FRESH DATA DELIVERY: JOINT SAMPLING AND ROUTING FOR MINIMIZING THE AGE OF INFORMATION

Poster & Demo Session — ACM MobiHoc 2025, Houston, TX

Adem Utku Atasayar, Aimin Li, Cagri Ari, and Elif Uysal

MIDDLE EAST TECHNICAL UNIVERSITY

Dept. of Electrical and Electronics Engineering, METU, Ankara, Türkiye

Introduction

- Real-time systems such as remote sensing, vehicular networks, and industrial IoT require *fresh* status updates to operate safely and efficiently. Traditional delay metrics cannot fully capture the staleness of information at the receiver. The **Age of Information (AoI)** quantifies this freshness by measuring how long it has been since the newest received update was generated.
- In networks with multiple heterogeneous routes—each with different delays and variances—the key challenge is deciding *when* to sample next and *which route* to use for forwarding.
- This work formulates and solves a joint sampling and routing problem for minimizing long-term average AoI. We show that the optimal policy has a remarkably simple **threshold structure**: a small set of AoI thresholds determines both when to wait and which route to select. These thresholds can be computed efficiently and stored compactly, making the policy practical for real-time embedded systems.

Takeaway: a handful of thresholds are sufficient to maintain data freshness adaptively across multiple routes.

System Model & Problem Description

- A single source generates status updates that are transmitted through one of N available routes to a monitor. The monitor sends an acknowledgment (ACK) upon receiving each update.

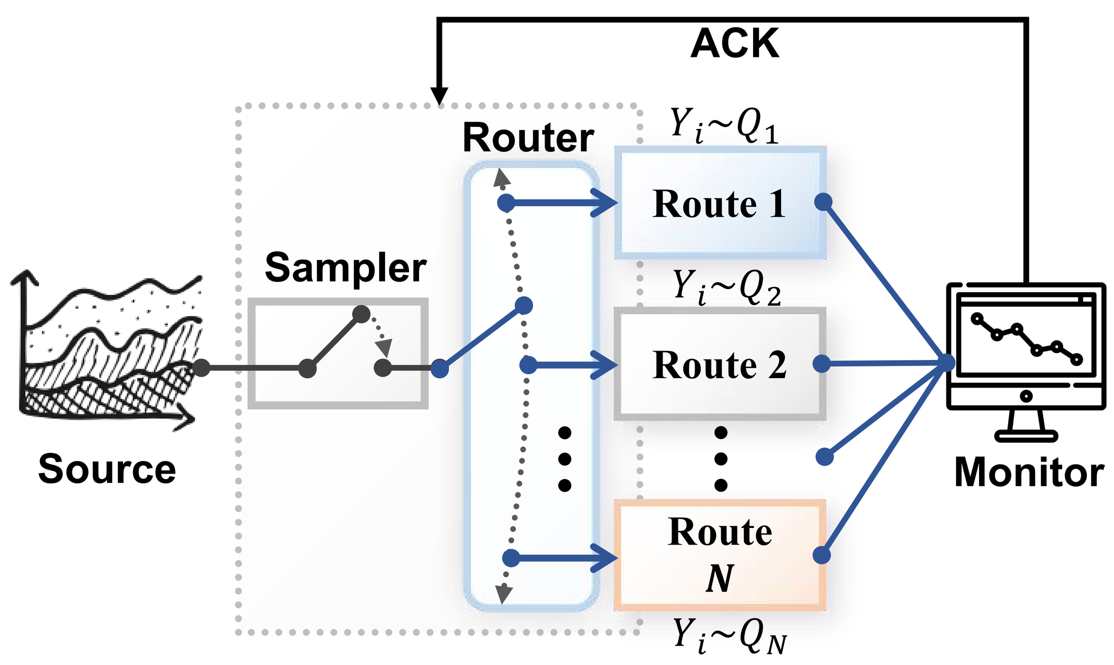

Figure 1: System Model

- At each ACK instant, the system must decide two things:
  - how long to wait before sampling the next update ($Z_i \geq 0$), and
  - which route $R_i \in \{1, \dots, N\}$ to use for transmission.
- Each route k has a stationary random delay distribution Q_k with mean μ_k and variance σ_k^2. Transmissions are non-preemptive, meaning that the source can send a new update only after the previous one has been delivered.
- The objective is to keep the information at the monitor as *fresh* as possible by choosing (Z_i, R_i) adaptively based on the current AoI to minimize the **long-term time-average AoI** observed at the monitor:

$$\lambda^* = \min_{\pi} \limsup_{T\to\infty} \frac{1}{T}\mathbb{E}\left[\int_0^T \Delta(t)\, dt\right]. \quad (1)$$

- Because the state (current AoI) is continuous and the actions are hybrid (discrete route, continuous wait), the problem is challenging but admits a simple optimal structure.

Acknowledgment

This work is supported by the European Union through ERC Advanced Grant 101122990-GO SPACE-ERC-2023-A. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

Results & Discussion

Theorem 1 (Structure of the Optimal Policy). For an N-route problem where the mean delay of each route satisfies $\mu_1 \geq \mu_2 \geq \cdots \geq \mu_N$ and the delay distribution of each route has infinite support, the jointly optimal sampling and routing policies exhibit the following threshold structure:

1. Optimal Routing: The optimal routing action at the i-th epoch, denoted by $R_i^\star$, is a monotonic non-decreasing step function of the observed delay Y_i, and can be determined by $K \leq N-1$ positive thresholds $0 < \tau_1 < \tau_2 \cdots < \tau_K$ and $K+1$ monotonic increasing index values $a_1 < a_2 < \cdots < a_{K+1} \in \mathcal{N}$:
$$R_i^\star = \sum_{k=1}^{K+1} (a_k - a_{k-1}) u(Y_i - \tau_{k-1}), \quad (2)$$
where $\tau_0 \triangleq 0$, $a_0 \triangleq 0$, and $u(t)$ is the unit step function:
$$u(t) \triangleq \begin{cases} 0, & t < 0 \\ 1, & t \geq 0. \end{cases} \quad (3)$$
2. Optimal Sampling: The optimal waiting time at the i-th epoch, denoted by $Z_i^\star$, follows a water-filling structure and can be determined by $K+1$ thresholds $\beta_1^\star < \beta_2^\star < \cdots < \beta_{K+1}^\star$ with $\beta_k^\star = \lambda^\star - \mu_{a_k}$,
$$Z_i^\star = (\beta_{R_i^\star} - Y_i)^+ = (\lambda^\star - \mu_{R_i^\star} - Y_i)^+. \quad (4)$$
where $\lambda^\star$ is the optimal average AoI defined in (1), and $(\cdot)^+$ is defined as $(\cdot)^+ \triangleq \max\{0, \cdot\}$.

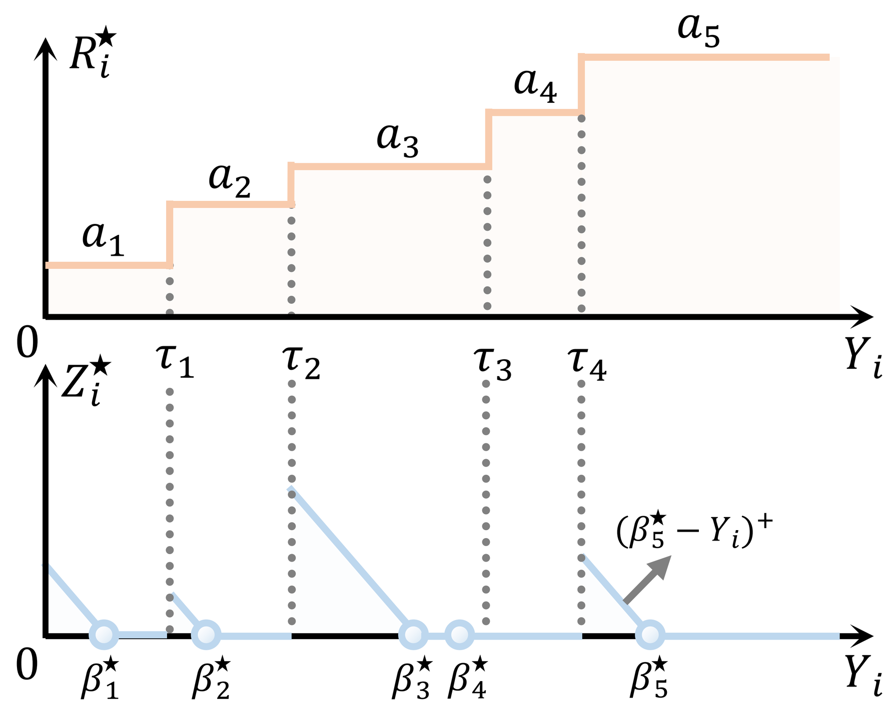

Figure 2: Threshold-based routing and waiting structure.

Optimization pipeline: Dinkelbach reformulation → average-cost MDP solved via ReaVI → threshold extraction.

Simulation Results.

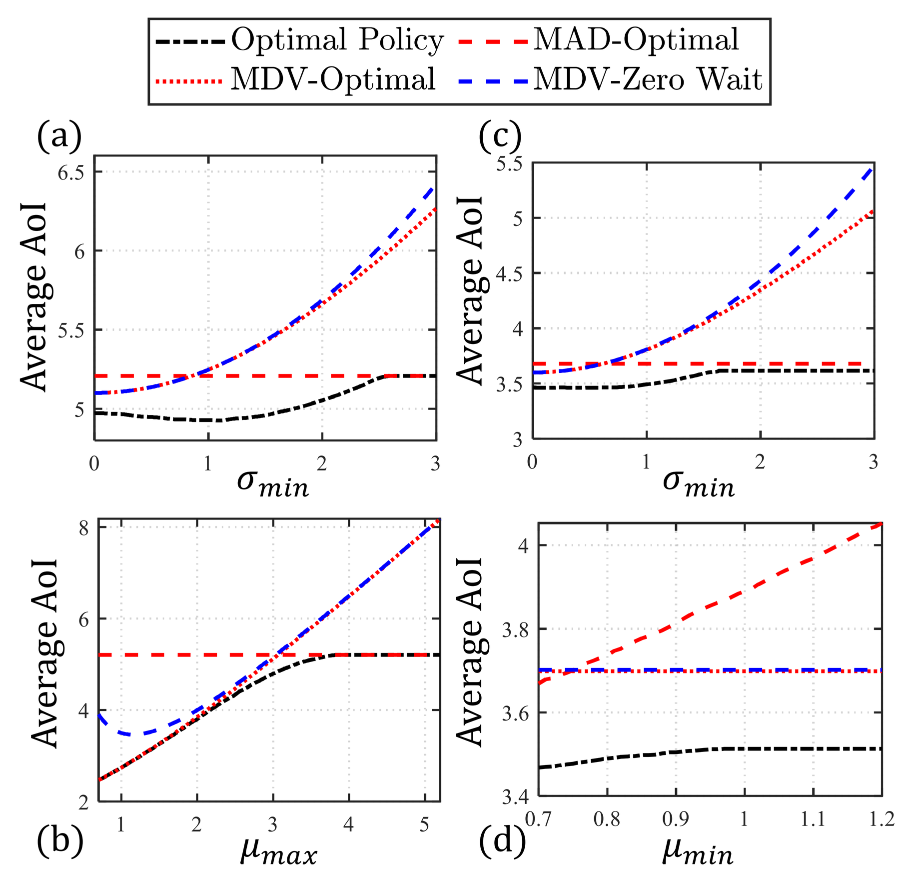

Figure 3: Simulation results for $N = 2$ and $N = 3$.

The simulations validate the proposed threshold-based policy under two- and three-route settings.

- **Figure 3(a)** reveals a counterintuitive effect: when an additional route is available, a higher delay variance can *improve* the average AoI, since the policy exploits the second route opportunistically.
- **Figure 3(b)** shows that as the mean delay μ_1 of route 1 increases, the benefit of joint routing first grows and then vanishes once μ_1 exceeds about 4, where a single fastest route becomes optimal.
- **Figures 3(c)–(d)** extend this to three routes: the policy dynamically drops the slowest path once its variance or mean exceeds a threshold, confirming the predicted switching structure.

Overall, the joint sampling–routing policy achieves up to **11% lower average AoI** compared to single-route baselines, showing that even seemingly suboptimal routes can enhance freshness when managed by the optimized handover policy.