What Signals Do Packet-pair Dispersions Carry?

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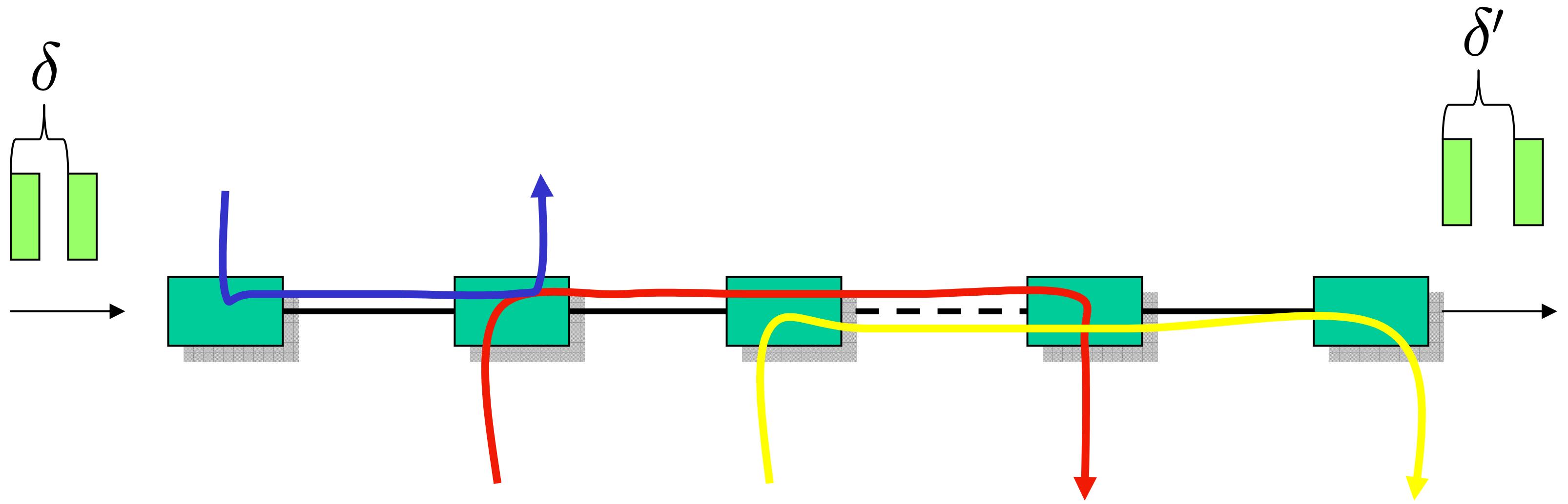
Outline

- Introduction
- Characterization of Packet-pair Probing
  - "Sampling & construction" model
  - Statistical properties of probing signals
- Probing Response Curves
- Implication on Bandwidth Estimation
- Conclusion

Introduction 1

- Packet-pair probing has been a major mechanism to measure link capacity, cross-traffic, and available bandwidth.



- Due to its end-2-end nature of packet-pair measurement, no network support is needed.

Introduction 2

- Unresolved questions in packet-pair measurements:
  – What information about the path is captured in the output packet-pair dispersions?
  – How are these signals encoded?
  – What are the statistical properties of these signals?

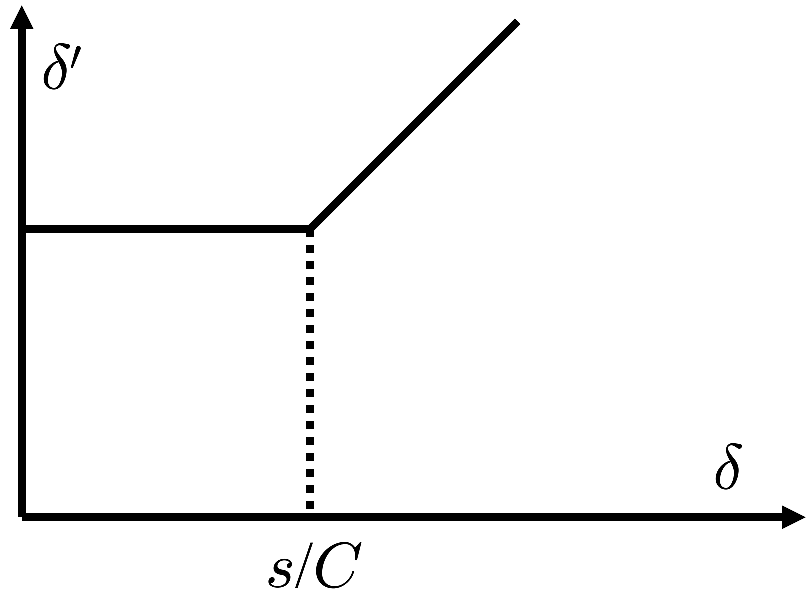
- Understanding these questions helps us extract path information from packet-pair dispersions.

- This paper answers these questions in the context of a single-hop path and bursty cross-traffic arrival.

Prior Work 1

- Start from the simplest case – an empty path
  - Jacobson 1988.

$$\delta' = \begin{cases} \frac{s}{C} & \delta \le \frac{s}{C} \\ \delta & \delta > \frac{s}{C} \end{cases}$$



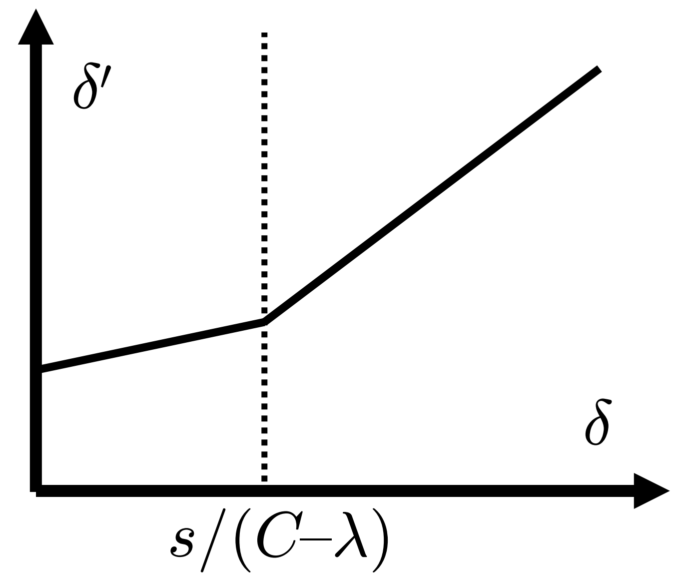
- This becomes the basic idea for bottleneck capacity measurements.

Prior Work 2

- Single-hop path with constant-rate fluid cross-traffic. (Melander et al, Dovrolis et al)

$$\delta' = \begin{cases} \frac{s}{C} + \frac{\lambda\delta}{C} & \frac{s}{\delta} \geq C - \lambda \\ \delta & \frac{s}{\delta} \leq C - \lambda \end{cases}$$

$$= \max\left(\delta, \frac{s + \lambda\delta}{C}\right).$$



- In multi-hop paths, the same thing holds to a certain extent.

Prior Work 3

- Single-hop path with bursty cross-traffic
  - Bolot 1993, Hu et al 2003
  - When the packet-pair shares the same queuing period

$$\delta' = \frac{s}{C} + \frac{y\delta}{C}$$

Output dispersion R.V.

The R.V. indicating cross-traffic intensity between the arrivals of the pair

  - When δ is sufficiently large (so that packet-pairs almost never share the same queuing period), the mean of the output dispersion is equal to δ.

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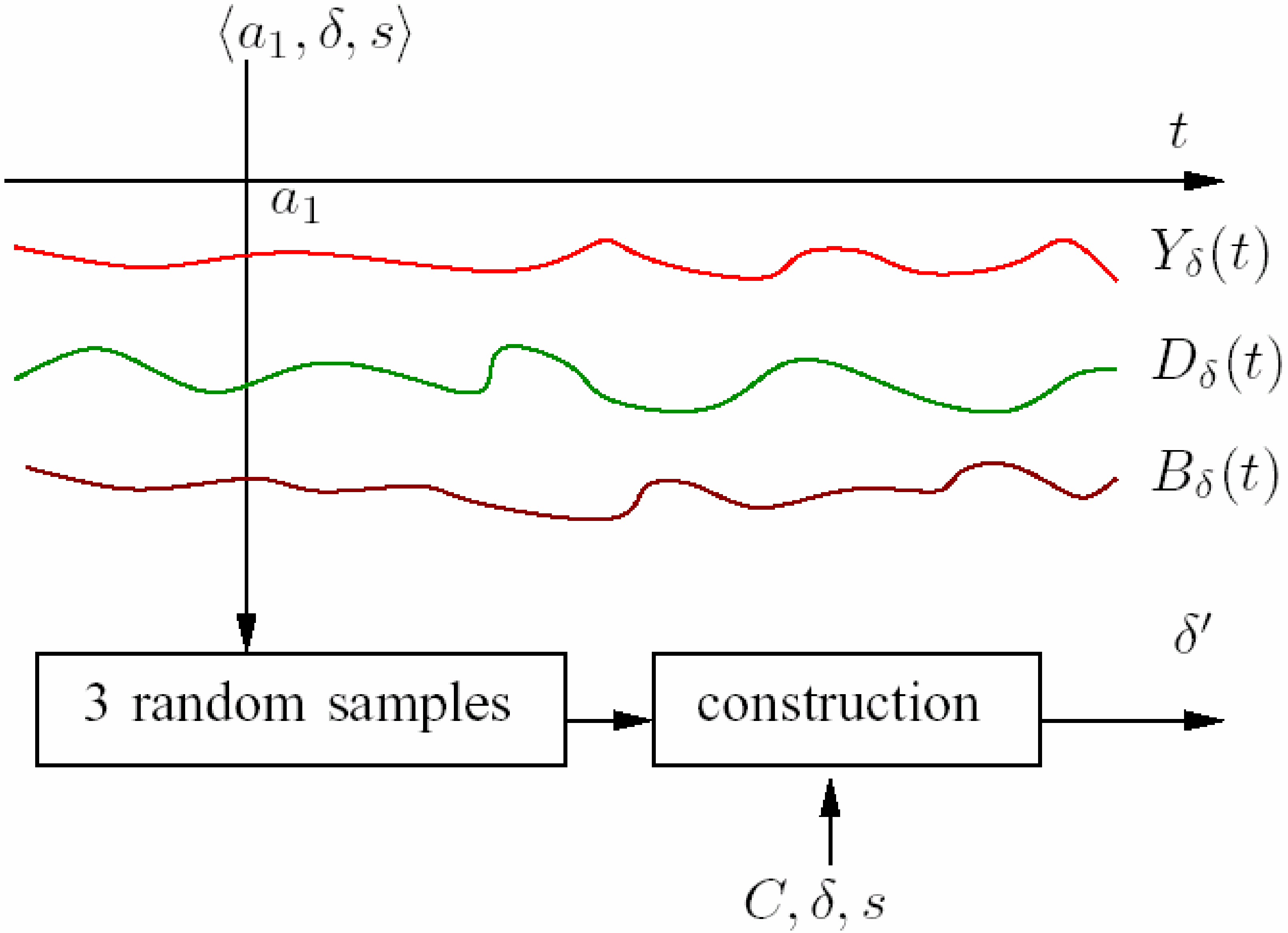
Sampling & Construction Model



What are the random processes? 1

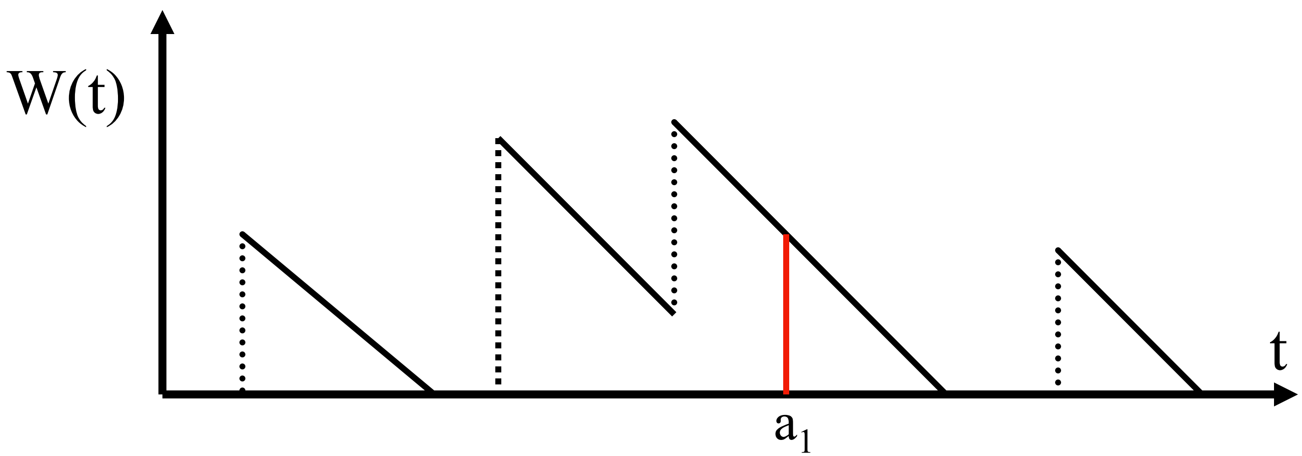
- The three processes which probing packet-pair inspects are all related to cross-traffic arrival.
- $Y_\delta(t)$, δ-interval cross-traffic intensity process, indicates the cross-traffic arrival rate in the time interval [t,t+δ].
- $B_\delta(t)$, δ-interval available bandwidth process, indicates the spare capacity in the time interval [t,t+δ].

What are the random processes? 2

- $D_\delta(t)$, δ-interval workload difference process, is defined as

$$D_\delta(t) = W(t+\delta) - W(t)$$

- W(t), workload process, indicates the remaining workload (in terms of the amount of service time) in the hop at time t.



Construction Procedure

- A packet-pair constructs its output dispersion signal using the following formulas

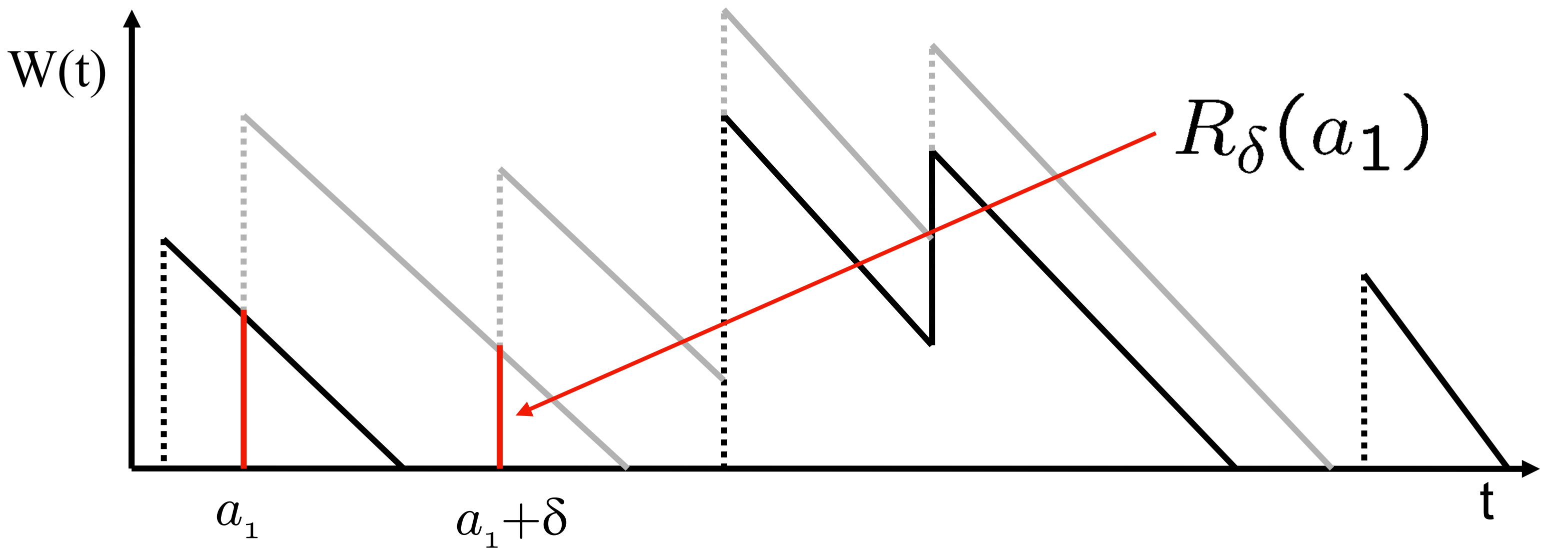
$$\delta' = \frac{Y_\delta(a_1)\delta}{C} + \frac{s}{C} + \max\left(0, \frac{B_\delta(a_1)\delta - s}{C}\right)$$
$$= \delta + D_\delta(a_1) + \max\left(0, \frac{s - B_\delta(a_1)\delta}{C}\right).$$

The hop idle time between the departure of the pair $\tilde{I}_\delta(a_1)$

Intrusion residual $R_\delta(a_1)$

Intrusion Residual $R_\delta(a_1)$

- $R_\delta(a_1)$ is the additional queuing delay imposed on the second probing packet by the first packet in the pair.



$$\delta' = \delta + D_\delta(a_1) + R_\delta(a_1)$$

The advantage of our model

- The ``sampling & construction” characterization of packet-pair probing holds *unconditionally*. It neither relies on any assumptions on cross-traffic arrival, nor imposes any restriction on input packet-pair dispersion δ.
- Using this characterization, we answered fully the question as to what information is contained in output dispersions and how it is encoded.

Statistical Properties of Probing Signals 1

- To facilitate information extraction from δ', we examine the statistics of each encoded signal.
- Assumption: cross-traffic arrival has ergodic stationary increments.
  - $Y_\delta(t)$ has time-invariant distribution with ensemble mean λ for any δ interval.
  - Ergodicity implies that the variance of $Y_\delta(t)$ decays to 0 when δ increases, for any t.

$$E[Y_\delta(t)] = \lambda.$$

$$\lim_{\delta\to\infty} Var[Y_\delta(t)] = 0.$$

$$\Bigg\} \lim_{\delta\to\infty} E[(Y_\delta(t)-\lambda)^2] = 0$$

Statistical Properties of Probing Signals 2

- As a consequence of our assumption (see details in the paper)
  - Both W(t) and $D_\delta(t)$ have time-invariant distributions.

$$E[D_\delta(t)] = E[W(t+\delta)] - E[W(t)] = 0$$

  - $B_\delta(t)$ has a time-invariant distribution

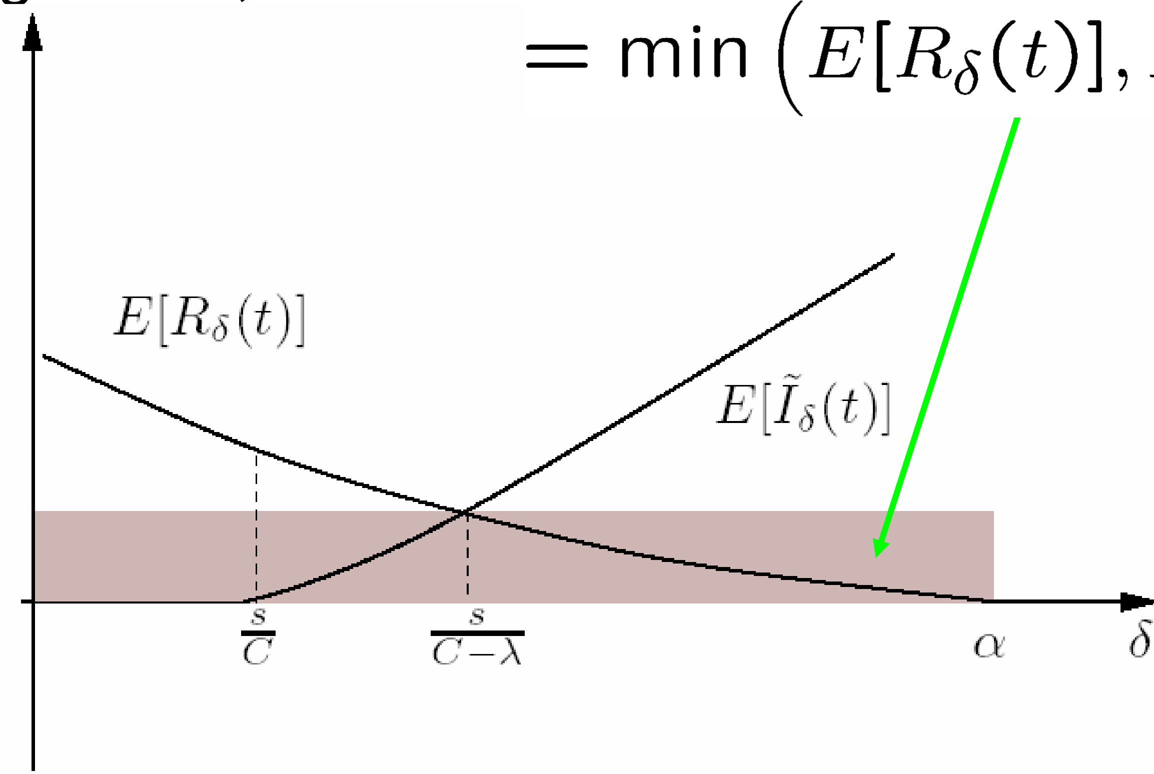
$$E[B_\delta(t)] = C - \lambda$$

$$\lim_{\delta \to \infty} Var[B_\delta(t)] = 0$$

Statistical Properties of Probing Signals 3

- Both $R_\delta(t)$ and $\tilde{I}_\delta(t)$ have time-invariant distributions, but their ensemble means depend on both δ and probing packet size s.
- Keeping s fixed, we have

$$= \min\left(E[R_\delta(t)], E[\tilde{I}_\delta(t)]\right)$$



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Probing response curve

- Link capacity C, cross-traffic λ , and available bandwidth C-λ are the pieces of information we are interested in extracting from packet-pair output dispersion random variable.
- This information is contained in E[δ'] as a function of input dispersion δ
  - E[δ'] : the probing response of the path at input dispersion point δ.
- The way to estimate E[δ'] is to probe many times and generate an output dispersion random process $\{\delta'_n\}$
  - The process has time-invariant distribution and its sample-path time-average is equal to E[δ']

Closed-form expression for probing response curve

- Based on our "sampling & construction" model and stationary cross-traffic arrival assumption, we get

$$E[\delta'] = \frac{\delta\lambda + s}{C} + \int_{s/\delta}^{C} \frac{x\delta - s}{C} dP_\delta(x)$$

$$= \delta + \int_{0}^{s/\delta} \frac{s - x\delta}{C} dP_\delta(x).$$

Distribution function of $B_\delta(t)$

$E[\tilde{I}_\delta(t)]$

$E[R_\delta(t)]$

Deviation from fluid response curve 1

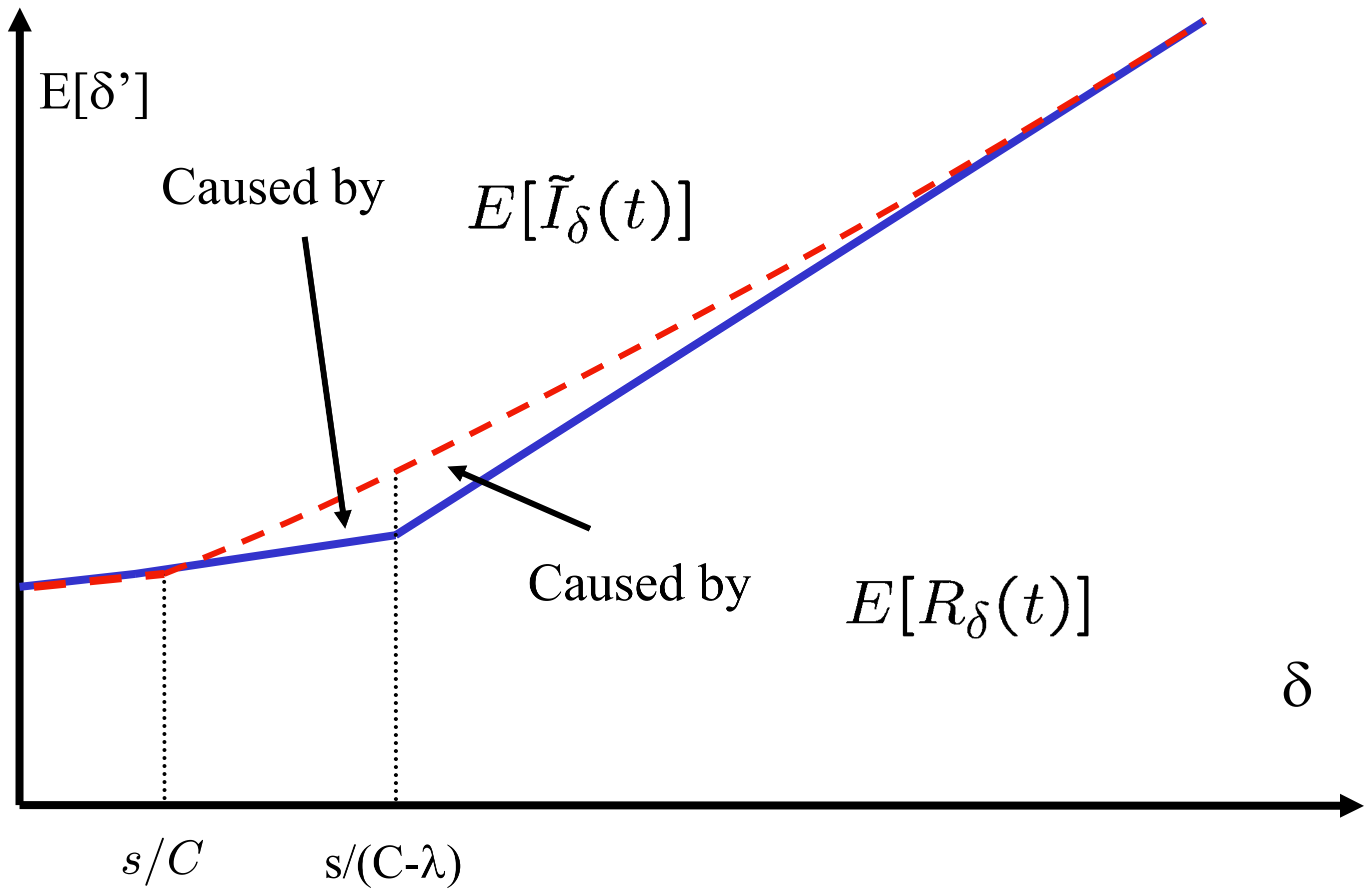
- The two terms $E[\tilde{I}_\delta(t)]$ and $E[R_\delta(t)]$ cause the response curve to deviate from that in fluid cross-traffic, which complicates information extraction.

$$E[\delta_n'] - \max\left(\delta, \frac{\delta\lambda + s}{C}\right) = \begin{cases} E[\tilde{I}_\delta(t)] & \frac{s}{\delta} \geq C - \lambda \\ E[R_\delta(t)] & \frac{s}{\delta} \leq C - \lambda. \end{cases}$$

Fluid response curve, where information can be easily extracted.

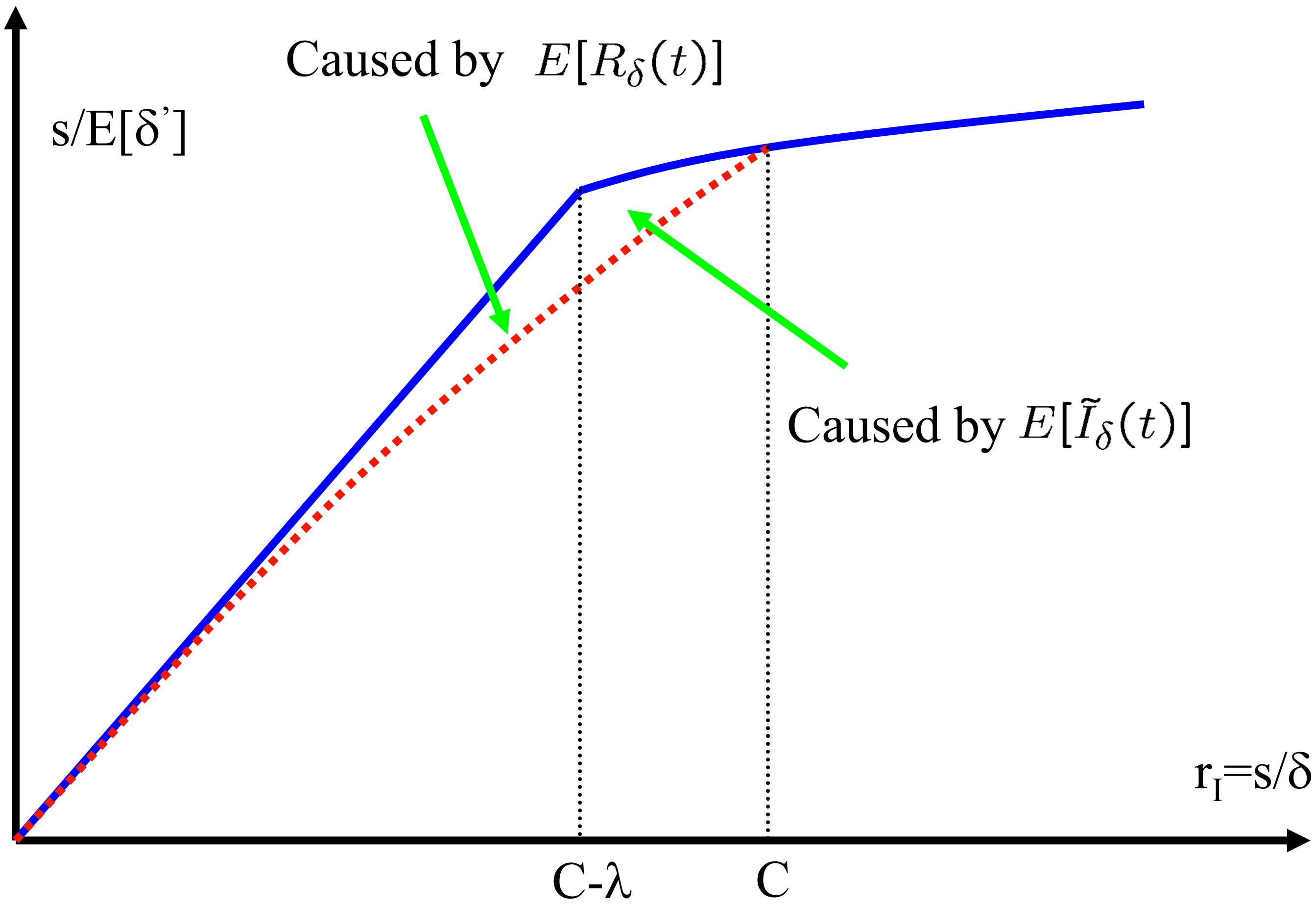
$$= \min\left(E[R_\delta(t)], E[\tilde{I}_\delta(t)]\right)$$

Deviation from fluid response curve 2



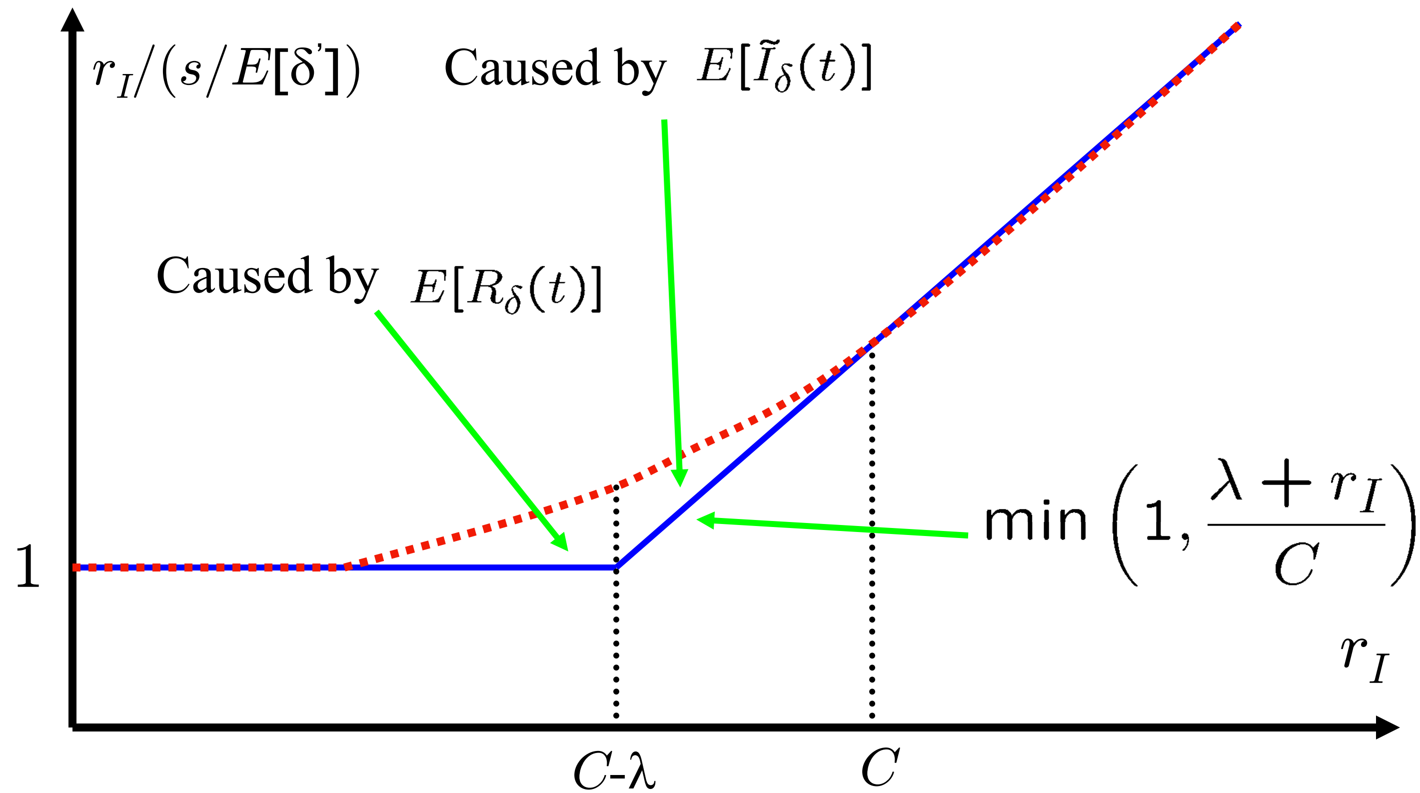
Deviation from fluid response curve 3

- Rate response curve is more convenient.



Deviation from fluid response curve 4

- A transformed version of rate response curve is even more convenient.



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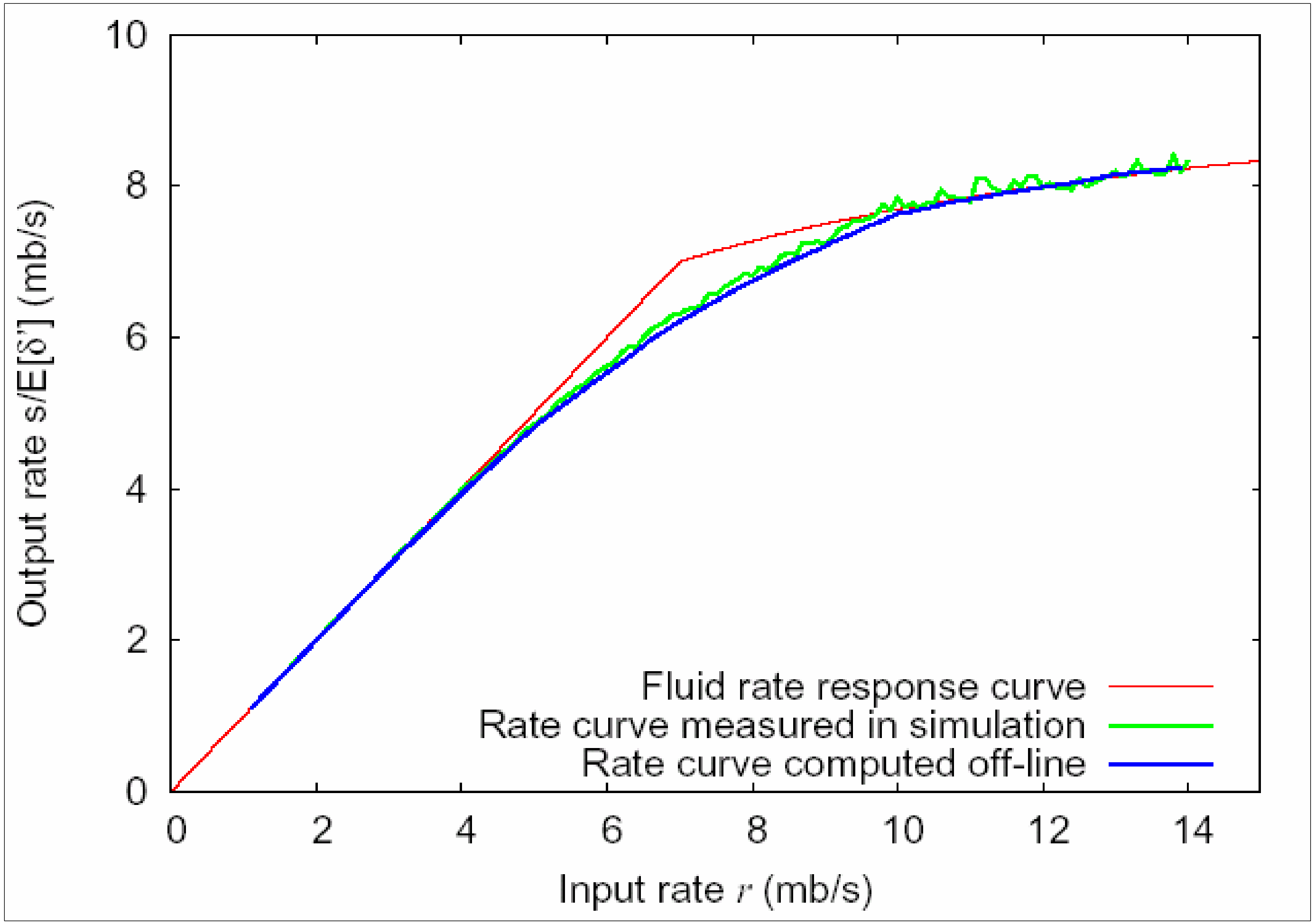
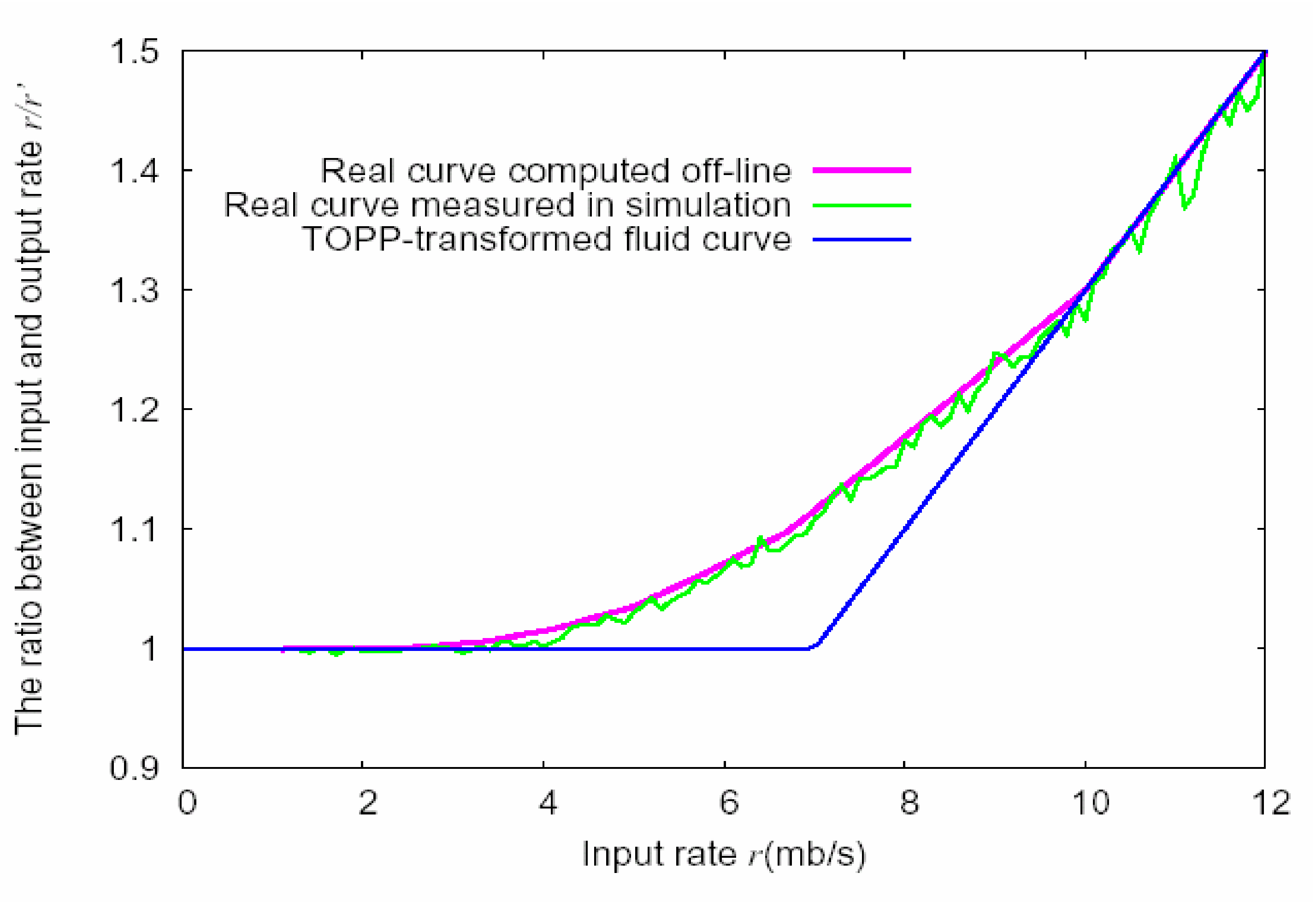
Computing response curves

- We proposed a method that computes $E[\delta']$ from cross-traffic arrival traces with high accuracy.
  - Given a trace, compute the sample-path $\delta'(t)$ in a time interval of the trace duration.
  - The sample-path $\delta'(t)$ is a piece-wise linear function, which allows accurate and easy computation of its time-average.
  - This time-average is a good approximation of $E[\delta']$ if the duration is sufficiently long.
- Alternatively, we can also measure the response using ns2 simulation.

Some results using Poisson CT 1



Some results using Poisson CT 2



Implication on two packet-pair measurement techniques

- TOPP uses the deviated portion of the response curve and produces inaccurate results.

	C	λ	C-λ
Real Value	10	3	7
TOPP Ns-2	35.97	32.33	3.64
TOPP Off-line	35.81	32.38	3.43

- Spruce uses the curve at input rate C, where no deviation occurs. Hence, spruce is unbiased in single-hop path.
- However, Spruce is subject to significant under-estimation in multi-hop paths due to the two noise terms we discussed here. We report more details in the future work.

Recent progress (not in the paper)

- Using the ``sampling & construction" model, we were able to show that the two noise terms converge in mean-square to 0 as packet-train length increases and that output dispersion δ' also converges in mean-square to the fluid response.

$$\lim_{n\to\infty} E\left[\left(\delta' - \max\left(\delta, \frac{s+\delta\lambda}{C}\right)\right)^2\right] = 0$$

- The trick is to treat the first and last packets in the train as a packet-pair, and treat probing packets in between as if they were from cross-traffic.

Conclusion

- We proposed a ``sampling & construction” model to characterize the signals contained in packet-pair dispersion.
- The presence of two positive-mean noise random signals impedes accurate information extraction from packet-pair output dispersions and response curves.
- The way to suppress the noise signals is to use large probing packet-size and long packet-trains instead of packet-pairs.
- Future work: extension to multi-hop paths.

Thank You!

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