End-to-end measurement of hop-by-hop available bandwidth

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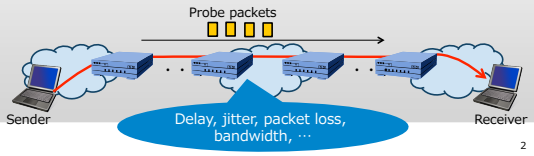
Background (1): End-to-end network measurement

- Delay, jitter, packet loss ratio, bandwidth-related information (physical capacity, **available bandwidth**), ⋯ of an end-to-end path between sender and receiver
- Active measurement: send probe packets from sender to receiver
  - Observe number of received packets, packet delay, arrival intervals, ⋯
- Important for performance improvement of network applications overlaid on underlay IP networks

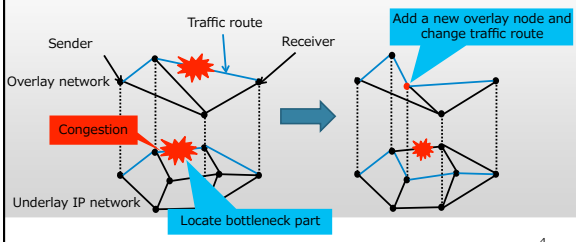


Background (2): Available bandwidth measurement

- End-to-end measurement of available bandwidth
  - Obtains available bandwidth of bottleneck on end-to-end path between sender and receiver hosts
  - Utilized for path/peer selection, application-level routing, congestion control, network tomography, ⋯
  - Various tools have been proposed, focusing on light-weight but accurate measurement
  - Existing tools can only know the available bandwidth value of bottleneck of the path
  - **They can NOT know bottleneck locations**
  - **They can NOT obtain bandwidth values of non-bottleneck parts of the path**

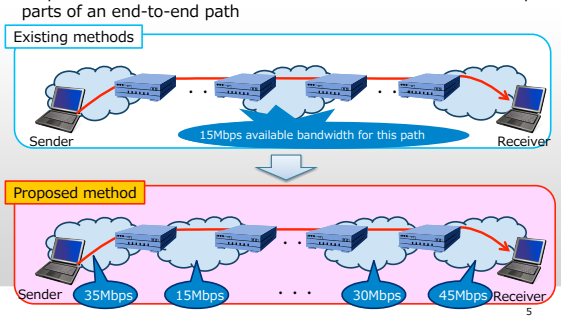
Background (3): Importance of hop-by-hop bandwidth measurement

- By measuring hop-by-hop available bandwidth, we can locate the bottleneck part of the path
  - Used for various higher-level controls for network applications



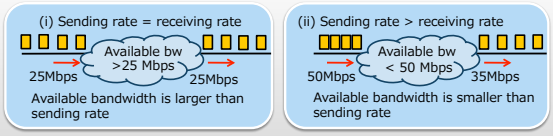
Research goals

- Propose a measurement method of available bandwidth of multiple parts of an end-to-end path



Principle of end-to-end available bandwidth measurement

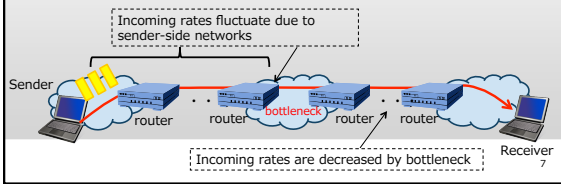
- Sender sends probe packets (measurement packet stream) at a certain rate and receiver observes receiving rate
  - Compares sending rate and receiving rate to estimate the available bw



- Existing methods repeat sending measurement streams with various sending rate to estimate the available bandwidth
  - E.g. binary search

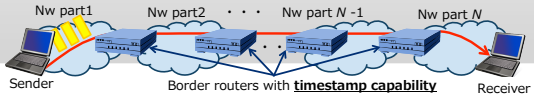
Difficulties on hop-by-hop measurement

- We can not directly control the incoming rate of measurement streams to a network part
  - Incoming rate is affected by network congestion levels of sender-side network parts
- Measuring receiver-side network parts from the bottleneck part is difficult
  - We can not expect higher incoming rate after passing through the bottleneck
  - However, some packets may pass through the bottleneck with higher rate than the bottleneck link bandwidth



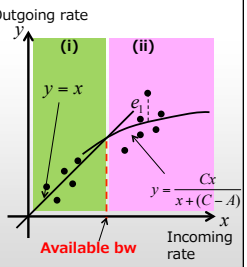
Proposed method (1)

- Assumption
  - Border routers between network parts can record the arriving time of incoming packets and write them to the packets as timestamps
- Steps
  - Sender sends measurement streams with various sending rates
  - Border routers record timestamp to packets
  - Receiver checks arriving times of packets and their timestamps
    - Collects **samples**, that are composed of (incoming rate, outgoing rate) for each network part
  - Calculate available bandwidths of all network parts based on the samples



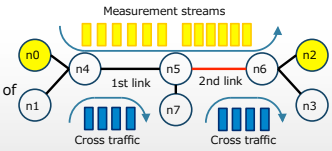
Proposed method (2)

- Calculation of available bandwidth
  - Plot samples to observe two regions
    - Region (i): incoming rate = outgoing rate
    - Region (ii): incoming rate > outgoing rate
  - Available bandwidth: border of two regions
    - Fitting of two lines by least squares method



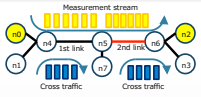
Performance evaluation environments

- Simulation by ns-2
  - Network topology
    - Two/five-hop network
    - All links have 100 [Mbps] of physical capacity
- Measurement stream
  - Equally-separated probing packets
  - Packet sending intervals: from 1.0×10^{-4} [s] to 2.0×10^{-3} [s] with 1.0×10^{-5} [s] step
- Cross traffic
  - Mean sending rate : (10, 20, 30, ···, 90) [Mbps]
  - Packet intervals: exponential distribution

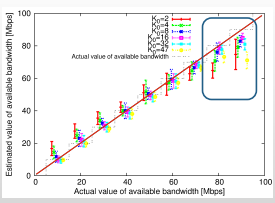


Evaluation results (1)

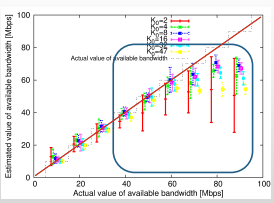
- Results with 2-hop network



Available bandwidth of 1st link: 70Mbps



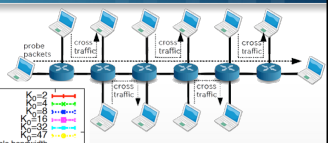
Available bandwidth of 1st link: 30Mbps

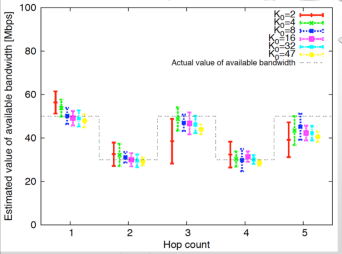


- We can measure the available bandwidth of 2nd link even when available bandwidth of 1st link is smaller than that of 2nd link

Evaluation results (2)

- Results with 5-hop network





Available bandwidth:
50, 30, 50, 30, 50 [Mbps]

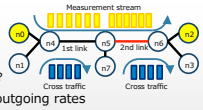
- We can maintain measurement accuracy when the number of network parts increases
- We can detect multiple bottleneck on the networks path

Summary and future work

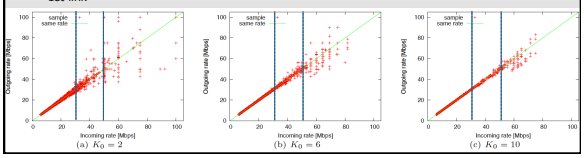
- Summary
  - Proposed an end-to-end measurement method of hop-by-hop available bandwidth with a tiny additional function on intermediate routers
  - Presented simulation results to confirm the effectiveness of the proposed method
    - We can measure the available bandwidth of a network part even when it is located at receiver side network from the bottleneck
- Future works
  - Implementation experiments
  - Construct measurement algorithm based on the proposed measurement principle
    - How to determine sending rates of measurement stream
    - How to decrease the number of measurement streams and the number of packets in each stream

Possibility of hop-by-hop measurement

- Can we measure available bw of latter network parts than a bottleneck part?
- Simulation experiments
  - Available bw of 1st and 2nd links: 30Mbps and 50Mbps
  - Sending rate of measurement stream: ~100Mbps
  - Observe incoming rate and outgoing rate at 2nd link
    - Is incoming rate larger than the available bw of 1st link?



- K_0: number of packets for calculating incoming and outgoing rates
- Results: Some packets passed through 1st link with higher rate than the available bandwidth
  - We can possibly measure the available bandwidth of 2nd link even when it is larger than the 1st link



Parameter K_0

- Calculation of available bandwidth
  - Plot samples to observe two regions
    - Region (i): incoming rate = outgoing rate
    - Region (ii): incoming rate > outgoing rate
  - Available bandwidth: border of two regions
    - Fitting of two lines by least squares method
- Parameter K_0: number of packets for calculating rates
  - Small K_0 can increase samples in region (ii), but brings larger estimation errors
  - Large K_0 can diminish estimation error, but the number of samples in region (ii) decreases by smoothing effect