Congestion Control in Converged Ethernet with Heterogeneous and Time-Varying Delays

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Background

Converged Ethernet (CE)

Storage Area Networks (SAN)
Deterministic, in-order, guaranteed delivery to be sent to/from storage devices.

Local Area Networks (LAN)
Traditional TCP/IP based Ethernet network for best effort data communications.

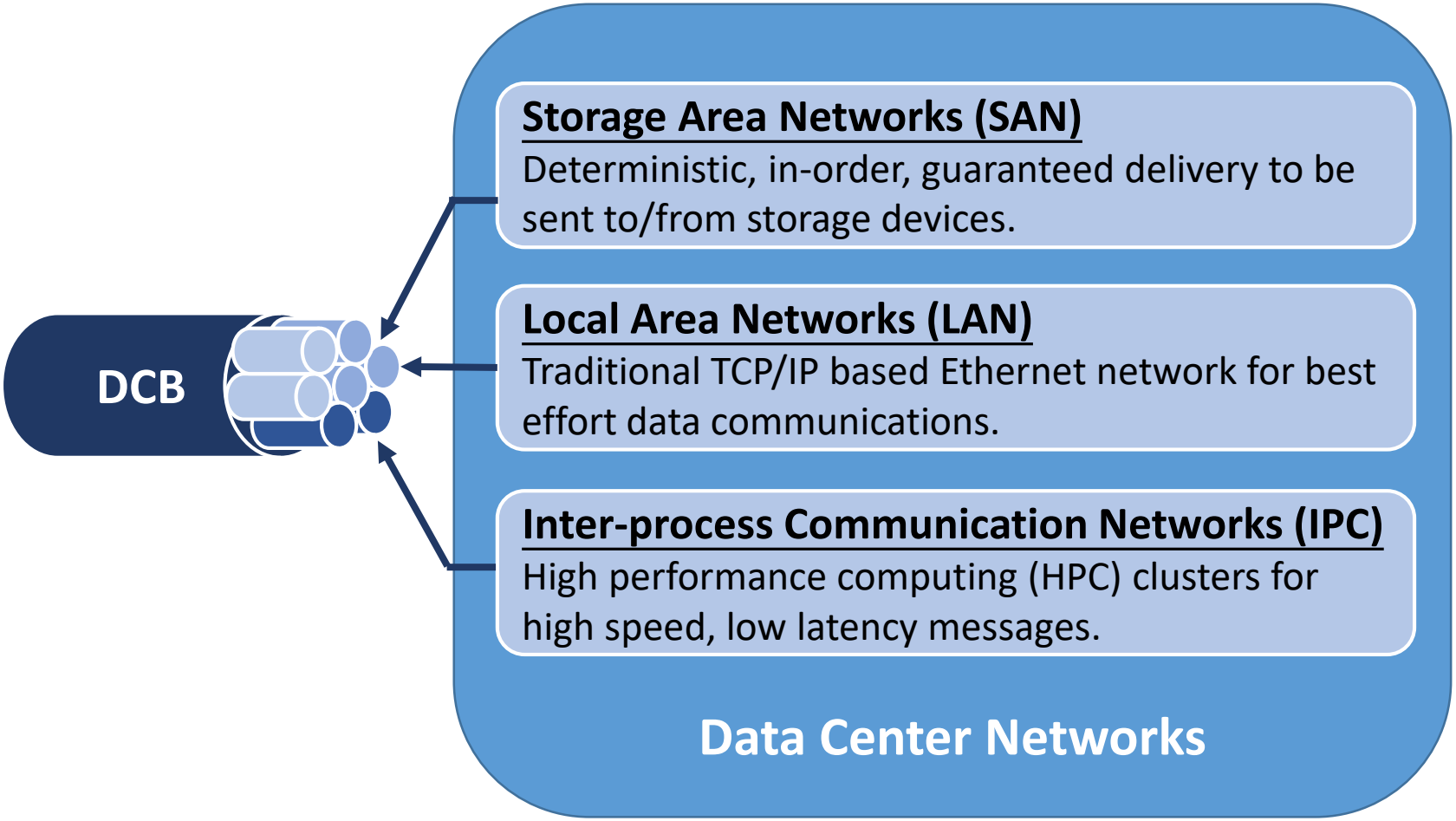
Inter-process Communication Networks (IPC)
High performance computing (HPC) clusters for high speed, low latency messages.

Data Center Networks

Background

Converged Ethernet (CE)

Enhance Ethernet as a unified fabric in data center.



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Congestion Control in CE

- Indispensable for losslessness and high utilization.
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  - Implemented in devices.
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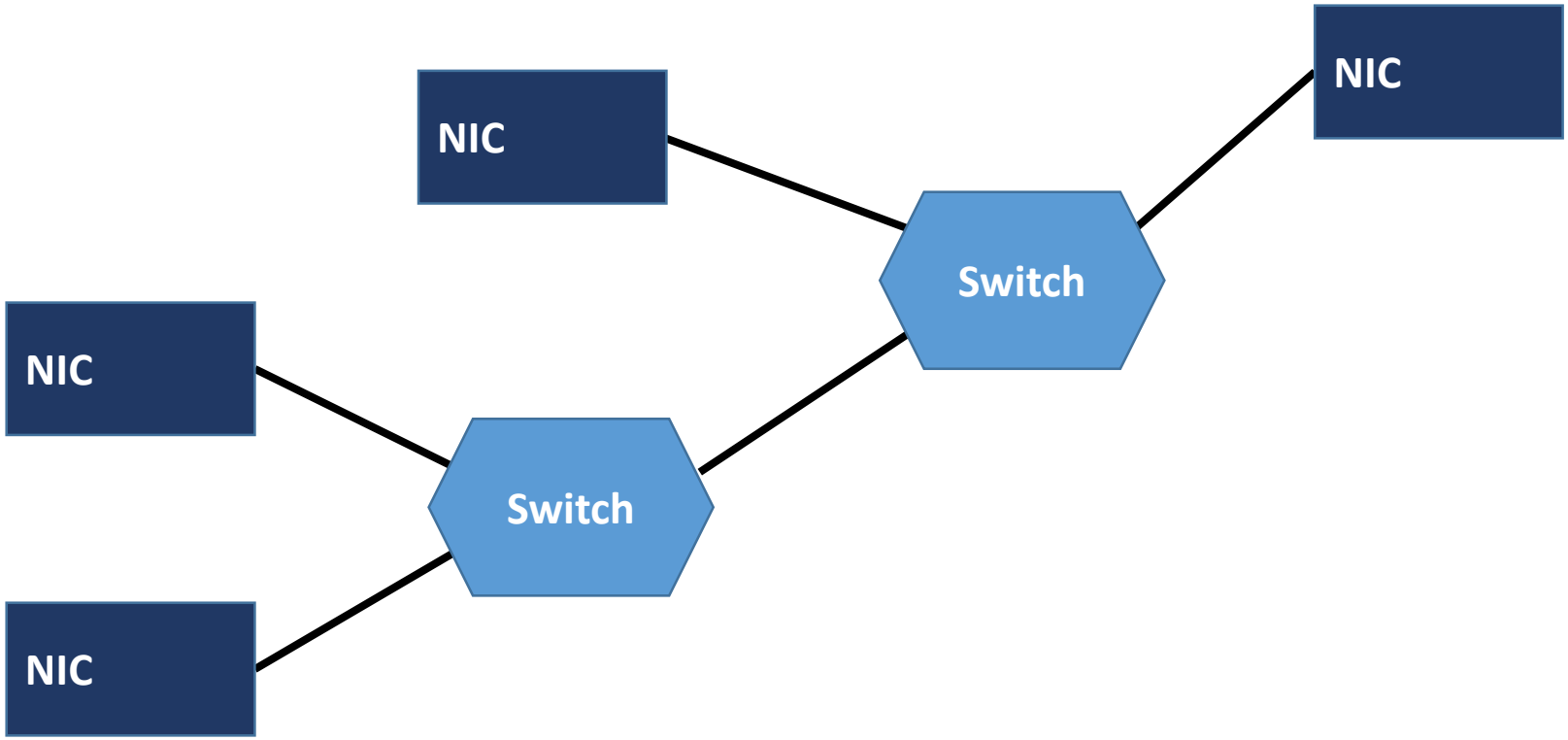
- Sliding Mode Congestion Control (SMCC) [Infocom'12]
  - Configuration-sensitive issue of QCN
  - Slide mode motion to be robust to the changes of system parameters and network configurations.

Background

Congestion Control in CE



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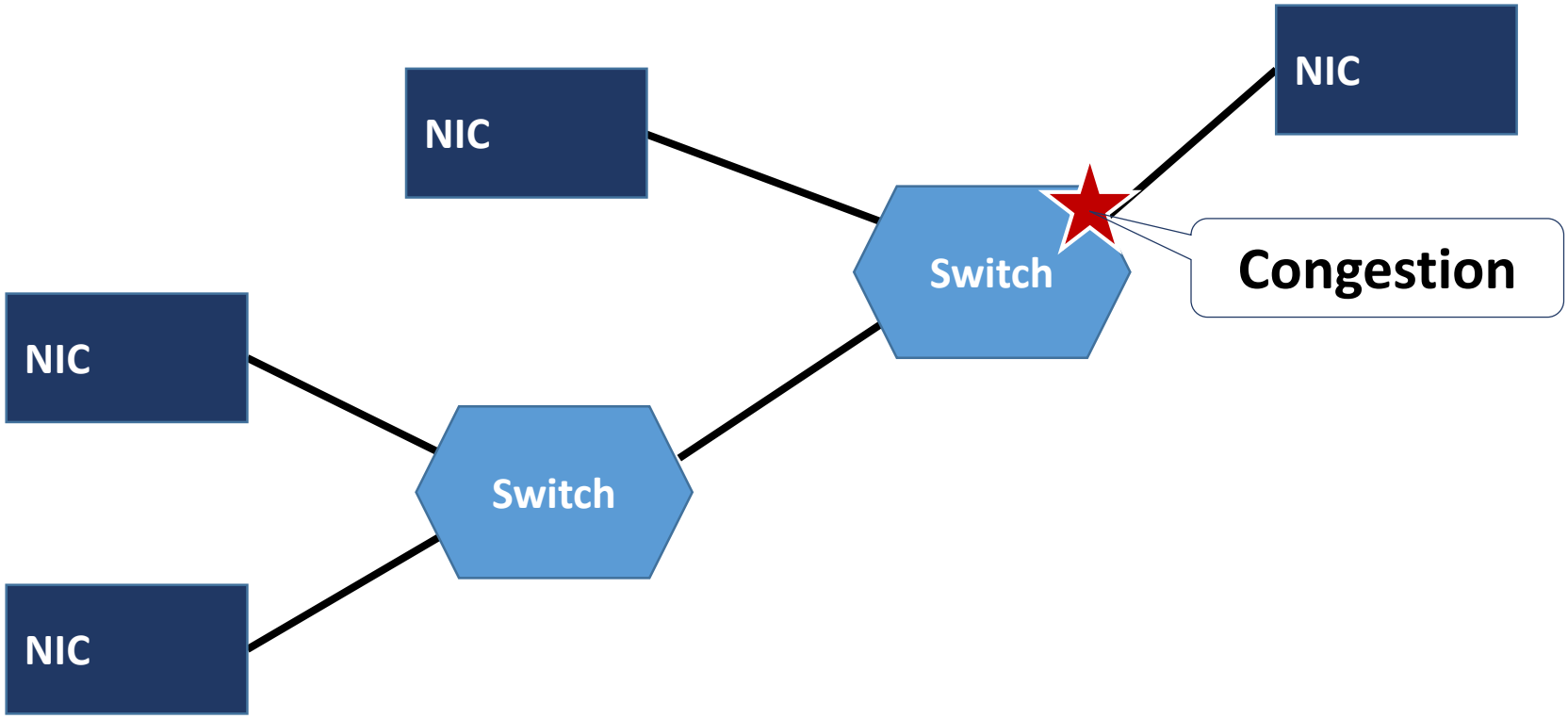

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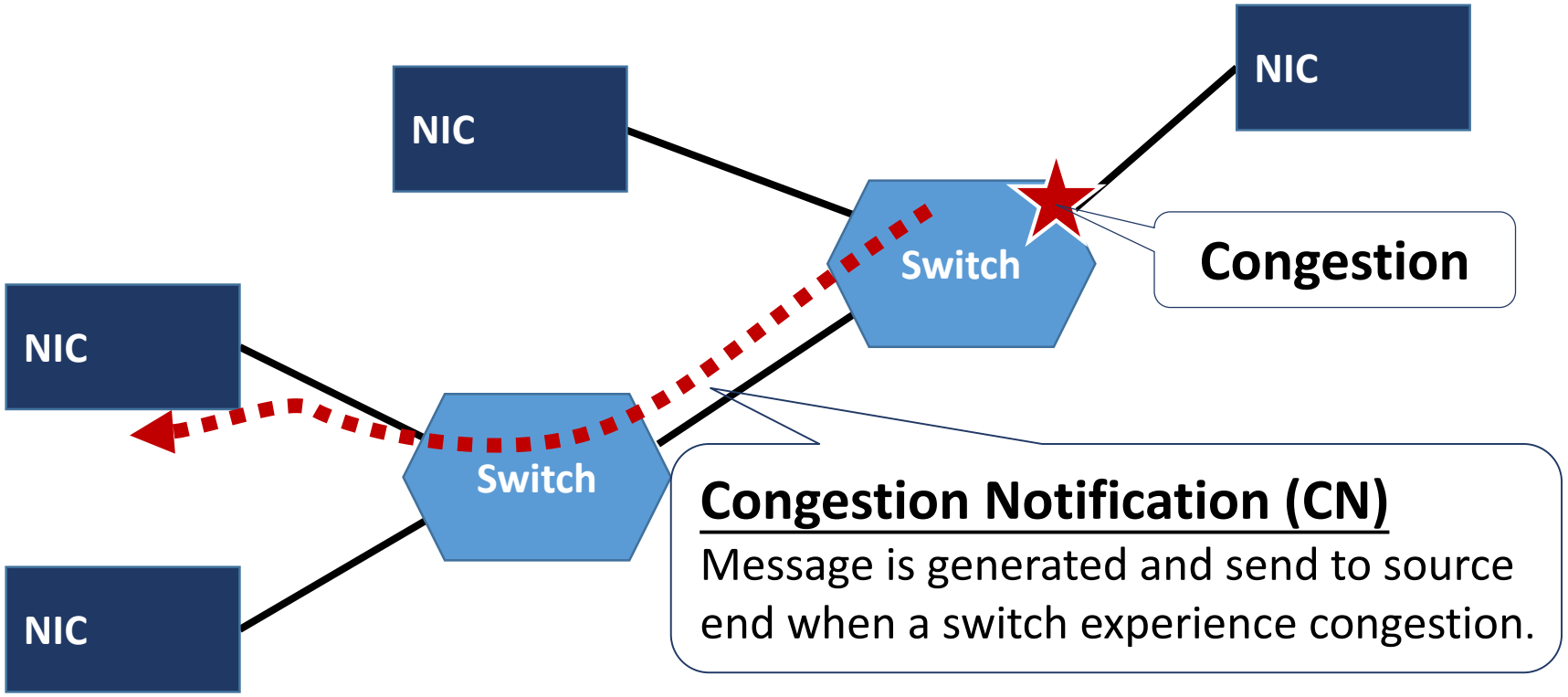
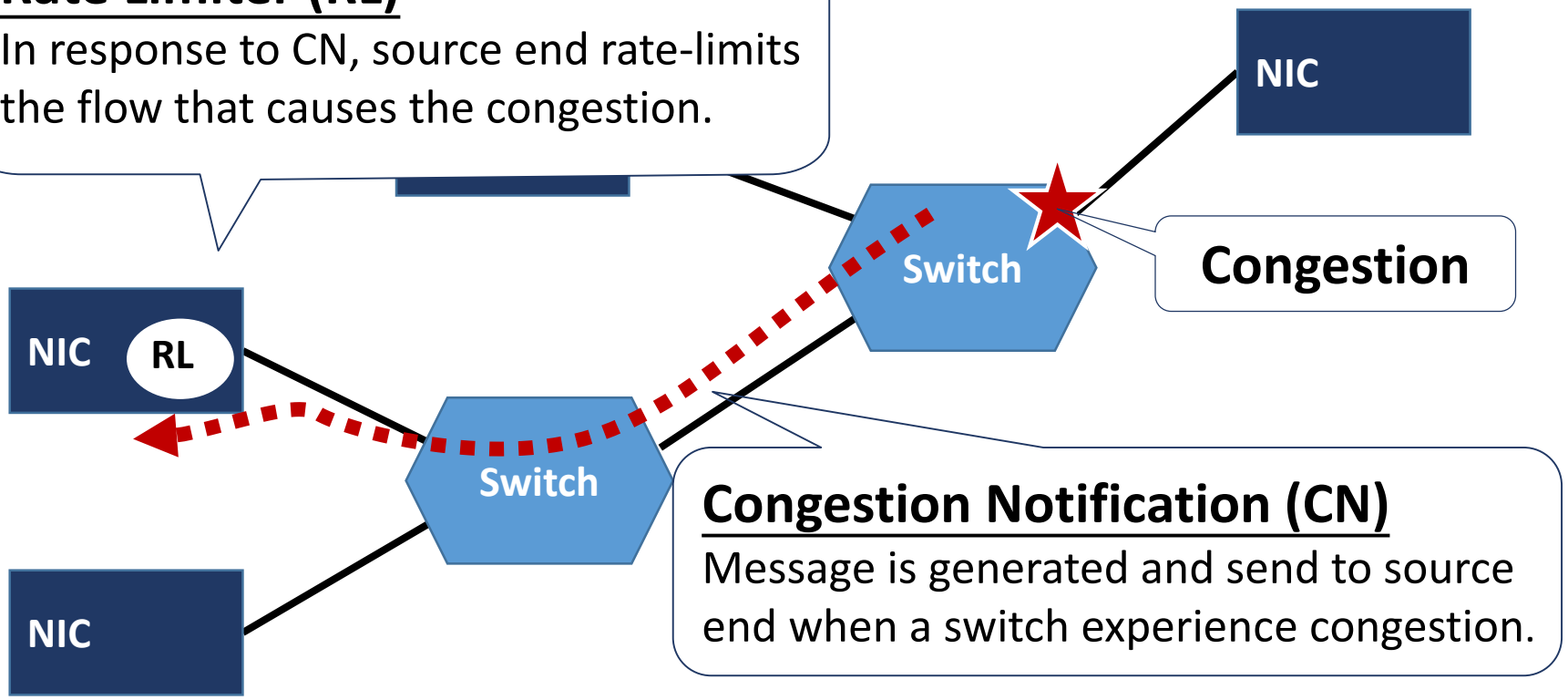


Background

Congestion Control in CE

Rate Limiter (RL)

In response to CN, source end rate-limits the flow that causes the congestion.



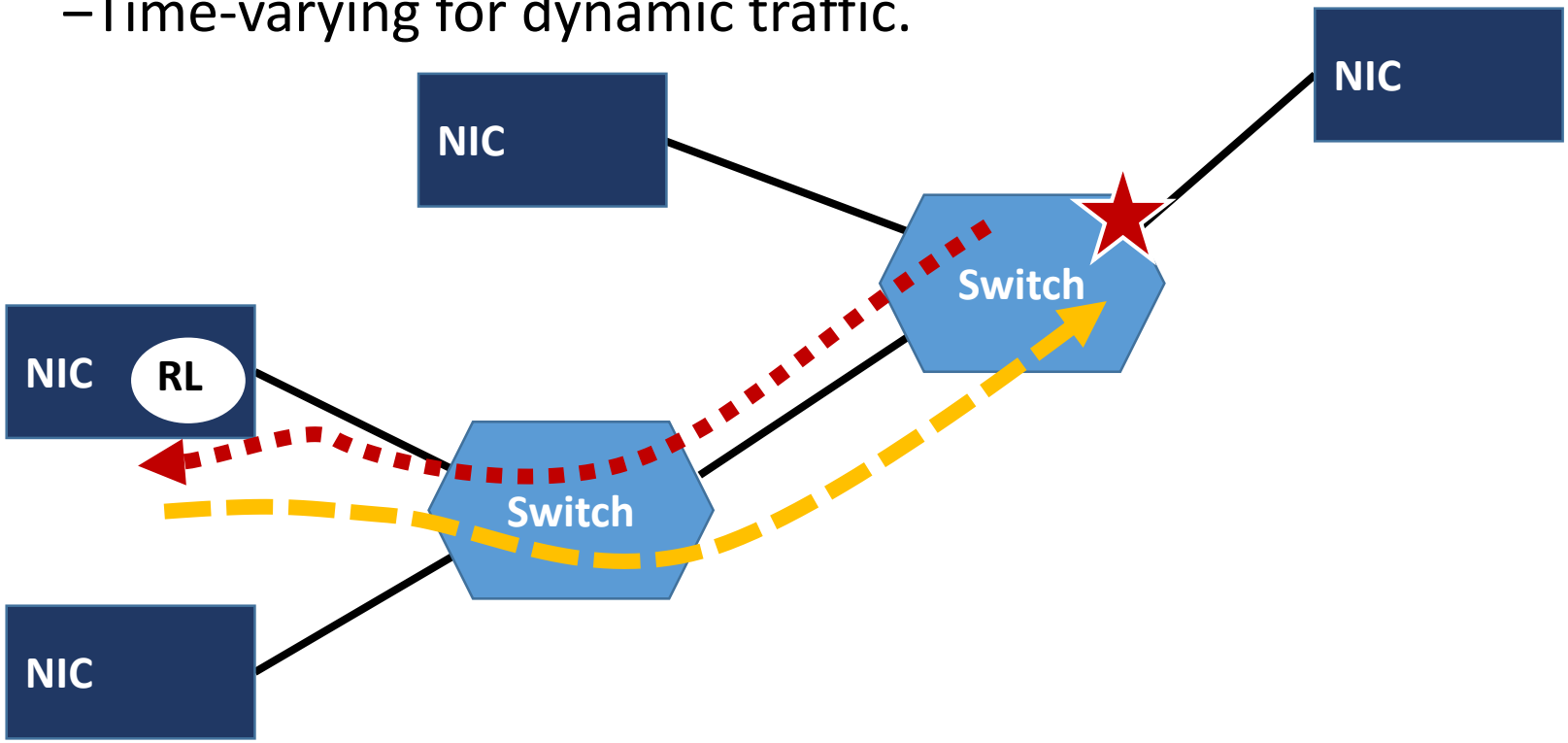
Congestion Notification (CN)

Message is generated and send to source end when a switch experience congestion.

Background

Heterogeneous and Time-Varying Delays

- Delays in the feedback loop
  - –Heterogeneous for different sources.
  - –Time-varying for dynamic traffic.

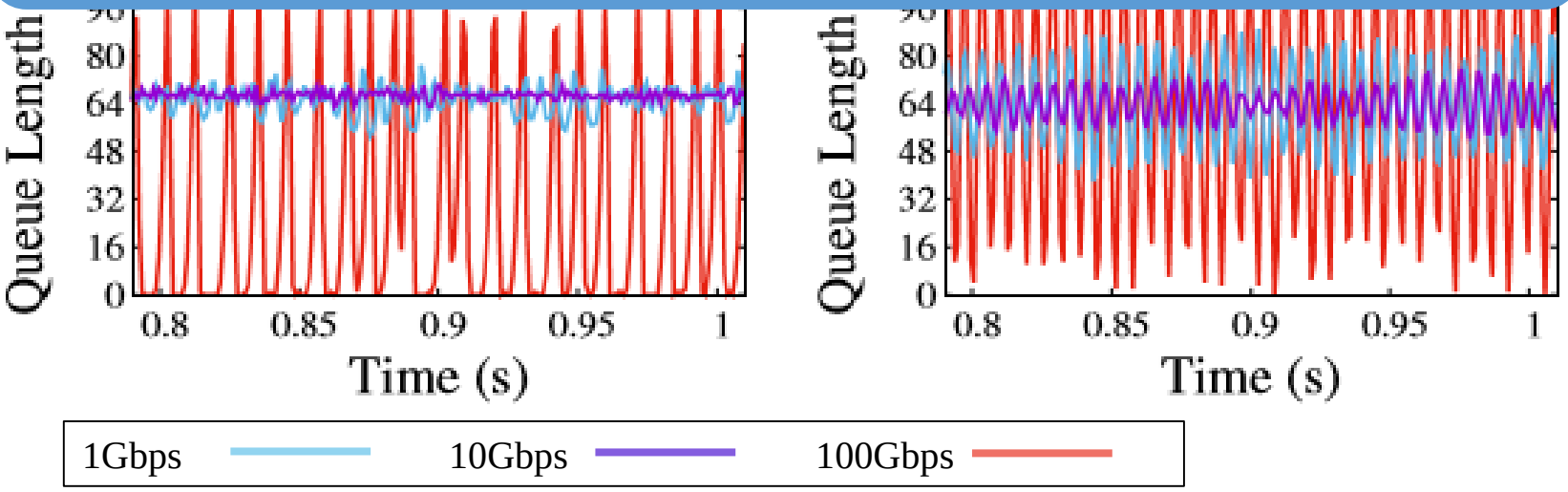


Background

Negative Impact of Delays

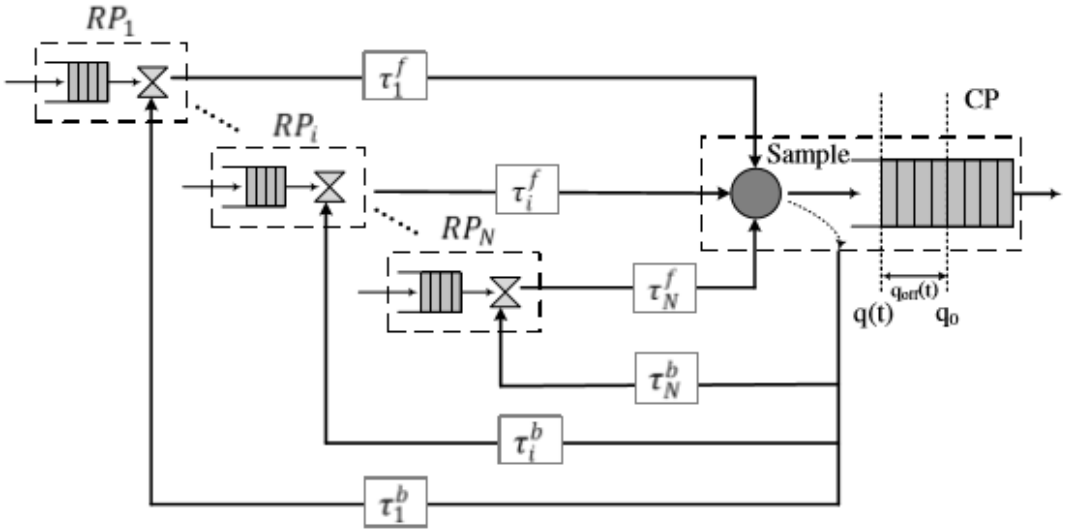
- Obstruct sources from obtaining the right congestion status timely
  - Error rate adjustment ➔ Overflow or Underflow
  - Heterogeneous and time-varying delays ➔ Complex
  - High speed Ethernet link ➔ More serious

Mitigate the negative impacts of delays



Model

Heterogeneous and Time-Varying Delays



The congested switch samples the packets

➔ Take the sample period T as slot

The k_{th} feedback is sent to source i

- Backward delay: $m_i^b(k) = \lceil \tau_i^b(k)/T \rceil$
- Forward delay: $m_i^f(k) = \lceil \tau_i^f(k)/T \rceil$
- Total delay: $m_i(k) = m_i^b(k) + m_i^f(k)$

Model

Rate Adjustments

k

Switch generates a feedback

$$F_b(k) = f\left(Q_f(k), Q_v(k), \cdots\right)$$

$k + m_i^b(k)$

Source i adjusts its rate according to $F_b(k)$

$$\Delta r_i\left(k + m_i^b(k)\right) = u\left(F_b(k)\right)$$

$k + m_j^b(k)$

Source j doesn't receive $F_b(k)$

$$\Delta r_j\left(k + m_j^b(k)\right) = 0$$

$k + m$

$m = \max\{m_i(k)\}$, incoming rate at switch

$$\begin{aligned}\Delta R(k+m) &= \sum \Delta r_j\left(k + m - m_j^f(k)\right) \\ &= \sum \Delta r_j\left(k + m_j^b(k)\right) + \varepsilon(k) \\ &= u\left(F_b(k)\right) + \varepsilon(k)\end{aligned}$$

Time/T

$$\varepsilon(k) = \sum \Delta r_j\left(k + m - m_j^f(k)\right) - \sum \Delta r_j\left(k + m_j^b(k)\right)$$

Model

Evolution of Switch Queue

- Q_f: Queue length offset to the target value q_0
- Q_v: Queue length variance

$$\begin{cases} \Delta Q_f(k+m) = Q_v(k+m) \\ \Delta Q_v(k+m) = T\big(u(k)+\varepsilon(k)\big) \end{cases}$$

$$\begin{cases} Q_f(k+m) = Q_f(k) + mQ_v(k) + T\sum_{i=1}^{m} i[u(k-i) + \varepsilon(k-i)] \\ Q_v(k+m) = Q_v(k) + T\sum_{i=1}^{m}[u(k-i) + \varepsilon(k-i)] \end{cases}$$

$$\begin{cases} \widehat{Q_f}(k) = Q_f(k) + mQ_v(k) + T\sum_{i=1}^{m} iu(k-i) \\ \widehat{Q_v}(k) = Q_v(k) + T\sum_{i=1}^{m} u(k-i) \end{cases}$$

$$\begin{cases} \Delta\widehat{Q_f}(k) = \widehat{Q_v}(k) + mT\varepsilon(k-m) \\ \Delta\widehat{Q_v}(k) = T\big(u(k)\big) + T\varepsilon(k-m) \end{cases}$$

Model

New Congestion Detector

$$\begin{cases} \widehat{Q_f}(k) = Q_f(k) + mQ_v(k) + T\sum_{i=1}^{m} iu(k-i) \\ \widehat{Q_v}(k) = Q_v(k) + T\sum_{i=1}^{m} u(k-i) \end{cases}$$

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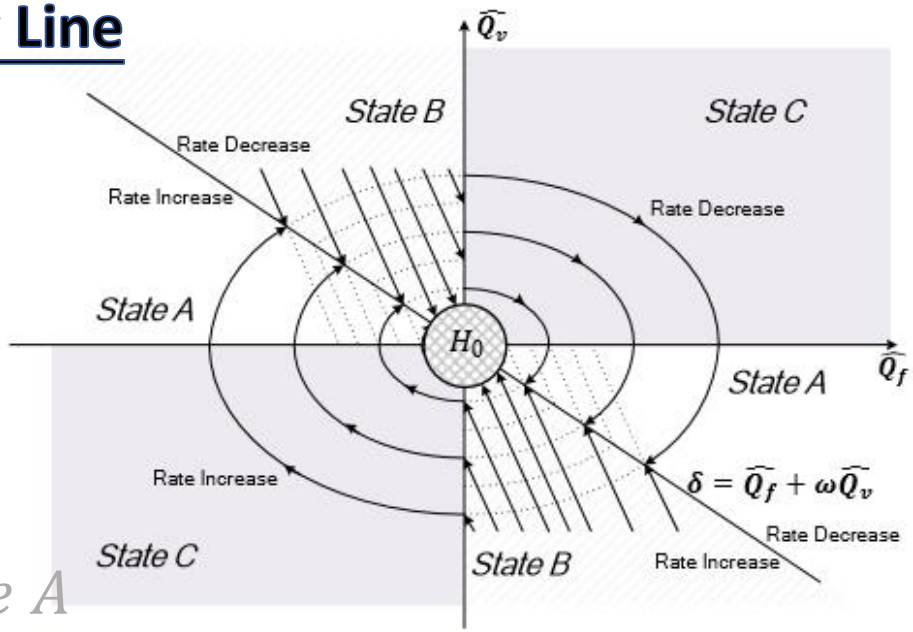
- $\left(\widehat{Q_f}(k), \widehat{Q_v}(k)\right)$ estimates the real evolution of the switch queue length with the impact of delays.
- $\left(\widehat{Q_f}(k), \widehat{Q_v}(k)\right)$ can be calculated at time k.
- $\left(\widehat{Q_f}(k), \widehat{Q_v}(k)\right) = (0,0)$ is the stable state.
- The disturbance ξ(k − m) is limited

Design

Sliding Mode Control Method

Step 1: Determining Boundary Line

- Quadrant I ➔ Overflow
- Quadrant III ➔ Underflow
- Quadrant II/IV
  - $\delta > 0$ ➔ Overflow
  - $\delta < 0$ ➔ Underflow



Step 2: Developing Rules Fulfilling Sliding Mode Motion

- $u(k) = \begin{cases} -a\widehat{Q_f}(k), \ in\ state\ A \\ -b\widehat{Q_v}(k), \ in\ state\ B \end{cases}$
- Satisfy $\delta(k) * \Delta\delta(k) < 0$

Step 3: Developing Reaching Process

- $u(k) = -c\widehat{Q_f}(k), in\ state\ C$

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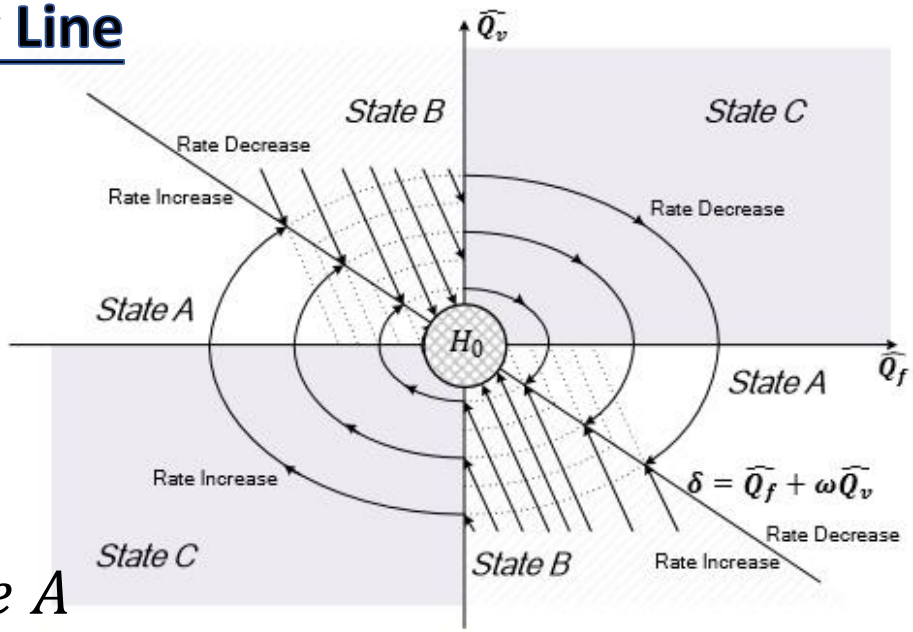

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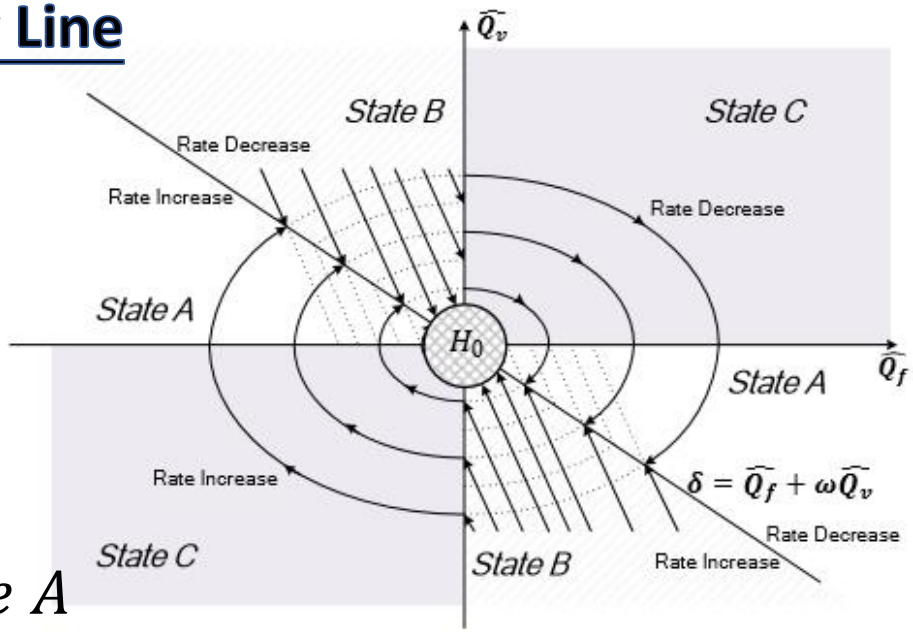

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Design

Delay-Tolerant Sliding Model (DSM) Congestion Control Scheme

Switch

- $$F_b(k) = \begin{cases} -a\widehat{Q_v}(k), if\ \widehat{Q_v}(k) * \left(\widehat{Q_f}(k) + \omega\widehat{Q_v}(k)\right) < 0 \\ -b\widehat{Q_v}(k), if\ \widehat{Q_f}(k) * \left(\widehat{Q_f}(k) + \omega\widehat{Q_v}(k)\right) < 0 \\ -c\widehat{Q_f}(k), if\ \widehat{Q_f}(k) * \widehat{Q_v}(k) > 0 \end{cases}$$
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- $$\begin{cases} m = \inf\{m \in N^+ : m_i(k) \leq m, \forall i, k\} \\ a \to \left[\frac{1}{p\ \max(Q_f + \omega Q_v) + \frac{m(m+1)}{2}} \frac{1}{T}\right]^- \\ b \to \left[\frac{1}{p\ \max(Q_v) + m} \frac{1}{T}\right]^- \\ c \to \left[\min\left\{\frac{1}{p\ \max(Q_v)} \frac{1}{T}, \frac{2}{T}\right\}\right]^- \\ \omega > m + p\ \max(Q_v) - 1 \end{cases}$$

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Delay-Tolerant Sliding Model (DSM) Congestion Control Scheme

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NIC

- $r \leftarrow r + F_b$

Properties

Complexity

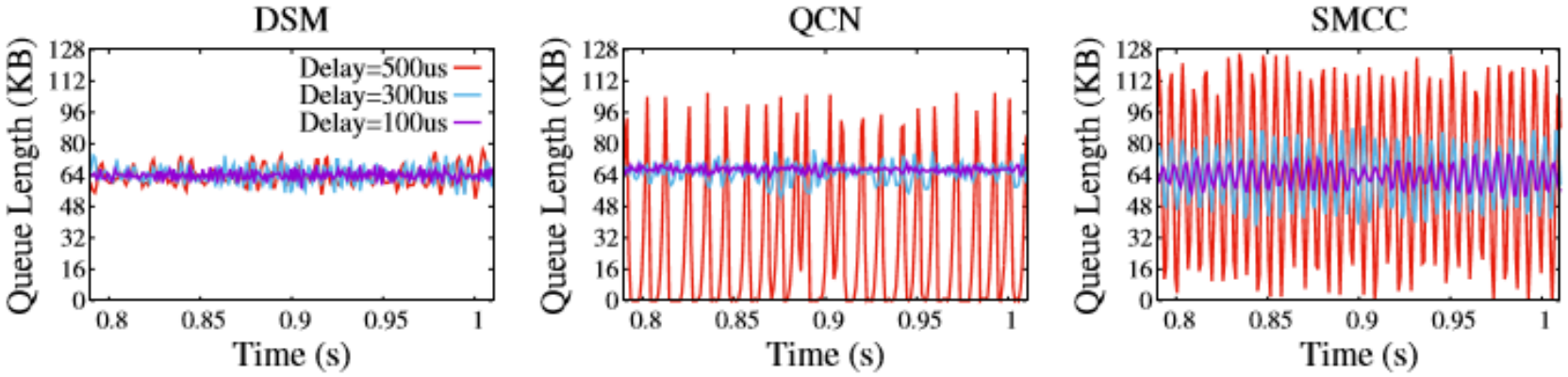
- Switch
  - Spatial complexity: $O(M)$
    - Memorize the last m feedbacks
  - Computing complexity: $O(1)$
    - Iteration Method

$$\begin{cases} S_1(k) = \sum_{i=1}^{m} F_b(k-i) \\ S_2(k) = \sum_{i=1}^{m} iF_b(k-i) \end{cases} \rightarrow \begin{cases} \widehat{Q_f}(k) = Q_f(k) + mQ_v(k) + TS_2(k) \\ \widehat{Q_v}(k) = Q_v(k) + TS_2(k) \\ S_1(k+1) = S_1(k) + F_b(k-m) \\ S_2(k+1) = S_1(k+1) + S_2(k) - mF_b(k-m) \end{cases}$$

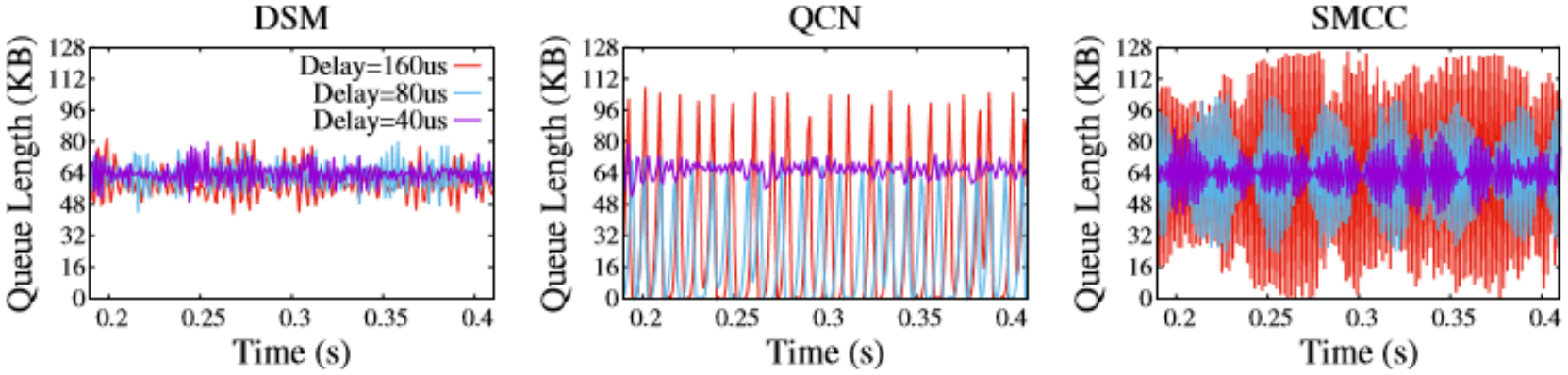
- NIC
  - Complexity: $O(1)$

Properties

Stability



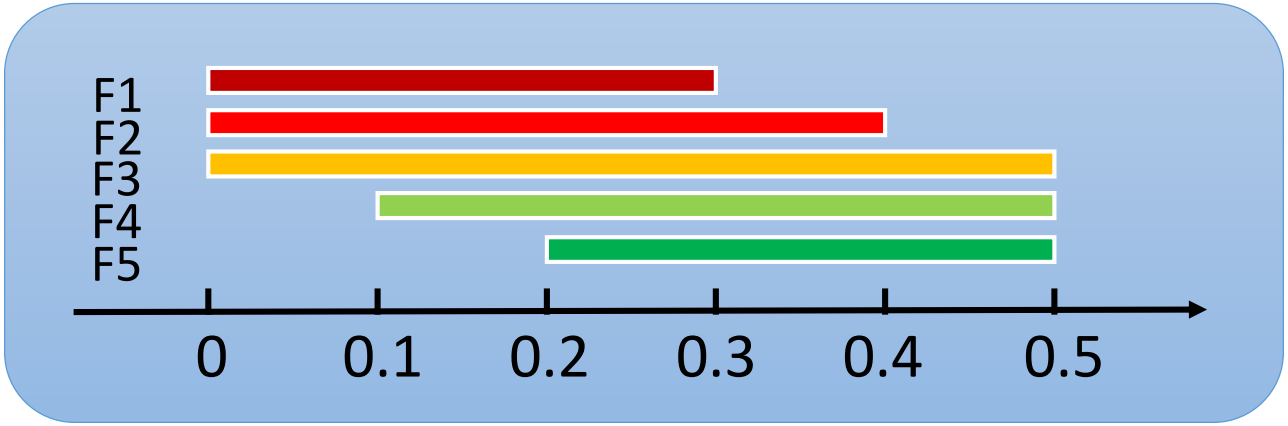
(a) Queue length evolutions in DSM, QCN and SMCC in 10*Gbps* Ethernet.

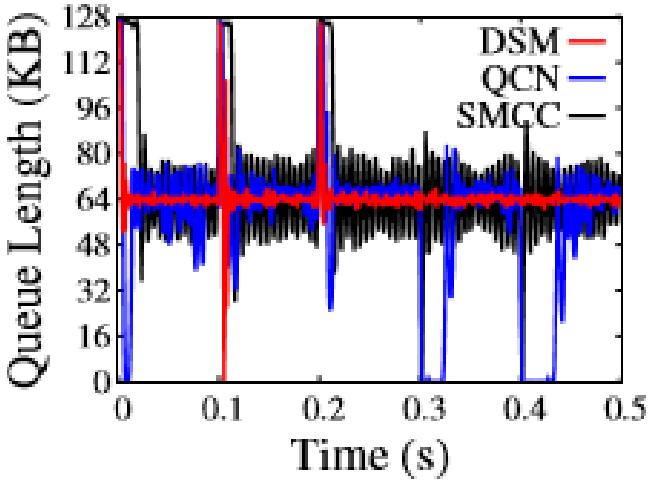


(b) Queue length evolutions in DSM, QCN and SMCC in 100*Gbps* Ethernet.

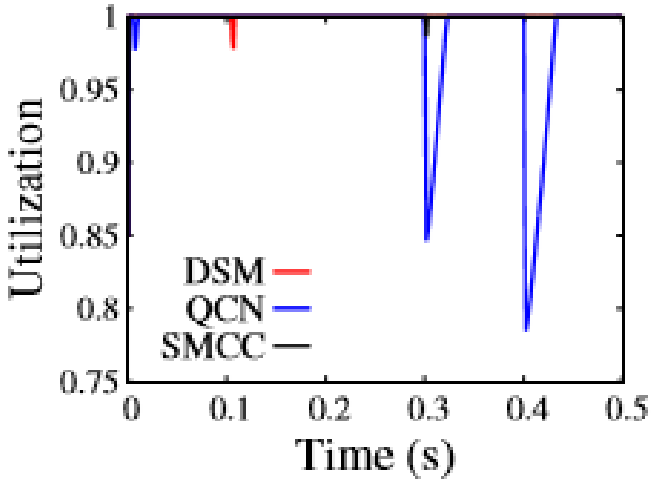
Properties

Responsiveness





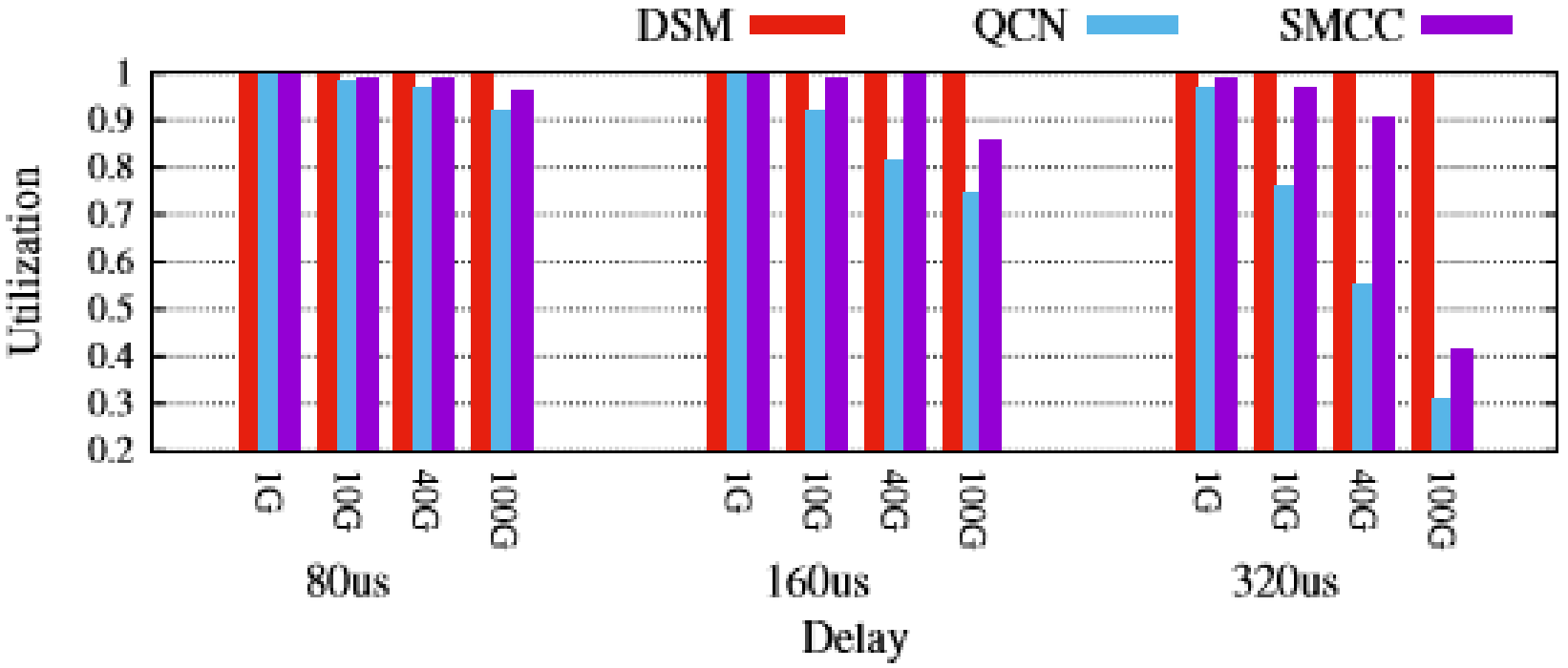
(a) Queue Length



(b) Utilization

Properties

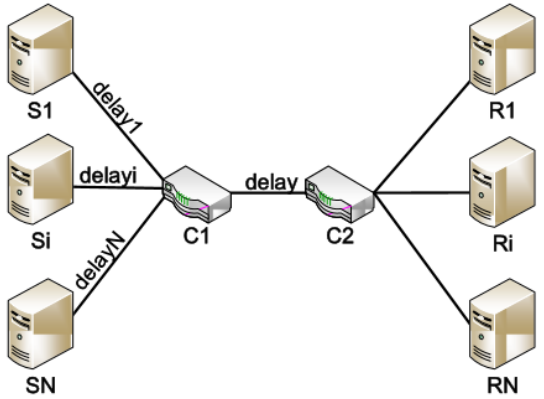
Adaptability

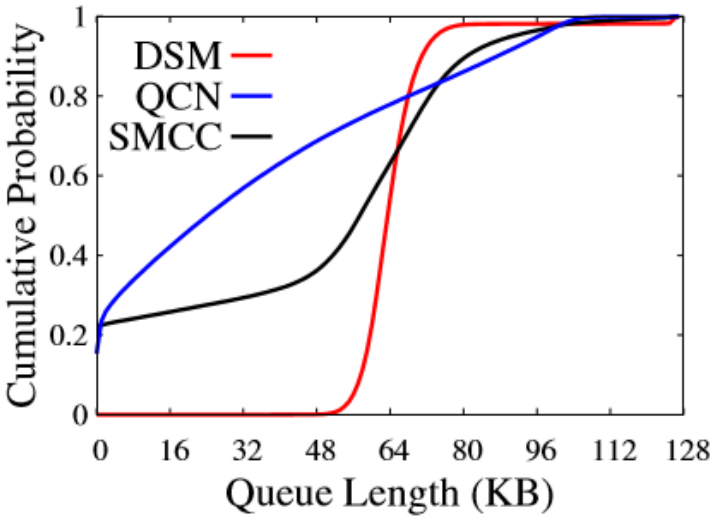


Evaluation

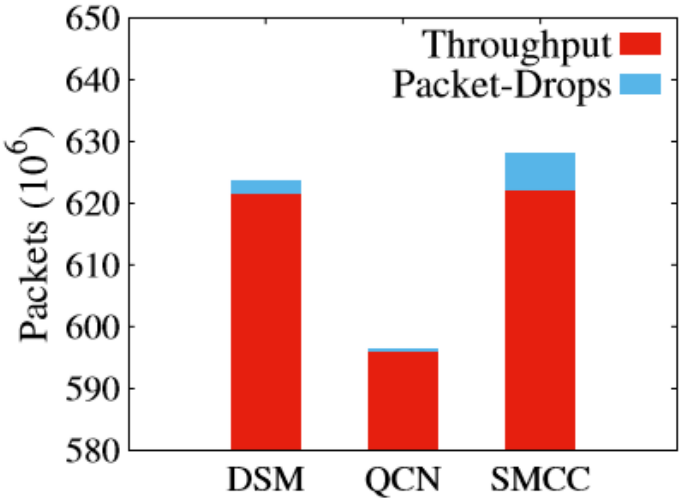
Heterogeneous and Time-Varying Delays

- Dumbbell topology
- 10Gbps links
- Random delays
- 100 times





(a) Queue Length

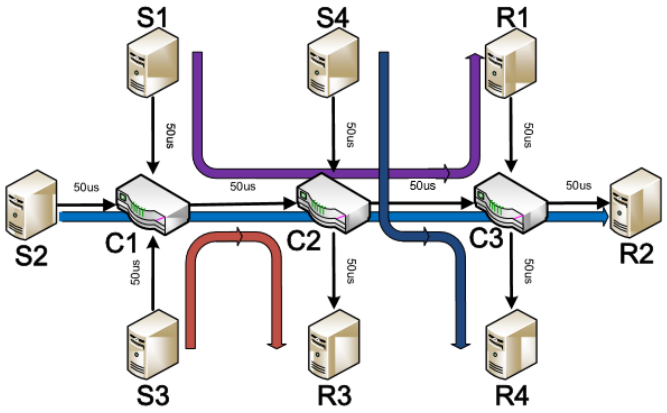


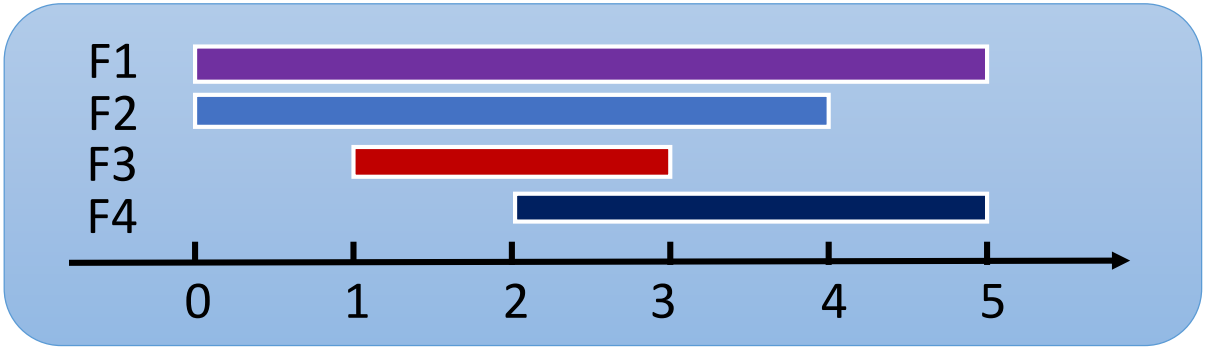
(b) Throughput and Packet-Drops

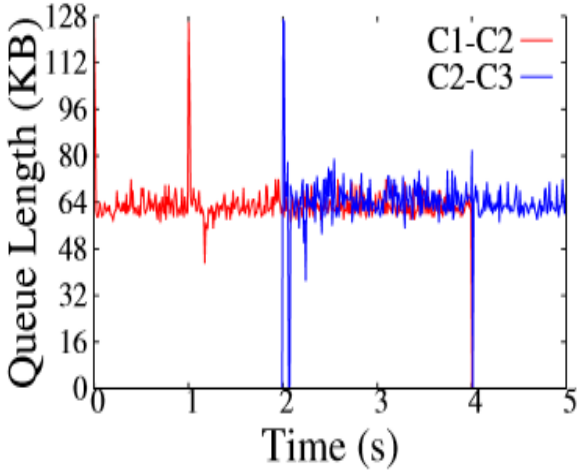
Evaluation

Multiple Bottlenecks Scenario

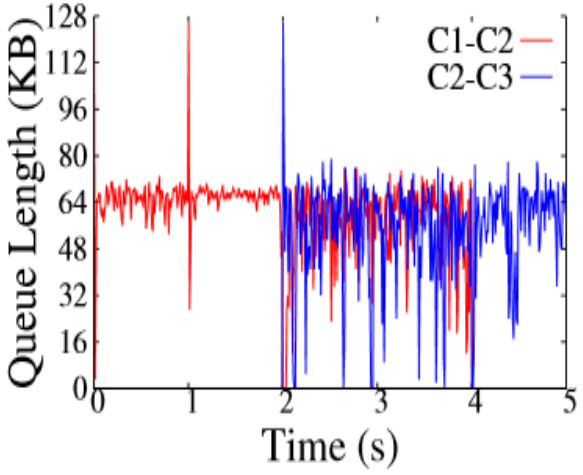
Long Flows



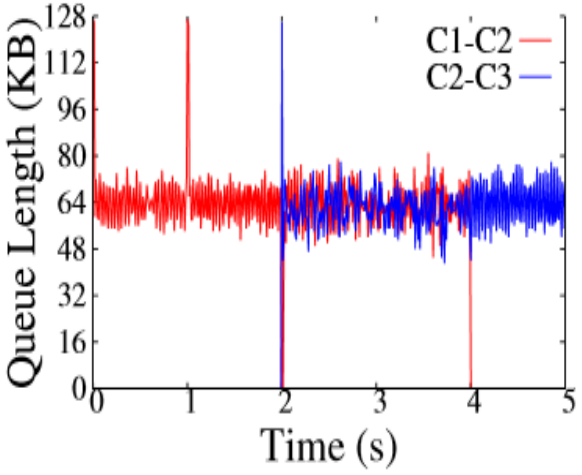




(a) DSM



(b) QCN



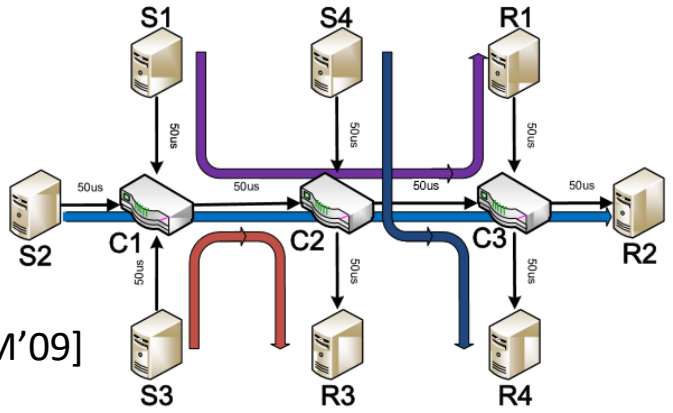
(c) SMCC

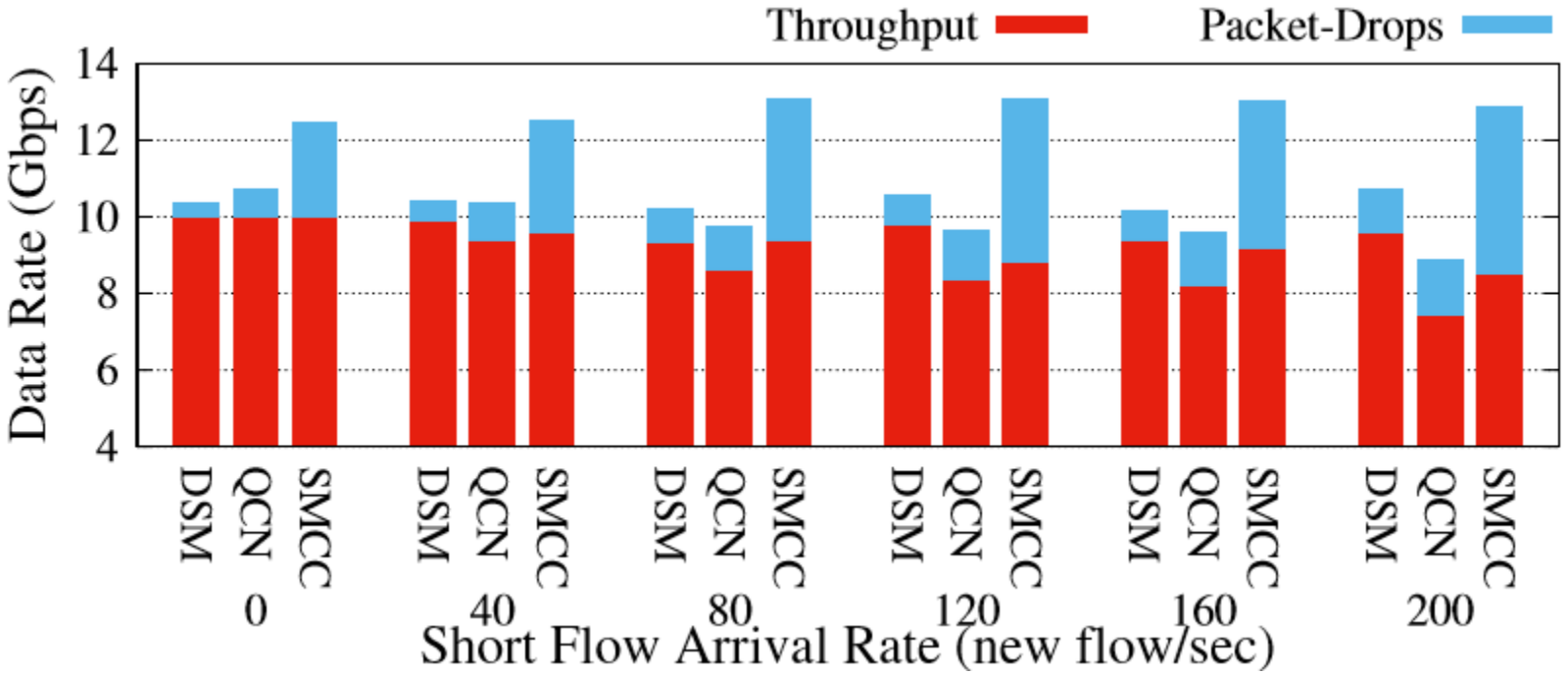
Evaluation

Multiple Bottlenecks Scenario

Mixed Flows

- 5 long-lived flows
- Short flows
  - Poisson arrival
  - Heavy-tailed flow size[SIGCOMM'09]





Conclusion

Mitigate the negative impacts of delays

- Model ➔ New congestion detector
  - Estimate the real congestion status with historical information.
  - Regard heterogeneous and time-varying feature as disturbances.

- Delay-tolerant Sliding Mode (DSM) scheme
  - New congestion detector ➔ Delay-tolerant
  - Sliding mode control method ➔ Robust to disturbances

- Properties of DSM
  - Complexity √
  - Responsiveness √
  - Stability √
  - Adaptability √
  - Heterogeneous and time-varying delays √
  - Multiple bottlenecks scenarios √

Thanks!

Q & A