycle & capture its status



TCP Modeling: Renewal Theory Models

Markov Chain Model

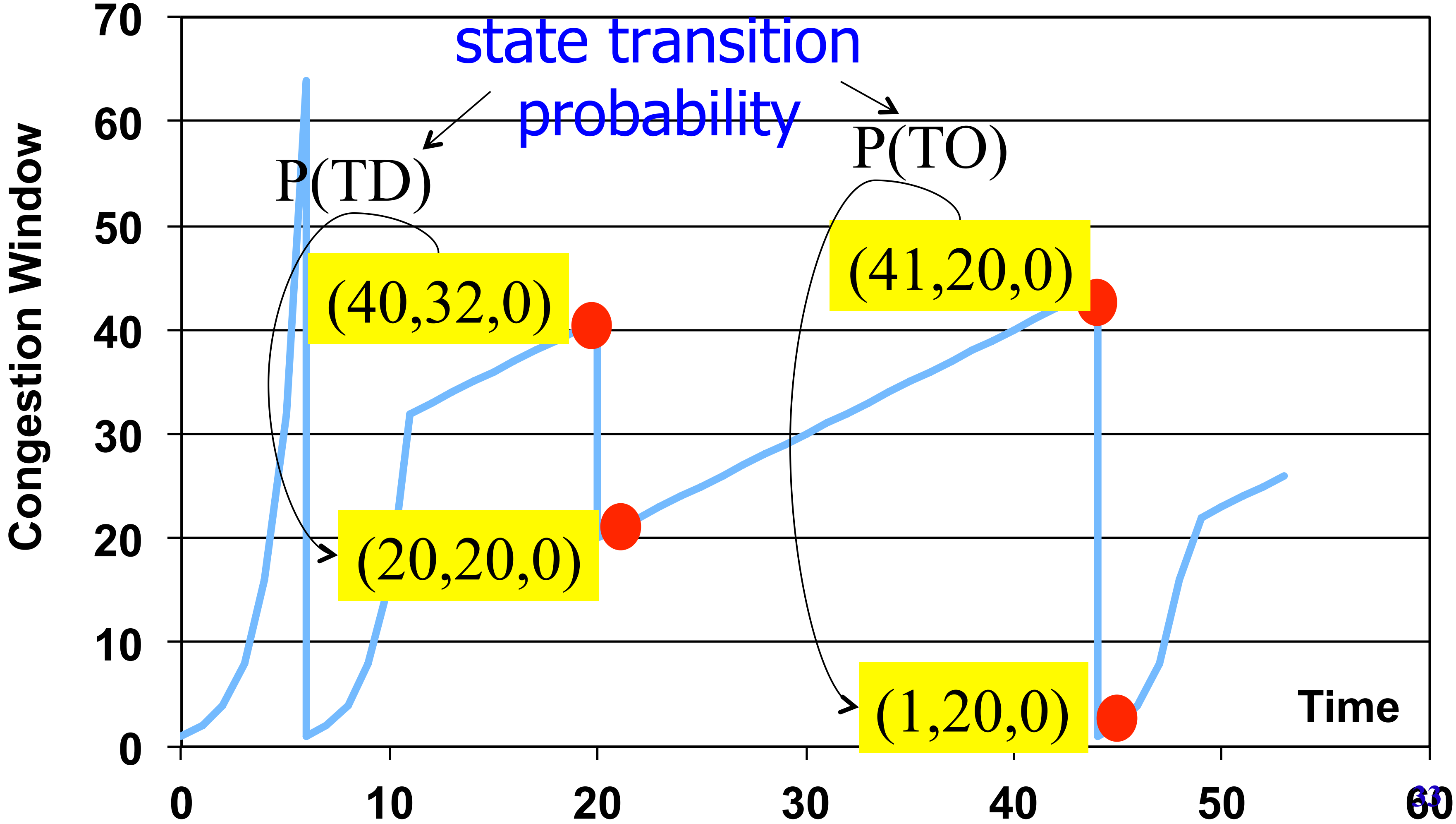
- State space



TCP Modeling: Renewal Theory Models

Markov Chain Model

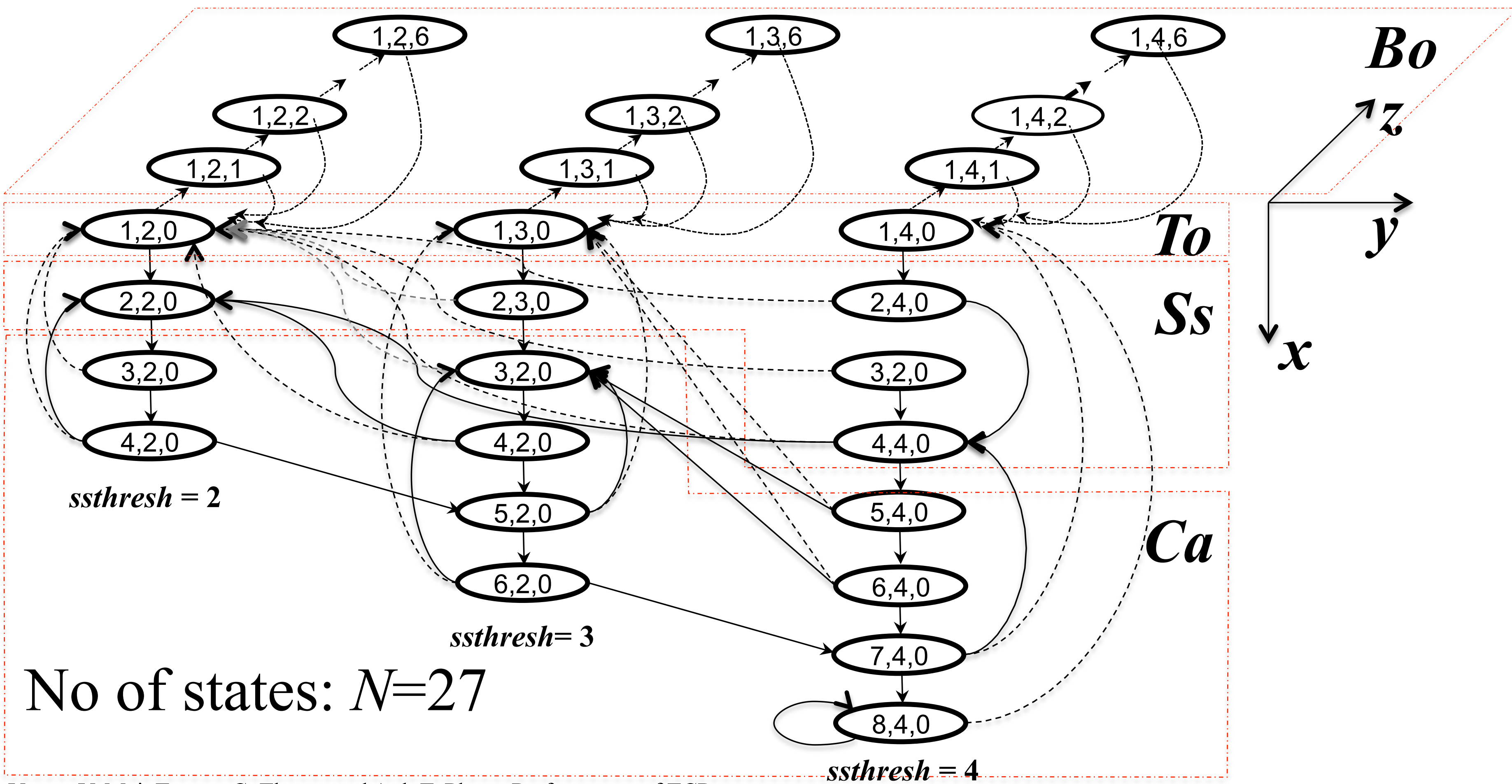
- State connection



TCP Modeling: Renewal Theory Models

Markov Chain Model

- An example of Markov chain for W_m=8, Max_BO=6



Vuong V. Mai, Truong C. Thang, and Anh T. Pham. Performance of TCP Over Free-Space Optical Atmospheric Turbulence Channels. JOCN 2013

TCP Modeling: Renewal Theory Models

Markov Chain Model

- Mathematical expression
  - Let P=[p_1 p_2 … p_N] be the matrix of steady-state probabilities, where p_i is the probability of the *i*-th state in the equilibrium
  - Let Q=[q_{ij}] be the transition matrix of the Markov chain with an element q_{ij} being the transition probability from the state *i* to the state *j*
    - *q_{ij}=f(packet loss, CW, phase): pre-calculated*

TCP Modeling: Renewal Theory Models

Markov Chain Model

- Mathematical expression

q_{ij}=f(packet loss, CW, phase): pre-calculated

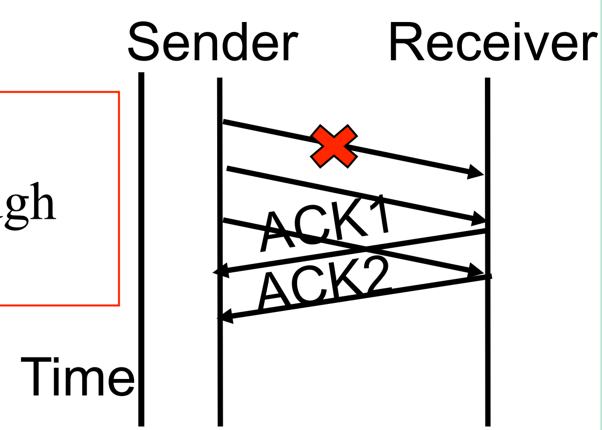
$$P_{TD} \approx \begin{cases} P_W(1)+P_W(2), W \geq 10 \\ P_W(1), 4 \leq W < 10 \\ 0, W < 4 \end{cases}$$

Prob of *i* losses from *W*:

$$P_W(i) = \binom{W}{i} p^i (1-p)^{W-i}$$

$$P_{TO} \approx \begin{cases} \sum_{i=3}^{W} P_W(i), W \geq 10 \\ \sum_{i=2}^{W} P_W(i), 4 \leq W < 10 \\ 1-P_W(0), W < 4 \end{cases}$$

Ex: W=3
Not enough
3 ACKs



Vuong V. Mai, Truong C. Thang, and Anh T. Pham. Performance of TCP Over Free-Space Optical Atmospheric Turbulence Channels.

TCP Modeling: Renewal Theory Models

Markov Chain Model

- Mathematical expression

$$\begin{cases} P = Q \times P \longrightarrow \text{the global balance equations} \\ \sum_{i=1}^{N} p_i = 1 \longrightarrow \text{the normalization condition} \end{cases}$$

  - Solve the set of Eqs by
    - Using Matlab to calculate Matrix equations
    - (or) Jacobi, Gauss-Seidel

- Having [p_1 p_2 ... p_N], calculate throughput

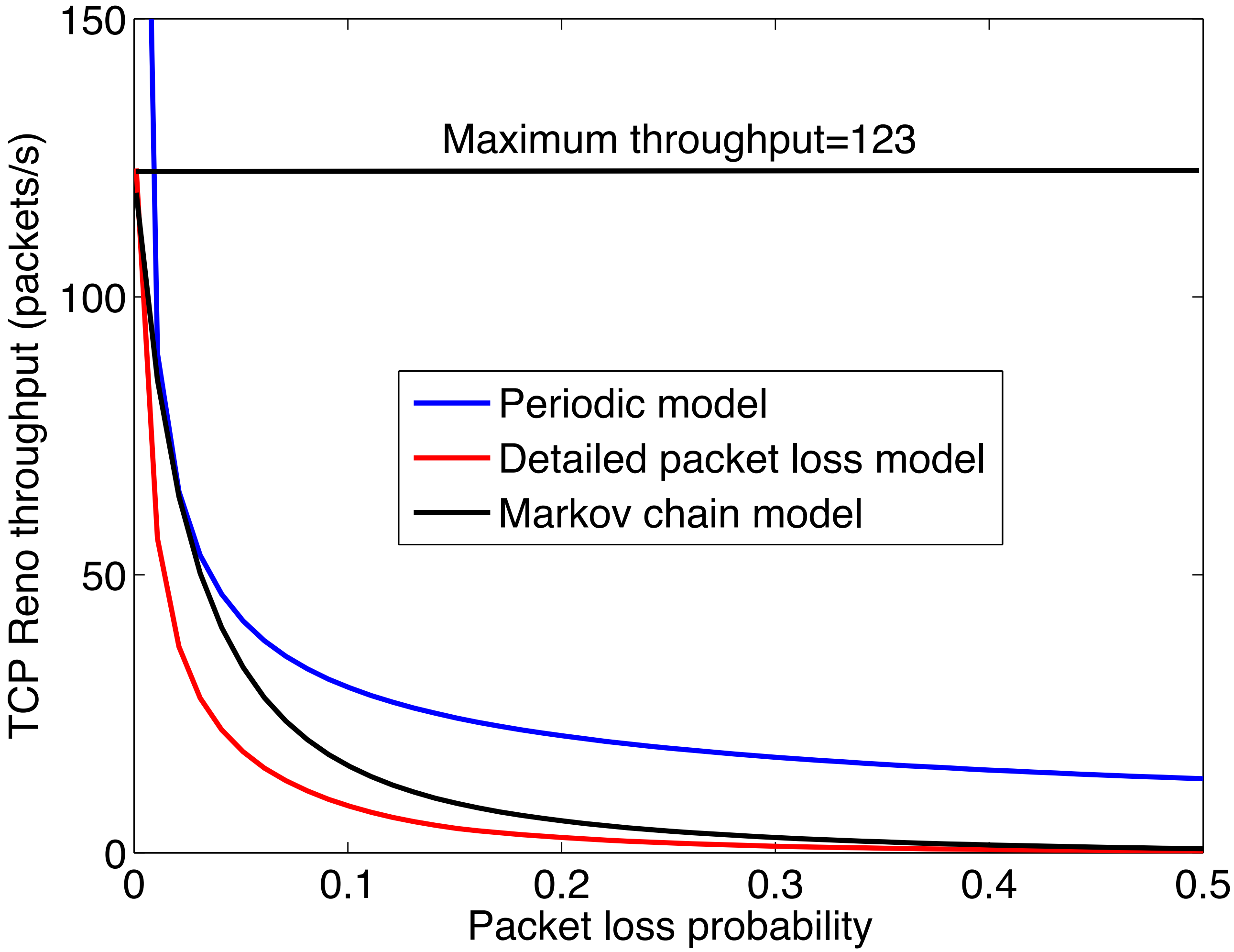
$$Th = \frac{\sum p_i CW_i}{\sum p_i RTT_i}$$

TCP Modeling: Renewal Theory Models

- Comparisons
  - Periodic Model/Detailed Packet Loss Model: closed form expressions
  - Markov chain:
    - exact form expression, thus having the highest accuracy
    - increasing Max CW significantly increases the state space, thus resulting in high complexity in deriving Markov chain

TCP Modeling: Renewal Theory Models

- Comparisons



$W_{m}=16$
$RTT=0.13$ second
$T_0=5*RTT$

Matlab code: https://drive.google.com/folderview?id=0B1dp1Sn8XIvCVEVPSlpRNlBFcW8&usp=sharing

TCP Modeling: Renewal Theory Models

- Advantages
  - In most case, throughput is given in closed form
    - Possible to investigate directly how different parameters like pack loss, RTT & Max CW impart throughput
- Disadvantages
  - Primary network parameters like topology & traffic are not taken into account
  - Consider for only one single TCP flow

"Single session & black-box network"

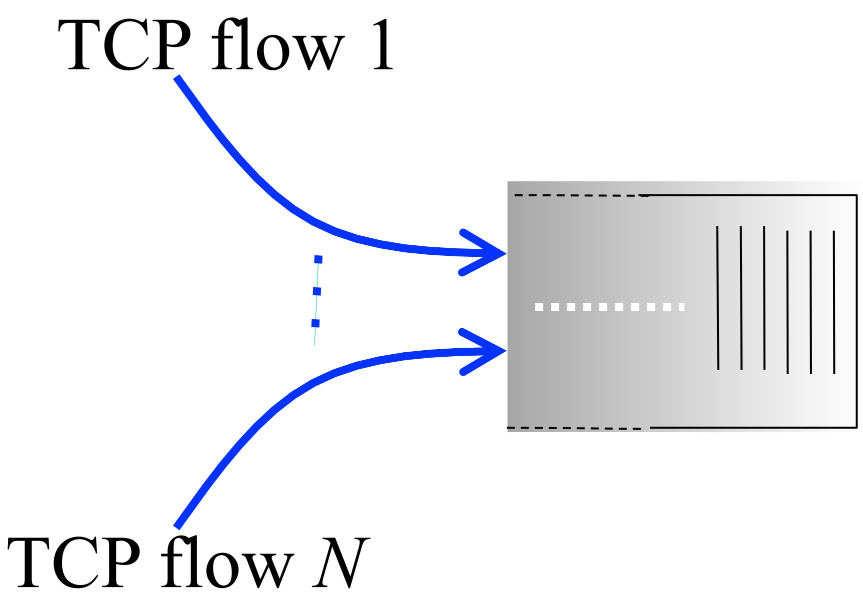
TCP Modeling: Fixed-point Methods

- Scope
  - Modeling of multiple TCP flows in arbitrary network
  - Combining TCP & network models into a framework for TCP-network modeling

“Multiple sessions & network-aware”

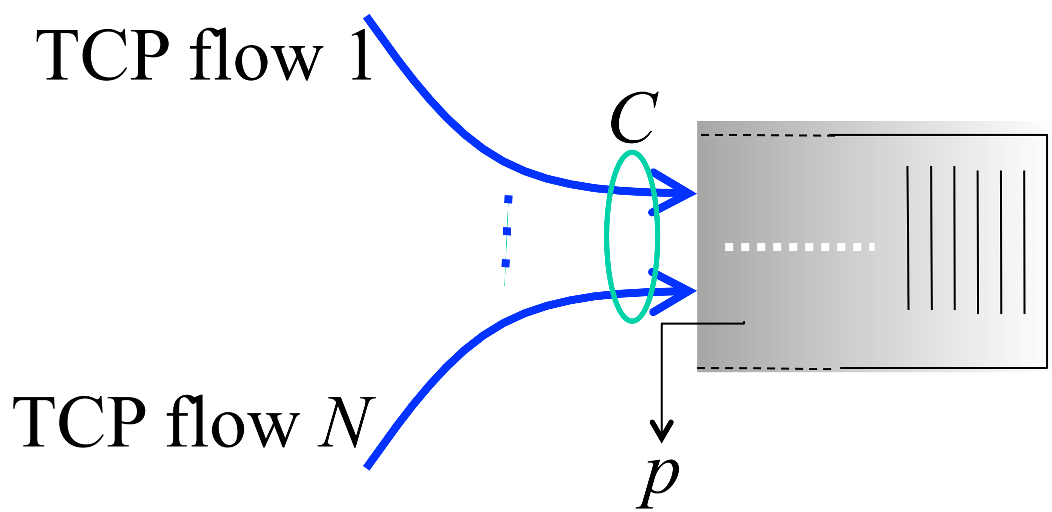
TCP Modeling: Fixed-point Methods

- Consider the simplest scenario
  - *N* flows going through a bottleneck router
  - Objective: TCP performance & queue performance



TCP Modeling: Fixed-point Methods

- Approach
  - View from queue
    - Arrival traffic: aggregated TCP traffics (*C*)
    - Packet loss: blocking pro (*p*) due to the limited buffer
  - View from TCP sources
    - All flows see same loss probability, *p*
    - TCP traffic rates (*throughput*)=*Th*(*p, RTT*)



TCP Modeling: Fixed-point Methods

- Approach
  - Solve a *fixed point* problem for *p*

$$
\begin{cases}
\sum_{i=1}^{N} Th_i(p, RTT_i) = C \\
p = Queue\_loss(C) \\
RTT_i = Propagation\_delay_i + Queue\_delay(C)
\end{cases}
$$

TCP source modeling

Queue modeling

  - Having *p, calculate*
    - TCP performance: *Th(.)*
    - Queue performance: *Queue_loss(.), Queue_delay(.)*

TCP Modeling: Fixed-point Methods

- Related studies
  - Different TCP source modeling:
    - Periodic model, detailed packet loss model, Markov chain model (renewal theory models)
  - Different queue modeling:
    - M/M/1/B, M/D/1/B
  - Extended network topology: multiple routers

TCP Modeling: Fixed-point Methods

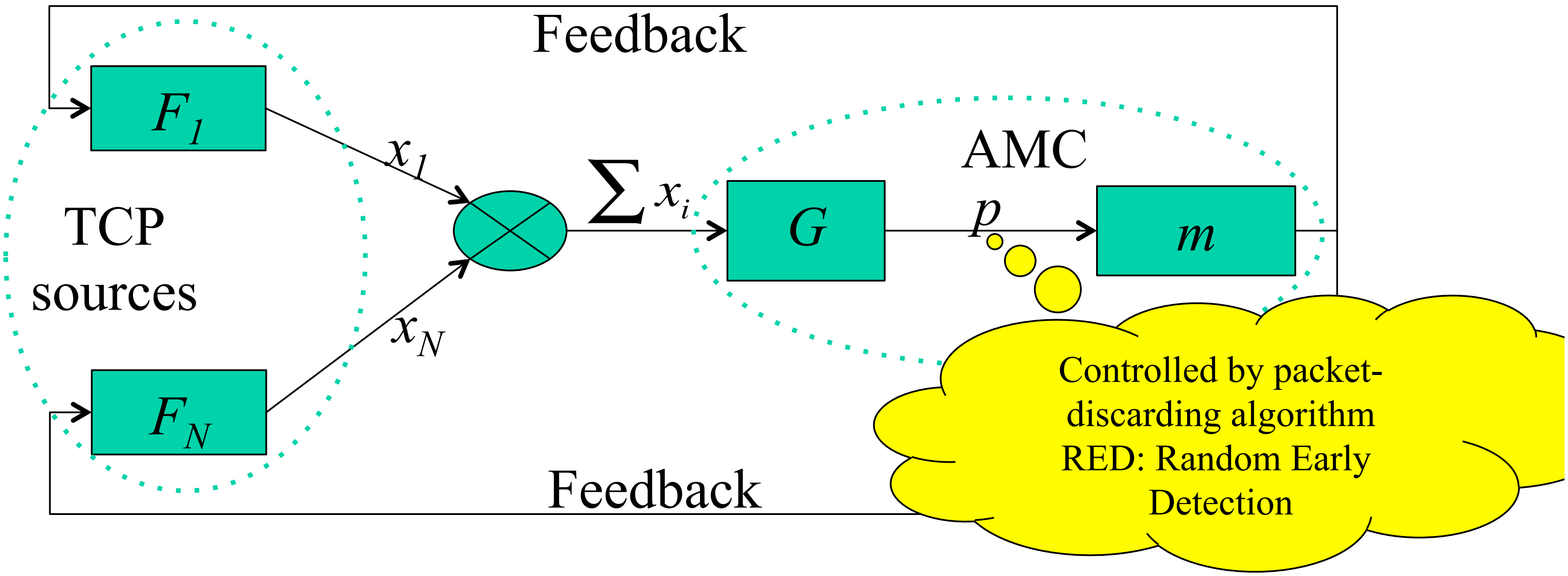
- Advantages
  - Well combine examined models for TCP sources and for network
  - Possible take into account critical network characteristics: topology, no. of flows
- Disadvantages
  - Numerical methods used to find the fixed-point in some frameworks require a great duel of implementation work. Ex: multiple routers ->need find a multi-dimensional fixed point

TCP Modeling: Control Theoretic Models

- Motivations
  - View from queue
    - So far, consider passive queue management
      - Packet drop event may cause senders to back-off
      - No early congestion warning
    - Possibly play an active role in controlling TCP connection by active queue management (AQM)
      - Perform preventive random packet drop before the buffer is full
      - Provide a feedback mechanism to notify senders of the onset of congestion
  - TCP/AQM modeling

TCP Modeling: Control Theoretic Models

- A model of control theory approach



Network congestion signal: *m(p)*
Price (sending cost): *p* (loss rate, delay, etc.)
TCP sending rate update rule: $x_s(t+1)=F_s(x_s(t), m(p(t)))$
AMC price update rule: $p(t+1) = G(\sum x_s(t), p(t))$

TCP Modeling: Control Theoretic Models

- Approach
  - Can reuse fixed-point methods

$$\begin{cases} \sum_{i=1}^{N} Th_i(p, RTT_i) = C \\ p = Queue\_loss(C) \\ RTT_i = Propagation\_delay_i + Queue\_delay(C) \end{cases}$$

TCP source modeling

AMC modeling

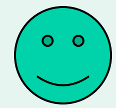
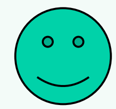
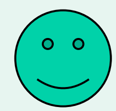
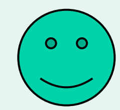
  - Combine with network optimization
    - Maximizing the different betw utilization and sending cost

    -> Design AMC operation (RED algorithm)

TCP Modeling: Control Theoretic Models

- Advantages
  - More insight interactions betw TCP sources & network
  - Possibly optimize TCP/AQM operations
- Disadvantages
  - Require feedback
  - Cost of increased complexity

TCP Modeling: TCP Modeling Comparisons

	Advantages & Disadvantages	Performance analysis	Protocol design
Renewal theory	- Single session & black-box network - Simple, most popular		
Fixed-point	- Multiple sessions & network-aware - Complex numerical analysis		
Control theoretic	- Multiple sessions & network-aware & network optimization - Require feedback - Cost of increased complexity		

Summary

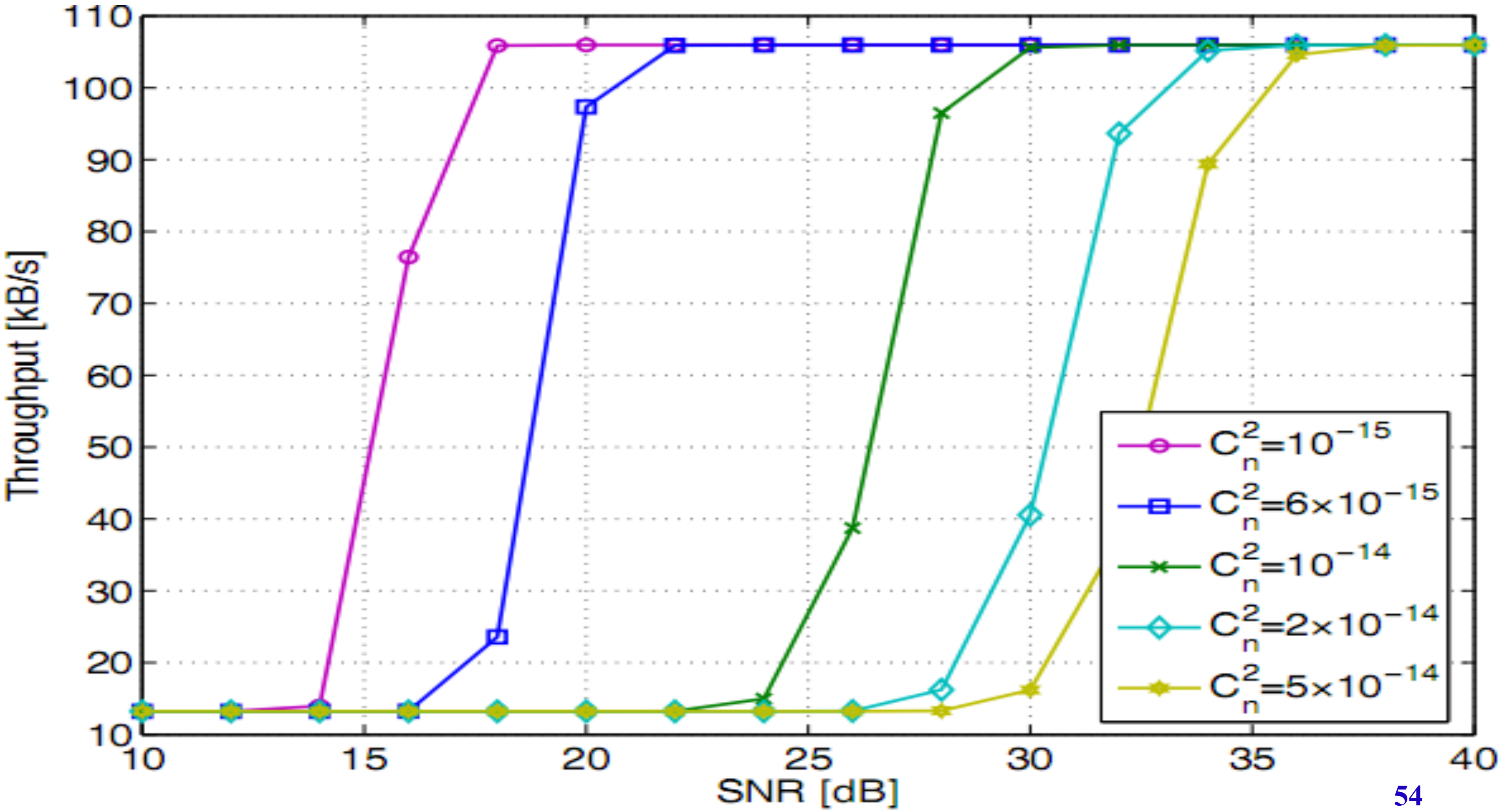
- Review TCP
  - Congestion control
    - Time-out, TD ACK, Delay RTT
    - SS, CA, TO, BO
  - TCP variants
    - Tahoe, Reno, NewReno, SACK, Vegas
- Survey TCP modeling
  - *Renewal theory*
    - Simple, detailed packet loss & Markov chain models
  - Fixed-point
  - Control theoretic

Recommended References

Short list	Contents
[1] M. Hassan and R. Jain. High Performance TCP/IP Networking: Concepts, Issues, and Solutions. Book 2003.	Review: TCP/IP fundamentals Review: Performance study of TCP/IP (measurement, simulation, modeling)
[2] Jitendra Padhye, Victor Firoiu, Don Towsley, and Jim Kurose. Modeling TCP throughput: a simple model and its empirical validation. SIGCOM 1998.	Renewal theory: detailed packet loss model
[3] Vuong V. Mai, Truong C. Thang, and Anh T. Pham. Performance of TCP Over Free-Space Optical Atmospheric Turbulence Channels. JOCN 2013.	Renewal theory: Markov chain model Renewal theory: Matlab codes https://drive.google.com/folderview?id=0B1dp1Sn8XIvCVEVPSlpRNlBFcW8&usp=sharing
[4] Ols'en, J.. Stochastic Modeling and Simulation of the TCP Protocol. Ph.D thesis 2003.	Survey: TCP modeling (Renewal theory, Fixed-point, Control theoretic)

My Related Studies

Performance of TCP over Free-Space Optical Atmospheric Turbulence Channels



My Related Studies

Throughput Analysis of TCP over Visible Light Communication Indoor Networks