X-armed Bandits for Optimizing Information Freshness in Robots Communication

Thanh Le, Yusheng Ji, Thanh-Trung Nguyen, John C.S. Lui

The Graduate University for Advanced Studies (SOKENDAI) - Japan

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1. Introduction
2. System model, metrics, and formulation
3. Sampling policies
4. Experimental results
5. Conclusion

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Application of Autonomous Mobile Robots (AMRs)

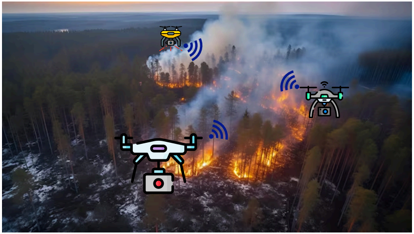

Figure: Drones observe their nearby environment and share their observations.

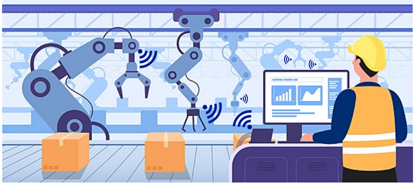

Figure: Robots and sensors in factory observe the manufacturing process and share the status to TV visualization.

AMRs: Tasks and Requirements

Tasks

- A group of AMRs that colaboratively solving a common task need to share their local observations
- An AMR that monitors a certain manufacturing process and send its observation to a remote monitor

Requirements

- Require latest observations from neighboring robots
- Need most recent status of a manufacturing process

$\rightarrow$ Require fresh information, characterized by a metric called Age of Information (AoI)

Optimize AMRs communication by minimize AoI

Age of Information (AoI)

- AoI is the metric to quantify information freshness
- Information usually has highest value when it is fresh
- The AoI at the monitor **increases linearly** in time when there is no update and is **reset to the delay** when an update is received
- Constraint: the communication channel can be congested when the sampling rate is too high

Contribution

- Study how to choose the sampling rate
- Implement a Proof of Concept (PoC) using 1-hop ad-hoc WiFi link
- Choose continuous sampling rate
- Visualize AoI for different sampling policies

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System model

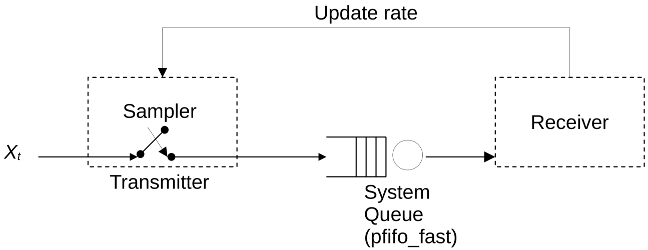

Figure: System model

- A source process X_t at **transmitter**
- Sample and send to a **receiver**
- 1-hop, ad-hoc Wifi 2.4GHz communication channel
- Sampled packets (with size 1kB) are sent via UDP
- Background traffic consumes an unknown amount of Wifi bandwidth
- Queueing discipline: single-server FIFO (linux kernel default)

Age of Information (AoI)

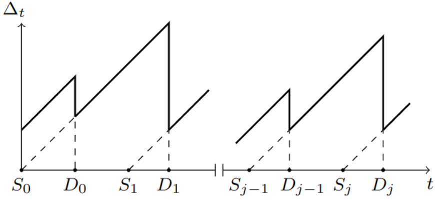

Figure: The evolution of AoI over time

Notations

The i^{th} sample is

- Sample at the **transmitter** at time S_i
- Deliver to the **receiver** at D_i

AoI

Let $U_t = max\{S_i : D_i \leq t\}$, the generation time of the freshest sample that has been delivered by time t. The AoI is defined by:

$$\Delta_t = t - U_t \tag{1}$$

Goal

$$\underset{\lambda}{\text{Minimize}} \quad \frac{1}{T}\sum_{t=1}^{T} \Delta_t \tag{2}$$

(3)

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Zero-wait policy

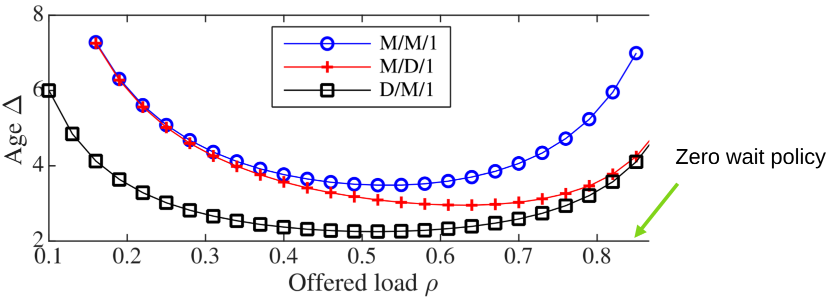

Figure: Theoretical AoI as a function of offered load for M/M/1, M/D/1, or D/M/1 queue[1].

Zero-wait policy

`Zero-wait` policy always sends update immediately after previous packet has been sent and leads to highest offered load.

[1] Sanjit Kaul, Roy Yates, and Marco Gruteser. "Real-time status: How often should one update?" In: *2012 Proceedings IEEE INFOCOM*. IEEE. 2012, pp. 2731–2735.

Finite difference policy (online learning)

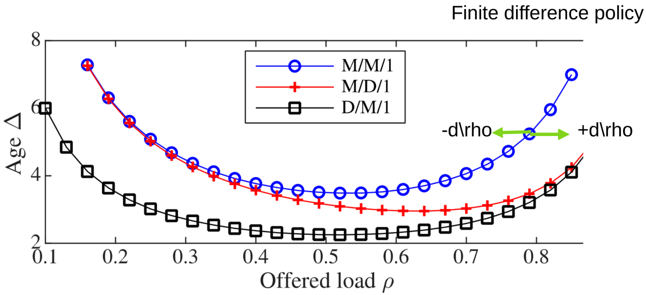

Figure: Theoretical AoI as function of offered load for M/M/1, M/D/1, or D/M/1 queue.

Finite diference policy

- Assume that the function of AoI w.r.t sampling rate (offered load) is convex
- Approximate the derivatives of AoI w.r.t sampling rate using nearby function values
- Use the derivatives to iteratively find the minimum

Problem - The AoI function in PoC is stochastic and has hard local optima.

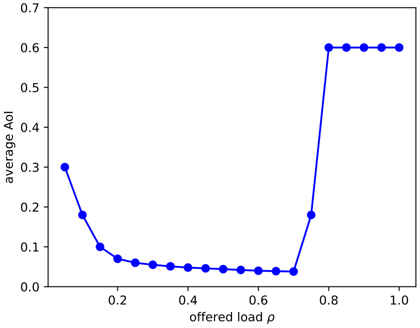

Figure: Average AoI as a function offered load on our PoC system.

- $\rho > 0.7$ is the critical point when the system becomes unstable
- Using finite difference method $\rightarrow$ cannot escape local optima within $[0.8, 1.0]$
- Note that

$$\rho = \frac{\text{throughput}}{\text{assumed maximum bandwidth}}$$

Solution X-armed bandit (XAB) policy (online learning)

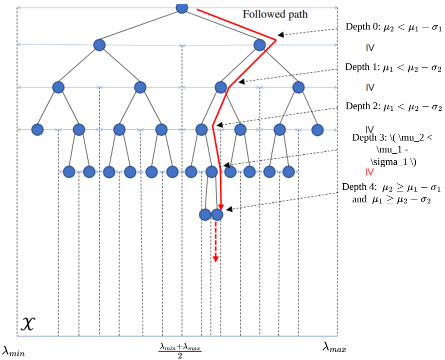

Figure: Illustration of X-armed bandits (XAB).

Hierarchical Parititioning XAB for Solving Blackbox Minimization Problem

- At depth 0, a single node cover the entire search space
- Split search space of each node into two equal partitions
- Randomly draw values from leaf nodes, until the **average** objective value of one branch **smaller** than the **average plus uncertainty** of objective value of another branch
- Iteratively traverse path with highest estimated objective value to evaluate

2

[2] Wenjie Li, Chi-Hua Wang, Guang Cheng, and Qifan Song. "Optimum-statistical collaboration towards general and efficient black-box optimization". In: *arXiv preprint arXiv:2106.09215* (2021).

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Experimental setup

Devices

- Two Rasberry Pi 4 devices placed two corners in our laboratory
- Testing duration per policy: 60s
- Search space: 5(ms/sample) to 50(ms/sample)
- Update packet size: 1kbyte
- Average over 10 independent trials

Traffic control to limit bandwidth

$ sudo tc qdisc add dev wlan0 root handle 1:0 tbf rate 1mbit burst 25kb limit 250kb

- Small bandwidth 1mbit/sec
- Small burst size and limit size

Result - Peak AoI

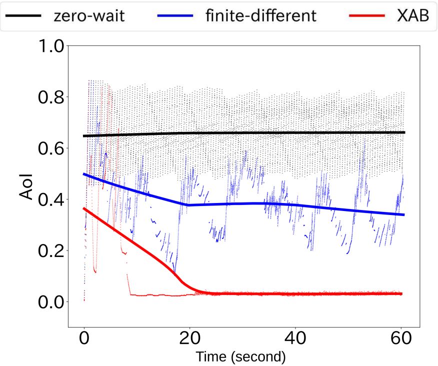


Figure: Average Peak AoI

Comments

- Zero-wait policy makes the network congested.
- Finite-difference policy was able to reduce AoI, but unable to converge
- XAB policy manages to gradually reduce AoI, and converge

Result - Number of Transmitted Packets

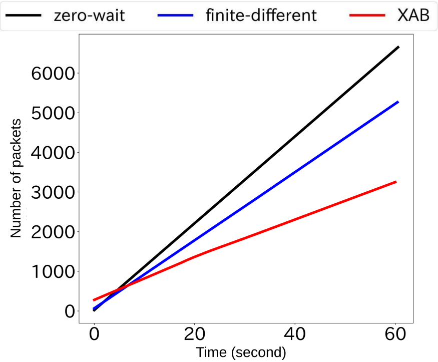
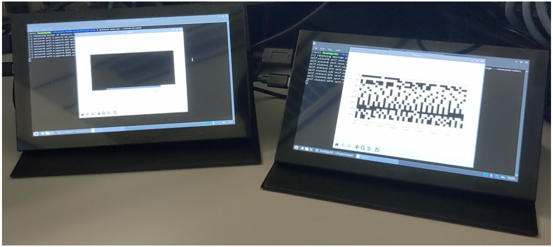


Figure: Total number of transmitted packets

- In average, `XAB` policy only sampled nearly 3000 packets within 60s
- `XAB` reduce about 50% of transmitted packets, in compared with `zero-wait` and `finite-difference`

Visualization of AoI



Left screen: Connected to Sender

- 2D image each black dot represents a packet
- Draw sequentially from left to right, up to down
- Draw when packet is sampled at sender

Right screen: Connected to Receiver

- Draw a black dot, represent the sampled timestamp, when packet is received
- Goal: Minimize AoI (reduce long consecutive white space)

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Conclusion

Summary

- Implemented a PoC status update system for AMRs communication via ad-hoc Wifi
- Applied `XAB` to reduce about 50% of transmitted packets, avoid network congestion, and minimize AoI

Future works

- Compare with other policies with discritized actions
- Scale to status update with multiple sources
- Incorporate data semantic to the sampling policies

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6 Related works

Optimal update rate to minimize M/M/1, D/M/1, and M/D/1 queues

Paper: Sanjit Kaul, Roy Yates, and Marco Gruteser. "Real-time status: How often should one update?" In: *2012 Proceedings IEEE INFOCOM*. IEEE. 2012, pp. 2731–2735

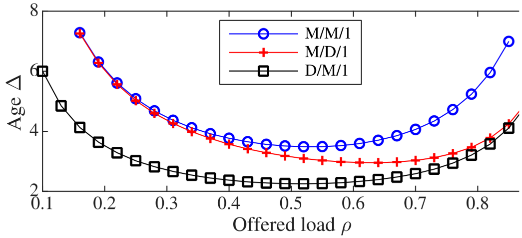

Figure: Compare AoI of different queueing models

Comments

- AoI is a deterministic convex function w.r.t offered load
- Easy to derive closed-form optimal sampling rate
- In our PoC, AoI is a stochastic non-convex function w.r.t offered load

Related works

Paper: Clement Kam, Sastry Kompella, and Anthony Ephremides. "Learning to sample a signal through an unknown system for minimum AoI". In: *IEEE INFOCOM 2019-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*. IEEE. 2019, pp. 177–182

Comments

- Using SALSA algorithm with tile coding to learn the sampling rate under lossless TCP/IP connection
- Discretize the sampling rate.

Related works

Paper: Vishrant Tripathi, Igor Kadota, Ezra Tal, Muhammad Shahir Rahman, Alexander Warren, Sertac Karaman, and Eytan Modiano. "Wiswarm: Age-of-information-based wireless networking for collaborative teams of uavs". In: *IEEE INFOCOM 2023-IEEE Conference on Computer Communications*. IEEE. 2023, pp. 1–10

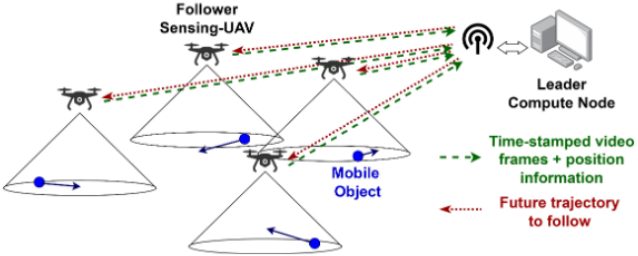

Figure: Leader node solve optimal sampling rate from multiple follower nodes to minimize AoI via WiFi. Using Whittle Index policy, time is synchronized.