Single-Hop Probing Asymptotics in Available Bandwidth Estimation: Sample-Path Analysis

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Outline

- Introduction
  - Constant -rate fluid cross-traffic model
  - Relationship to existing techniques

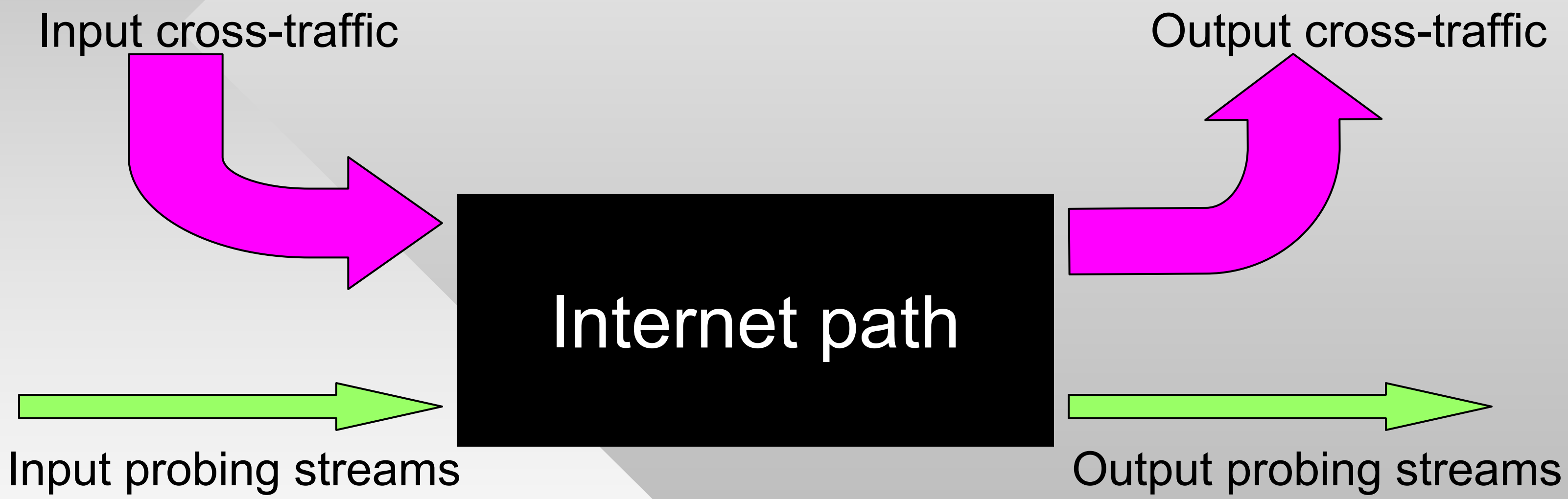
Prior work

- General Bursty Cross-Traffic Model
- Experimental Verifications
- Implications to Existing Techniques
- Conclusion

Our work

Problem

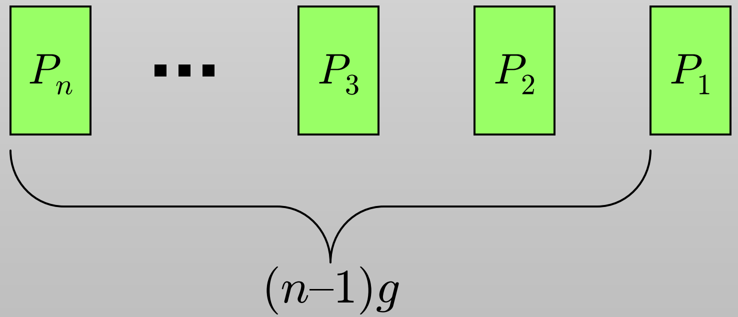
- Measuring path avail-bw using probing streams:



- Basic question: the relationship between input, output, and the measurement goal: avail-bw

Single-Hop Fluid Model 1

- Assuming Constant-rate Fluid Cross-traffic
  - Constant Cross-traffic intensity λ in any time-interval
  - Constant Avail-bw $A = C - \lambda$ in any time-interval
- Probing rate/gap of packet train
  - Probing gap: g
  - Probing rate: $r = s/g$

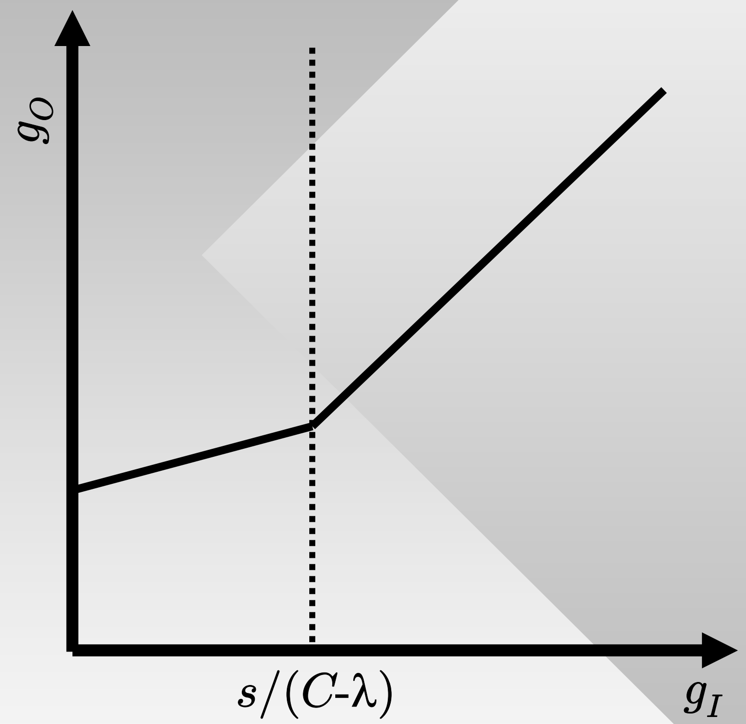


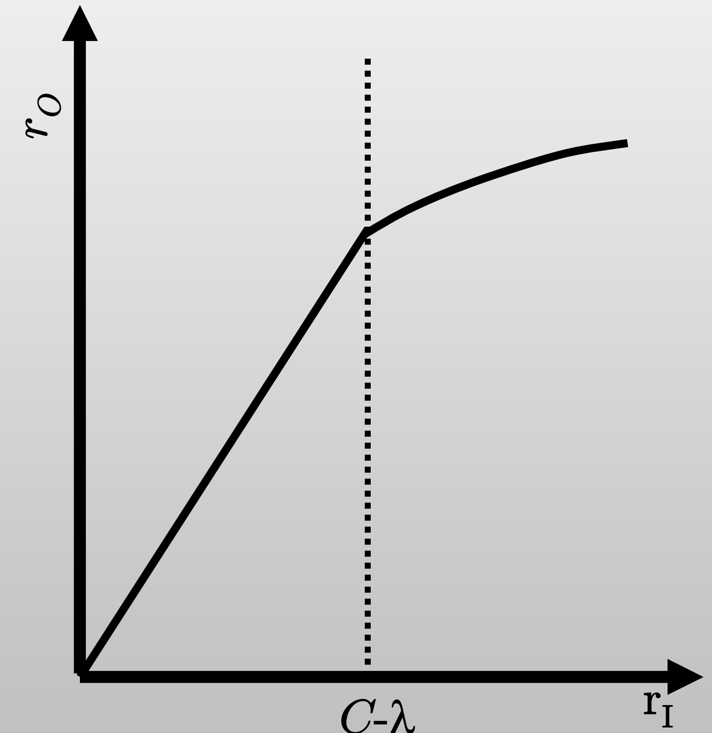
- Fluid models:

$$r_O = \begin{cases} C\frac{r_I}{r_I+\lambda} & r_I \geq C - \lambda \\ r_I & r_I \leq C - \lambda \end{cases}$$

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

Single-Hop Fluid Model 2

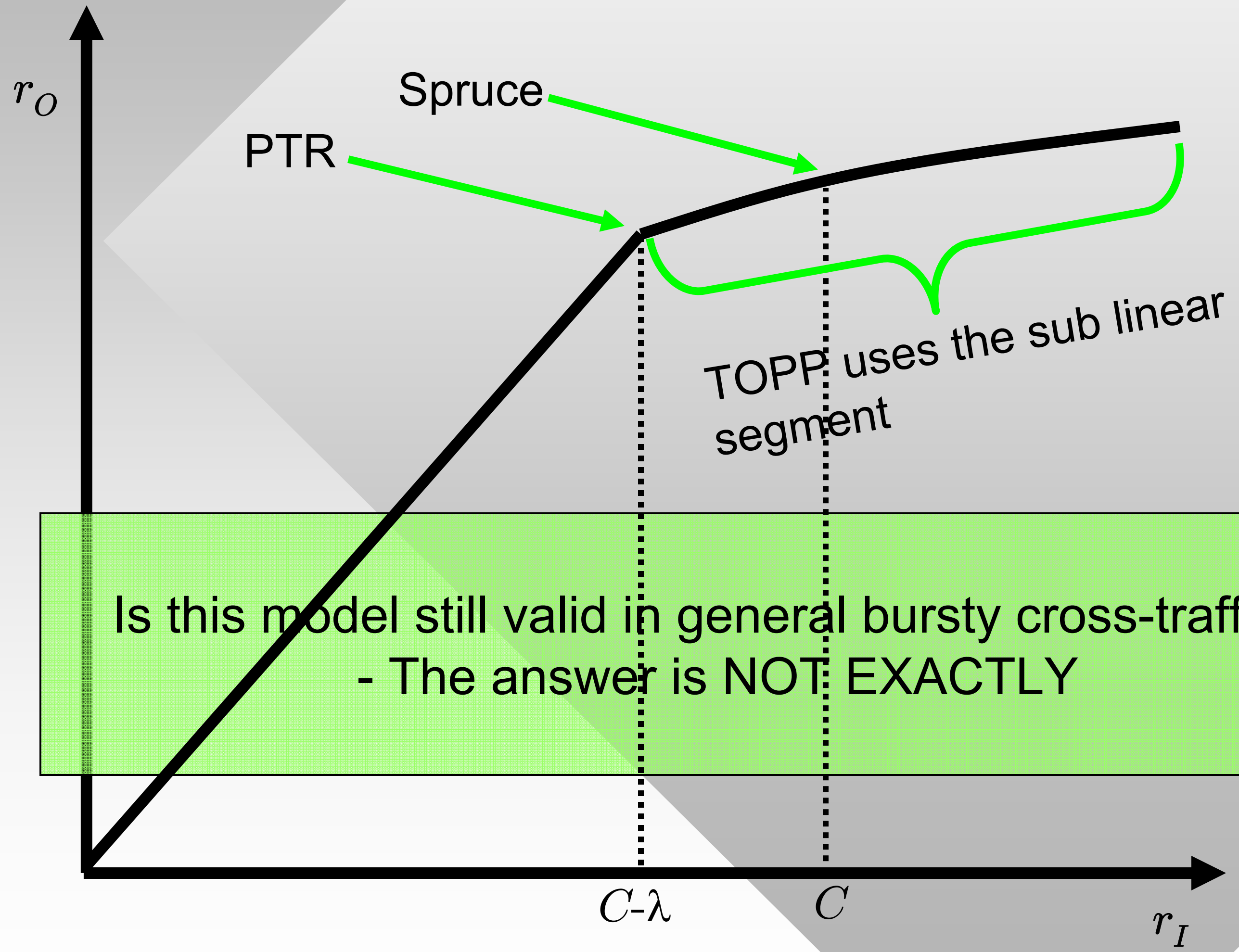




$$g_O = \begin{cases} \frac{s+g_I\lambda}{C} & g_I \le \frac{s}{C-\lambda} \\ g_I & g_I \ge \frac{s}{C-\lambda} \end{cases}$$

$$r_O = \begin{cases} C\frac{r_I}{r_I+\lambda} & r_I \ge C - \lambda \\ r_I & r_I \le C - \lambda \end{cases}$$

How Existing Techniques Relate to Fluid Models



Is this model still valid in general bursty cross-traffic ?
- The answer is NOT EXACTLY

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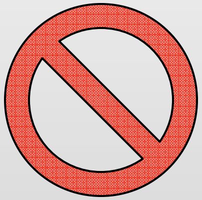
Extending to Bursty Cross-Traffic

- For the gap model, we adapt it to

$$E[g_O] = \begin{cases} \frac{s+g_I\lambda}{C} & g_I \le \frac{s}{C-\lambda} \\ g_I & g_I \ge \frac{s}{C-\lambda} \end{cases}$$



- g_O now varies, we change it to the asymptotic average

$$E[g_O] = \lim_{k\to\infty} \frac{1}{k} \sum_{i=1}^{k} g_O^{(i)}$$

- Cross-traffic rate is no longer a constant, λ is interpreted as its long-term average.

$$\lambda = \lim_{t\to\infty} \frac{V(t)}{t}$$

Real Asymptotic Model

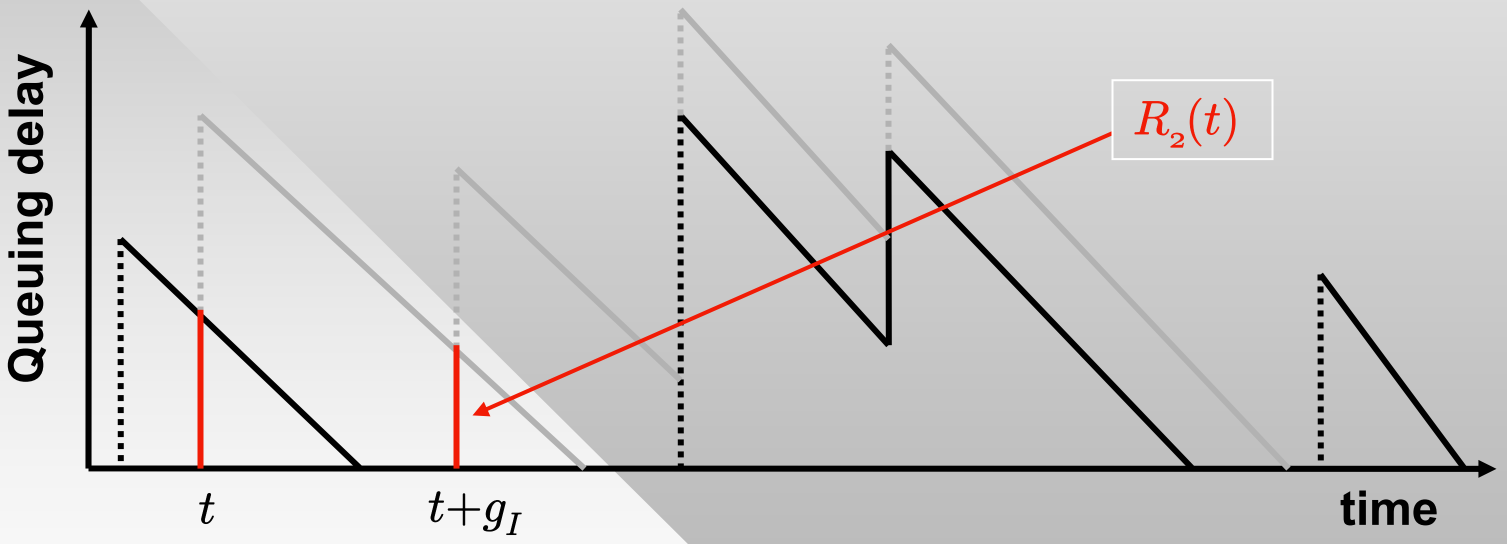
- With proof, we offer the following gap model in bursty cross-traffic:

$$E[g_O] = \begin{cases} \frac{s+g_I\lambda}{C} + \frac{E[\tilde{I}(t,t+(n-1)g_I)]}{n-1} & g_I \leq \frac{s}{C-\lambda} \\ g_I + \frac{E[R_n(t)]}{n-1} & g_I \geq \frac{s}{C-\lambda} \end{cases}$$

- The two additional terms are zero in fluid traffic, but are often POSITIVE in bursty cross-traffic.

What is the term $E[R_n(t)]/(n\text{-}1)$

- $R_n(t)$ is the additional queuing delay imposed on the last packet P_n by the first n-1 packets in the same probing train when the train arrives into the hop at time t. It is called intrusion residual.



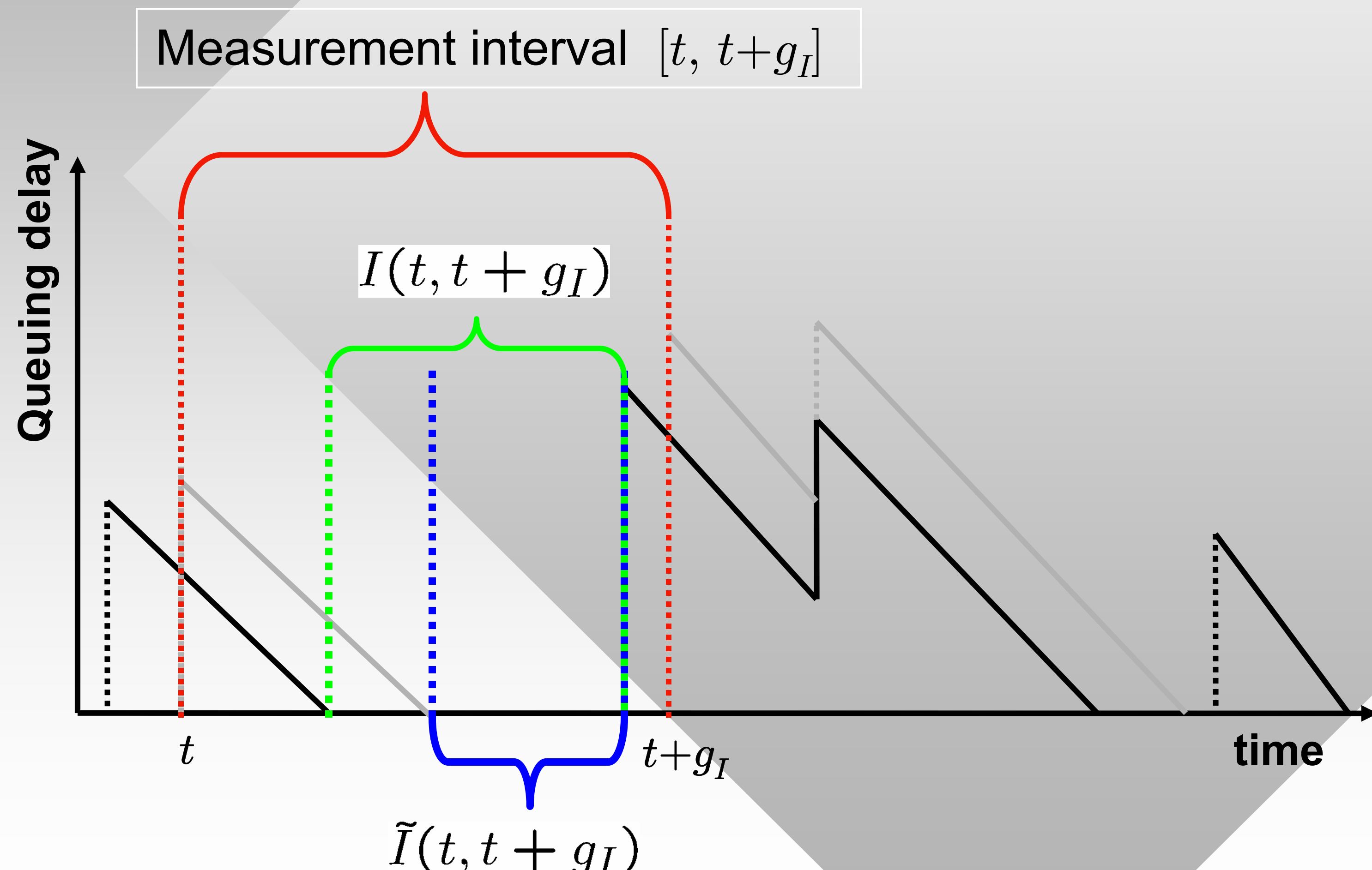
- $E[R_n(t)]$ is the asymptotic time average of $R_n(t)$

$$E[R_n(t)] = \lim_{\tau \to \infty} \frac{1}{\tau} \int_0^{\tau} R_n(t)dt$$

What is the term $\frac{E[\tilde{I}(t, t+(n-1)g_I)]}{n-1}$

$[t, t+(n-1)g_I)]$	The measurement interval of a packet train when it arrives to the hop at time t.
$\tilde{I}(t, t+(n-1)g_I)$	The amount of hop idle time in that measurement interval after the hop is visited by the packet train at time t.
$E[\tilde{I}(t, t+(n-1)g_I)]$	Asymptotic time average of the hop idle time within the measurement interval of a packet train.

What is the term $\frac{E[\tilde{I}(t, t + (n-1)g_I)]}{n-1}$



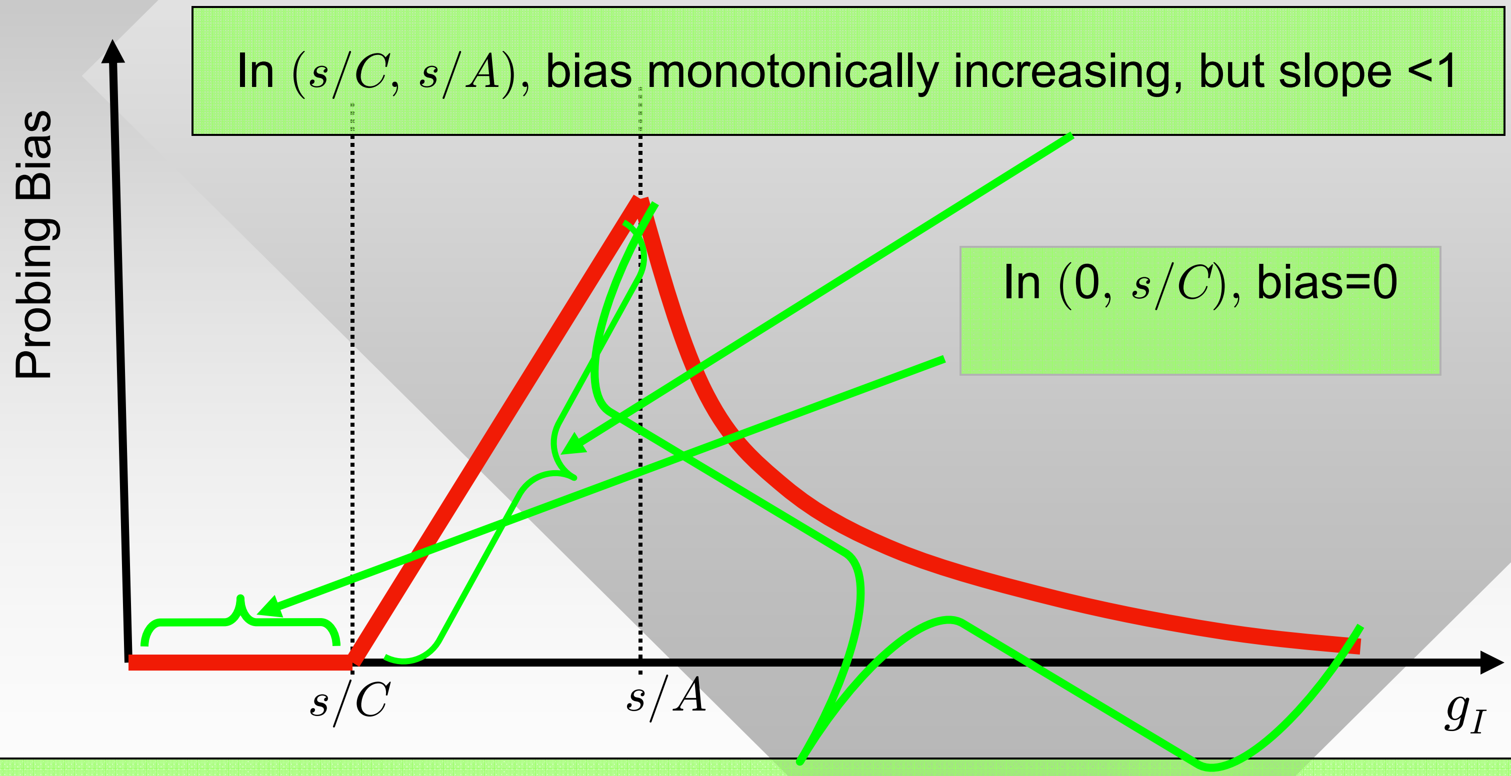
Probing Bias

- The following two terms, called probing bias, are the difference between fluid model and real asymptotic model.

$$\beta(g_I, s, n) = \begin{cases} \frac{E[\tilde{I}(t,t+(n-1)g_I)]}{n-1} & g_I \leq \frac{s}{C-\lambda} \\ \frac{1}{n-1} E[R_n(t)] & g_I \geq \frac{s}{C-\lambda} \end{cases}$$

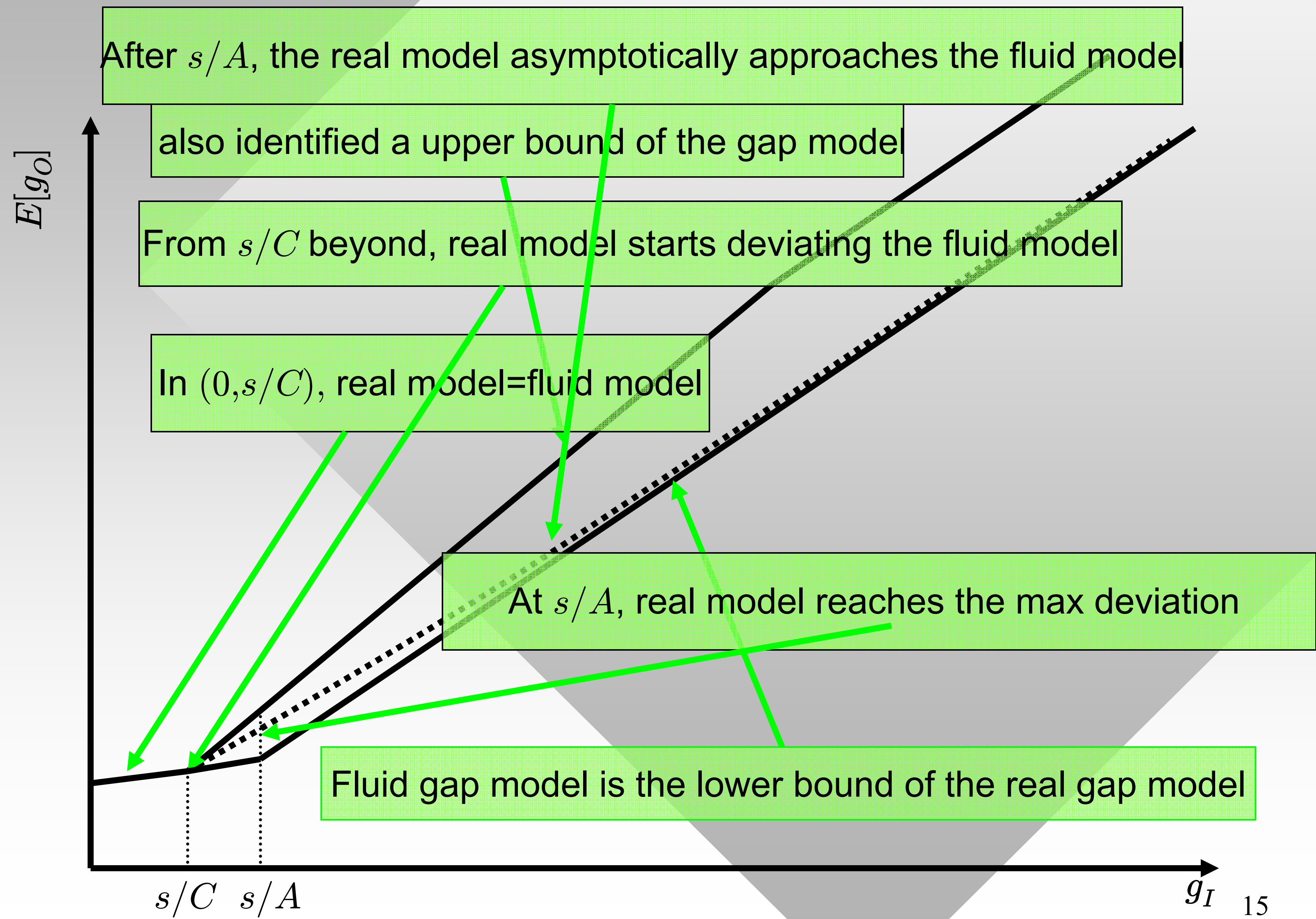
- The closed-form expression of probing bias is given in the paper.

Probing Bias VS. Input Gap g_I

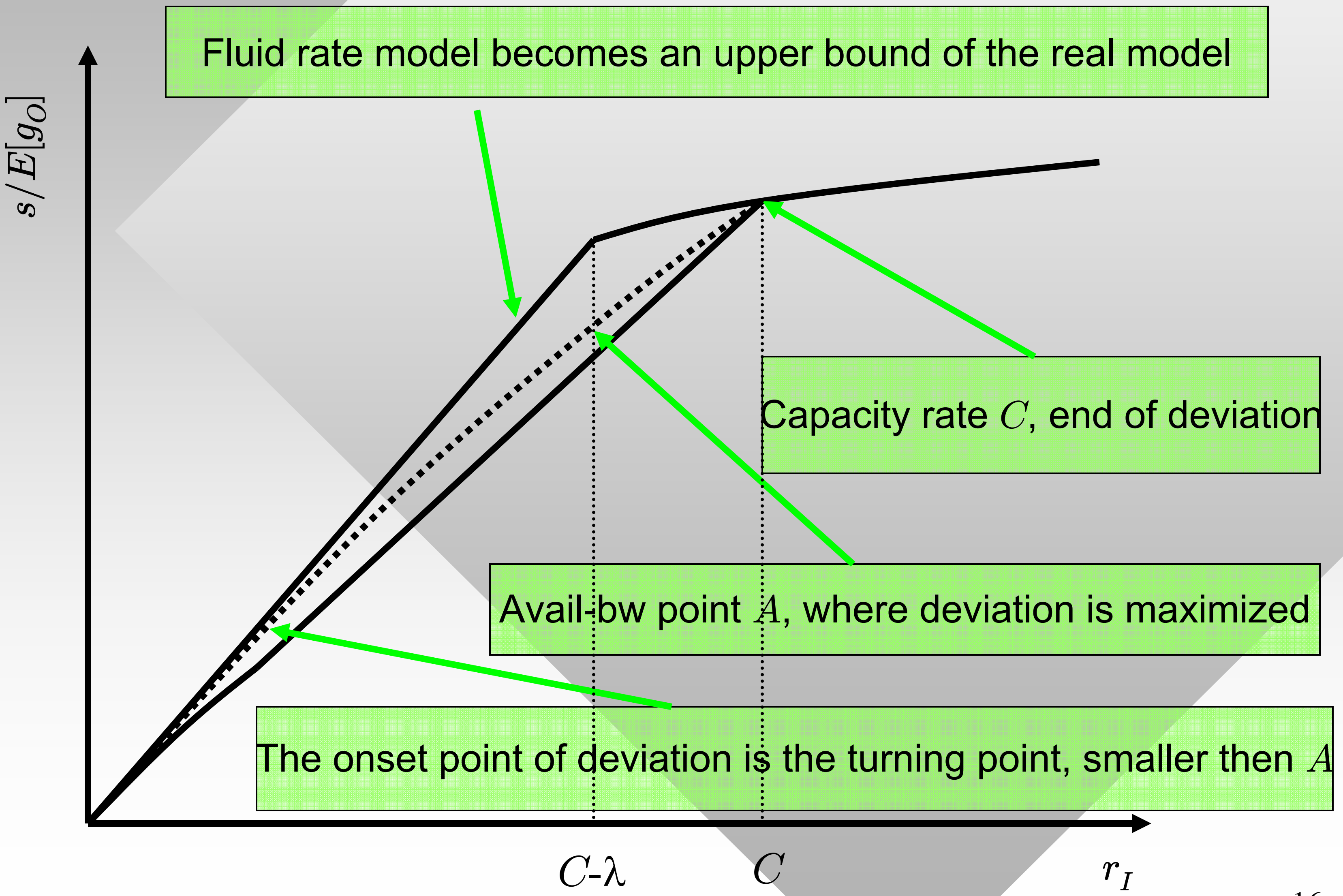


When g_I>s/A, bias monotonically decreases and asymptotically converges to 0.

Gap Model in Bursty Cross-traffic



Rate Model in Bursty Cross-traffic



Impact of Packet-train Parameters

- Larger packet size pushes the real model closer to the fluid model
  - Sampling interval increases, cross-traffic variance decreases, cross-traffic is more like fluid.
- Longer packet train also pushes the real model closer to the fluid model.
  - Non-intuitive, the paper offers an explanation using random walk theory.
- Fluid models are <u>tight</u> bounds for real models

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Period Testing 1

- The deviation phenomena were first observed in periodic cross-traffic such as CBR
- $E[g_O]$ can be easily computed , since it is equal to the time average of $g_O(t)$ in one period:

$$E[g_O] = \frac{1}{T}\int_0^T g_O(t)dt$$

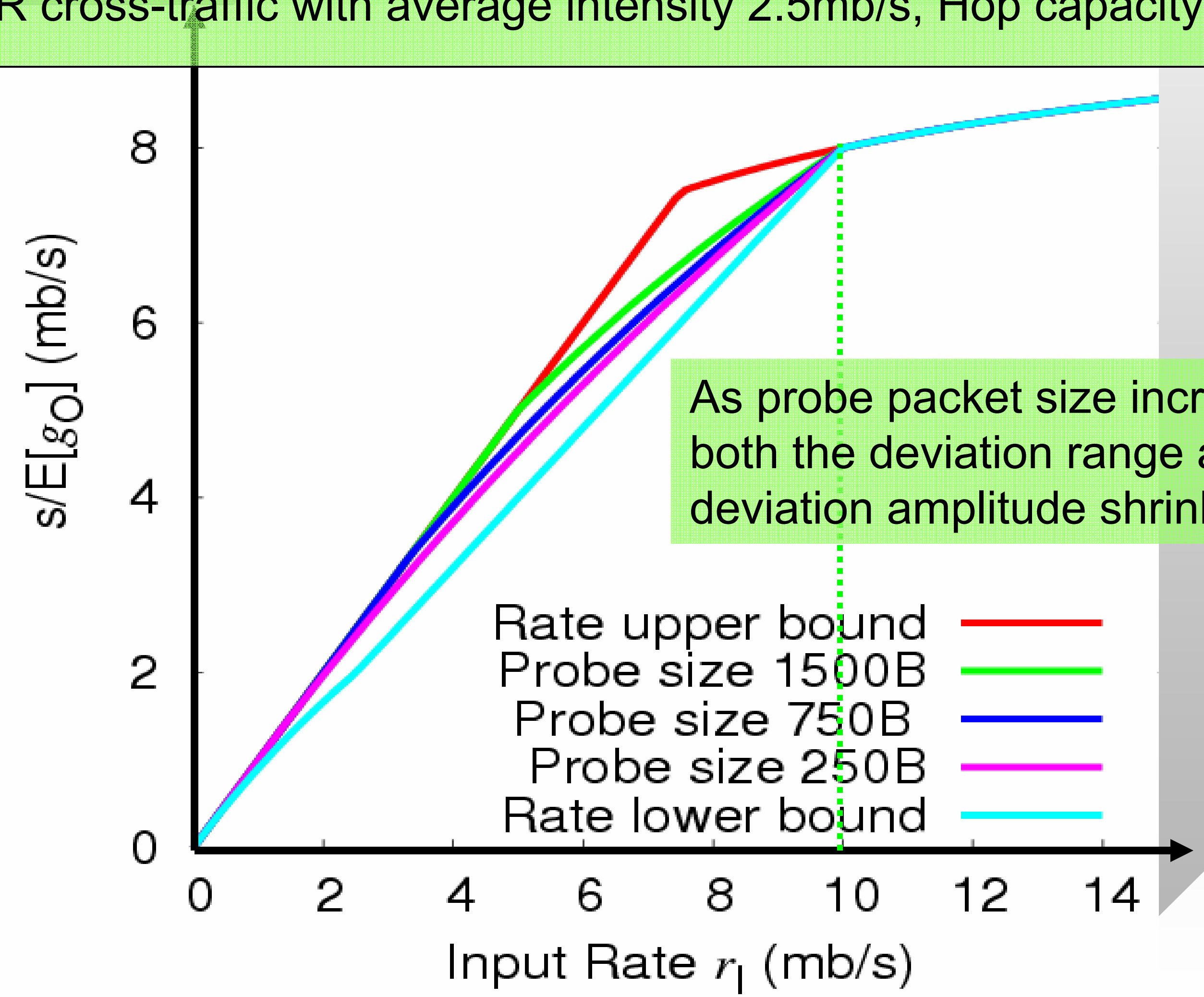
  - Where $g_O(t)$ is the output gap of a packet train when it arrives at the hop at time t.
  - Notice that $g_O(t)$ is also a periodic function of time with the same period T as that of the cross-traffic.

Period Testing 2

- Period Testing approximates the time average of $g_O(t)$ in $[0, T]$
  - By sampling it at a set of equally spaced time instances and taking the average of those samples.
- The number of samples is chosen so that
  - Using more samples makes little difference
  - Results agree with fluid model when $0 < g_I < s/C$

Packet-Pair Rate Curve in CBR

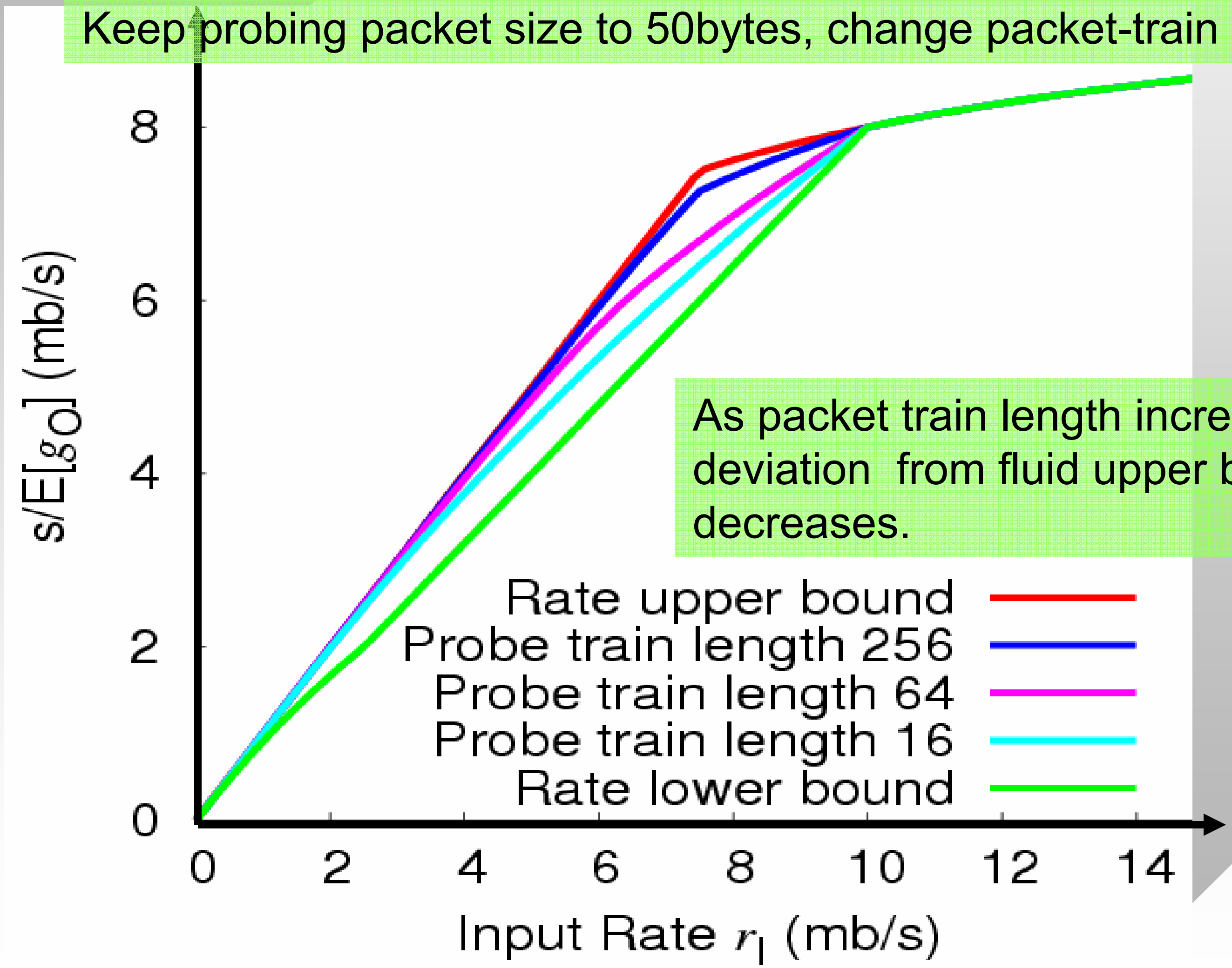
CBR cross-traffic with average intensity 2.5mb/s, Hop capacity C=10mb/s



As probe packet size increases, both the deviation range and deviation amplitude shrink.

Packet-train Rate Curve in CBR

Keep probing packet size to 50bytes, change packet-train length

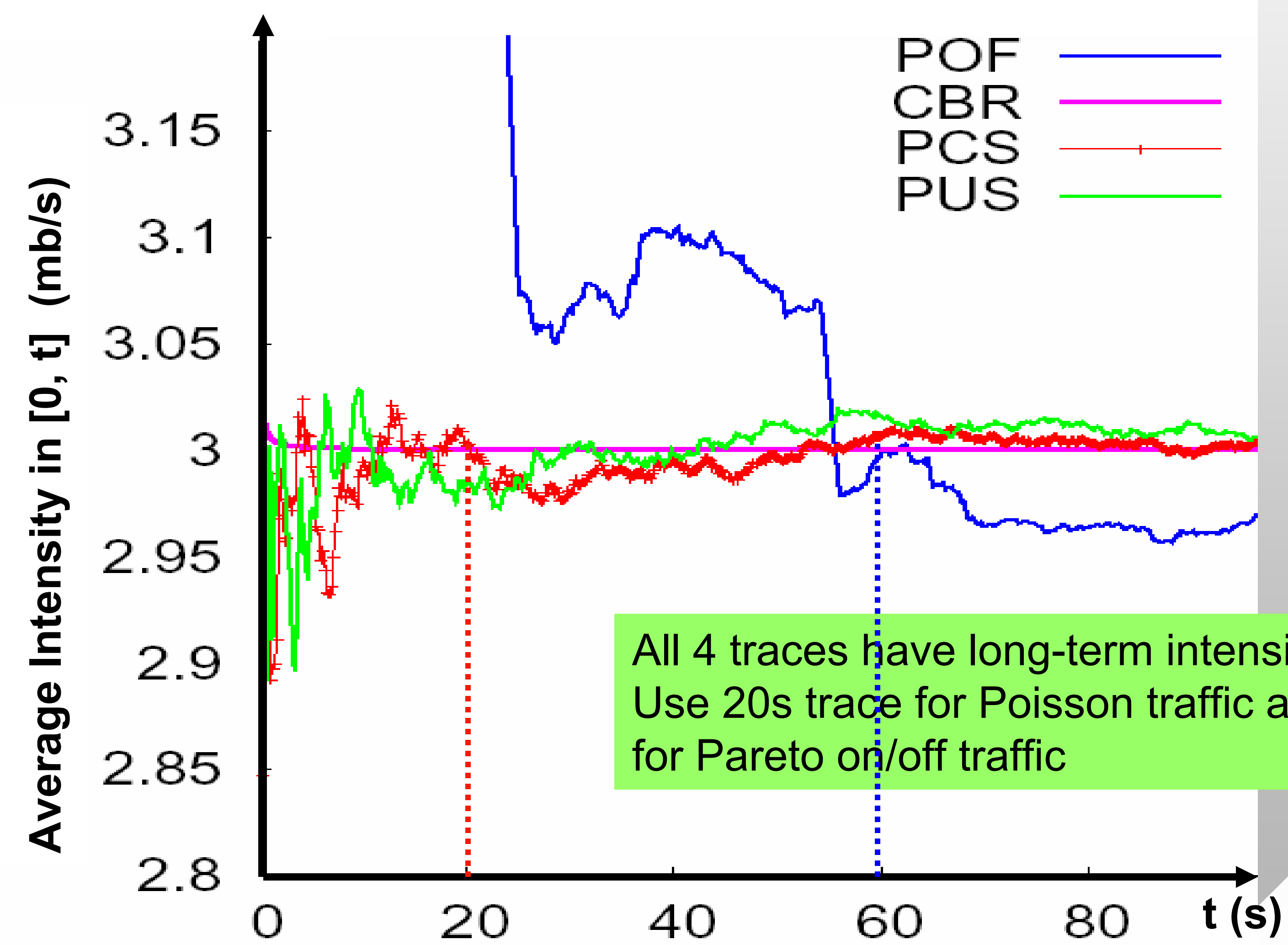


As packet train length increases, the deviation from fluid upper bound decreases.

Trace-driven Testing

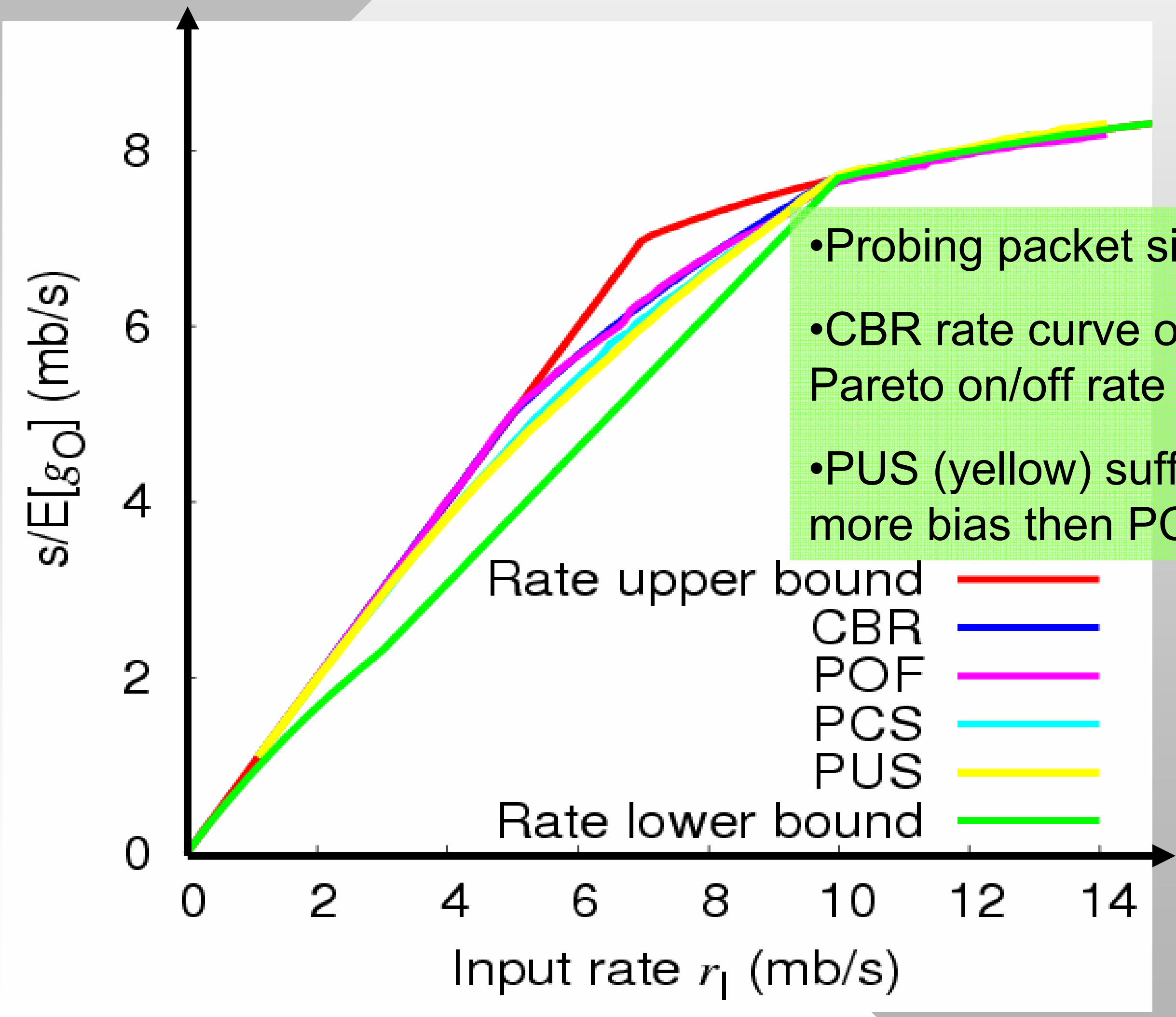
- Allows examining the asymptotic model in different types of cross-traffic
- Use time average of $g_O(t)$ in a finite time interval $[0, \alpha]$ to approximate $E[g_O]$
- α is chosen so that the cross-traffic intensity in $[0, \alpha]$ is close to its long term average
- $g_O(t)$ can be computed based on cross-traffic trace and hop capacity C, when $t+(n\text{-}1)g_I < \alpha$

Cross-traffic Traces



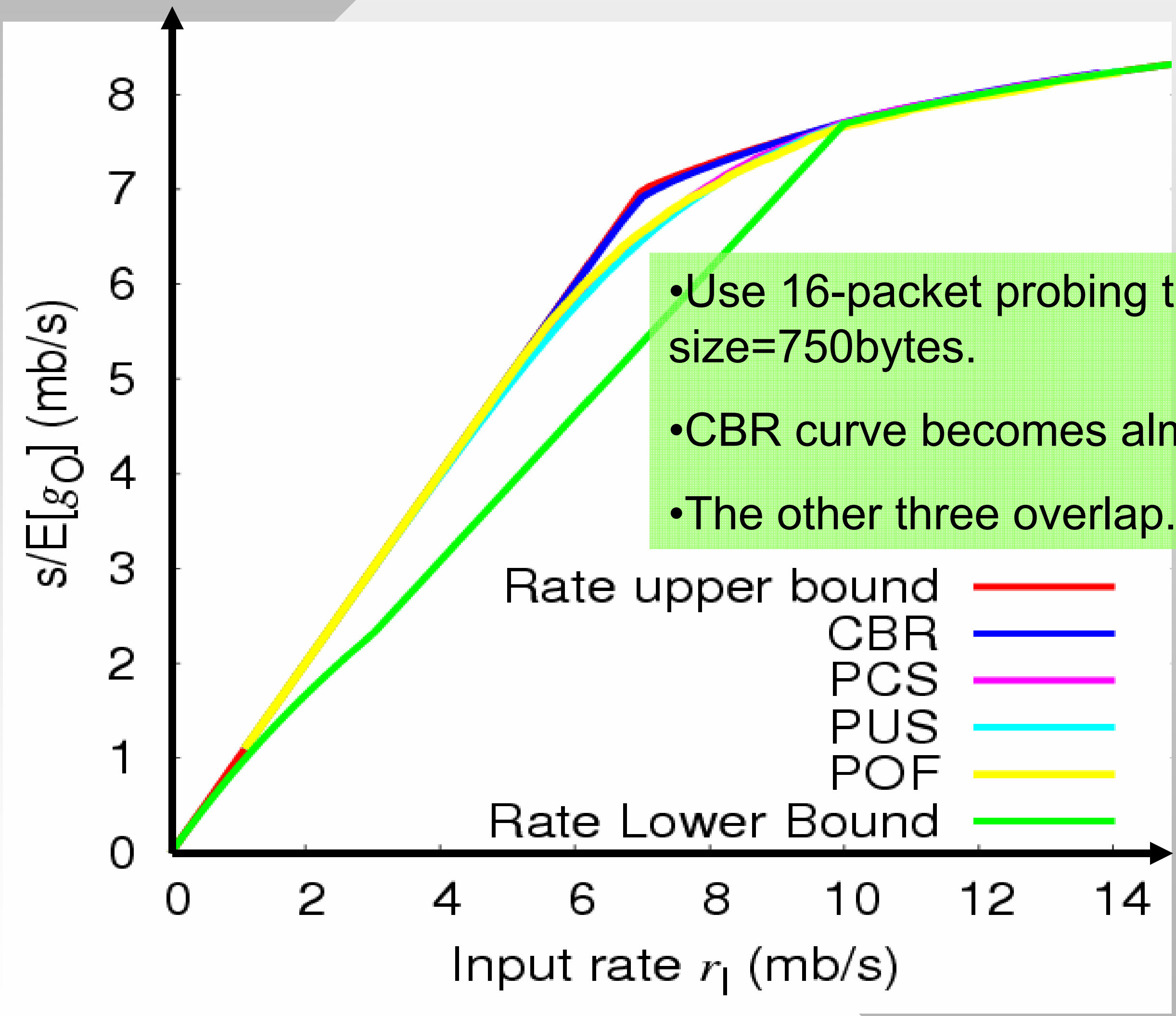
All 4 traces have long-term intensity 3mb/s
Use 20s trace for Poisson traffic and 60s trace for Pareto on/off traffic

Packet-Pair Rate Curves



- Probing packet size=750bytes.
- CBR rate curve overlap with Pareto on/off rate curve
- PUS (yellow) suffers slightly more bias then PCS

Packet-Train Rate Curves



- Use 16-packet probing train, packet size=750bytes.
- CBR curve becomes almost unbiased.
- The other three overlap.

Probing bias VS. Cross-traffic Burstiness

- The results so far shows that:
  - As probing packet size or train length increases, probing bias vanishes.
  - The vanishing rate depends on cross-traffic burstiness. CBR>Poisson>Pareto on/off
  - Although Pareto on/off is more bursty than Poisson, at certain time interval, the traffic variance can be smaller than Poisson, causing less probing bias in its rate curve.

- More discussion is in the paper

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Implication to existing techniques 1

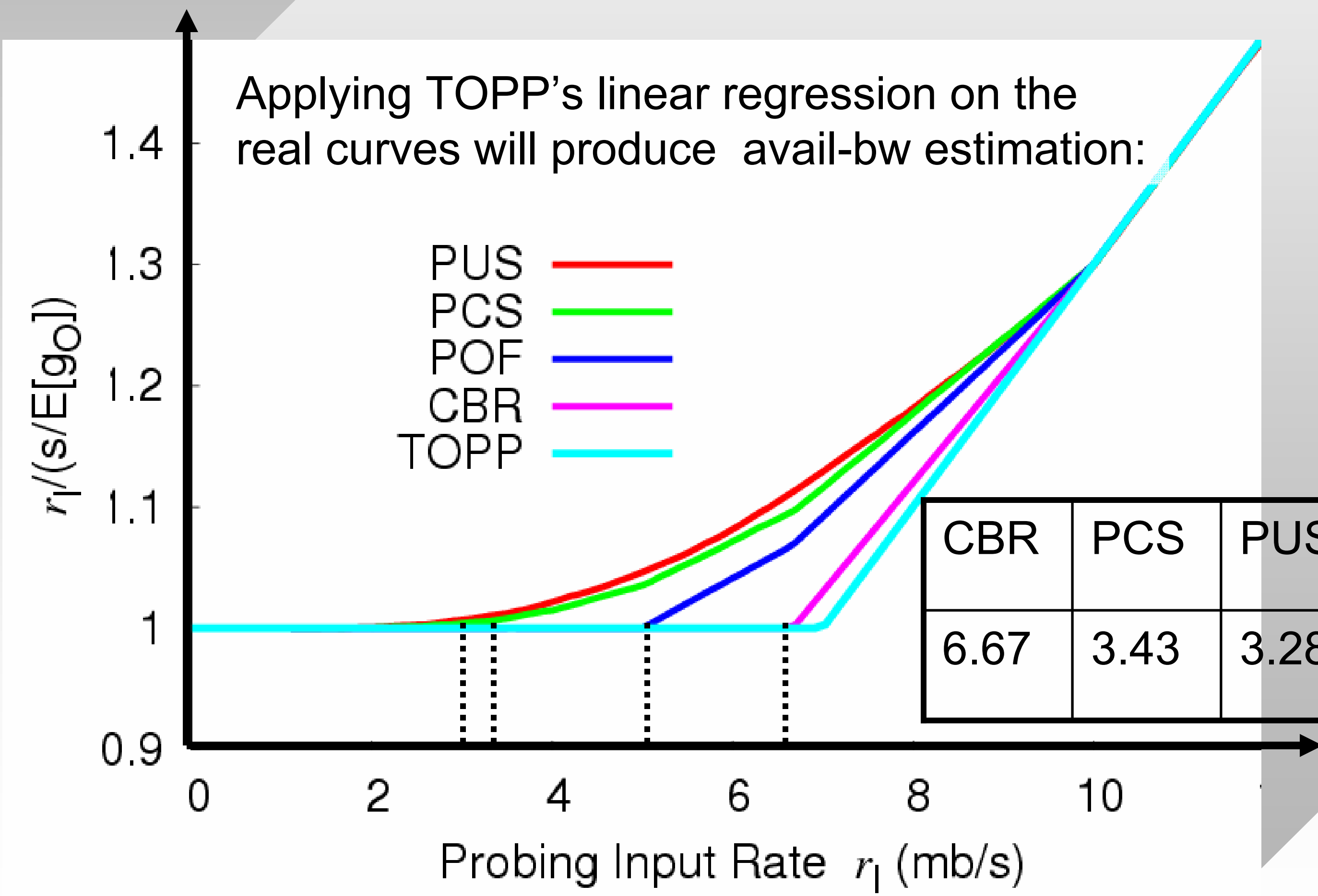
- TOPP use a transformed rate curve which is piece-wise linear in fluid cross-traffic

$$\frac{r_I}{r_O} = \begin{cases} 1 & r_I \leq C - \lambda \\ \frac{r_I + \lambda}{C} & r_I \geq C - \lambda \end{cases}$$

- Real asymptotic curves are not the same as the fluid models. This can cause significant under estimation of avail-bw even in a single-hop path

Implication to existing techniques 2

Applying TOPP's linear regression on the real curves will produce avail-bw estimation:



CBR	PCS	PUS	POF
6.67	3.43	3.28	5.02

Implication to existing techniques 3

- Searching for the turning point (PTR) as available bandwidth causes negative bias
  - However, this bias can be mitigated to negligible level using long packet train.
- Sampling cross-traffic (Spruce) with $r_I \geq C$ is unbiased in single-hop path
  - At this input rate, the real model agrees with fluid model.

Conclusions

- We developed an understanding of single-hop bandwidth estimation in busty cross-traffic that extends prior fluid models
- Cross-traffic burstiness implies bandwidth underestimation to several existing techniques. The underestimation can be mitigated using long train and large packet size
- Future work is to extend our understanding to multi-hop bandwidth estimation

Thank You!