Proposal and Evaluation of Attractor Perturbation-based Rate Control for Stable End-to-end Delay

Midori Waki, Naoki Wakamiya, Masayuki Murata
Osaka University, Japan

Fluctuations in the Internet and Delay-sensitive Application

- Best-effort network
  - Delay, delay jitter, and packet loss observed by a session always fluctuate
  - Origin of fluctuation in the Internet cannot be predicted or controlled by an individual session
    e.g. changes in number of sessions and amount of traffic
- Delay-sensitive application
  - Internet Protocol TeleVision (IPTV) and video conference
  - Delay fluctuation would cause performance degradation of these applications

Suppression of delay fluctuations is important
especially for delay-sensitive applications

Difficulty in Suppression of Delay Fluctuation

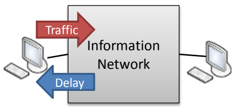
- Packet scheduling at routers
  - Equipping all intermediate nodes with the algorithm is impractical in large-scale information network
- Multipath routing
  - Relying on prior knowledge of delay variation , which is unpredictable in general

Ever-increasing size and complexity of information network
prevent accurate inference of network condition

A mechanism that has following features is desirable
- adopted to end system
- not relying on prior knowledge
- adaptable to change of network condition

Purpose and Approach

We propose a rate control mechanism
to stabilize end-to-end delay without prior knowledge



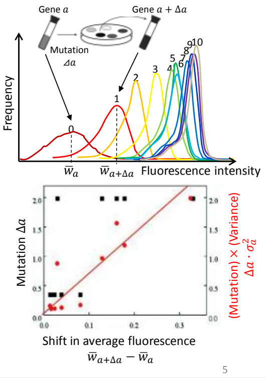
- We go back to the simplest paradigm
  - Consider network as a black box
  - Apply a force and observe response
  - Obtain desired result by putting appropriate force to system
- Ability to estimate response against force is required
  - Use **Attractor Perturbation** concept in cell biology

Attractor Perturbation (AP) Model

- General relationship between inherent fluctuation and response
- Given measurable variable w, which could be influenced by force a, when applying Δa (change in force) to system, average of w is perturbed as follows:

$$\underbrace{\overline{w}_{a+\Delta a}-\overline{w}_{a}}_{\text{Shift in average}}=\overset{\text{Constant coefficient}}{b}\,\underbrace{\sigma_{a}^{2}}_{\text{Measured variance}}\,\underbrace{\Delta a}_{\text{Force change}}$$

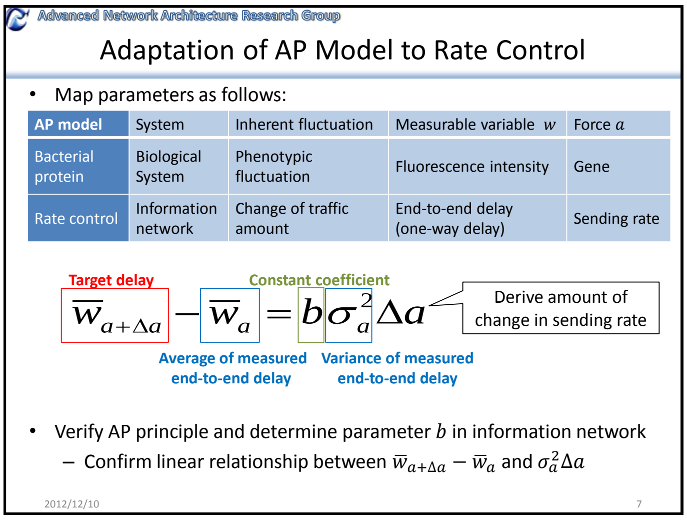
AP model gives amount of change in force
to obtain shifted average
from current condition



K. Sato, Y. Ito, T. Yomo, and K. Kaneko, "On the relation between fluctuation and response in biological systems," *National Academy of Sciences*, vol. 100, pp. 14086–14090, Nov. 2003.

Review of Our Research

- Adaptation of AP Model to Rate Control
- Verification of AP principle and parameter b in information network
  - Simulation in packet-based network
  - Analysis in M/D/1 queuing system (omitted from presentation)
- Behavior of our proposal
- Simulation experiments
  - Simulation setting
  - Evaluation metrics
  - Evaluation results



Adaptation of AP Model to Rate Control

- Map parameters as follows:

AP model	System	Inherent fluctuation	Measurable variable w	Force a
Bacterial protein	Biological System	Phenotypic fluctuation	Fluorescence intensity	Gene
Rate control	Information network	Change of traffic amount	End-to-end delay (one-way delay)	Sending rate

Target delay

Constant coefficient

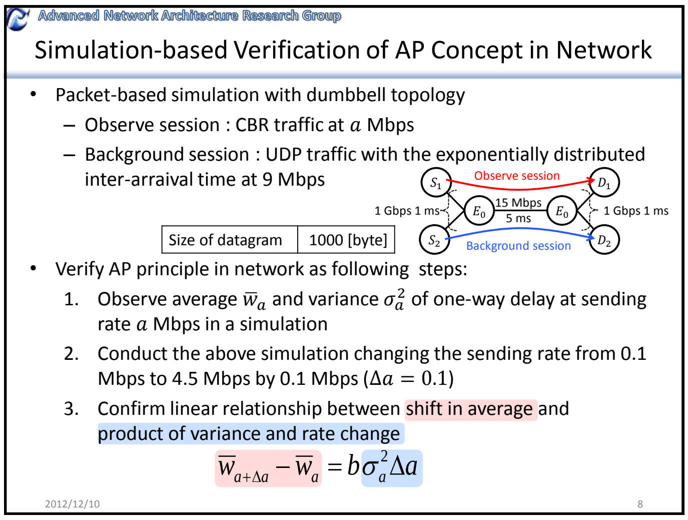
$$\boxed{\overline{w}_{a+\Delta a}} - \boxed{\overline{w}_a} = b\boxed{\sigma_a^2}\Delta a$$

Derive amount of change in sending rate

Average of measured end-to-end delay

Variance of measured end-to-end delay

- Verify AP principle and determine parameter b in information network
  - Confirm linear relationship between $\overline{w}_{a+\Delta a} - \overline{w}_a$ and $\sigma_a^2\Delta a$



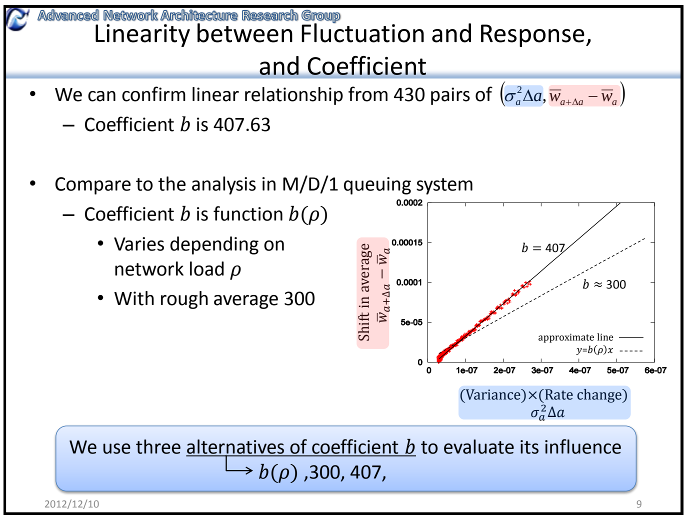
Simulation-based Verification of AP Concept in Network

- Packet-based simulation with dumbbell topology
  - Observe session : CBR traffic at a Mbps
  - Background session : UDP traffic with the exponentially distributed inter-arraival time at 9 Mbps

Size of datagram	1000 [byte]

- Verify AP principle in network as following steps:
  1. Observe average $\overline{w}_a$ and variance σ_a^2 of one-way delay at sending rate a Mbps in a simulation
  2. Conduct the above simulation changing the sending rate from 0.1 Mbps to 4.5 Mbps by 0.1 Mbps ($\Delta a = 0.1$)
  3. Confirm linear relationship between shift in average and product of variance and rate change

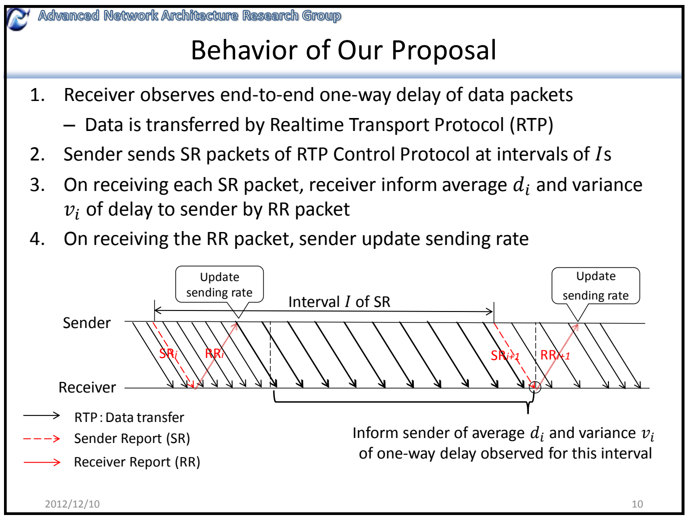
$$\overline{w}_{a+\Delta a} - \overline{w}_a = b\sigma_a^2\Delta a$$



Linearity between Fluctuation and Response, and Coefficient

- We can confirm linear relationship from 430 pairs of $(\sigma_a^2\Delta a, \overline{w}_{a+\Delta a} - \overline{w}_a)$
  - Coefficient b is 407.63
- Compare to the analysis in M/D/1 queuing system
  - Coefficient b is function $b(\rho)$
    - Varies depending on network load ρ
    - With rough average 300

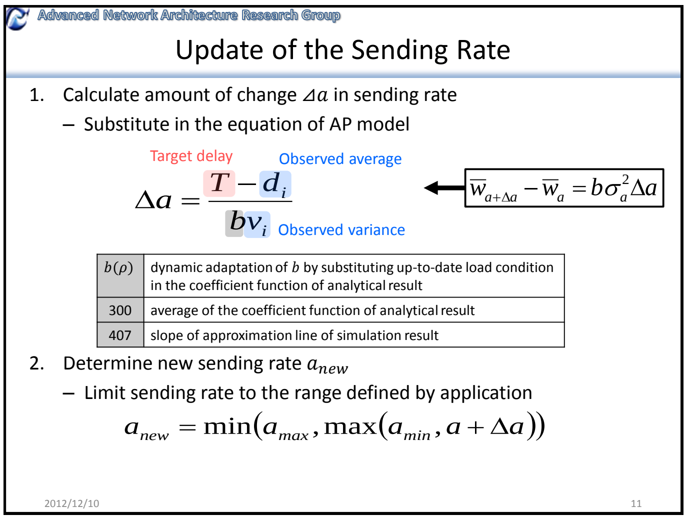
We use three alternatives of coefficient b to evaluate its influence
$\hookrightarrow b(\rho)$,300, 407,



Behavior of Our Proposal

1. Receiver observes end-to-end one-way delay of data packets
   - Data is transferred by Realtime Transport Protocol (RTP)
2. Sender sends SR packets of RTP Control Protocol at intervals of I s
3. On receiving each SR packet, receiver inform average d_i and variance v_i of delay to sender by RR packet
4. On receiving the RR packet, sender update sending rate

Inform sender of average d_i and variance v_i of one-way delay observed for this interval



Update of the Sending Rate

1. Calculate amount of change Δa in sending rate
   - Substitute in the equation of AP model

Target delay

Observed average

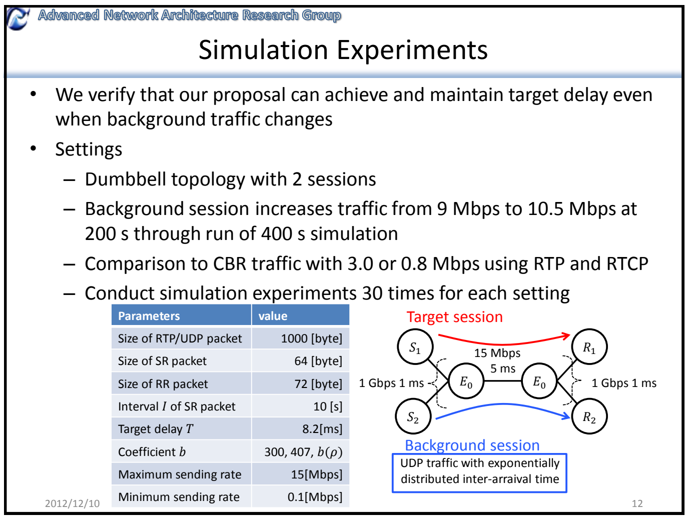
$$\Delta a = \frac{T - d_i}{b v_i} \longleftarrow \boxed{\overline{w}_{a+\Delta a} - \overline{w}_a = b\sigma_a^2\Delta a}$$

Observed variance

$b(\rho)$	dynamic adaptation of b by substituting up-to-date load condition in the coefficient function of analytical result
300	average of the coefficient function of analytical result
407	slope of approximation line of simulation result

2. Determine new sending rate a_{new}
   - Limit sending rate to the range defined by application

$$a_{new} = \min(a_{max}, \max(a_{min}, a + \Delta a))$$



Simulation Experiments

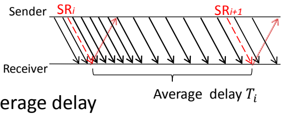
- We verify that our proposal can achieve and maintain target delay even when background traffic changes
- Settings
  - Dumbbell topology with 2 sessions
  - Background session increases traffic from 9 Mbps to 10.5 Mbps at 200 s through run of 400 s simulation
  - Comparison to CBR traffic with 3.0 or 0.8 Mbps using RTP and RTCP
  - Conduct simulation experiments 30 times for each setting

Parameters	value
Size of RTP/UDP packet	1000 [byte]
Size of SR packet	64 [byte]
Size of RR packet	72 [byte]
Interval I of SR packet	10 [s]
Target delay T	8.2[ms]
Coefficient b	300, 407, $b(\rho)$
Maximum sending rate	15[Mbps]
Minimum sending rate	0.1[Mbps]

UDP traffic with exponentially distributed inter-arraival time

Evaluation Metrics

- Mean square error M : difference between average delay and target delay
  - $M = \frac{1}{n+1} \sum_{i=0}^{n} (T_i - T)^2$



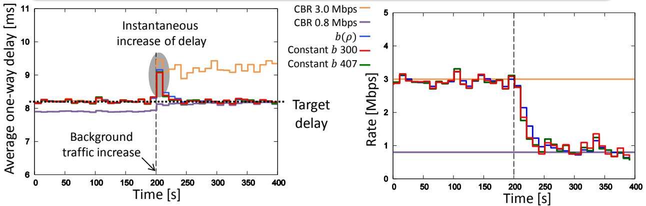
- Coefficient of variation C: stability of average delay
  - $C = \frac{1}{\bar{T}} \sqrt{\frac{1}{n+1} \sum_{i=0}^{n} (T_i - \bar{T})^2}$
- Delay jitter J: Maximum difference between average delay and target delay
  - $J = \max_{0 \le i \le n} \{|T_i - T|\}$

n : Number of SR packets sent in whole simulation time
T_i : Average delay of successfully received RTP packets that are sent in i-th control interval
$\bar{T}$: Average of T_i $(0 \le i \le n)$
T : Target delay

An Example of Temporal Variations

- Average delay of CBR 3.0 Mbps are longer than target delay after background traffic increase.
- Average delays of our proposal stay close to target delay
- Instantaneous increase of delay is basically unavoidable
  - The duration can be shorten by shorter control interval

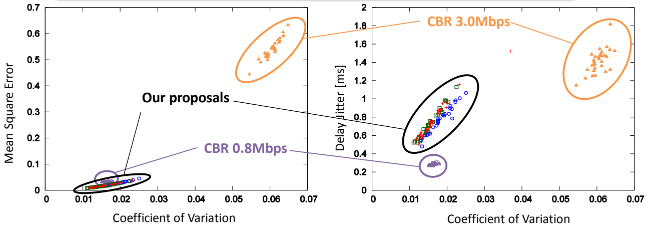
Our proposal can achieve and maintain target delay
except for the period right after sudden load increase



Evaluation results

- Our proposal results in larger delay jitter than CBR 0.8Mbps due to instantaneous increase of delay after load increase
- Setting of coefficient b did not influence rate control very much

Without prior knowledge or parameter tuning
our proposal can accomplish stable end-to-end delay
facing to sudden load increase



Conclusion and Future Work

- Conclusion
  - Propose a novel rate control mechanism to achieve and maintain target delay in dynamically changing environment
  - Prove that attractor perturbation principle holds in packet-based network as well as general M/D/1 queuing system
  - Confirm effectiveness of our proposal through simulation experiments
- Future Work
  - Further evaluation to verify the insensitivity of our proposal to characteristics of a network
  - Comparison with other non-bio-inspired mechanisms for delay jitter suppression