Communication Networks
Research Group
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Shaping Delay Distributions for Information Freshness: From Sampling to Routing, Preemption, and a Fundamental Limit

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Communication Networks Research Group (CNG)
METU

Invited talk
MOSC Workshop in conj. with WiOpt 2026
Ohio State University, Columbus, OH

June 6, 2026

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Information Freshness is Now a KPI for 6G

TN-NTN Networks

V2X Communications

IIoT Applications

Digital Twins

Age of Information (AoI)

- AoI measures how fresh the data is at destination, defined as

$$\Delta(t) = t - U(t)$$

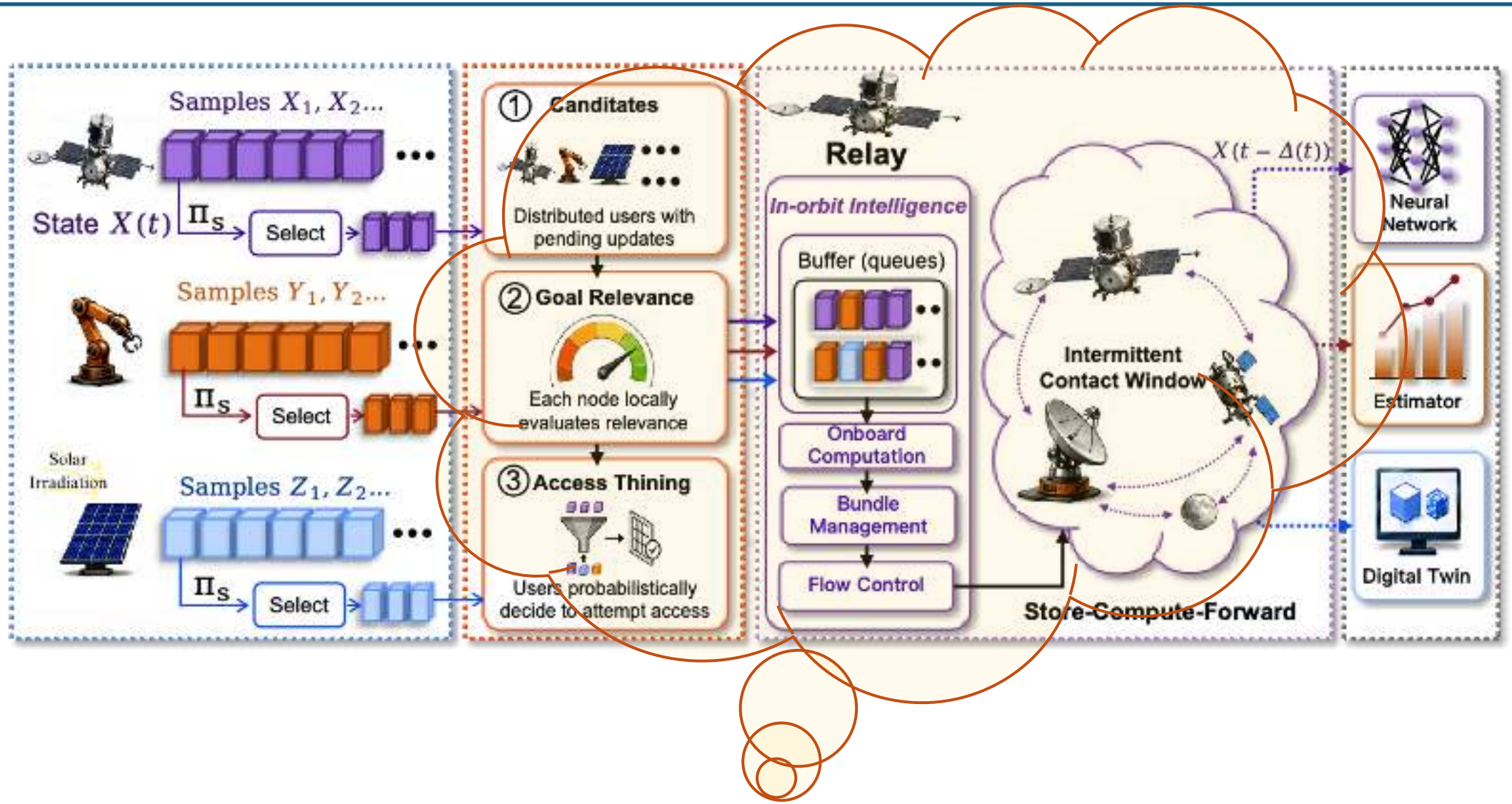
- $U(t)$: generation time of the newest update packet available at destination at time t

Today's Road Map

Knob 1	Knob 2	Limit
When to Sample?	How to Shape the Delay?	How fresh can data ever be?

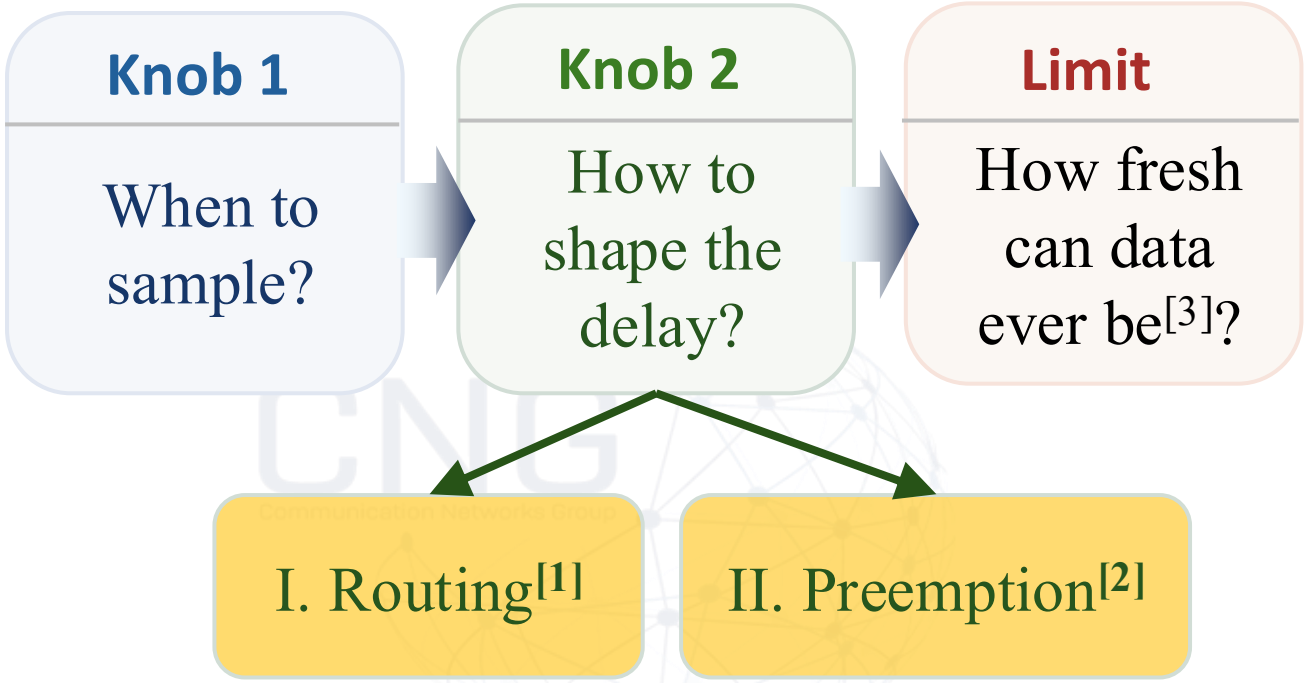
Three Surprizes, One Principle

Sampling under Random Delay



Age related cost functions basic tool for goal oriented sensing over next generation networks:

Outline of the Talk



[1] Adem Utku Atasayar, Aimin Li, Çağrı Arı, Elif Uysal "Fresh Data Delivery: Joint Sampling and Routing for Minimizing the Age of Information", ***ACM Mobihoc*, 2025.**

[2] Aimin Li, Yiğit İnce, Elif Uysal "Taming the Heavy Tail: Age Optimal Preemption", ***IEEE ISIT, 2026.***

[3] Adem Utku Atasayar, Elif Uysal "A Universal Lower Bound on the Total Cost of Age-Aware Status Update Systems", ***To be published.***

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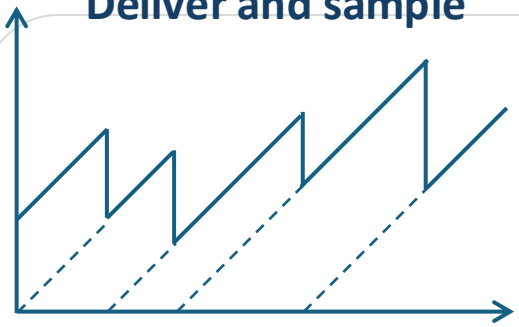
Knob 1. When to Sample?

When to Sample?

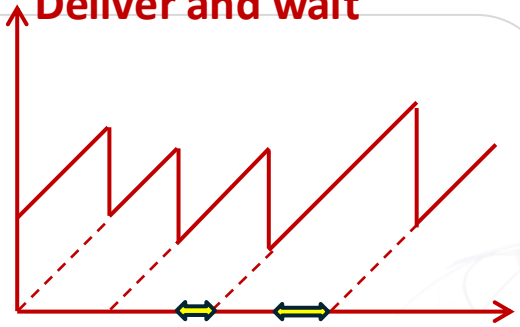
The intuition

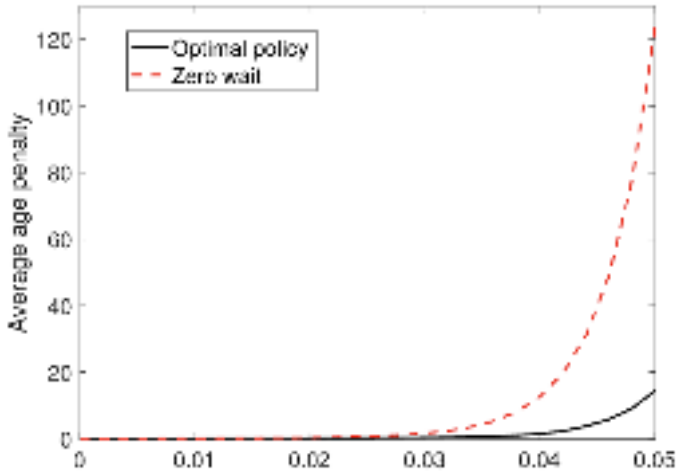
Deliver and sample



The reality

Deliver and wait





Zero-Wait vs. AoI-Optimal Sampling

$$W_i^* = (\beta - Y_i)^+$$

Waiting time before the i+1-th transmission.

Random delay of the i-th transmission.

- **Given any distribution of the delay Y**, we can solve for the threshold β.
- Generally, $\beta > 0$. In the presence of random delays, waiting a bit can greatly reduce average AoI.
- The optimal AoI **is related to the distribution of the delay Y**.

Surprise #1: Work-conserv

How about we control the distribution of Y?

[4] Yin Sun, Elif Uysal, Roy D. Yates, C. Emre Koksal, Ness B. Shr

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Knob 2. How to Shape the Delay?

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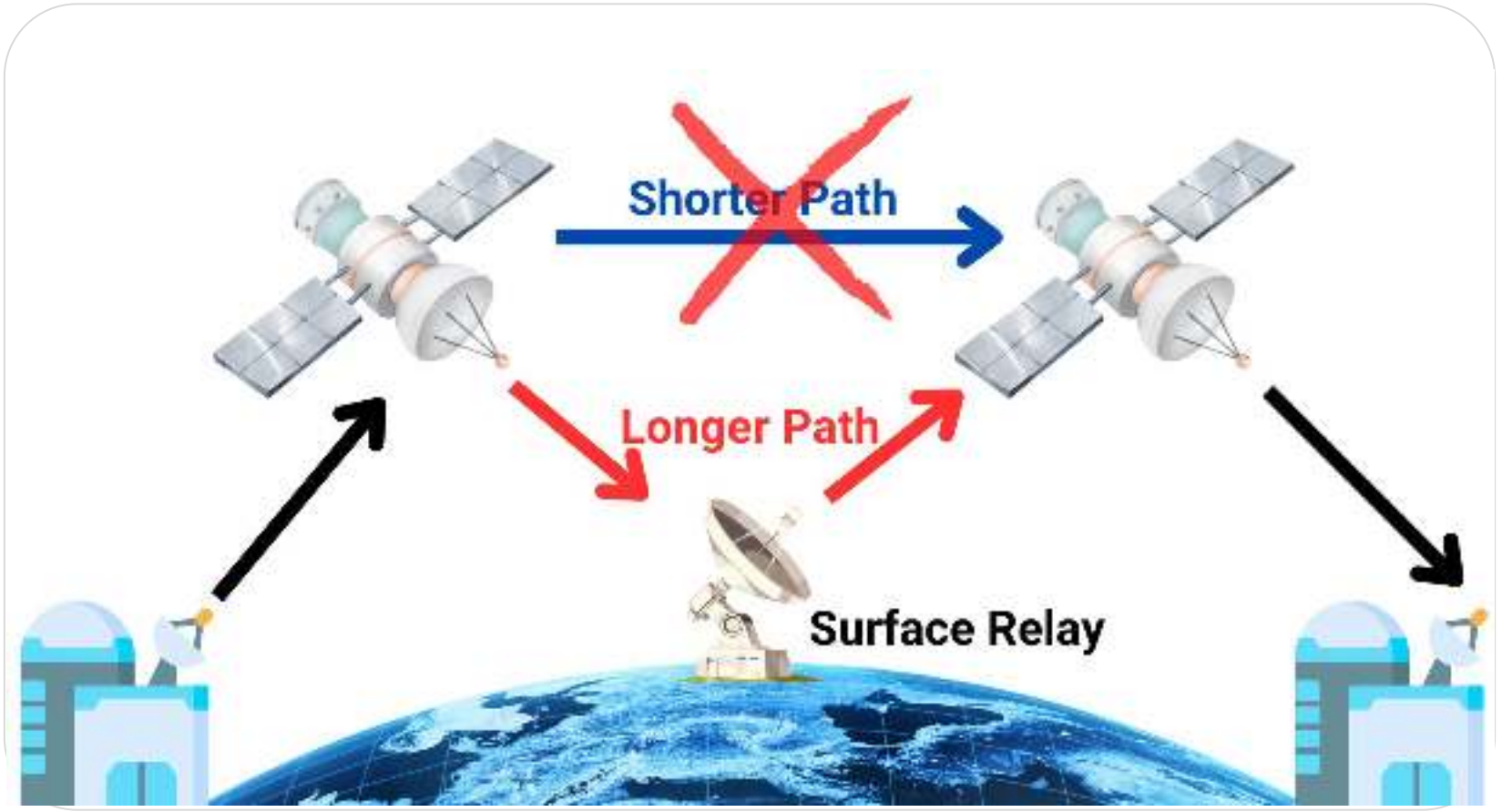
How to Shape the Delay? I. Routing

The delay distributions can be controlled by routing



- **Using Inter-satellite Links**: Low avg delay, intermittent availability

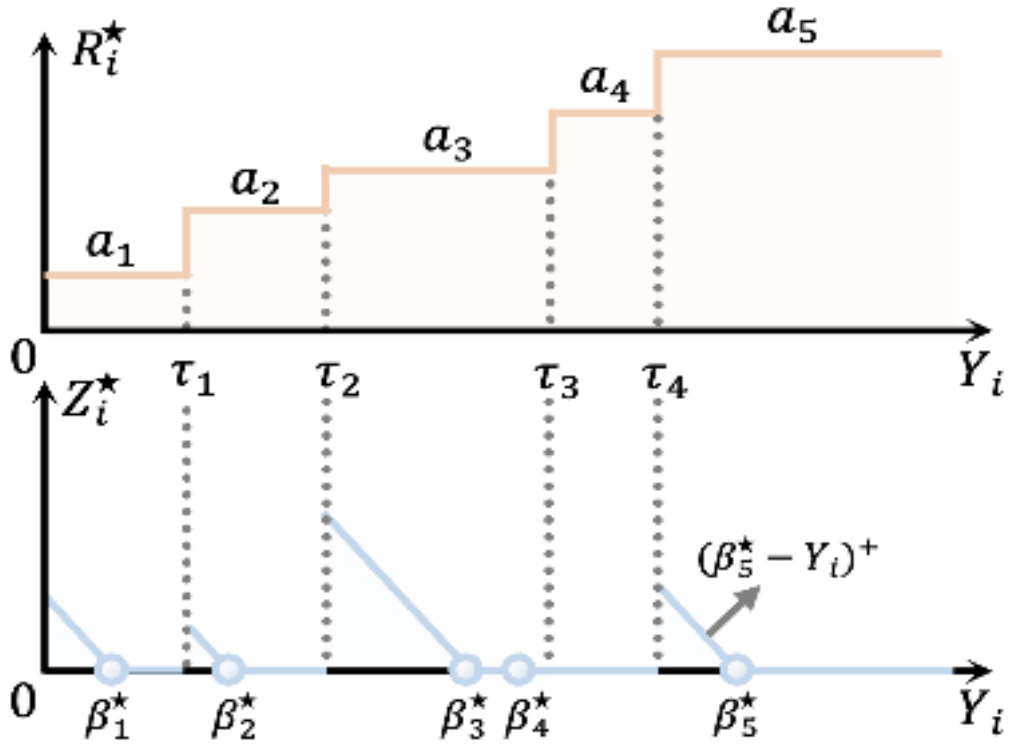
- **Ground relaying**: Available, but longer RTT

Question: how to jointly design routing+sampling?

[1] Adem Utku Atasayar, Aimin Li, Çağrı Arı, Elif Uysal, "Fresh Data Delivery: Joint Sampling and Routing for Minimizing the Age of Information", ***ACM Mobihoc*, 2025.**

How to Shape the Delay? I. Routing

Threshold handover + route-dependent waiting



Optimal Routing

- **Threshold Handover:** pick a single route on each interval $Y_i \in [\tau_{k-1}, \tau_k)$, just a step function.
- **Monotonicity**: as Y_i grows, the policy steps to faster routes.

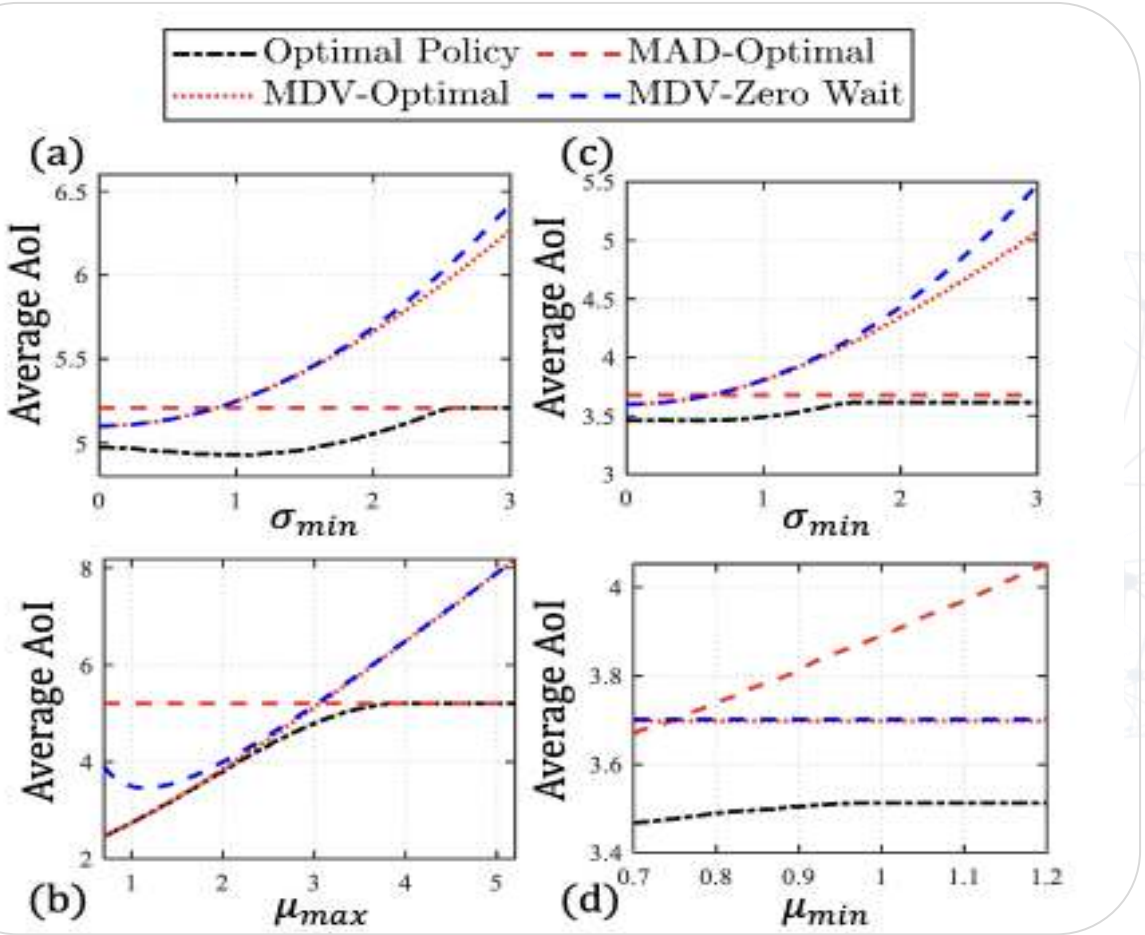
Optimal Sampling

Wait until AoI hits a *route-dependent threshold* β_k^*.

[1] Adem Utku Atasayar, Aimin Li, Çağrı Arı, Elif Uysal, "Fresh Data Delivery: Joint Sampling and Routing for Minimizing the Age of Information", ***ACM Mobihoc*, 2025.**

How to Shape the Delay? I. Routing

Numerical Insight



Joint Routing Beats Single-Route

In a two-routes setting, our proposed policy yields clear gains.

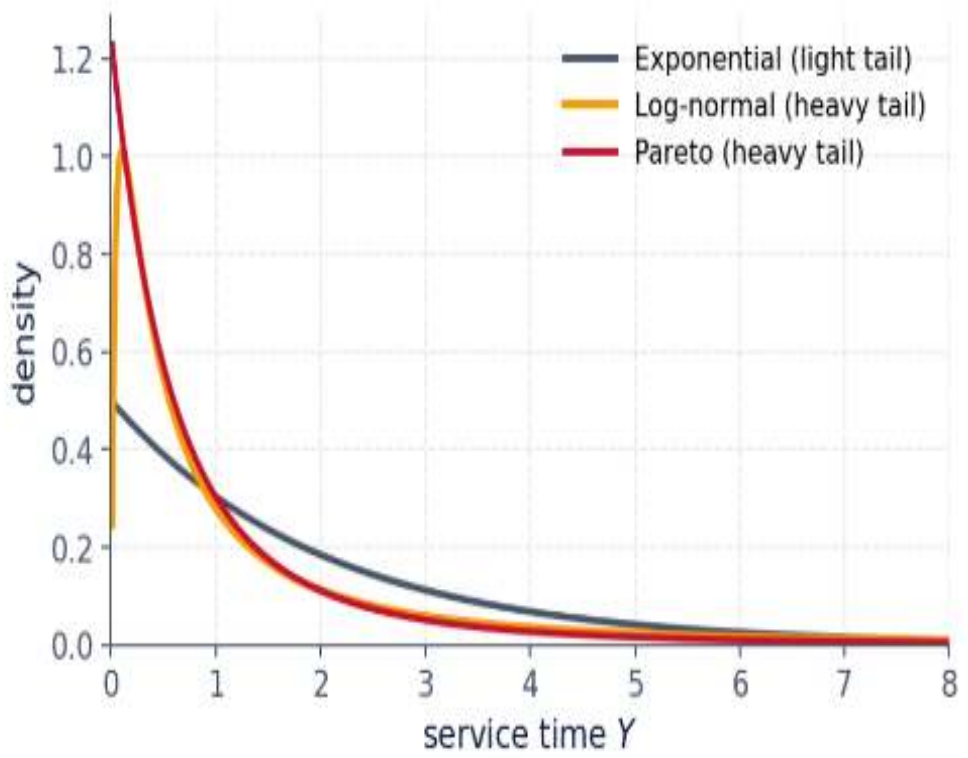
Slow Routes Still Matter

Even routes with ***higher mean delays*** can contribute under an optimized handover policy.

Surprise #2: Bad-looking routes can help improve freshness.

How to Shape the Delay? II. Preemption

Delay Distribution



Increasing Mean Residual Life (IMRL)

The longer a packet has been in service, the longer it is likely to still take.

Non-preemptive sampling waits passively → head-of-line blocking

Preemption

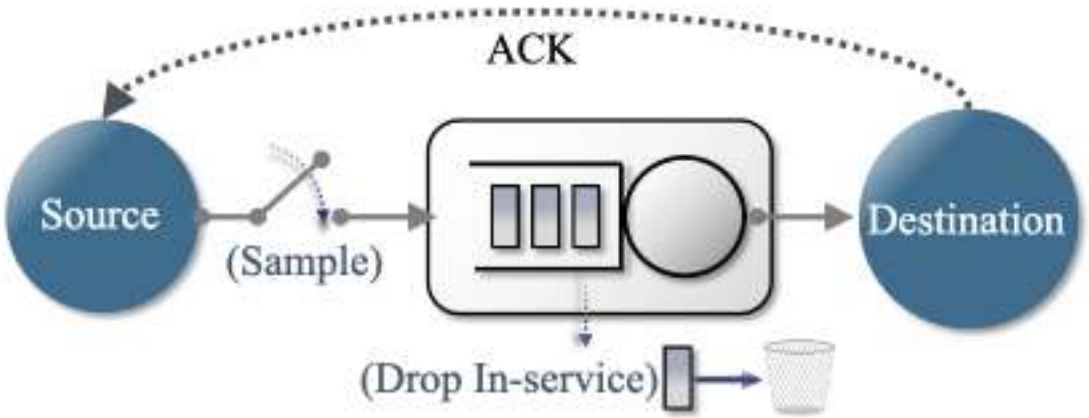
Drop the in-service stale packet and restart with a fresh sample.

Trade-off: truncate heavy tail vs. lose service progress + sampling and preemption cost

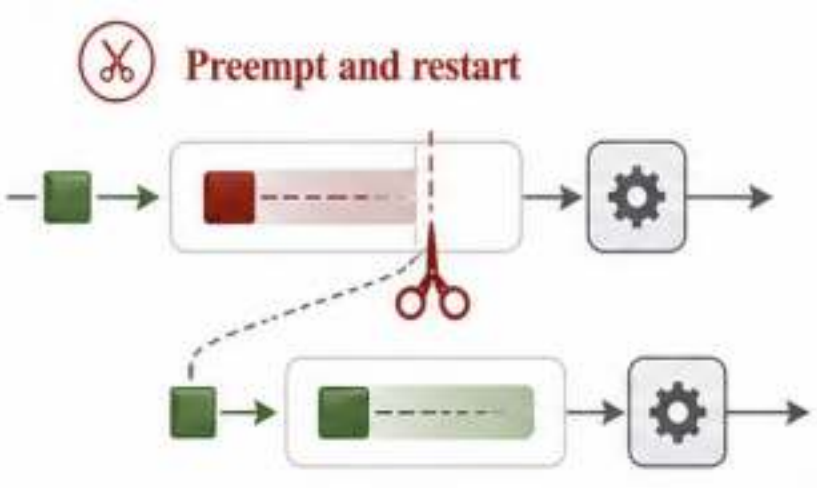
Question: how to jointly design preemption + sampling?

[2] Aimin Li, Yiğit İnce, Elif Uysal "Taming the Heavy Tail: Age Optimal Preemption", ***IEEE ISIT, 2026***

How to Shape the Delay? II. Preemption



System Model[2]



- **Sampling:** The source can be sampled and transmitted at any time.
- **Preemption:** The source interrupts the on-going transmission and samples a new/fresh packet for transmission.

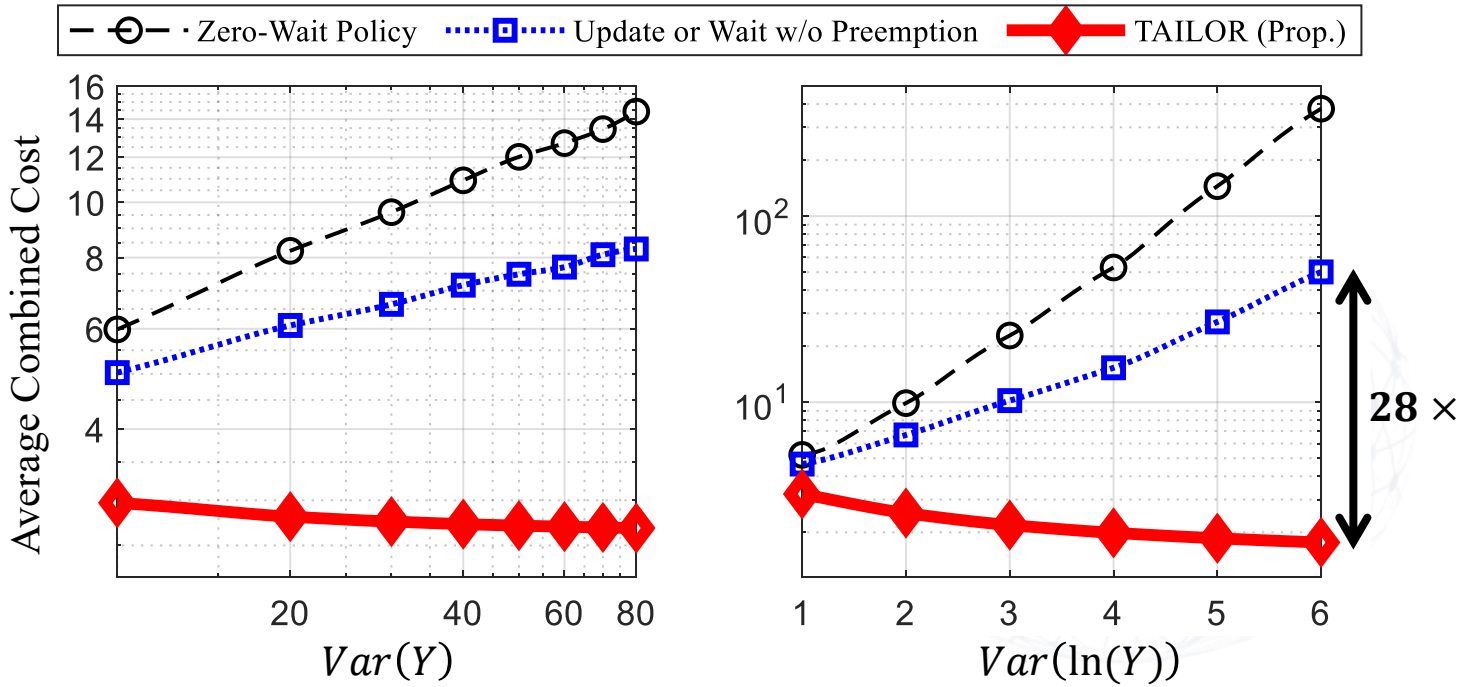
Impulse Control Formulation

- **Hybrid discrete-continuous state:** AoI, service age, channel mode (idle/busy)
- **Impulse Action:** Sample (idle) or preempt (busy), sampling costs κ_s, preemption costs κ_p.

[2] Aimin Li, Yiğit İnce, Elif Uysal "Taming the Heavy Tail: Age Optimal Preemption", ***IEEE ISIT, 2026***

How to Shape the Delay? II. Preemption

Numerical Insight



a) Pareto II

b) Log-normal

28× Gain

Compared to *Update or Wait* paper, TAILOR reduces average cost by up to **28×**

Higher Variance → Lower AoI Cost

Average cost decays with the variance of the delay!

Surprise #3: Variance is not a liability — it's an opportunity, if you can act on it.

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Knob 3. How fresh can data ever be?

How fresh can data ever be?

A lower bound that holds for ANY policy, ANY channel.

Theorem (Universal Lower Bound on Avg Cost)

For any policy, any channel, the total average cost:

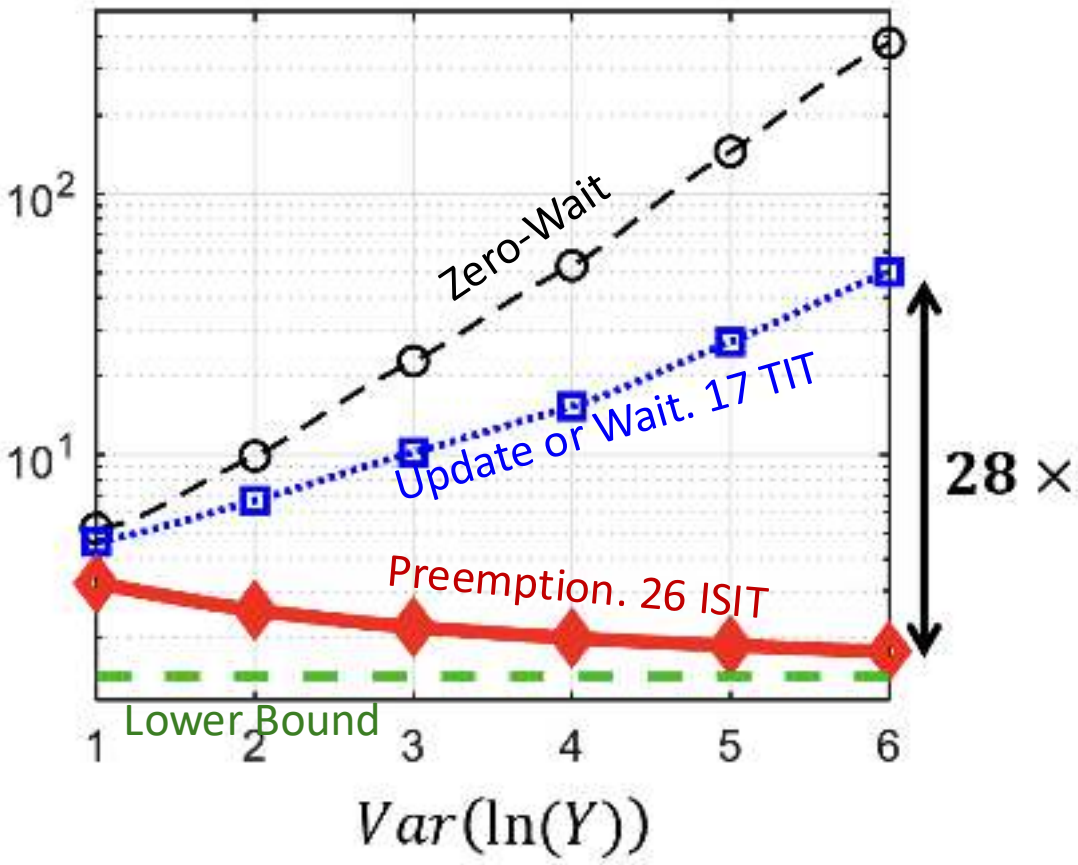
$$\lim_{T\to\infty} \frac{1}{T}\int_0^T \Delta(t)\, dt + c_s f_s + c_t f_t$$

AoI | Sampling cost | Transmission cost

where

- f_s: The long-run average sampling rate
- f_t: The long-run average transmission rate

is bounded below by $\sqrt{2(c_s + c_t)}$.



✓ Through preemption, we are close to the lower bound.

How fresh can data ever be? General age penalties

Closed-form lower bounds for a broad class of age penalty functions.

For general non-decreasing age penalties $g(.)$, the lower bound is given by:

$$inf_a\{aG(1/a) + (c_s + c_t)a\}$$

where $G(u) = \int_0^u g(x)dx$

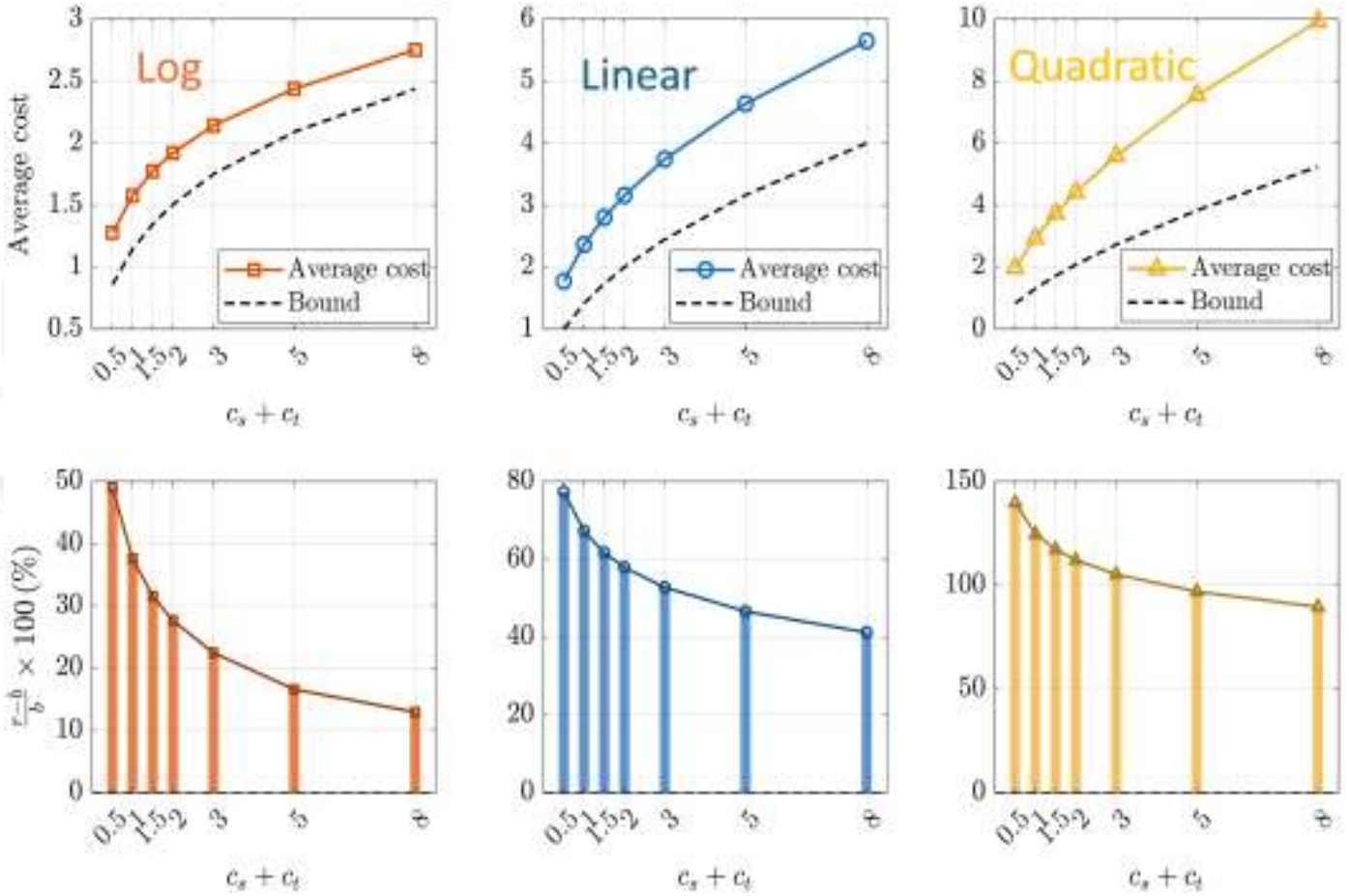
The framework yields a closed-form expression in many cases of interest.

Log penalty $g(x) = \ln(x+1)$:

$$-ln\left(W_{-1}\left(-e^{-(1+c_s+c_t)}\right)\right)$$

Power-law penalty $g(x) = x^{\alpha}$:

$$\left(\frac{(\alpha+1)(c_s+c_t)}{\alpha}\right)^{\frac{\alpha}{\alpha+1}}$$



The bound is tighter for sublinear penalties and larger operational costs.

How fresh can data ever be? Peak AoI form of the bound

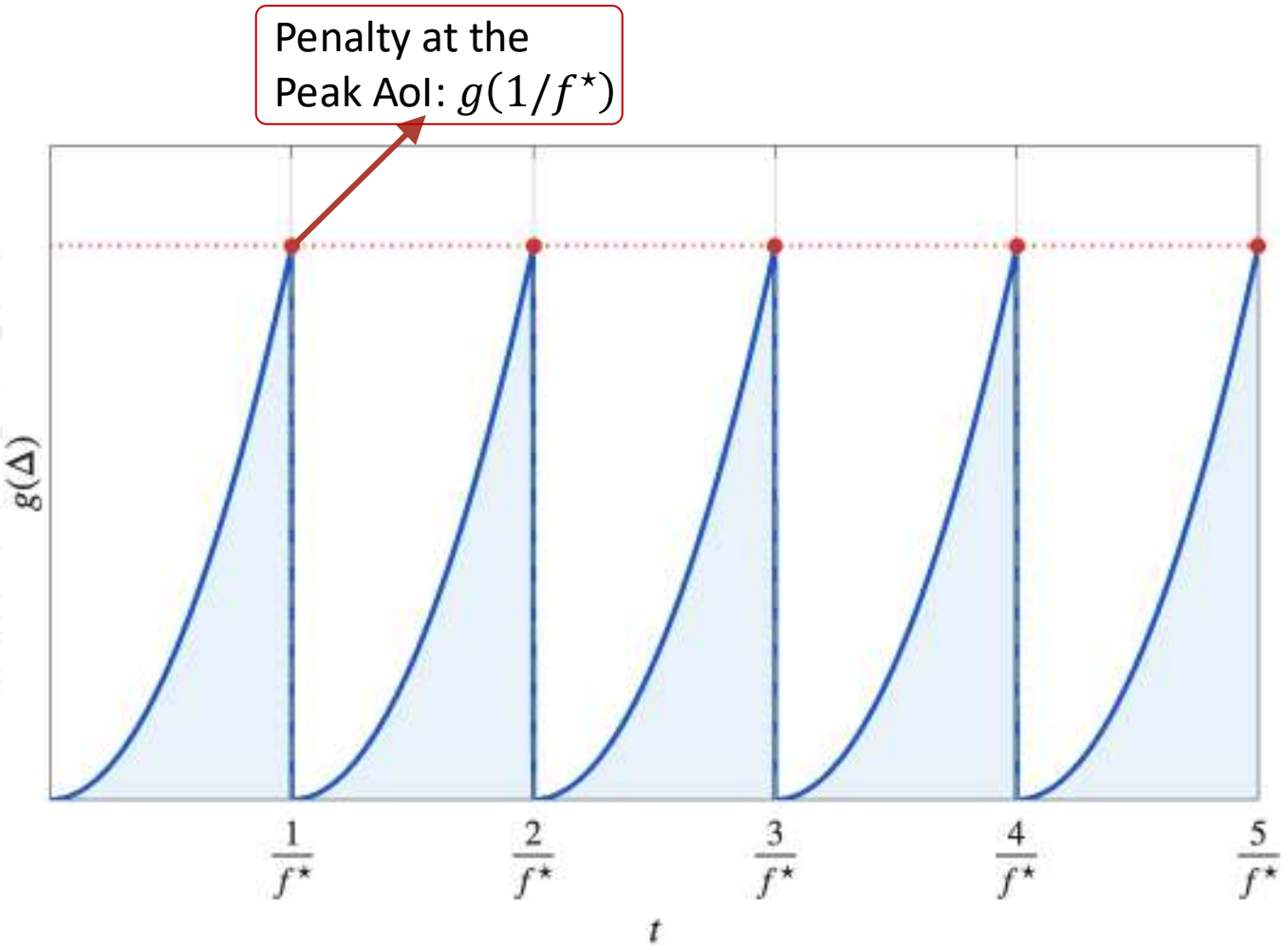
Lower bound = $g(1/f^\star)$

Where $f^\star$ solves
$inf_f\{fG(1/f) + (c_s + c_t)f\}$

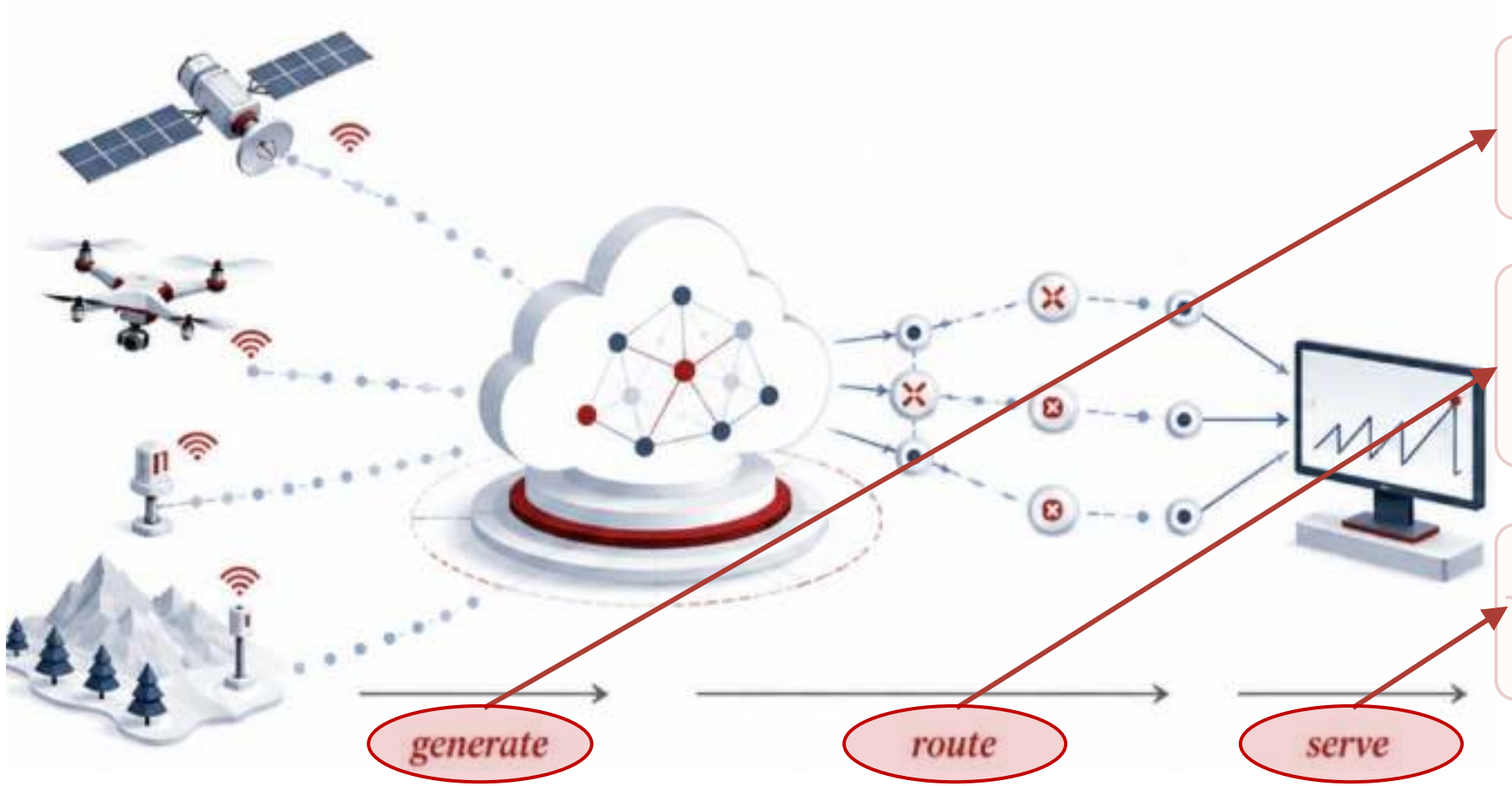
Lemma: Avg total cost of the optimal zero-delay policy equals its Peak AoI penalty.

Serves as our lower bound.

✓ The Peak Age governs the optimal age-cost tradeoff.



From three control levers to one message



Generate:

When to sample?

Route:

Which route should be used?

Serve:

When to preempt in service?

Don't react to the delay distribution — shape it.

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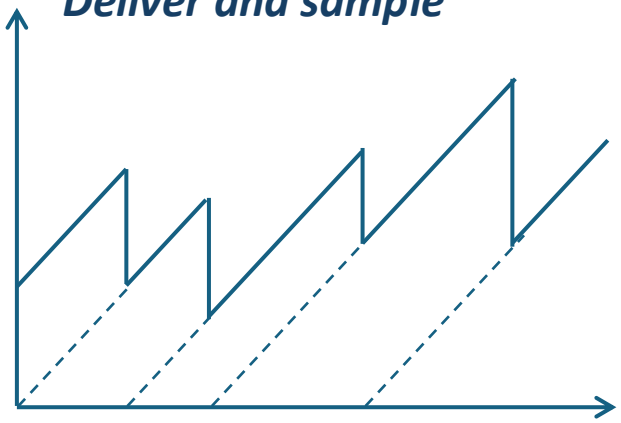
One More Thing: *Idle Space*

Idle Space as a harvestable resource

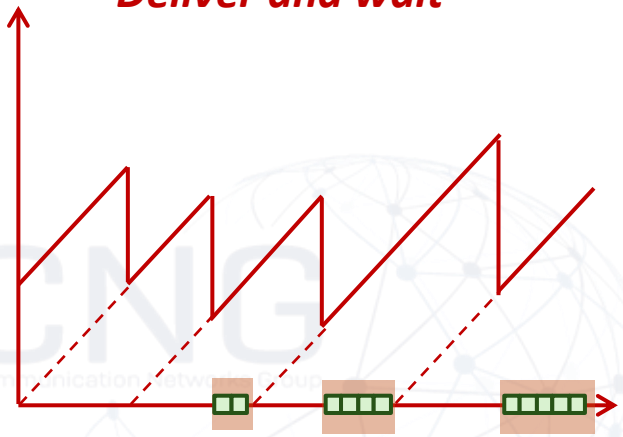
The intuition

Deliver and sample



The reality

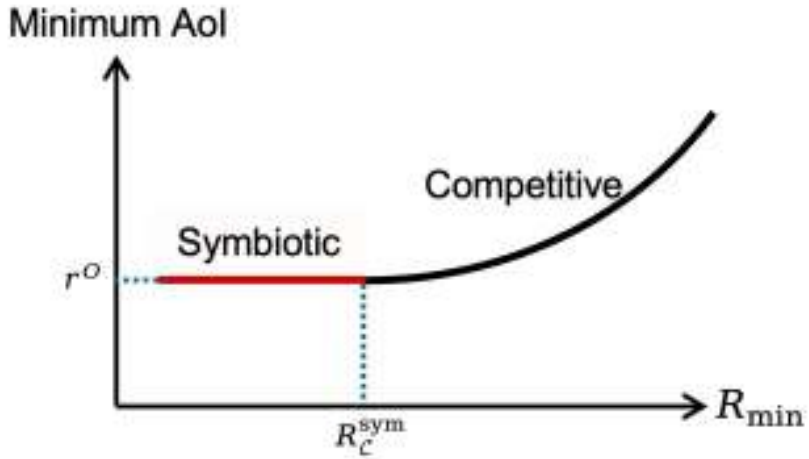
Deliver and wait



Idle Space Throughput Packet

Key Insight

Symbiotic then competitive



Takeaway 5

Structural *waiting* is not only a byproduct of optimal control.

It's a *harvestable resource* for throughput-oriented flows !!

[5] Aimin Li and Elif Uysal "Systems and Methods for Harvesting Self-Generated Idle Space in Goal-Oriented Communications", Patent app., 2026.

[6] Aimin Li and Elif Uysal "*Idle Space*: Harvestable Throughput From AoI-Optimal Waiting", to be published, 2026.

Idle Space as a harvestable resource

- **Across QAoI, AoII, MSE, and Value of Information, etc, the same *structural waiting* keeps *reappearing*.**

Opportunity: *Idle Space*

- **How to jointly schedule *goal-oriented* and *throughput flows* to harvest idle space optimally? This is the next frontier.**

Sampling • Routing • Preemption

Thank You

On Behalf of Communication Networks Research Group (CNG)

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