

THE ROLE OF PASTA IN NETWORK MEASUREMENT

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POISSON ARRIVALS SEE TIME AVERAGES (PASTA)

WELL KNOWN PROPERTY OF STOCHASTIC SYSTEMS

- States that Poisson observers make **unbiased** measurements
- Very general formulation given by Wolf (1982)

A 'CONVENTIONAL WISDOM' IN NETWORK MEASUREMENT

- Used to justify Poisson probing for delay and loss
- Used to justify exponential separation of probe trains
- Assumed to ensure bias-free measurement
- Assumed to do no harm
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BUT NETWORK MEASUREMENT NOT SO SIMPLE..

ACTIVE PROBING: A DIVERSITY OF AIMS AND TECHNIQUES

- Use crafted probe **patterns**, not just single probes
- Streams not memoryless, in fact **use** probe-traffic interactions
- Methods begin with end-to-end data, but try to reach **inside** the network
(Example: available bandwidth at third hop)

RAISES QUESTIONS ABOUT ROLE OF PASTA

- Averages of what? Can it apply to just anything?
- Is Poisson probing necessarily optimal?
- When should exponential separations not be used?
- What role does PASTA play in network inference?

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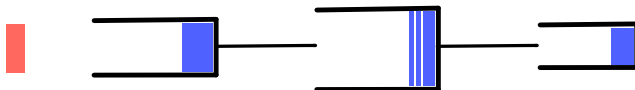
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OUR FOCUS: END-TO-END DELAY



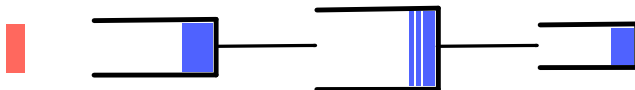
THE PROBING TASK

- Observable: $Z(t)$ end-to-end delay seen by probes
- Target: $Z^*(t)$ delay of packet arriving to **unperturbed system**

TWO PROBING SCENARIOS

- Non-intrusive: virtual probes of zero size: $x = 0$
- Intrusive: real probes of finite size: $x > 0$

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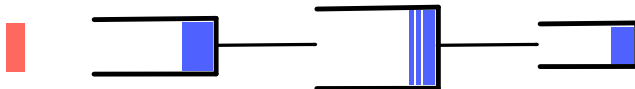
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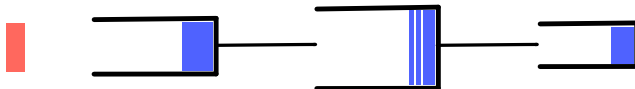
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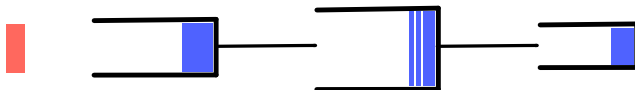
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$$(P_{\text{ROBES}} + M)/M/1$$

SETTING

- CT: Poisson process, intensity λ_T
- PT: stationary ergodic process, intensity λ_P
- Network model: single FIFO queue, exponential service times
- *Waiting time* $W(t)$ equals *Virtual delay* (delay of zero-sized packets)

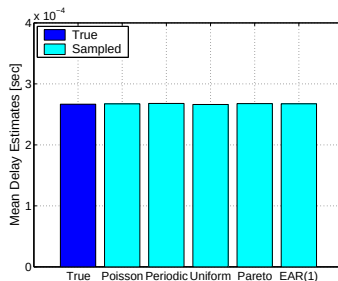
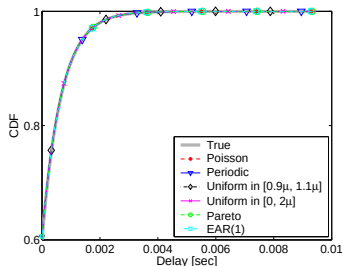
SAMPLING BIAS, NON-INTRUSIVE CASE

CT: Poisson

Probes: Poisson, Periodic, Renewal, EAR with $x = 0$

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All probing streams exhibit zero sampling bias, not just Poisson!

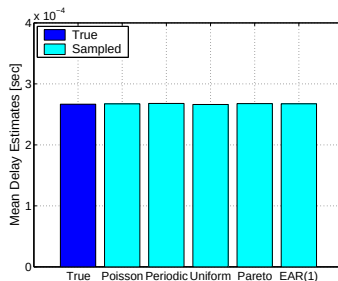
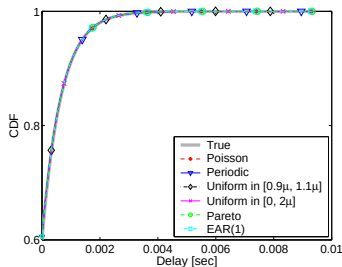
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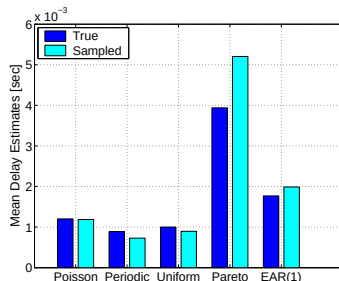
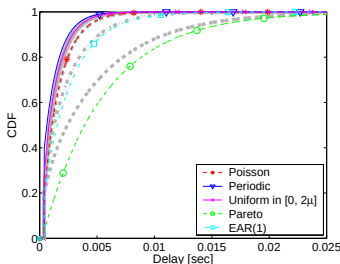
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Only Poisson samples without bias, PASTA works!

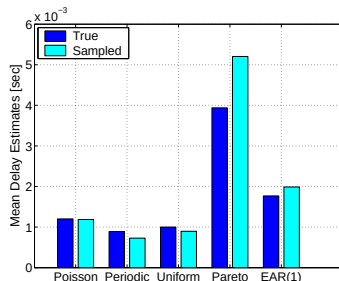
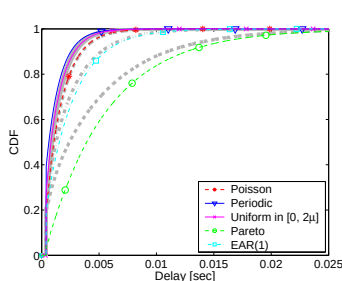
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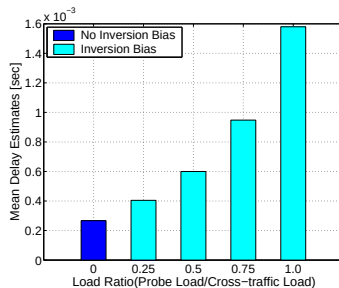
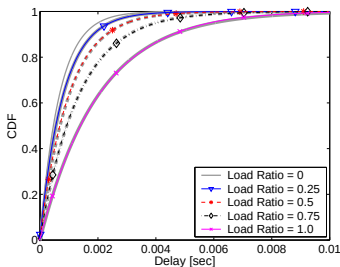
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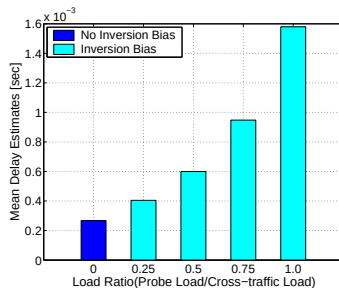
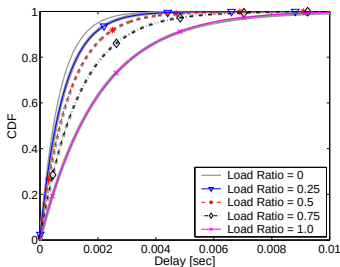
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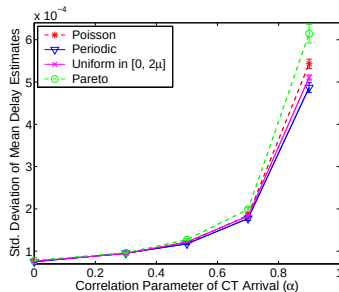
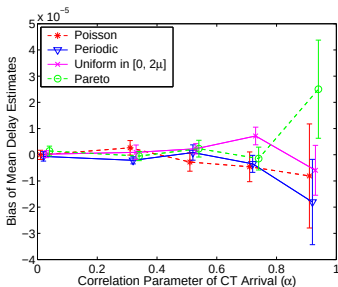
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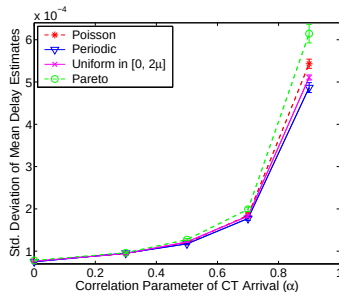
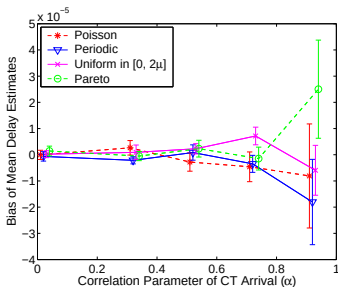
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Poisson does not have the smallest variance!

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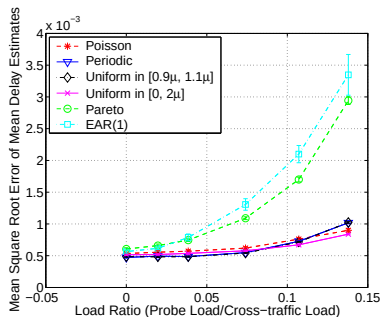
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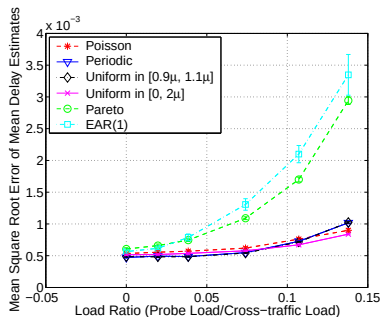
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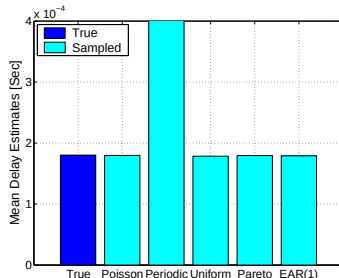
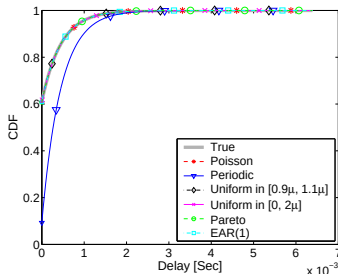
THE NEED FOR TECHNICAL ASSUMPTIONS

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Phase locking creates sampling bias - Lack of *joint ergodicity*
 ‘Technical assumptions’ have real impact

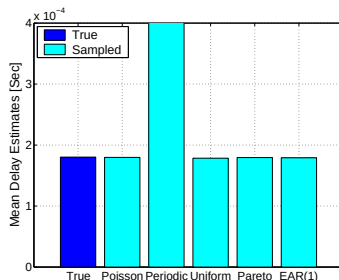
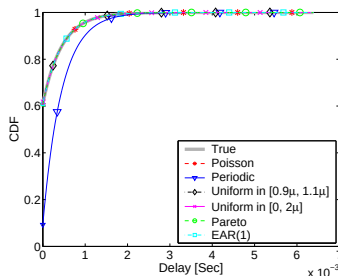
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PROOF BY PICTURE SUMMARY

- Zero-sampling bias not unique to Poisson (in non-intrusive case)
- PASTA talks about bias, is silent on variance
- PASTA is not optimal for variance or MSE
- PASTA is about sampling only, is silent on inversion
- Technical conditions matter

GENERAL SYSTEM: NON-INTRUSIVE CASE

SETTING

- PT: stationary ergodic point process $\mathcal{P}$, intensity λ_P
- CT: stationary ergodic marked point process $\mathcal{T}$, intensity λ_T
Stochastic network details: subsumed into marks of $\mathcal{T}$
- **General network model**: traditional tandem network, non FIFO, feedback, correlated nodes, persistent CT..
- Observable $Z(t)$: end-to-end delay
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Aim: to establish the almost sure convergence

$$\lim_{N \rightarrow \infty} \frac{1}{N} \sum_{n=1}^N f(Z(T_n)) = E[f(Z^*(0))]$$

for any positive function f based on probe samples at times $\{T_n\}$.

MAIN RESULT

THEOREM

If the product shift acting on the product space of $\mathcal{P}$ and $\mathcal{T}$ is ergodic and the PT and CT are independent, then the convergence holds.

Or

NIJEASTA: *Non-Intrusive Jointly Ergodic Arrivals See Time Averages.*

Result follows from standard results from Palm Calculus on marked point processes, and the pointwise ergodic theorem.

A PRACTICAL RESULT

THEOREM

The product space $\mathcal{F}$ of $\mathcal{P}$ and $\mathcal{T}$ is ergodic whenever at least one of them is a mixing process, and the other ergodic.

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NIMASTA: *Non-Intrusive Mixing Arrivals See Time Averages.*

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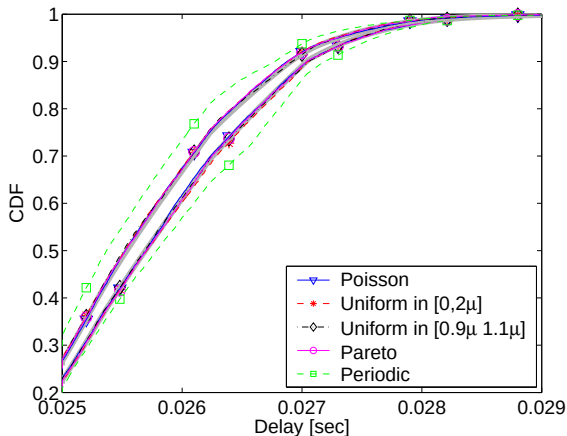
Significance:

the prober can **choose** to send mixing probes, avoiding phase-lock

Mixing examples:

- all PT used above except periodic
- truncated Poisson
- can extend to probe patterns, can extend to jitter

NIMASTA WORKS



Even with TCP, have zero-sampling bias providing probes are **mixing**

GENERAL SYSTEM: INTRUSIVE CASE

SETTING: AS BEFORE, BUT NOW

- Observable $Z(t)$ no longer $W(t)$
- $Z(t) \neq Z^*(t) \rightarrow$ inversion needed
- $Z(t)$, $Z^*(t)$ and $W(t)$ now depends on the probe size

Question: can the total bias still be zero?

$$\lim_{N \rightarrow \infty} \frac{1}{N} \sum_{n=1}^N f(Z(T_n)) = E[f(Z^*(0))] \quad ??$$

A PARTIAL SOLUTION: RARE PROBING

The Idea: keep probe size constant but send rarely

THEOREM

Holds if system is Markov (α -Doeblin) with exponentially decaying memory.

Note: both inversion and sampling bias go to zero.

THE CASE AGAINST PASTA

SUMMARY:

- Zero-sampling bias not unique to Poisson (in non-intrusive case)
- PASTA talks about bias, is silent on variance
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CONSEQUENCES:

- **Inflexibility:** Poisson probing a lost optimisation opportunity.
- **Inapplicability to probe patterns:** Active probing depends on probe patterns. NIMASTA applies, PASTA not.
- **Beyond delay, inversion bias dominates:**
When target far from observable, PASTA becomes irrelevant.

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Example: Uniform (i.i.d.) separations on $[0.9\mu, 1.1\mu]$

- Suitable for separating probe patterns, not only probes,
- Generic, to allow freedom in probe pattern design: we specify pattern separations, not the entire process,
- Compatible with mixing, to reduce the risk of phase-lock,
- Tunable, to enable bias/variance tradeoffs.