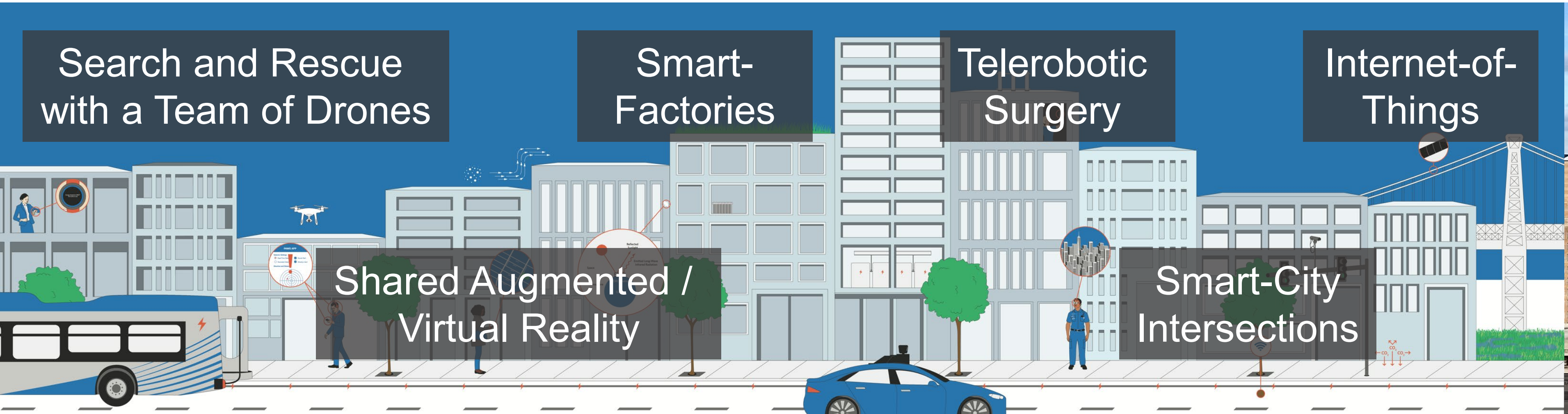
WiSwarm at the Edge: Wireless Networking for Collaborative Teams of UAVs

Igor Kadota
Assistant Professor
Department of Electrical and Computer Engineering

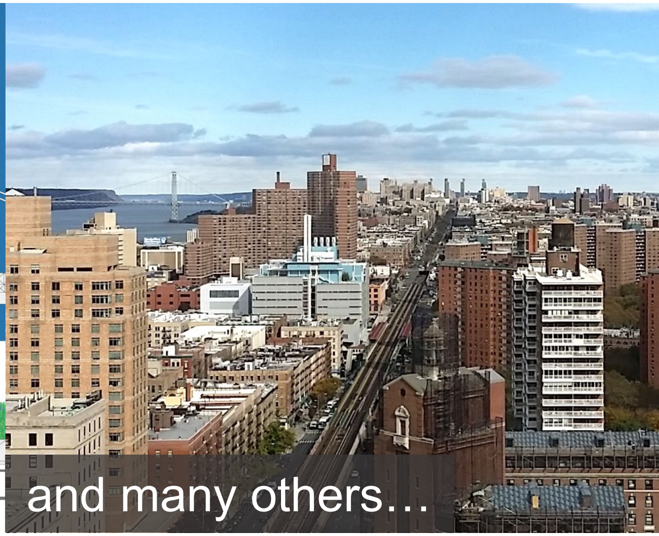
WiCI Seminars, Oct. 2025

Northwestern | McCORMICK SCHOOL OF ENGINEERING

Motivation: Future Applications



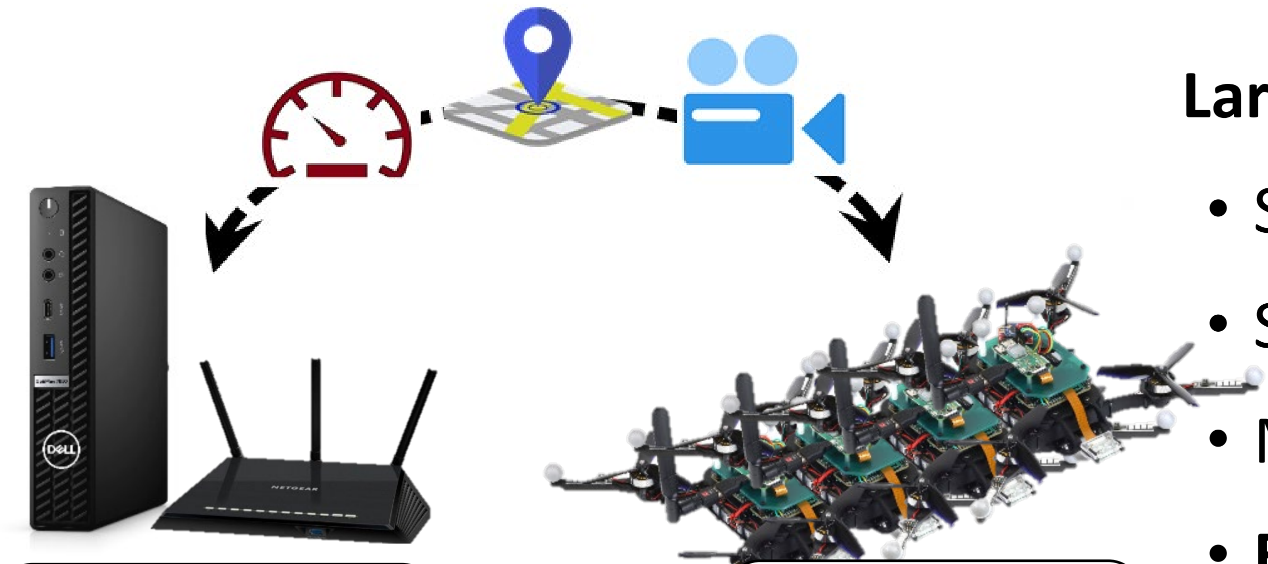
Courtesy of Columbia Engineering



Rural applications (discussed at **AraFest'25**):

- Sprayer teleoperation and monitoring
- Animal herding via UAVs
- Autonomous precision planting
- UAV/UGV fleet control

Motivation: Future of Networking



Data-driven application

Data-driven application

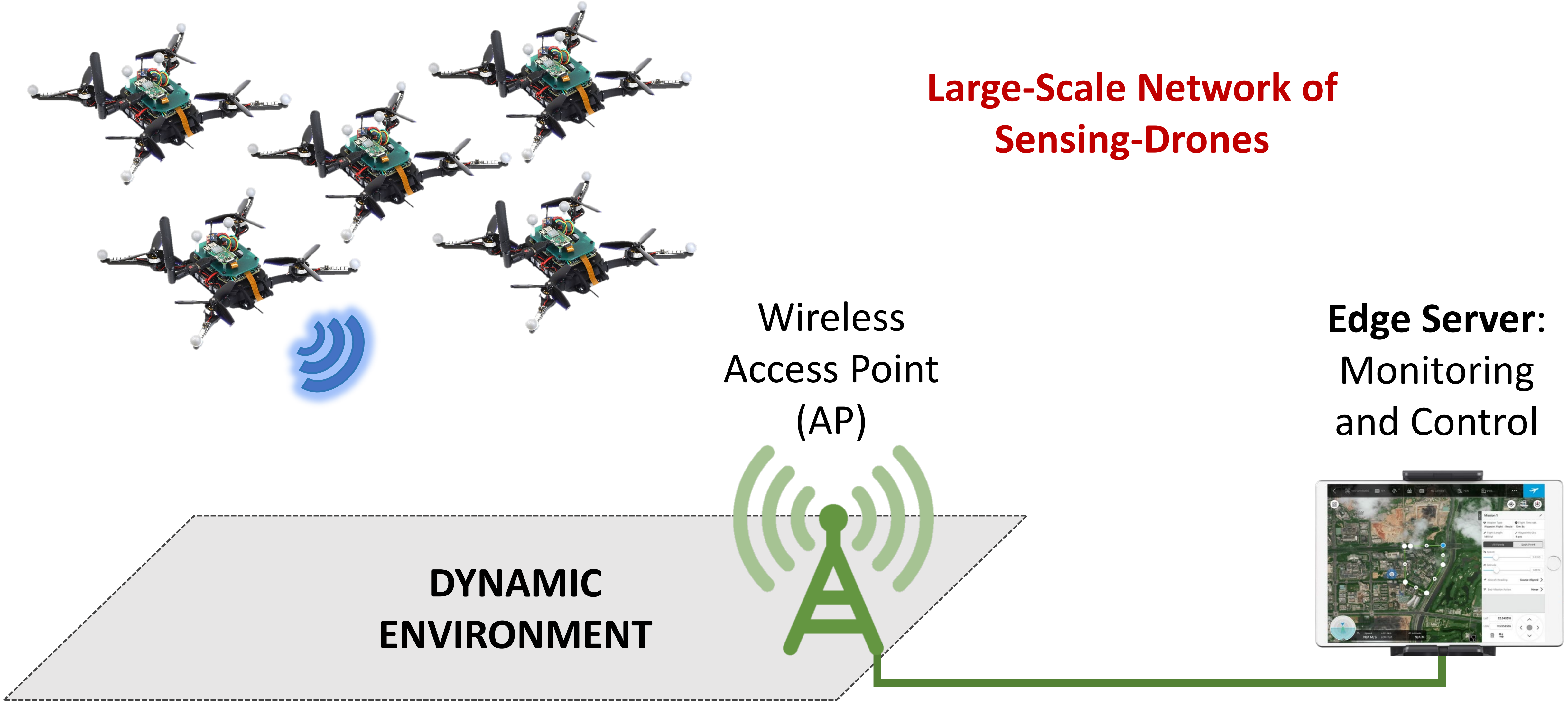
Customized communication network that fulfills specific requirements

Large-scale time-sensitive applications:

- Smart Cities (Autonomous vehicles)
- Smart-Factories (Machines)
- Multi-robot formations (Robots)
- **Exploration of dynamic environments (Drones)**
- IoT platforms for agriculture (Sensors)

⋮

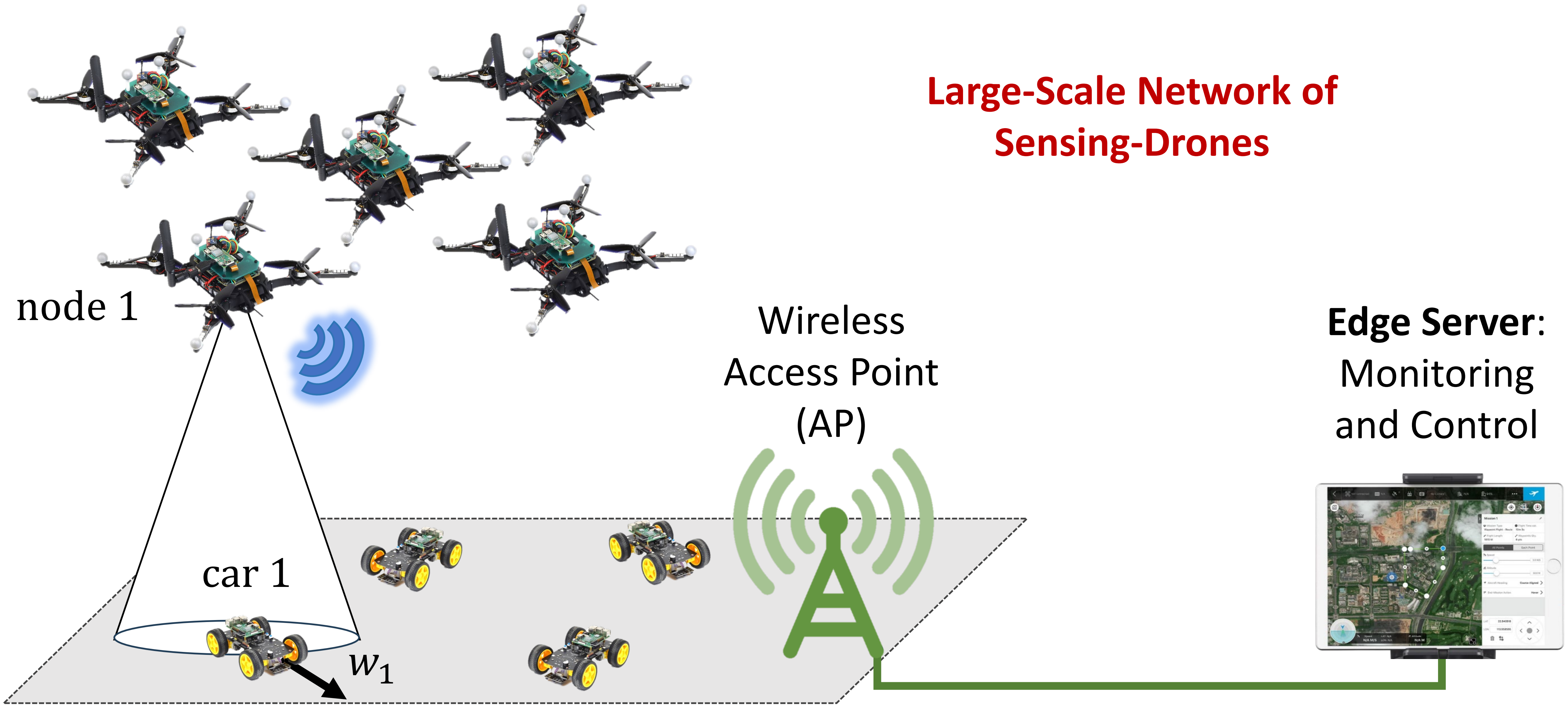
In this talk: Time-Sensitive Application



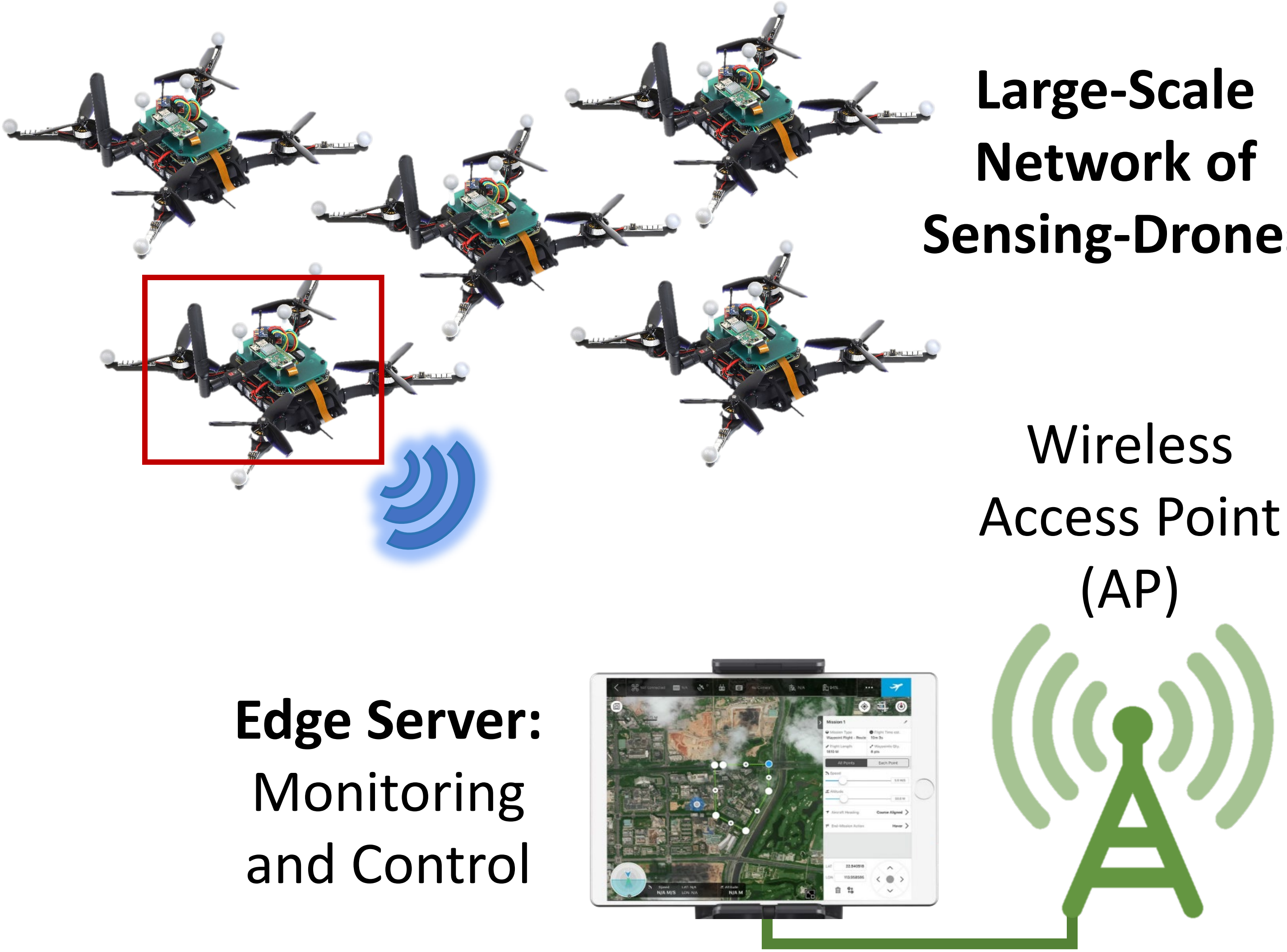
WiSwarm was introduced in
IEEE INFOCOM 2023

Collaboration with
V. Tripathi, E. Tal,
M. Rahman, A. Warren,
S. Karaman, E. Modiano

In this talk: Time-Sensitive Application



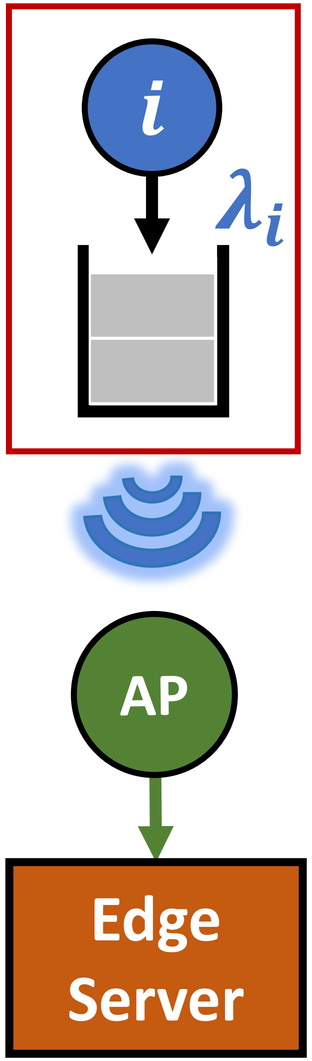
In this talk: Time-Sensitive Application



Large-Scale Network of Sensing-Drones

Wireless Access Point (AP)

Edge Server: Monitoring and Control



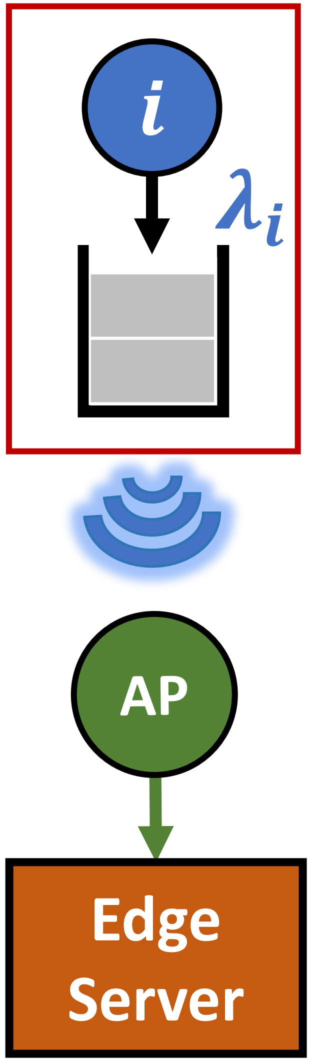
Time-Sensitive Information

Queueing

Wireless Channel Access

Outline

- **Theory:**
  - Introduction to Age-of-Information using a Simple System →



Outline

- **Theory:**
  - Introduction to Age-of-Information using a Simple System
  - Formulation of the AoI Minimization Problem in a Wireless Network

Minimizing the Age of Information in Broadcast Wireless Networks

Igor Kadota, Elif Uysal-Biyikoglu, Rahul Singh and Eytan Modiano

***Abstract*— We consider a wireless broadcast network with a base station sending time-sensitive information to a number of clients. The Age of Information (AoI), namely the amount of time that elapsed since the most recently delivered packet was generated, captures the freshness of the information. We formulate a discrete-time decision problem to find a scheduling policy that minimizes the expected weighted sum AoI of the clients in the network. To the best of our knowledge, this is the**

providing a minimum throughput. Fig. 1 illustrates the case of two sequences of packet deliveries that have the same throughput but different delivery regularity. In general, a minimum throughput requirement can be fulfilled even if long periods with no delivery occur, as long as those are balanced by periods of consecutive deliveries.

Minimizing the AoI is particularly challenging in wireless

Outline

- **Theory:**
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  - Theoretical Results: Lower Bound and Scheduling Policies

Optimizing Age of Information in Wireless Networks with Throughput Constraints

Igor Kadota, Abhishek Sinha and Eytan Modiano
Laboratory for Information & Decision Systems, MIT

Abstract—Age of Information (AoI) is a performance metric

mth packet delivered by sensor i is the most recent. Then, the

Outline

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- **Generalizations:** Packet Generation + Queueing + Scheduling Policies

Minimizing the Age of Information in Wireless Networks with Stochastic Arrivals

Igor Kadota
Massachusetts Institute of Technology
kadota@mit.edu

Eytan Modiano
Massachusetts Institute of Technology
modiano@mit.edu

ABSTRACT

We consider a wireless network with a base station serving multiple traffic streams to different destinations. Packets from each stream

networks, other performance requirements are increasingly relevant. In particular, the Age of Information (AoI) is a performance metric that was recently proposed in [26, 27] and has been receiving

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Yin Sun, I.K., Rajat Talak, and Eytan Modiano

Age of Information: A New Metric for Information Freshness

Morgan and Claypool Publishers, 2019.

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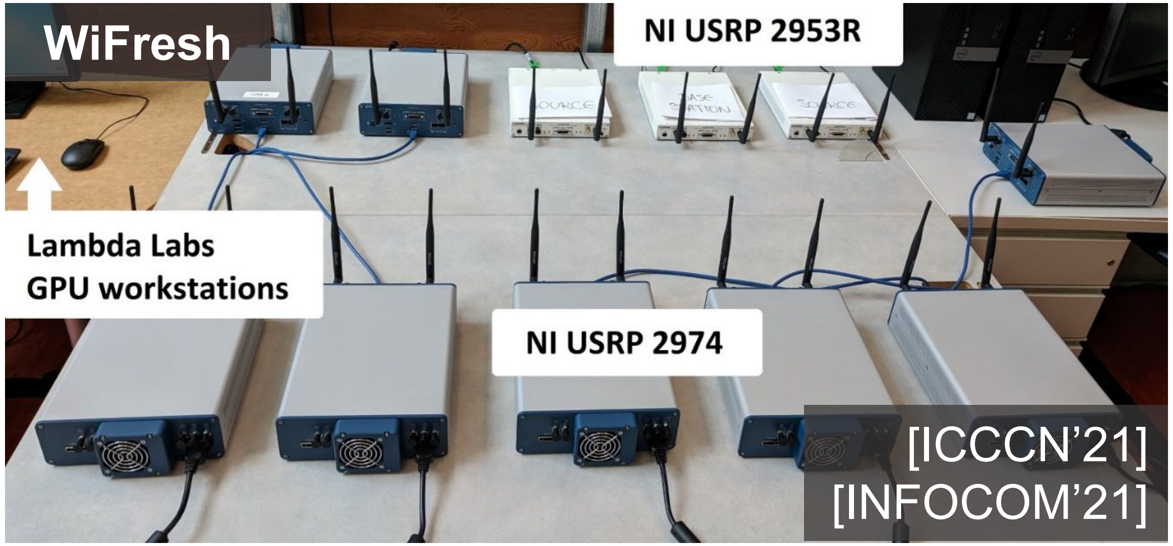
- **System Implementation in a SDR Testbed and Flight Tests with Drones**



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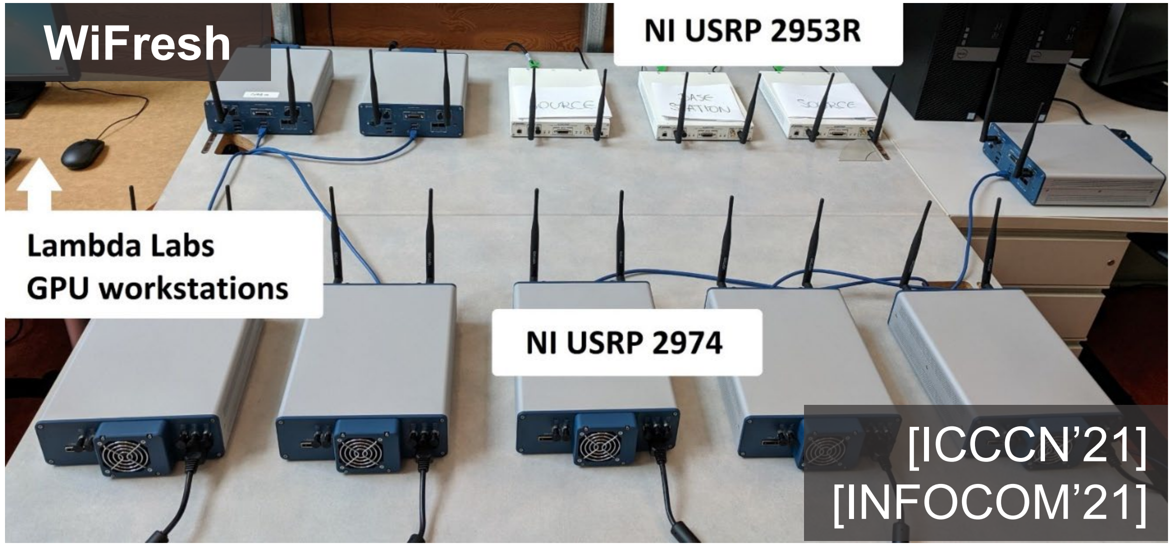
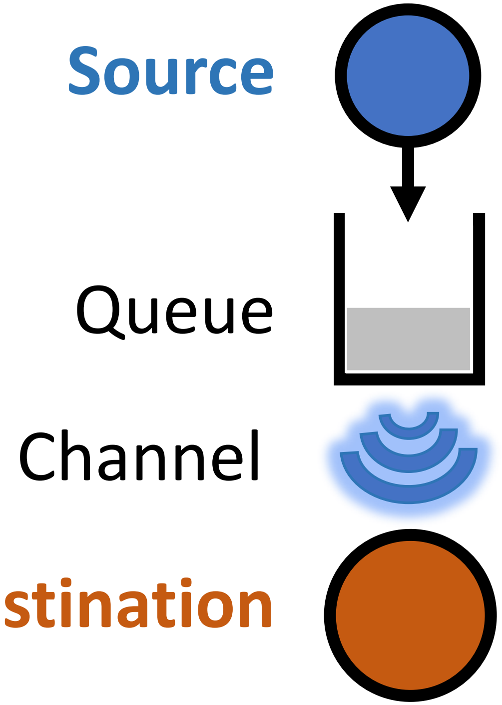
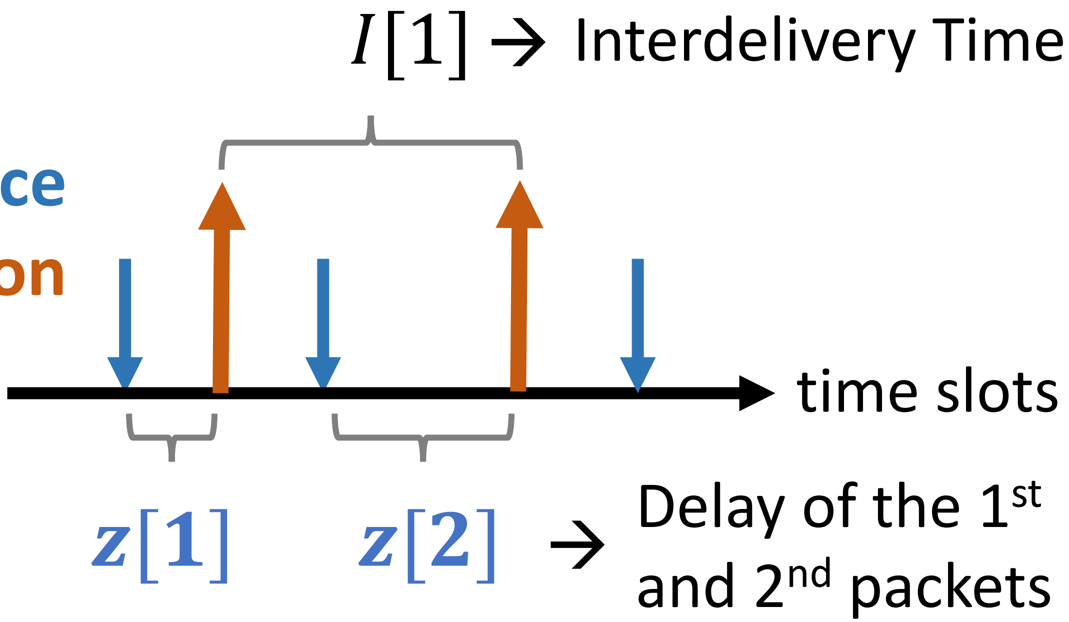


Background: Age-of-Information

Packet generation at the source

Delivery of packets to the destination



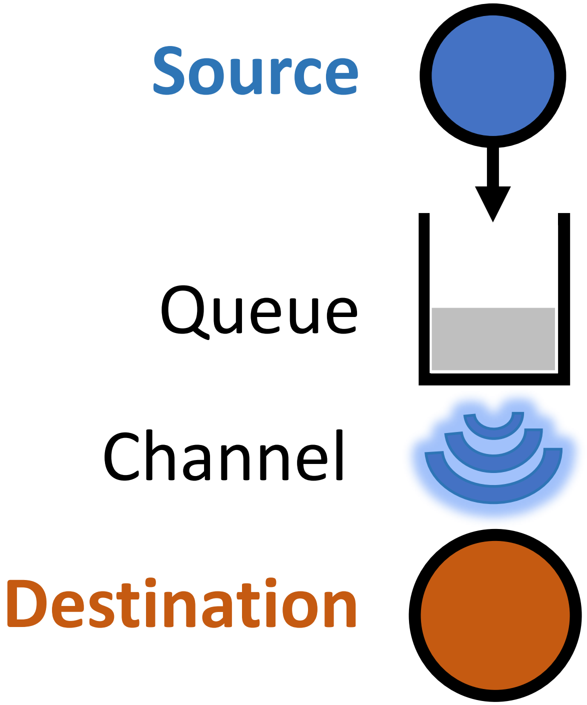


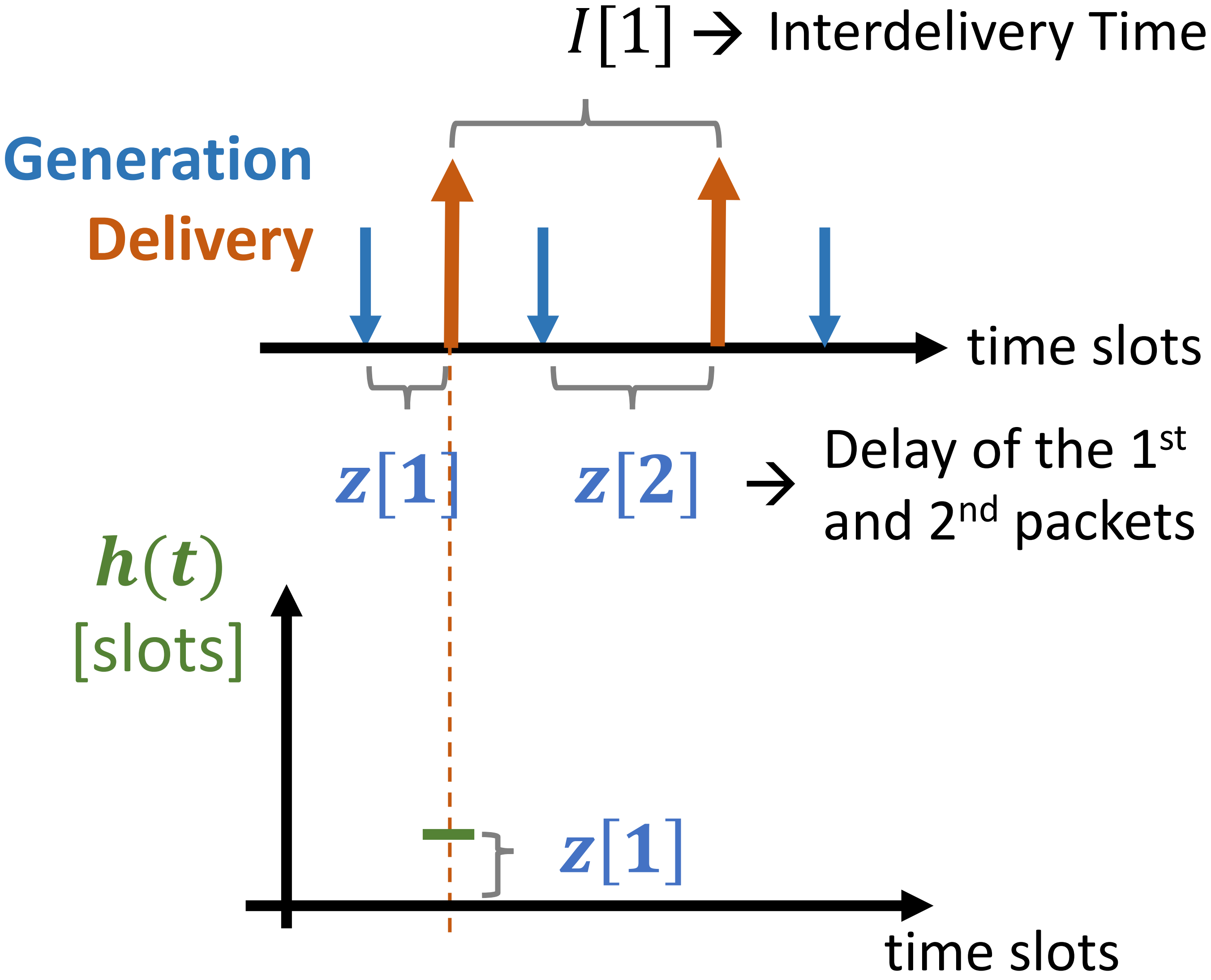
How old is the information at the destination?

S. Kaul, R. Yates, and M. Gruteser, "Real-Time Status: How Often Should One Update?," IEEE INFOCOM, 2012.

Background: Age-of-Information

AoI: time elapsed since the generation of the freshest received packet





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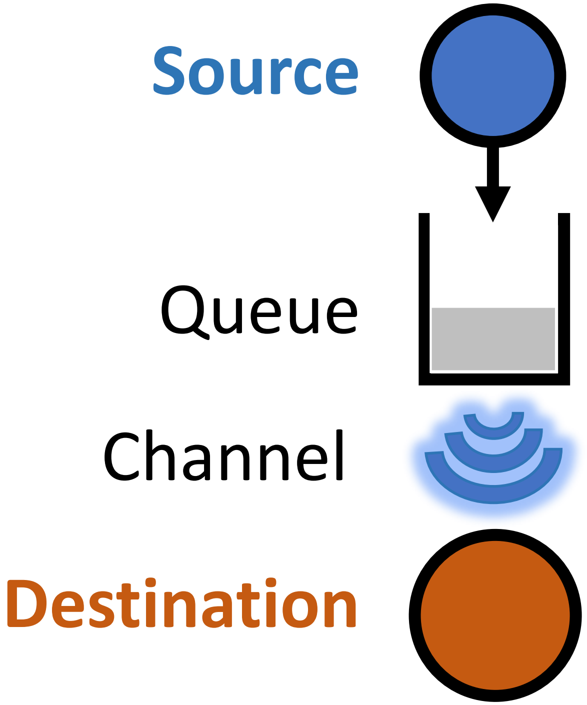

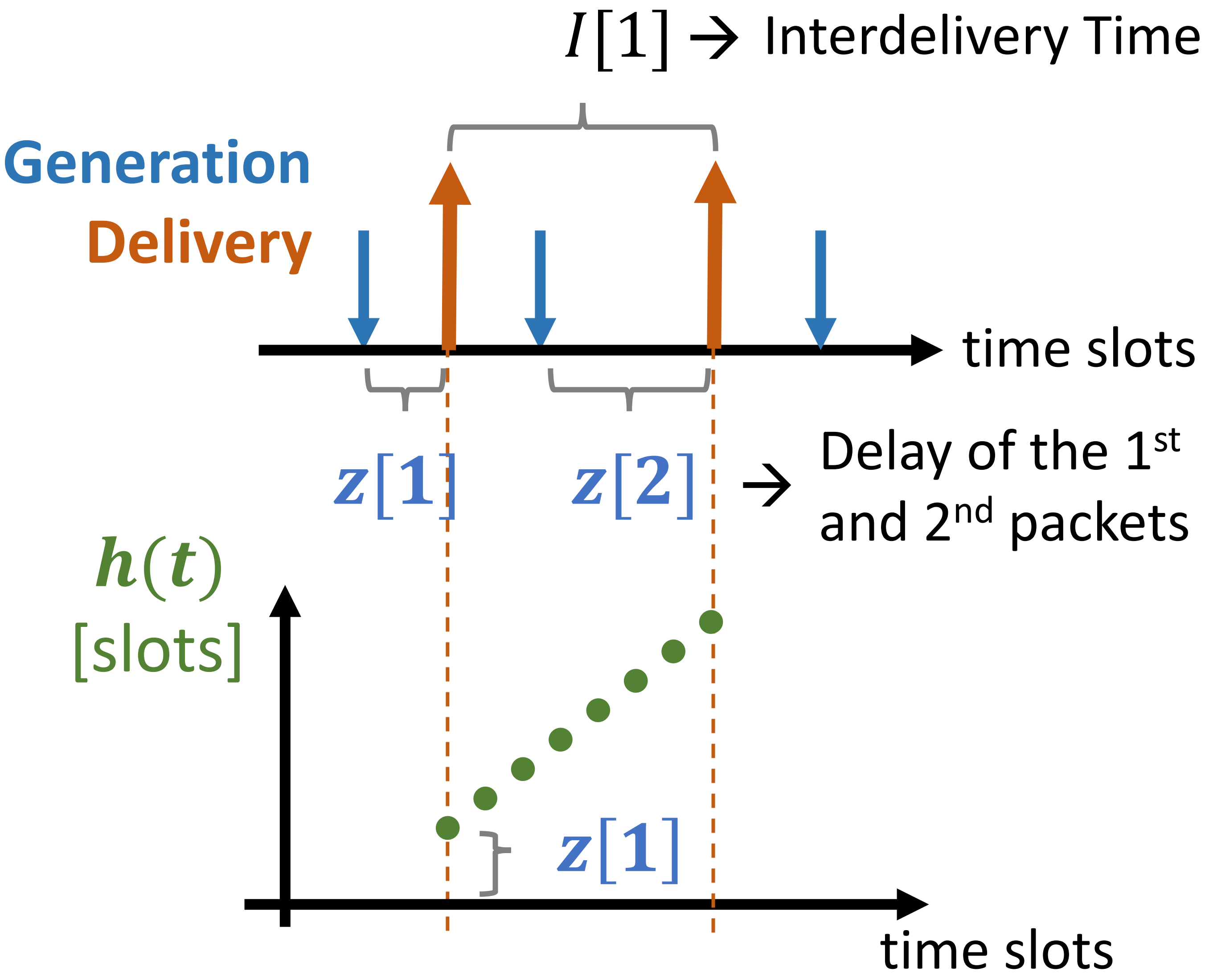

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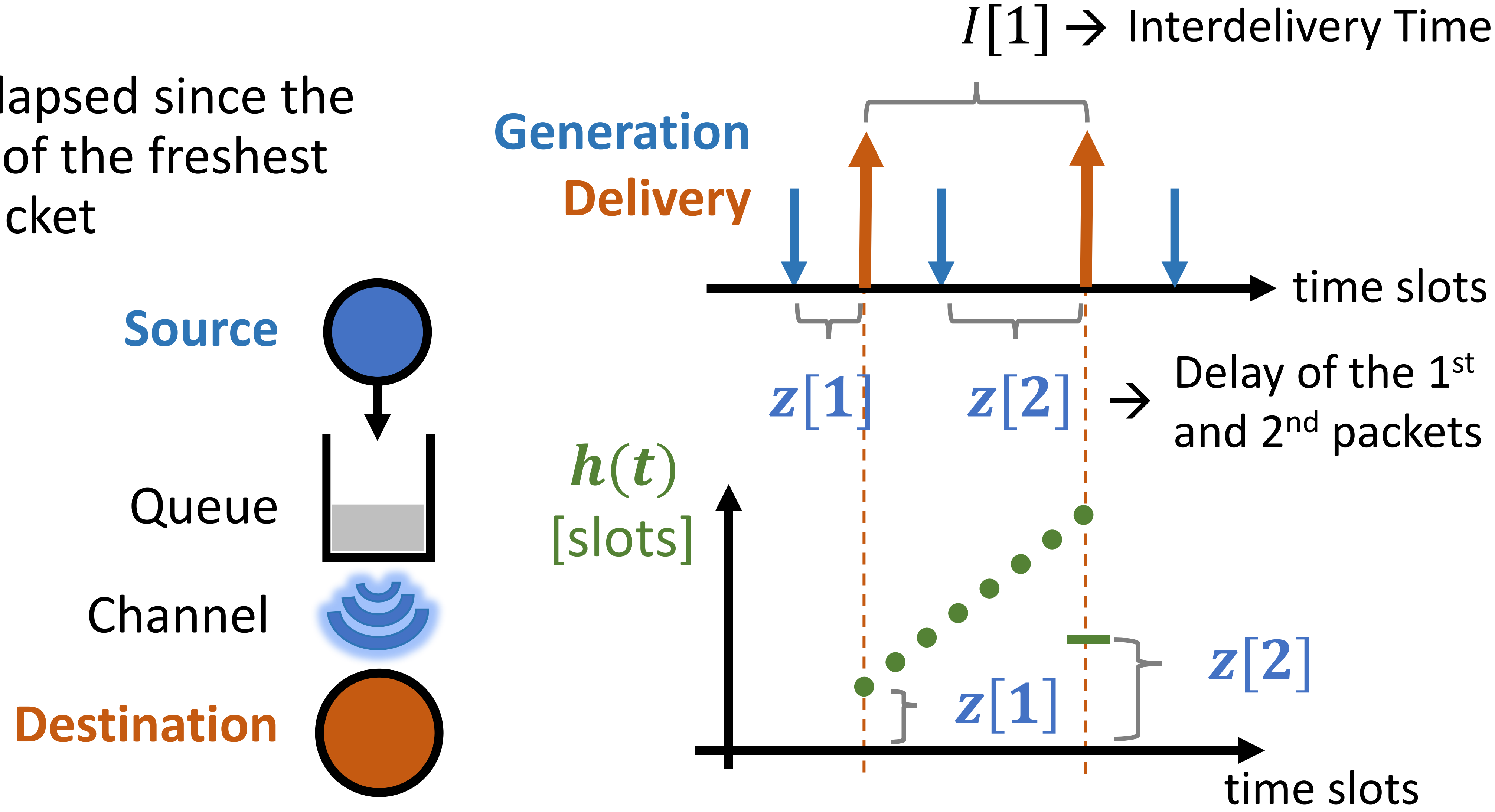

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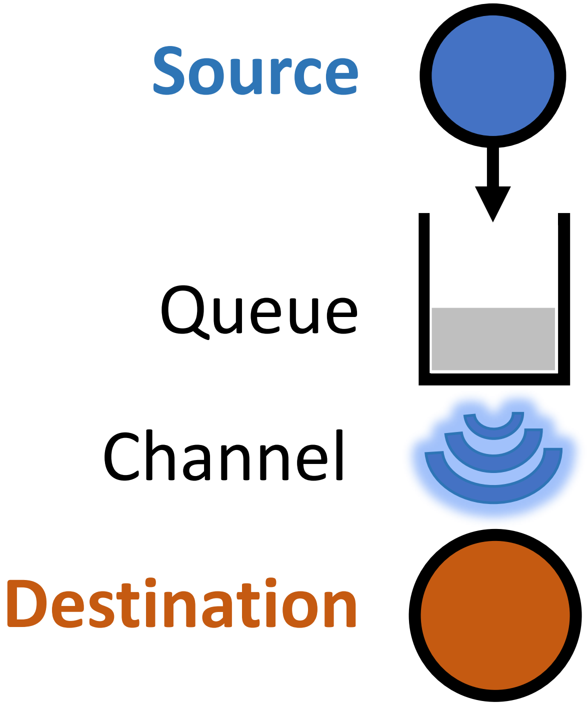
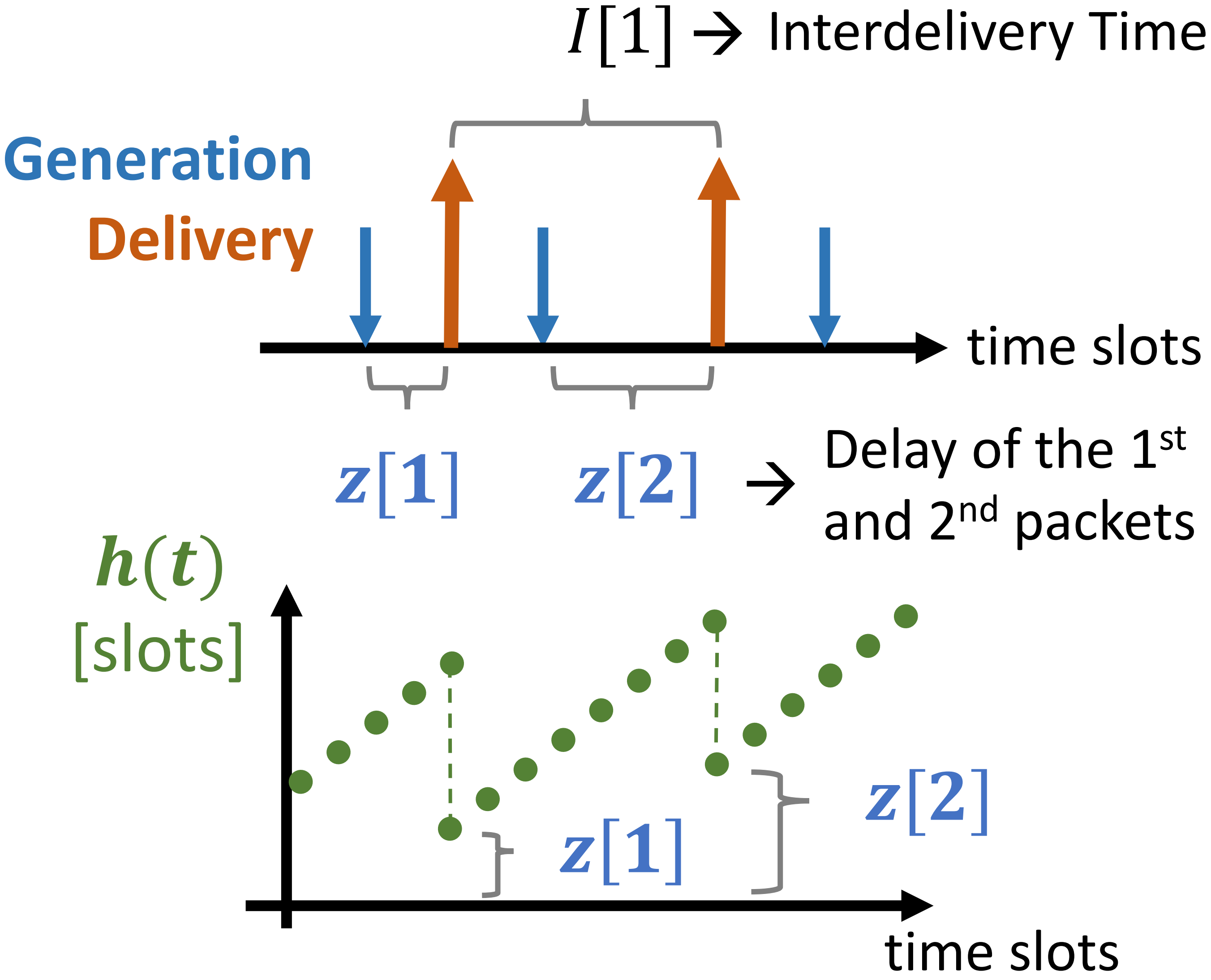
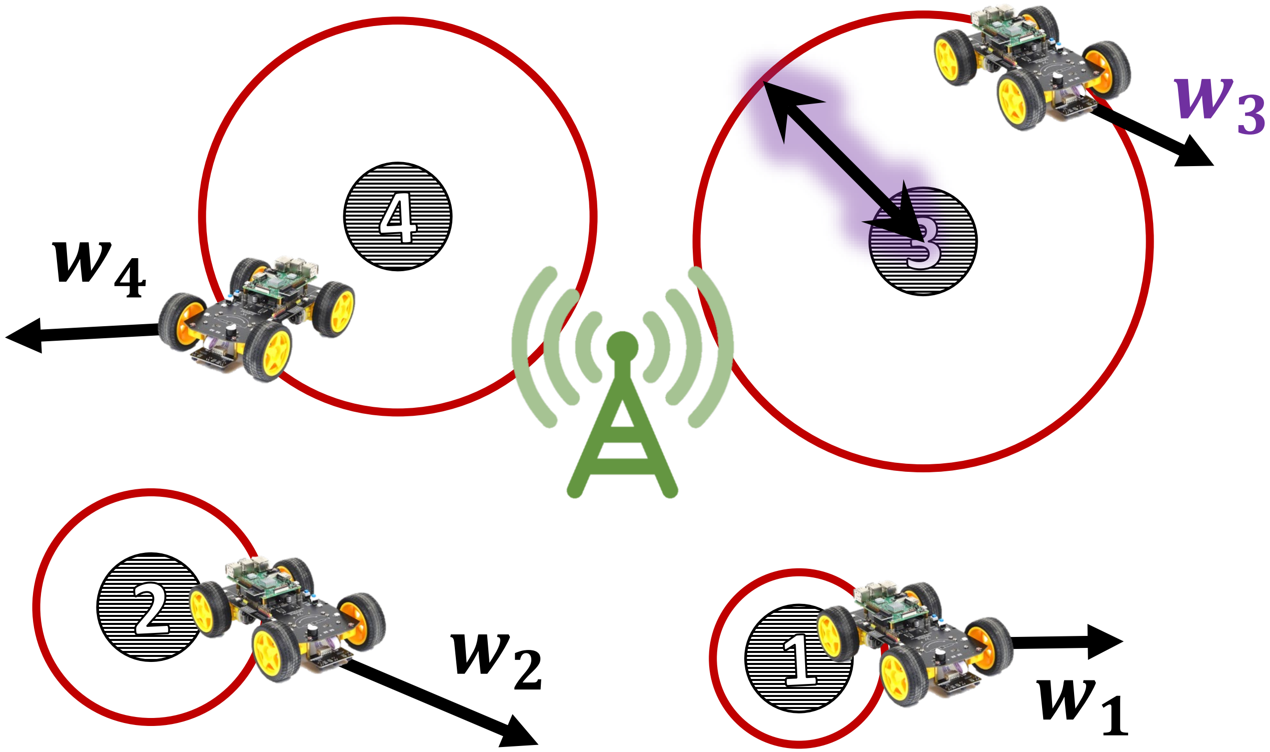


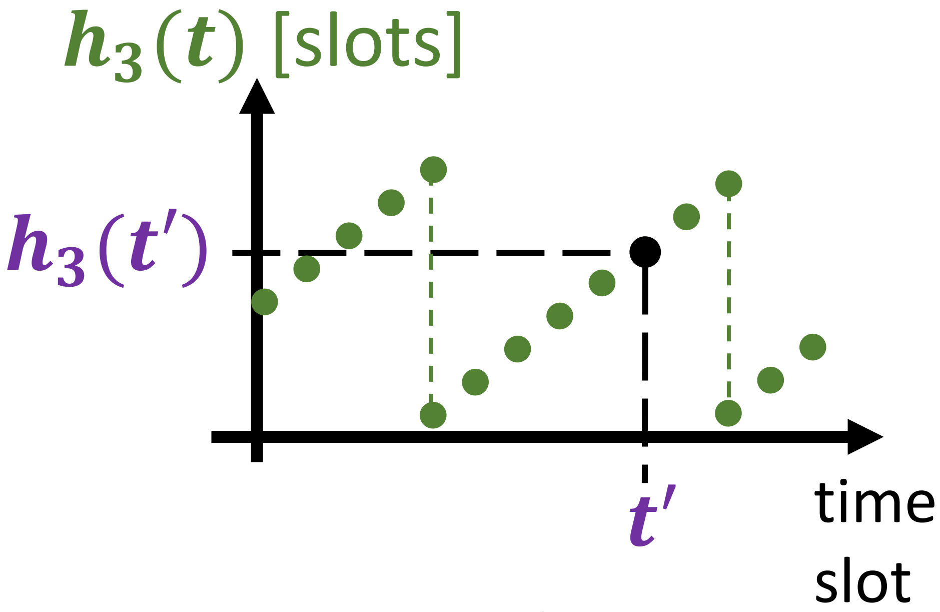


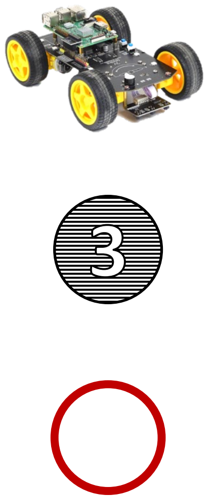
S. Kaul, R. Yates, and M. Gruteser, "Real-Time Status: How Often Should One Update?," IEEE INFOCOM, 2012.

Background: AoI and Position Uncertainty

From the perspective of the edge server:
Position uncertainty of car 3 in slot t'
is given by the **radius** $w_3 h_3(t')$







current position of car

last known position
(from last packet received)

position uncertainty

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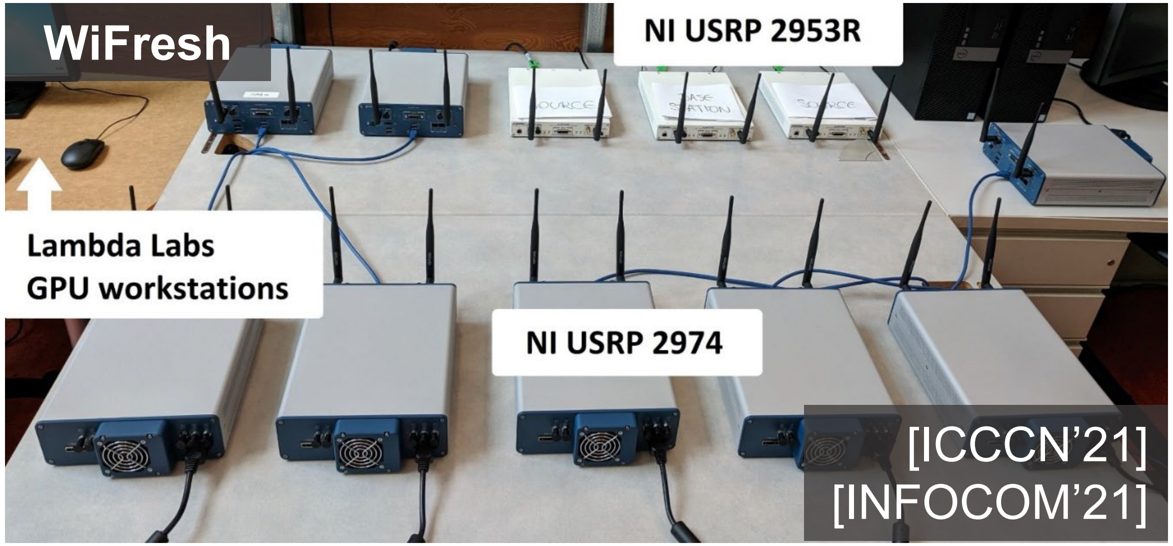
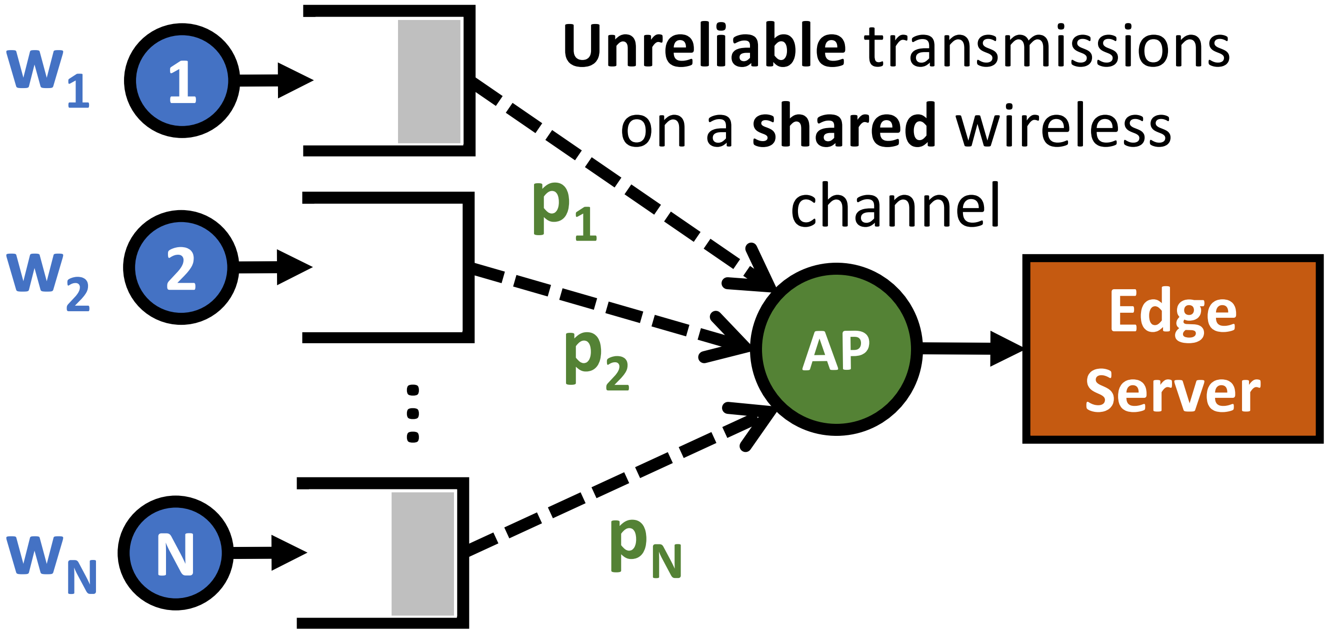
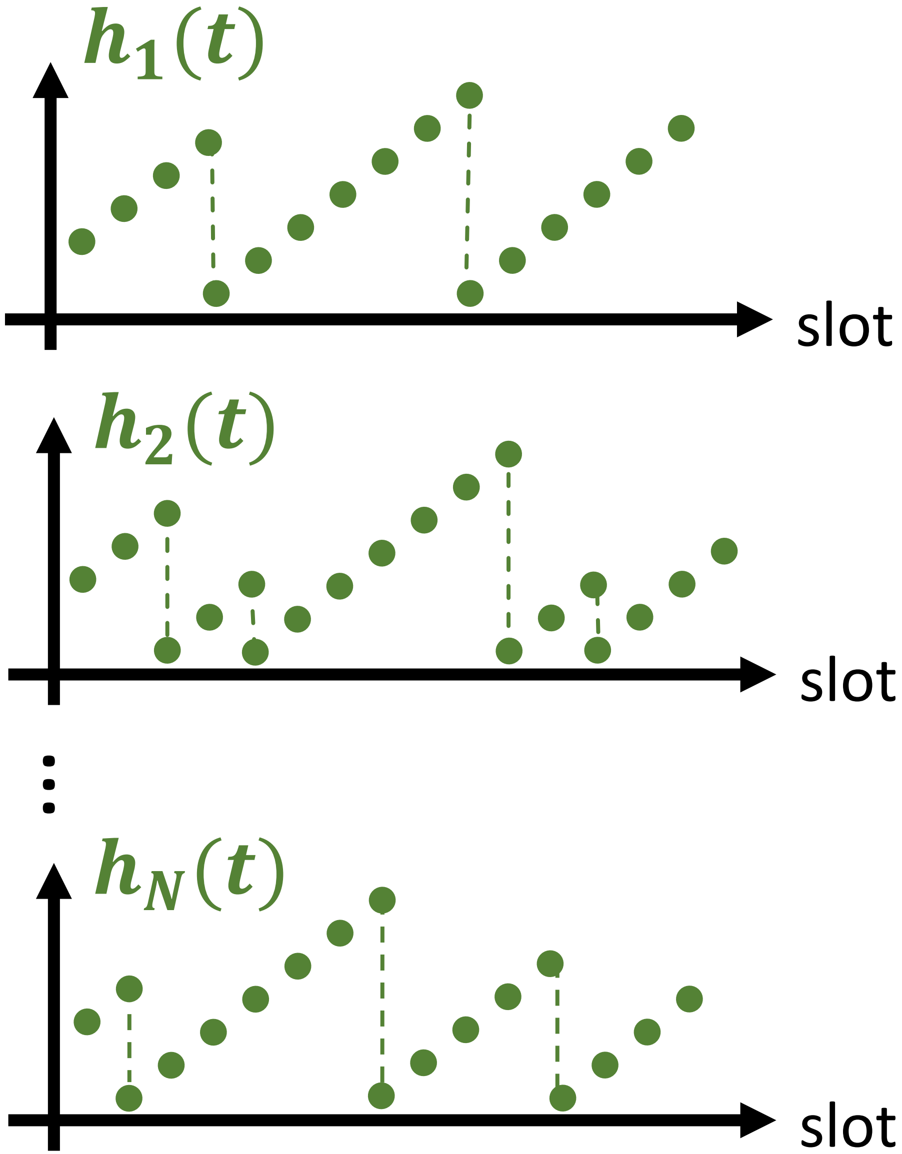


Network Model

Packet generation and **queueing**



Unreliable transmissions on a **shared** wireless channel



Weight $w_i > 0$ represents **priority** of source i

Probability $p_i \in (0,1]$ represents **quality of the link**

I. K., A. Sinha, E. Uysal-Biyikoglu, R. Singh, E. Modiano, "Scheduling Policies for Minimizing Age of Information in Broadcast Wireless Networks," IEEE/ACM ToN, 2018.

Network Model

Packet g

w_1 1

w_2 2

w_N N

For simplicity, in this talk, we assume that:

- Sources generate fresh packets at will

As a result, the AoI evolves as follows:

$$\boldsymbol{h(t+1)} = \begin{cases} 1, & \text{if packet is delivered in slot t} \\ \boldsymbol{h(t)} + 1, & \text{otherwise} \end{cases}$$

slot

slot

slot

Weight $w_i > 0$ represents **priority** of source i

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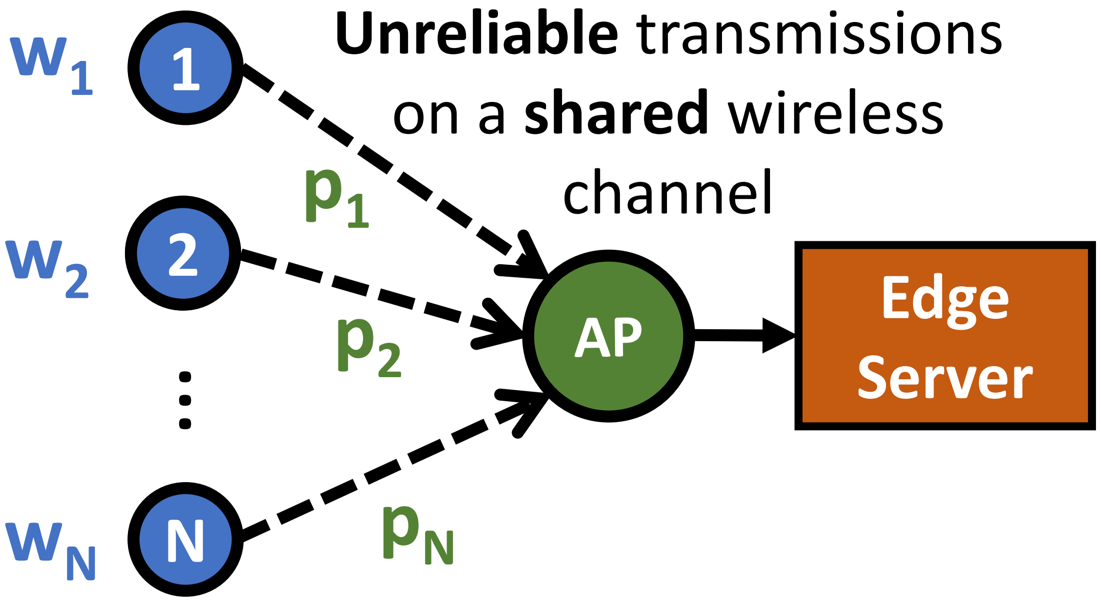
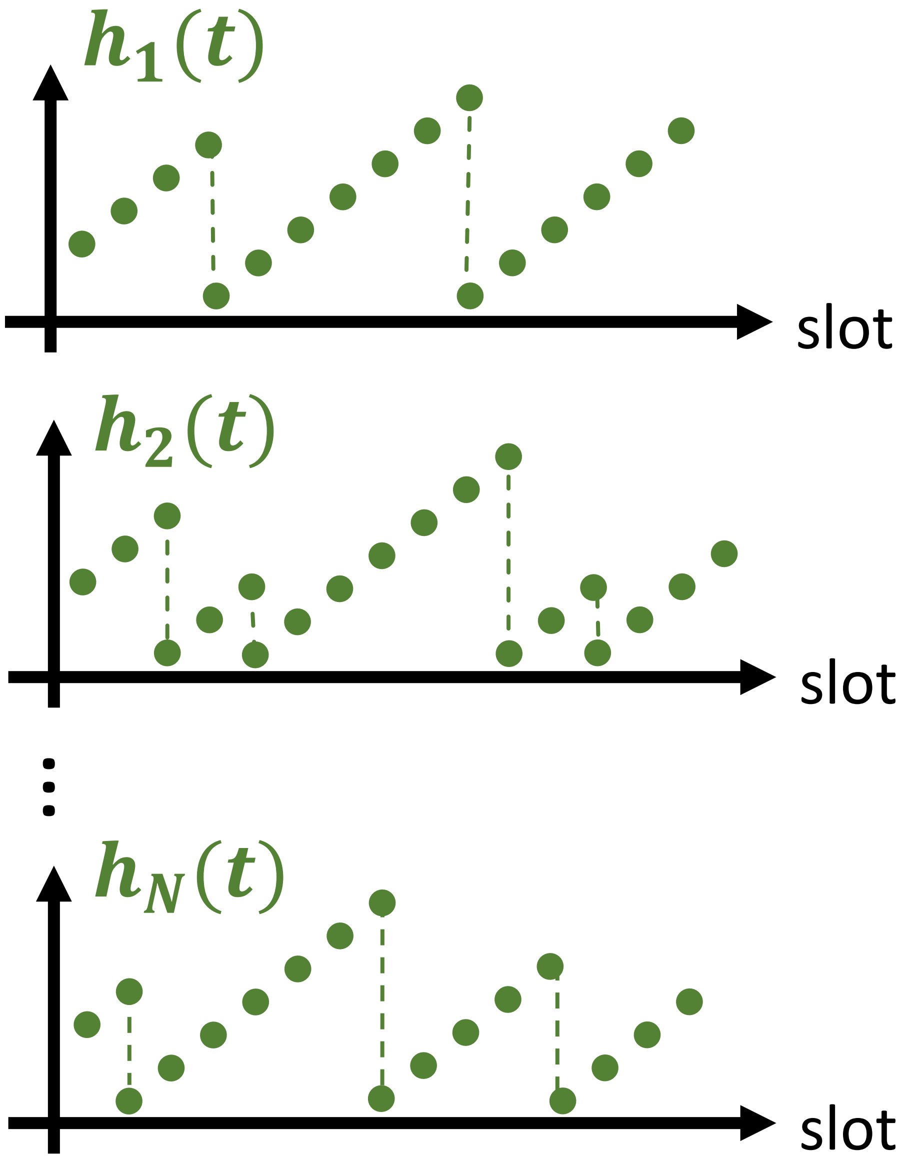
Network Model

For simplicity: Packet generation at will





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Network Model: Objective Function

<u>Goal</u>: find a **transmission scheduling policy $\boldsymbol{\pi}^*$** $\in \Pi$ that minimizes the Expected Weighted Sum Age-of-Information (**EWSAoI**):

$$\mathbb{E}[J^*] = \min_{\pi \in \Pi} \left\{ \lim_{T \to \infty} \mathbb{E}[J_T^\pi] \right\}, \text{where } \mathbb{E}[J_T^\pi] = \frac{1}{TN} \sum_{t=1}^{T} \sum_{i=1}^{N} \boldsymbol{w_i} \mathbb{E}[\boldsymbol{h_i^\pi(t)}]$$

Class of non-anticipative policies Π. Arbitrary policy $\pi \in \Pi$.

I. K., A. Sinha, and E. Modiano, "Scheduling Algorithms for Optimizing Age of Information in Wireless Networks with Throughput Constraints," IEEE/ACM ToN, 2019. [conference version received the best paper award at IEEE INFOCOM 2018]
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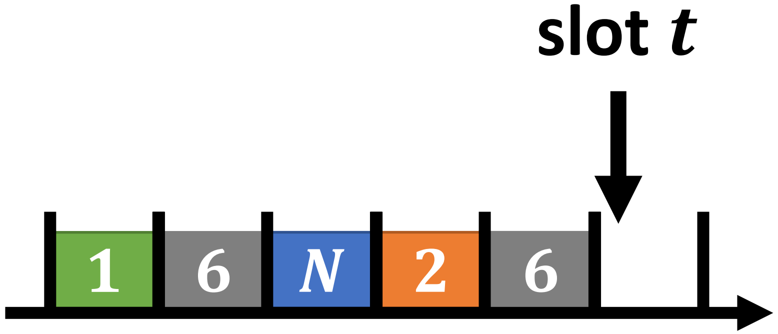
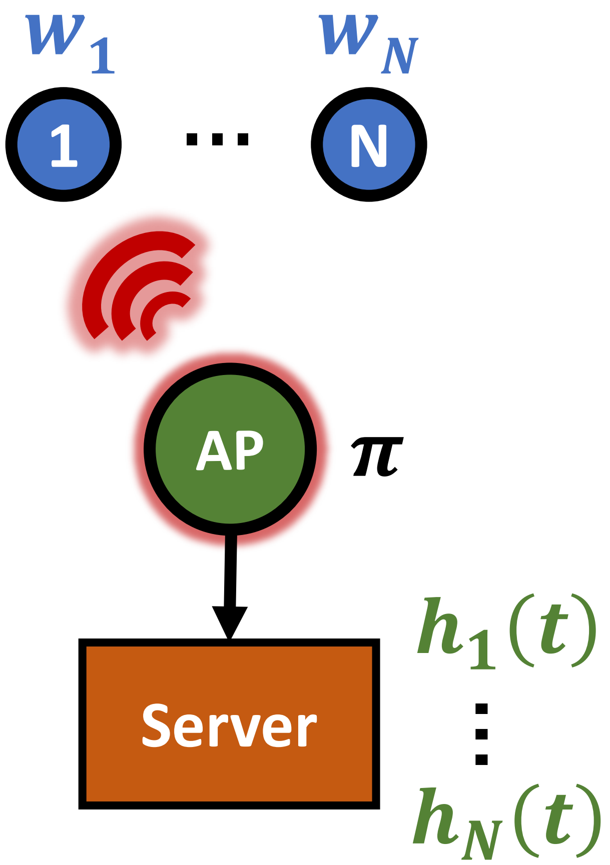
Network Model: Scheduling Policy π

Scheduling decision during slot t:

1) AP selects a single source $i \in \{1,2,\ldots,N\}$ $[u_i(t) = 1$ and $u_j(t) = 0, \forall j \neq i]$





Class of non-anticipative policies Π. Arbitrary policy $\pi \in \Pi$.

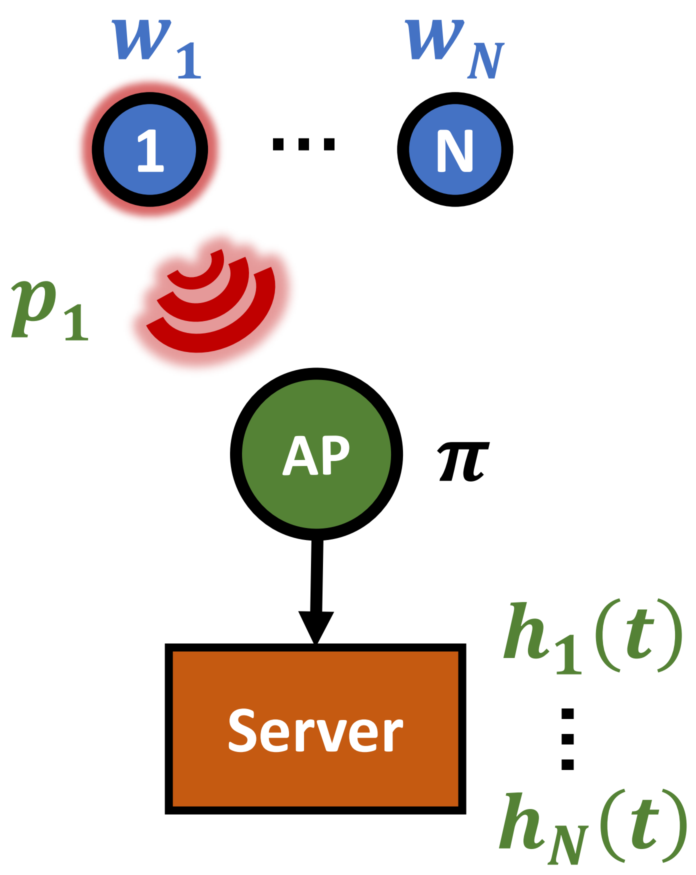
Network Model: Scheduling Policy π

Scheduling decision during slot t:

1) **AP selects** a single source $i \in \{1,2,\ldots,N\}$
   $[u_i(t) = 1$ and $u_j(t) = 0, \forall j \neq i]$

2) **Selected source** generates and transmits a packet to the AP

3) Packet is **delivered** to the AP w.p. p_i
   $[d_i(t) = 1$ and $d_j(t) = 0, \forall j \neq i]$ and transmission error occurs w.p. $1 - p_i$



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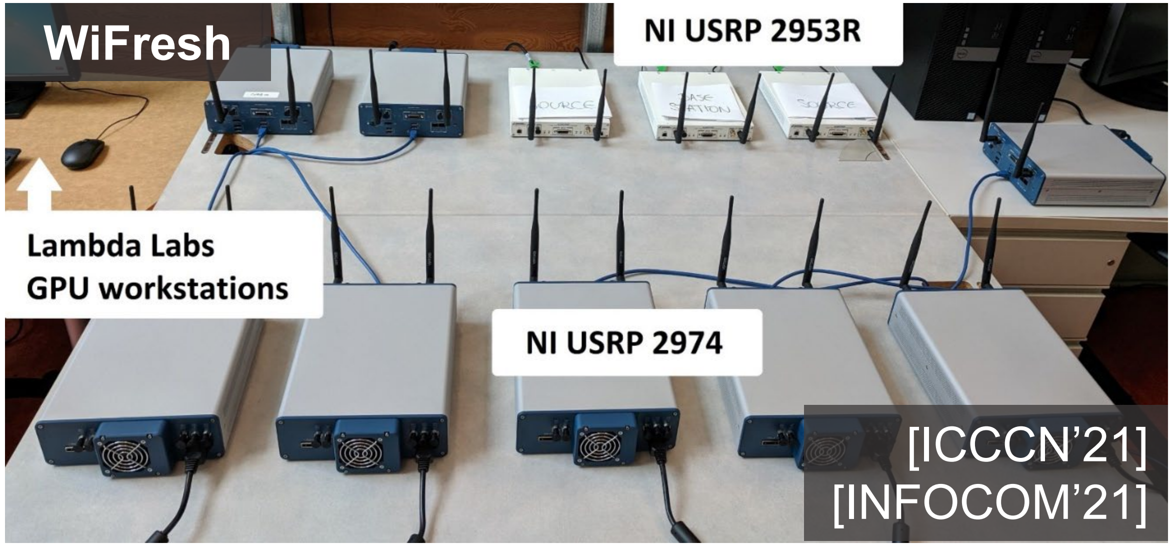

Goal: find a **transmission scheduling policy** $\boldsymbol{\pi}^*$ that selects, in each slot t, the optimal source to poll in order to minimize the EWSAoI.

Dynamic Programming to compute the AoI-optimal policy

I. K., "Transmission Scheduling of Periodic Real-Time Traffic in Wireless Networks," M.S. dissertation, MIT LIDS, 2016.
Y. Sun, I. K., R. Talak, and E. Modiano, *Age of Information: A New Metric for Measuring Information Freshness*. Morgan & Claypool, 2019.

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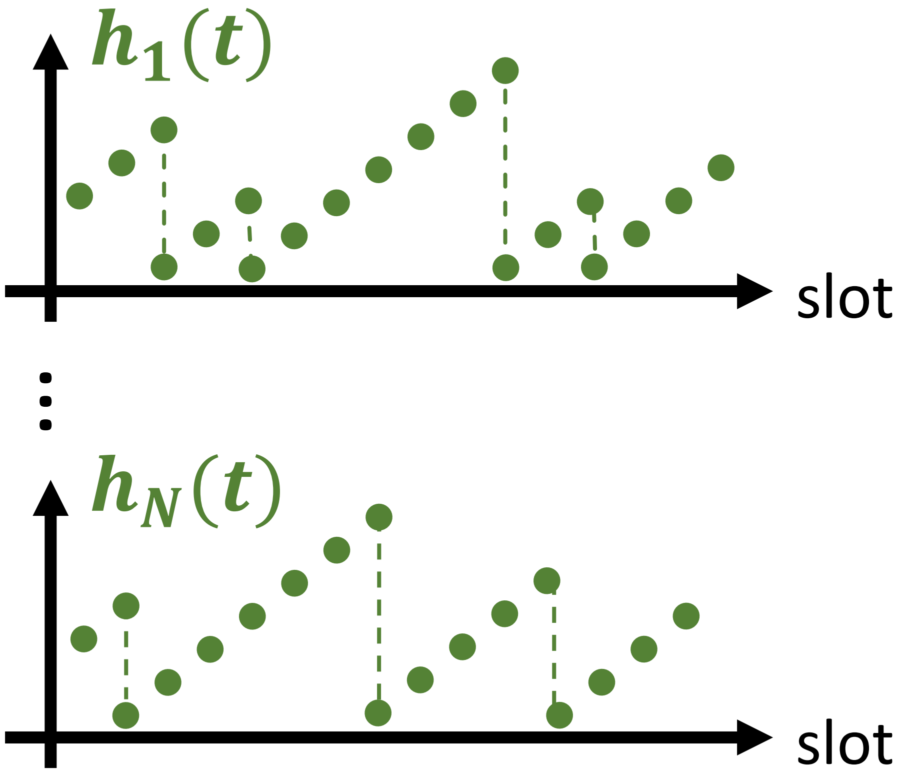
Dynamic Programming to compute the AoI-optimal policy

Greedy Policy is AoI-optimal for networks with $p_i = p$ and $w_i = w$

Proof: Stochastic Coupling to compare Greedy with any other admissible policy



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Greedy Policy is AoI-optimal for networks with $\boldsymbol{p_i} = \boldsymbol{p}$ and $\boldsymbol{w_i} = \boldsymbol{w}$

Lower Bound: for any given network with $(\boldsymbol{N}, \boldsymbol{w_i}, \boldsymbol{p_i})$: $\lim_{T\to\infty} \mathbb{E}[J_T^\pi] \geq \boldsymbol{L_B}$

where :

$$\boldsymbol{L_B} = \frac{1}{2N}\left(\sum_{i=1}^{N}\sqrt{\frac{\boldsymbol{w_i}}{\boldsymbol{p_i}}}\right)^2 + \frac{1}{N}\sum_{i=1}^{N}\boldsymbol{w_i}$$

Proof: Sample path + Fatou's Lemma + Generalized Mean Inequality

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Then: low-complexity policy $\pi \in \Pi$ with performance guarantee.

Performance Guarantee for $\boldsymbol{\pi}$: for any given network with $(\boldsymbol{N}, \boldsymbol{w_i}, \boldsymbol{p_i})$

$$\boldsymbol{L_B} \leq \mathbb{E}[\,J^*] \leq \mathbb{E}[\,J^\pi] \leq \boldsymbol{\beta^\pi} \boldsymbol{L_B}$$

Means that π is $\boldsymbol{\beta^\pi}$-optimal

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Means that π is $\boldsymbol{\beta^\pi}$-optimal

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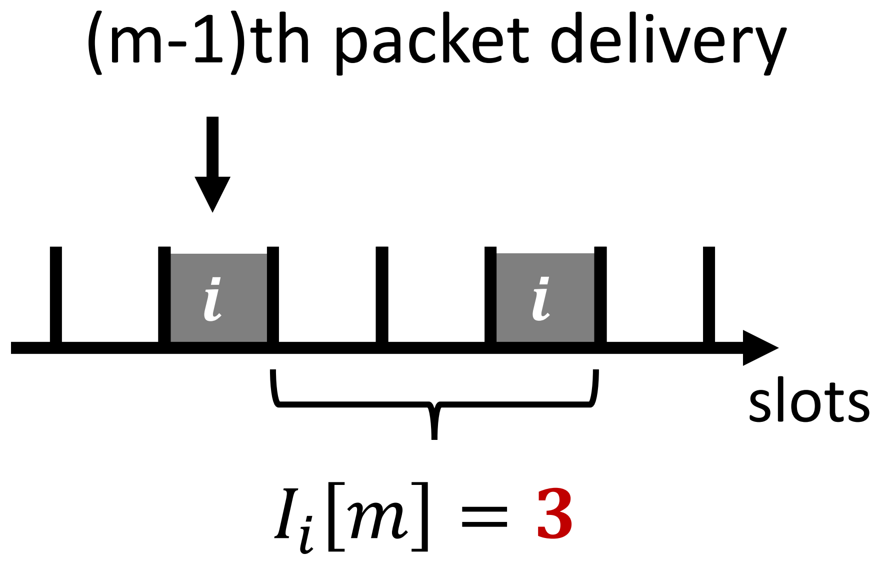
AoI from a different perspective

Lemma:

$$\lim_{T\to\infty} J_T^{\pi} \triangleq \lim_{T\to\infty} \frac{1}{TN}\sum_{t=1}^{T}\sum_{i=1}^{N} \boldsymbol{w_i h_i(t)} = \frac{1}{N}\sum_{i=1}^{N} \frac{\boldsymbol{w_i}}{2}\left[\frac{\overline{\mathbb{M}}[\boldsymbol{I_i^2}]}{\overline{\mathbb{M}}[\boldsymbol{I_i}]}+1\right], \text{wp1}$$

where $I_i[m]$ is the inter-delivery time of node i and $\overline{\mathbb{M}}[I_i]$ is the **sample mean** of $I_i[m]$.

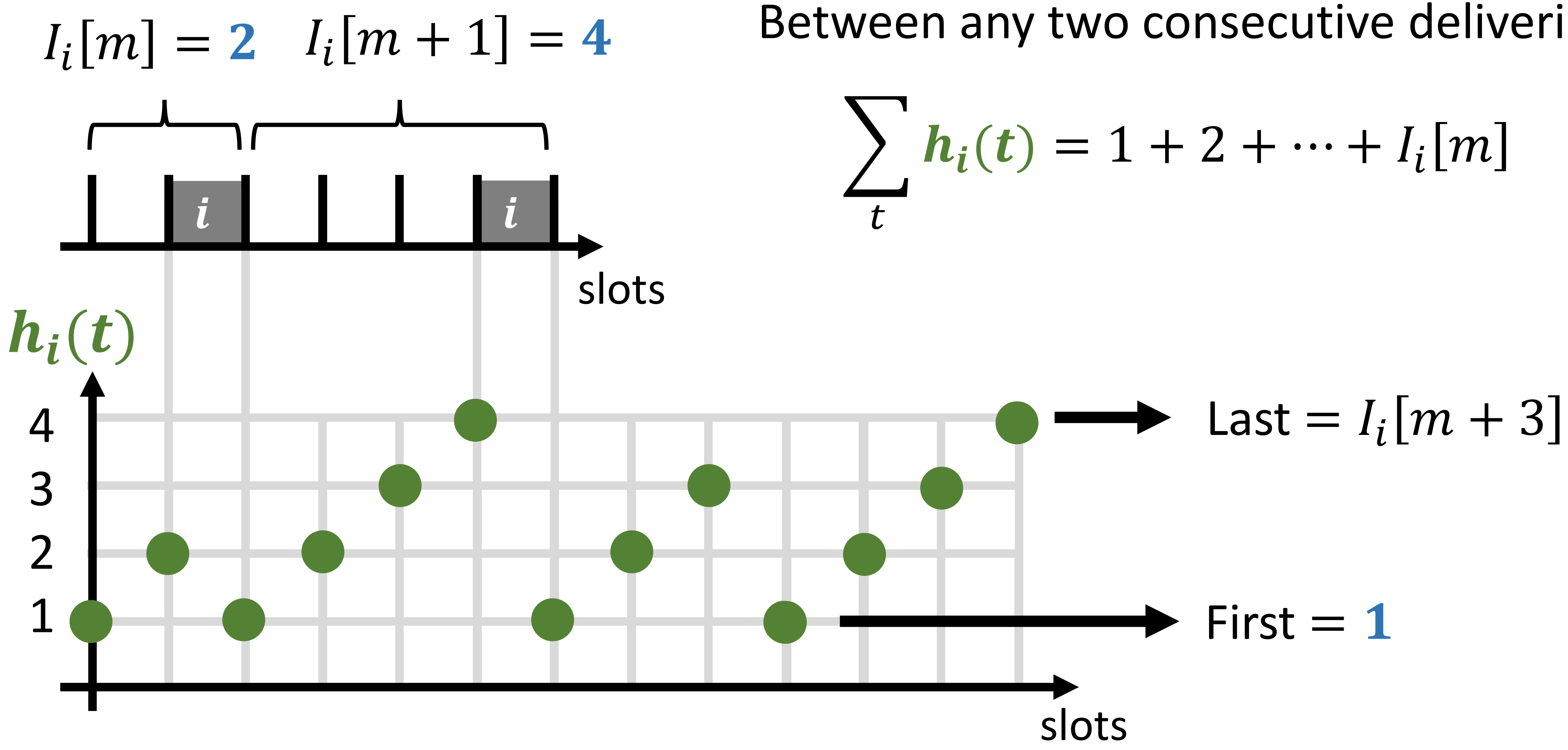
$$\lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} \boldsymbol{h_i(t)} = \frac{1}{2}\left[\frac{\overline{\mathbb{M}}[\boldsymbol{I_i^2}]}{\overline{\mathbb{M}}[\boldsymbol{I_i}]}+1\right], \text{wp1}$$



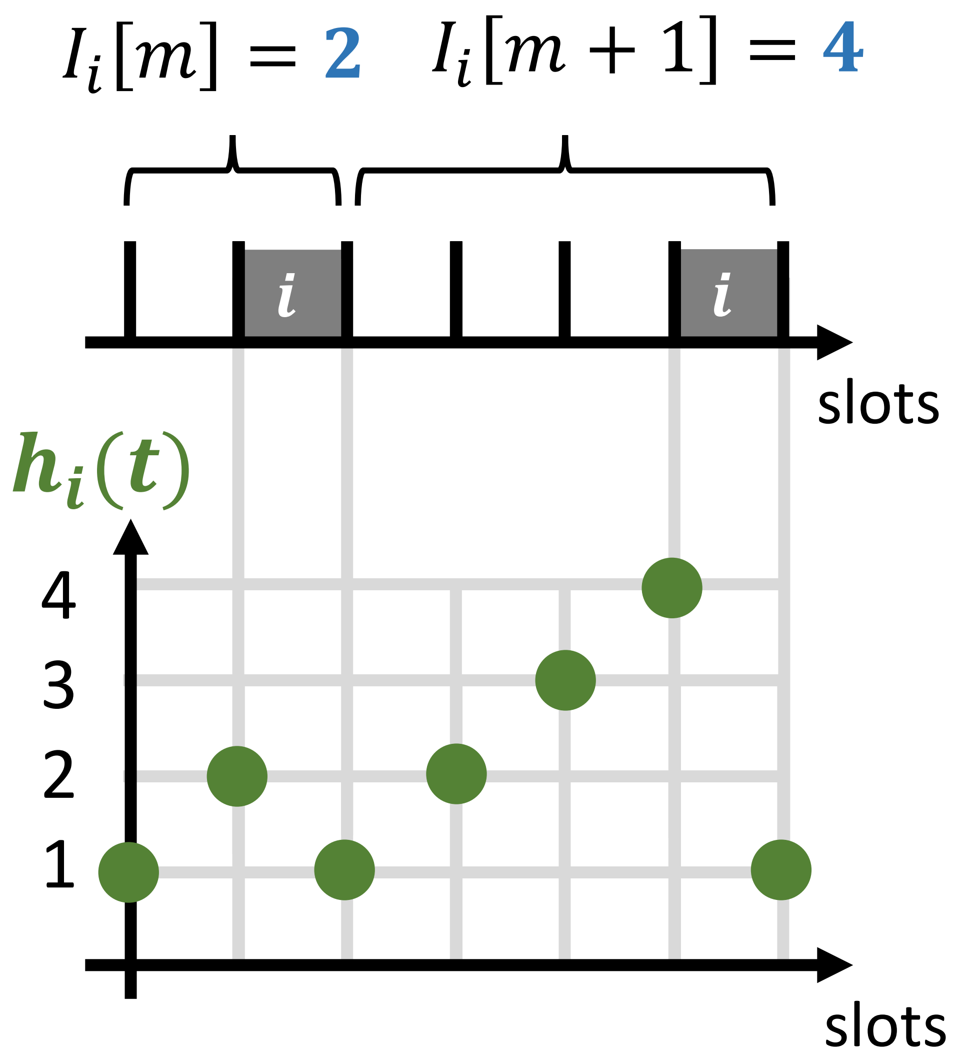
Intuition of the proof

Between any two consecutive deliveries:

$$\sum_t \boldsymbol{h_i(t)} = 1 + 2 + \cdots + I_i[m]$$



Intuition of the proof



Between any two consecutive deliveries:

$$\sum_t h_i(t) = \frac{I_i[m]^2 + I_i[m]}{2}$$

Hence, the **time-average AoI** is:

$$\frac{1}{T}\sum_{t=1}^{T} h_i(t) \approx \frac{1}{\bar{\mathbb{M}}[I_i]}\left[\frac{\bar{\mathbb{M}}[I_i^2] + \bar{\mathbb{M}}[I_i]}{2}\right]$$

$$\frac{1}{T}\sum_{t=1}^{T} h_i(t) \approx \frac{1}{2}\left[\frac{\bar{\mathbb{M}}[I_i^2]}{\bar{\mathbb{M}}[I_i]} + 1\right]$$

Lower Bound

Lemma:

$$\lim_{T\to\infty} J_T^{\pi} \triangleq \lim_{T\to\infty} \frac{1}{TN}\sum_{t=1}^{T}\sum_{i=1}^{N} \boldsymbol{w_i h_i(t)} = \frac{1}{N}\sum_{i=1}^{N} \frac{\boldsymbol{w_i}}{2}\left[\frac{\overline{\mathbb{M}}[\boldsymbol{I_i^2}]}{\overline{\mathbb{M}}[\boldsymbol{I_i}]} + 1\right], \text{wp1}$$

Theorem:

$$\lim_{T\to\infty} \mathbb{E}[J_T^{\pi}] \geq \boldsymbol{L_B}, \text{where } \mathbf{L_B} = \frac{1}{2N}\min_{\pi\in\Pi}\left\{\sum_{i=1}^{N} \boldsymbol{w_i}\mathbb{E}\left[\overline{\mathbb{M}}[I_i^{\pi}]\right]\right\} + \frac{1}{2N}\sum_{i=1}^{N}\boldsymbol{w_i}$$

Proof outline: applying Fatou's Lemma to the non-negative sequence J_T^{π} and then the generalized mean inequality $\overline{\mathbb{M}}\left[I_i^2\right] \geq (\overline{\mathbb{M}}[I_i])^2$.

Lower Bound

Lemma:

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Theorem:

$$\lim_{T\to\infty} \mathbb{E}[J_T^{\pi}] \geq \boldsymbol{L_B}, \text{where } \mathbf{L_B} = \frac{1}{2N}\left(\sum_{i=1}^{N}\sqrt{\frac{\boldsymbol{w_i}}{\boldsymbol{p_i}}}\right)^2 + \frac{1}{2N}\sum_{i=1}^{N}\boldsymbol{w_i}$$

<u>Proof outline</u>: applying Fatou's Lemma to the non-negative sequence J_T^{π} and then the generalized mean inequality $\overline{\mathbb{M}}[I_i^2] \geq (\overline{\mathbb{M}}[I_i])^2$.

Performance Guarantees

- **Performance Guarantee for π:** for any given network with (N, w_i, p_i)

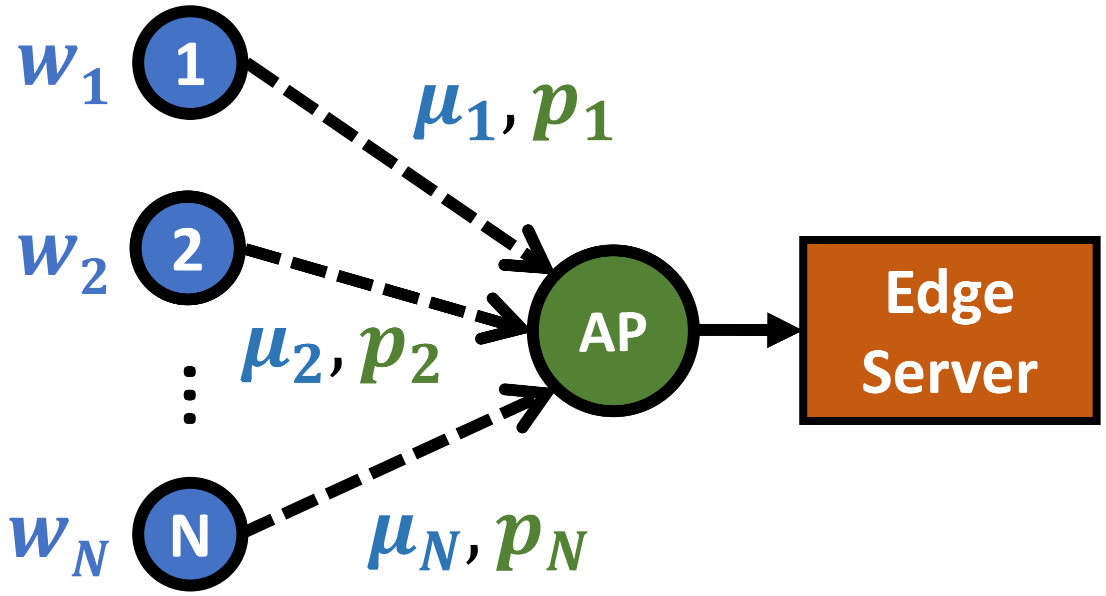
$$L_B \le \mathbb{E}[J^*] \le \mathbb{E}[J^\pi] \le \beta^\pi L_B$$

- Three **scheduling policies** with performance guarantees:

Scheduling Policy	Proof Technique	Optimality Ratio
Optimal Stationary Randomized Policy	Renewal Theory	**2**-optimal
Age-Based Max-Weight Policy	Lyapunov Optimization	**2**-optimal
Whittle's Index Policy	RMAB Framework	**8**-optimal

Stationary Randomized Policies

- **Randomized Policy R:** in slot t, select source i with probability μ_i.
- $d_i^R(t) \sim Ber(\mu_i p_i)$ and $I_i^R[m] \sim Geo(\mu_i p_i)$ iid for node i



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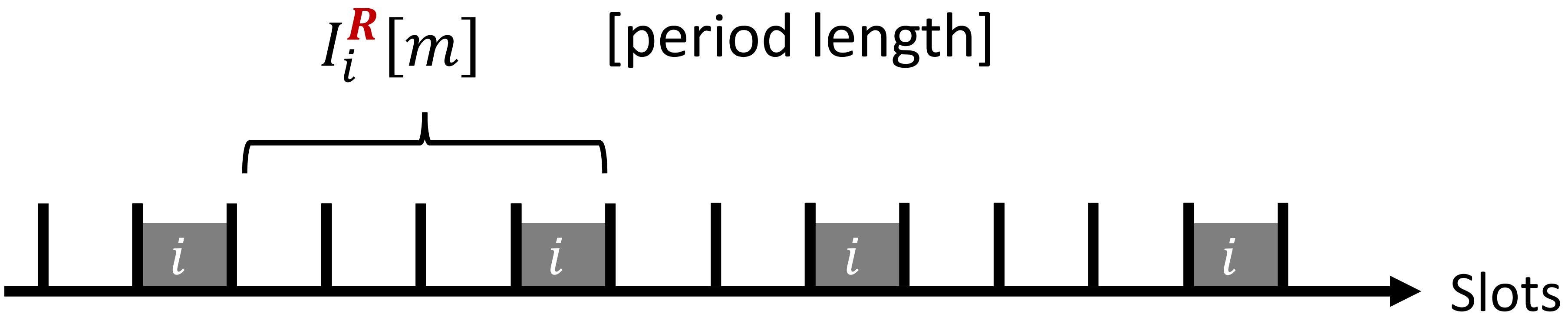
- $d_i^{\boldsymbol{R}}(t) \sim Ber(\boldsymbol{\mu_i p_i})$ and $I_i^{\boldsymbol{R}}[m] \sim Geo(\boldsymbol{\mu_i p_i})$ iid for node i
- Sequence of packet deliveries from node i is a **renewal process**



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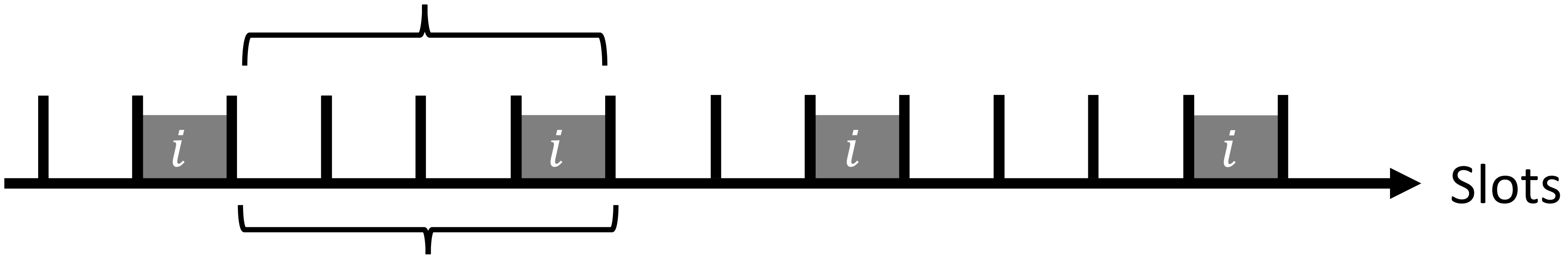
- $d_i^{\boldsymbol{R}}(t) \sim Ber(\boldsymbol{\mu_i} \boldsymbol{p_i})$ and $I_i^{\boldsymbol{R}}[m] \sim Geo(\boldsymbol{\mu_i} \boldsymbol{p_i})$ iid for node i
- Sequence of packet deliveries from node i is a **renewal process**
- Sum of $\boldsymbol{h_i^R(t)}$ is a **renewal-reward process:**

$I_i^{\boldsymbol{R}}[m]$ [period length]



$$\sum_t \boldsymbol{h_i^R(t)} = \frac{\left(I_i^{\boldsymbol{R}}[m]\right)^2 + I_i^{\boldsymbol{R}}[m]}{2}$$ [reward in one period]

Stationary Randomized Policies

- **Randomized Policy R:** in slot t, select source i with probability $\boldsymbol{\mu_i}$.
- $d_i^{\boldsymbol{R}}(t) \sim Ber(\boldsymbol{\mu_i p_i})$ and $I_i^{\boldsymbol{R}}[m] \sim Geo(\boldsymbol{\mu_i p_i})$ iid for node i
- Sequence of packet deliveries from node i is a **renewal process**
- Sum of $\boldsymbol{h_i^R(t)}$ is a **renewal-reward process:**
  - Period length $\mathbb{E}\left[I_i^{\boldsymbol{R}}\right] = (\boldsymbol{\mu_i p_i})^{-1}$ and reward is $\mathbb{E}\left[\left(I_i^{\boldsymbol{R}}\right)^2 + I_i^{\boldsymbol{R}}\right]/2 = (\boldsymbol{\mu_i p_i})^{-2}$

Hence, by the elementary renewal theorem:

$$\lim_{T\to\infty} \mathbb{E}\left[J_T^{\boldsymbol{R}}\right] = \frac{1}{N}\sum_{i=1}^{N} \boldsymbol{w_i} \frac{\mathbb{E}[\,reward_{\,i}\,]}{\mathbb{E}[\,period_{\,i}\,]} = \frac{1}{N}\sum_{i=1}^{N} \frac{\boldsymbol{w_i}}{\boldsymbol{\mu_i p_i}}$$

Stationary Randomized Policies

- **Randomized Policy R:** in slot t, select source i with probability μ_i.
- **Optimal Randomized policy R*:** $(\mu_i^*)_{i=1}^N = \underset{\mu_i,\forall i}{\operatorname{argmin}} \left\{ \frac{1}{N} \sum_{i=1}^N \frac{w_i}{\mu_i p_i} \right\}$

  The optimal solution is $\mu_i^* = \frac{\sqrt{w_i/p_i}}{\sum_{j=1}^N \sqrt{w_j/p_j}} \propto \sqrt{w_i/p_i}$

- **EWSAoI:** $\lim_{T\to\infty} \mathbb{E}[J_T^{R^*}] = \frac{1}{N} \sum_{i=1}^N \frac{w_i}{\mu_i^* p_i} = \frac{1}{N} \left(\sum_{i=1}^N \sqrt{\frac{w_i}{p_i}} \right)^2$

Stationary Randomized Policies

Thm: for any given network configuration, **optimal randomized R*** is **2-optimal**

- **EWSAoI:** $\lim_{T\to\infty} \mathbb{E}\left[J_T^{R^*}\right] = \frac{1}{N}\sum_{i=1}^{N} \frac{w_i}{\mu_i^* p_i} = \frac{1}{N}\left(\sum_{i=1}^{N}\sqrt{\frac{w_i}{p_i}}\right)^2$
- **Lower Bound:** $\lim_{T\to\infty} \mathbb{E}[J_T^{\pi}] \geq L_B$, where $L_B = \frac{1}{2N}\left(\sum_{i=1}^{N}\sqrt{\frac{w_i}{p_i}}\right)^2 + \frac{1}{N}\sum_{i=1}^{N} w_i$
- **Performance guarantee:** $L_B \leq \lim_{T\to\infty} \mathbb{E}\left[J_T^{R^*}\right] \leq 2L_B$ **[2-optimal]**

Age-Based Max-Weight policy

- Lyapunov Function: $L(t) = \frac{1}{N}\sum_{i=1}^{N} \gamma_i h_i(t)$, where $\gamma_i > 0$ is a constant
- Lyapunov Drift: $\Delta(t) = \mathbb{E}\{ L(t+1) - L(t) \mid h_i(t) \}$

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- Lyapunov Drift: $\Delta(t) = \mathbb{E}\{\, L(t+1) - L(t) \mid h_i(t) \,\}$
- Substituting $h_i(t+1) = h_i(t)[1 - d_i(t)\,] + 1$ into the drift

$$\Delta(t) = -\frac{1}{N}\sum_{i=1}^{N} \gamma_i h_i(t) p_i \mathbb{E}[u_i(t) | h_i(t)] + \frac{1}{N}\sum_{i=1}^{N} \gamma_i$$

- **MW policy:** in slot t, schedule node ($u_i(t) = 1$) with highest $\gamma_i h_i(t) p_i$

Age-Based Max-Weight policy

Thm: for any given network configuration, MW with $\boldsymbol{\gamma_i} = \boldsymbol{w_i / \mu_i^* p_i}$ is **2-optimal**

MW policy: in slot t, select node with highest $\boldsymbol{w_i p_i h_i^2(t)}$

Age-Based Max-Weight policy

Thm: for any given network configuration, MW with $\gamma_i = w_i/\mu_i^* p_i$ is **2-optimal**

MW policy: in slot t, select node with highest $w_i p_i h_i^2(t)$

- <u>Proof outline</u>:

  MW minimizes drift while optimal randomized R* does not. Thus:

  $$\Delta^{MW}(t) \le \Delta^{R^*}(t)$$

  Manipulating the expression and substituting $\gamma_i = w_i/\mu_i^* p_i$, gives:

  $$L_B \le \lim_{T\to\infty} \mathbb{E}[J_T^{MW}] \le \lim_{T\to\infty} \mathbb{E}[J_T^{R^*}] \le 2L_B$$

  Hence, **Age-Based Max-Weight is 2-optimal.**

Summary of Results

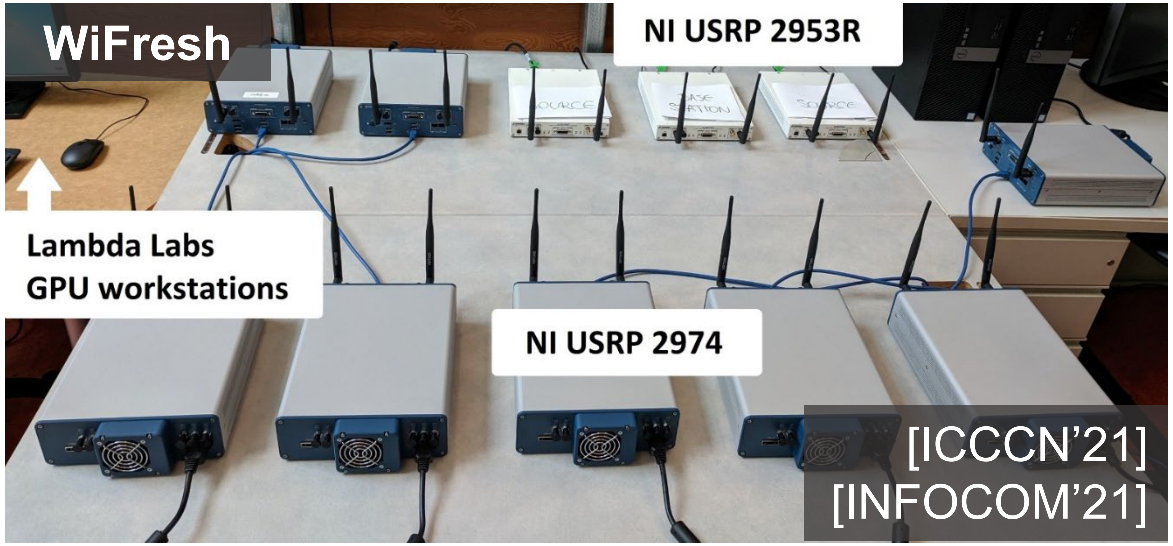
- **Performance Guarantee for π:** for any given network with (N, w_i, p_i)

$$L_B \leq \mathbb{E}[J^*] \leq \mathbb{E}[J^\pi] \leq \beta^\pi L_B$$

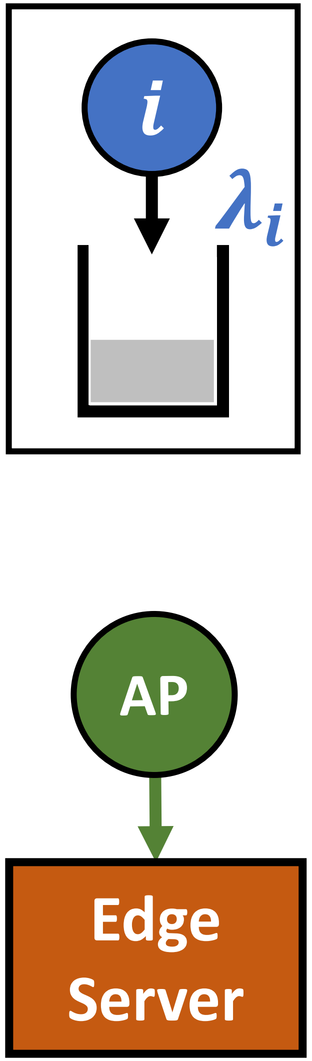
Scheduling Policy	Decision in slot t	Performance Guarantee	Simulation Result
Greedy	highest $h_i(t)$	optimal when symmetric	optimal when symmetric
Randomized	node i w.p. $\propto \sqrt{w_i/p_i}$	2-optimal	~ 2-optimal
Age-Based Max-Weight	highest $w_i p_i h_i^2(t)$	2-optimal	**close to optimal**

Outline

- **Theory:**
  - Introduction to Age-of-Information using a Simple System
  - Formulation of the AoI Minimization Problem in a Wireless Network
  - Theoretical Results: Lower Bound and Scheduling Policies
- **System Implementation in a SDR Testbed and Flight Tests with Drones**



WiFi: Network of Sensing-Drones



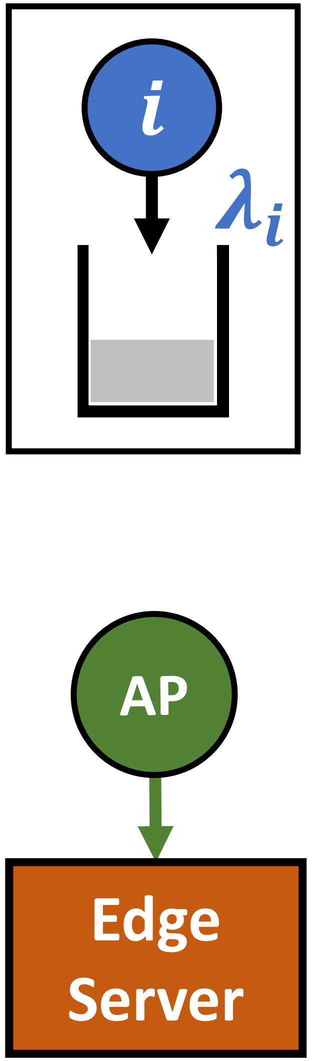
Generates time-sensitive information

FCFS queue

Wireless Access Point uses **Random Access**

Keeps track of the information

WiSwarm: Network of Sensing-Drones



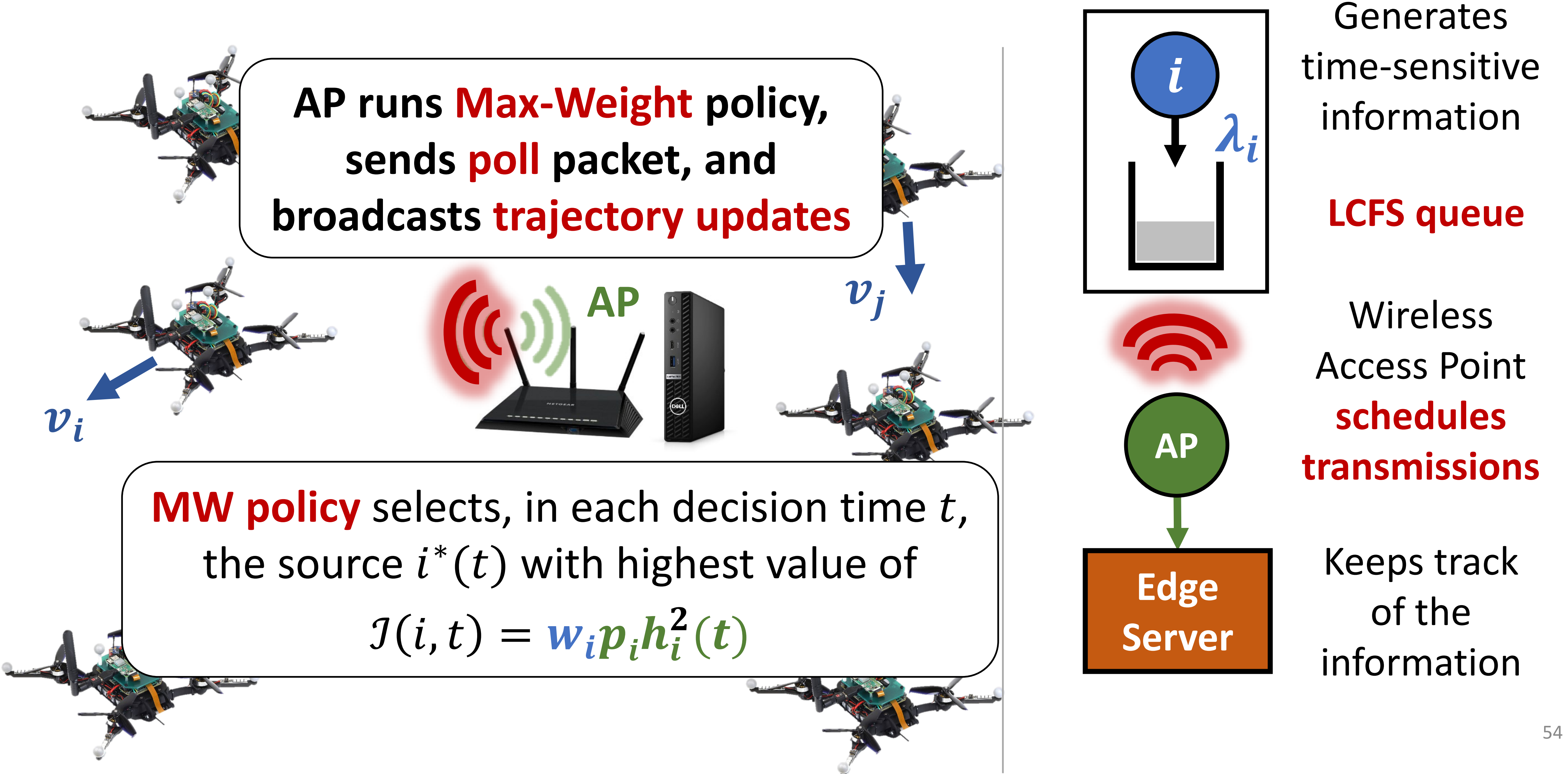
Generates time-sensitive information

LCFS queue

Wireless Access Point **schedules transmissions**

Keeps track of the information

WiSwarm: Network of Sensing-Drones



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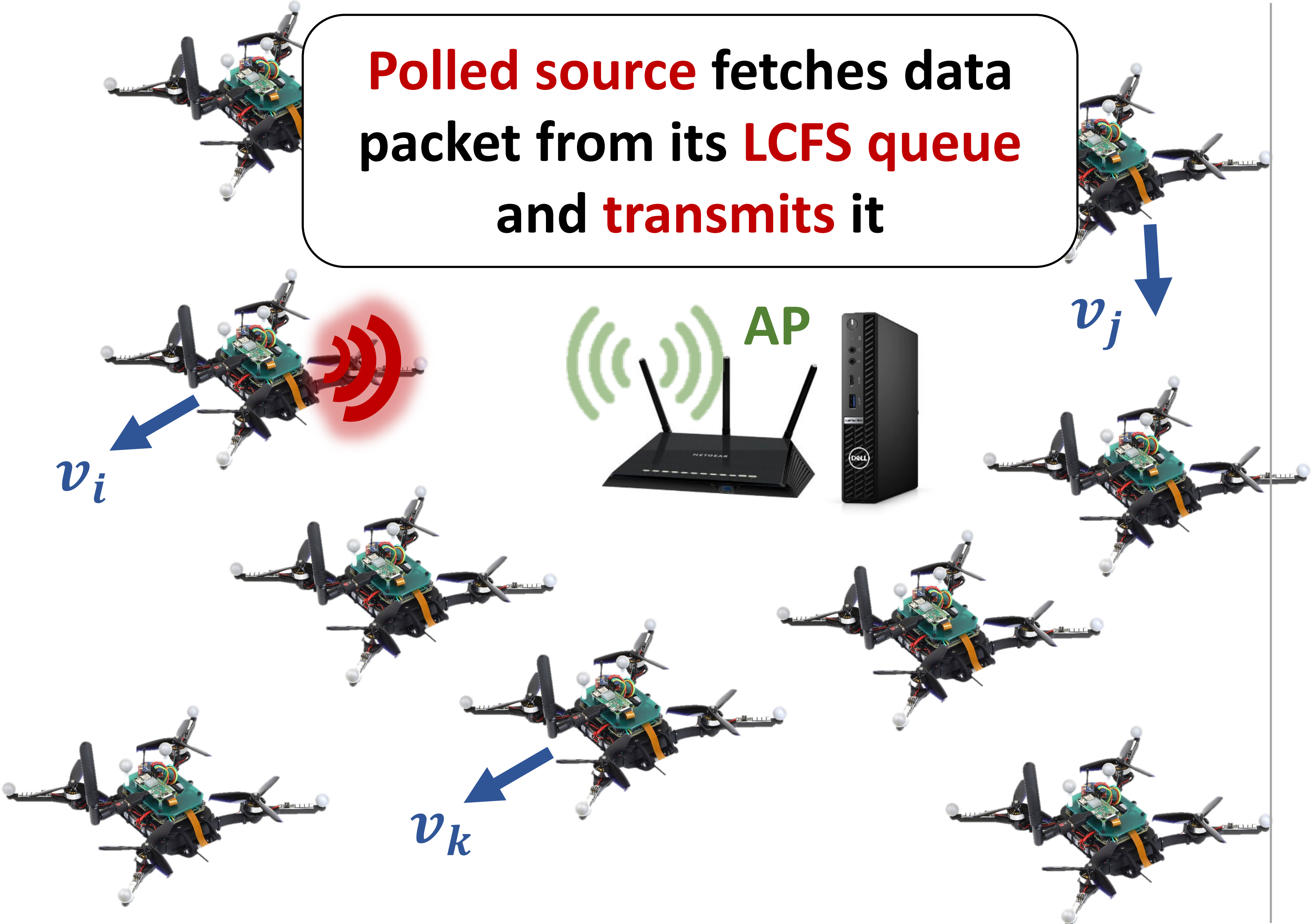

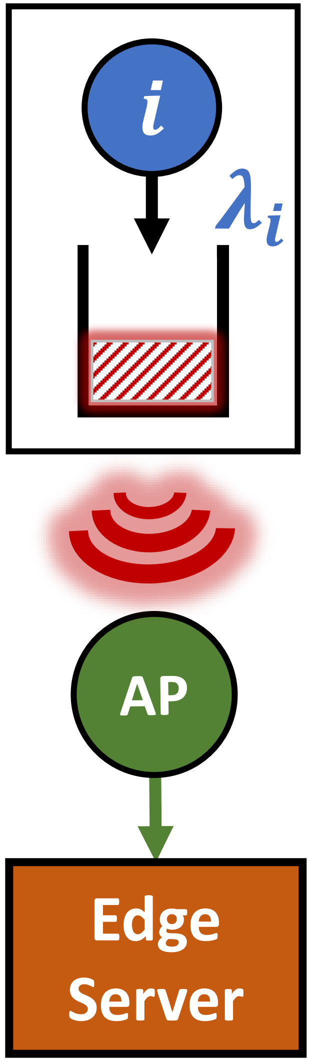

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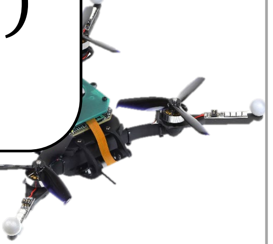
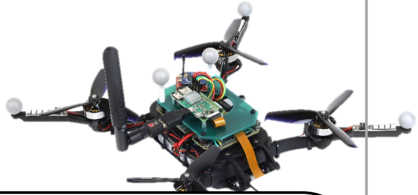
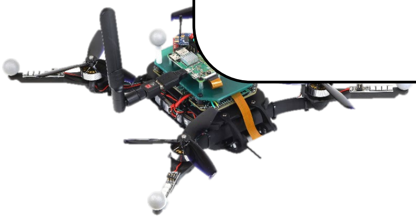


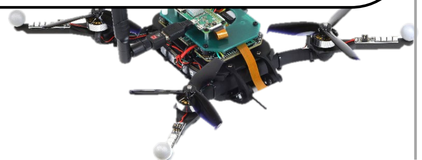
AP updates its belief about the network state ($\hat{h}_i(t)$, $\hat{p}_i(t)$) and about the environment

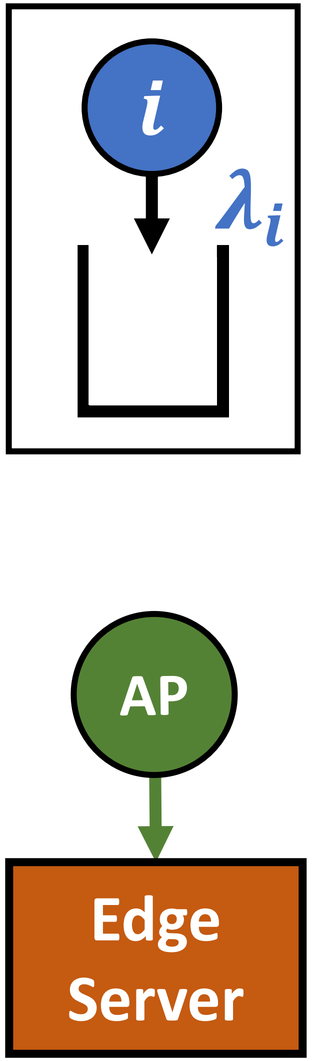


MW policy selects, in each decision time t, the source $i^*(t)$ with highest value of

$$\mathcal{J}(i,t) = w_i(t)\ \hat{p}_i(t)\hat{h}_i^2(t)$$







Generates time-sensitive information

LCFS queue

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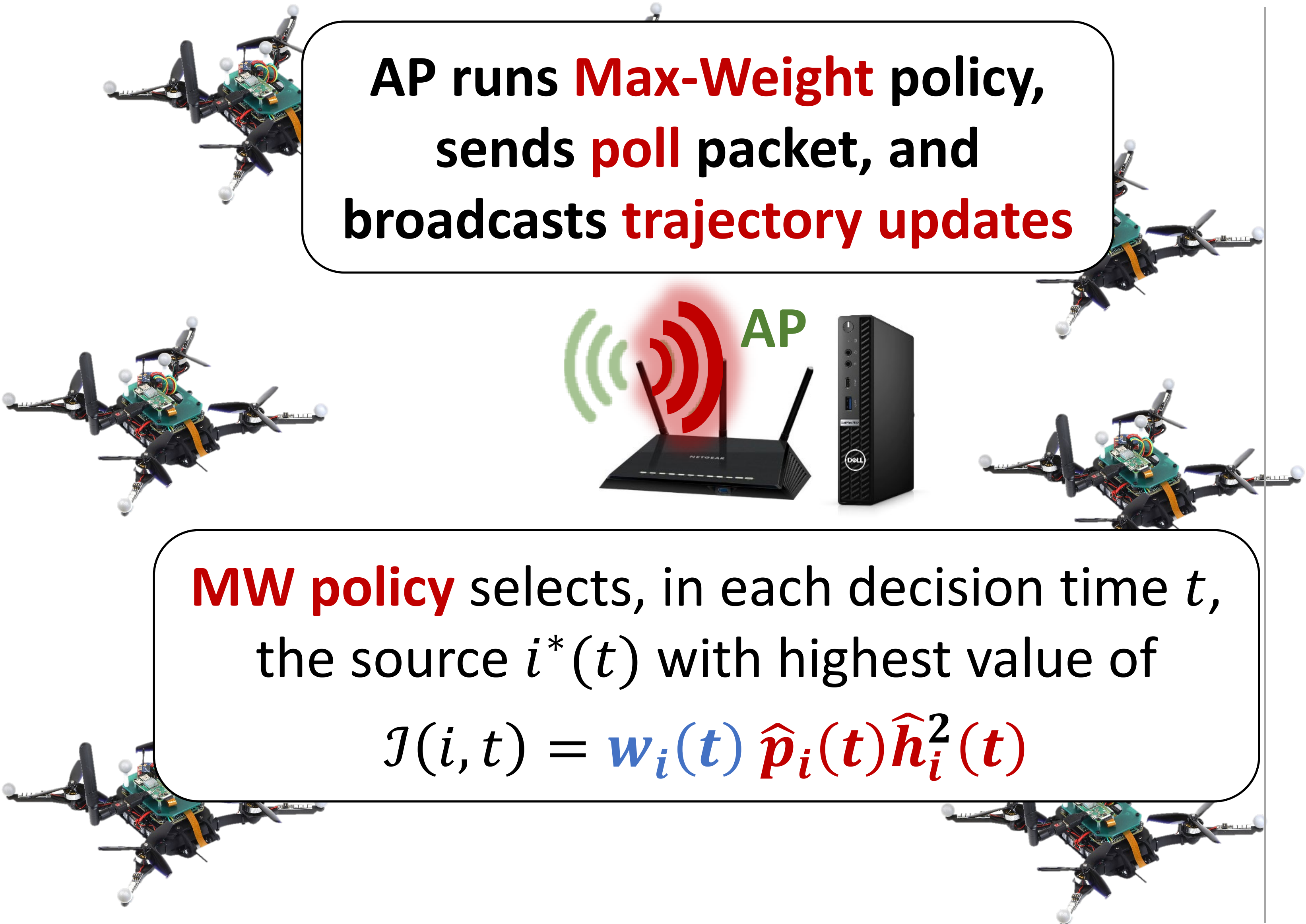
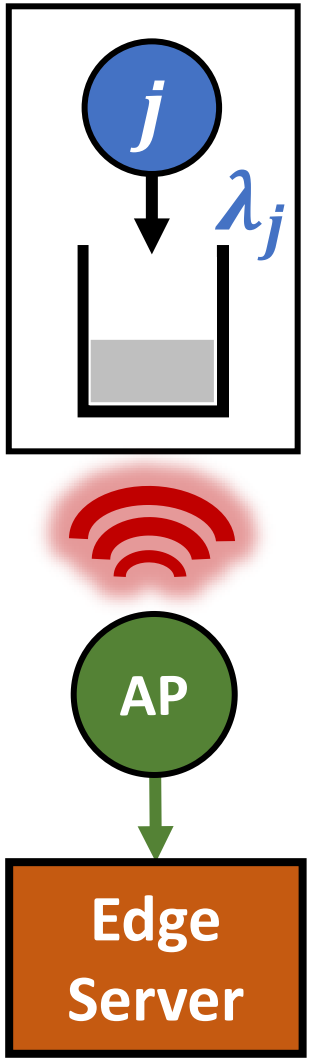


AP runs Max-Weight policy, sends poll packet, and broadcasts trajectory updates

MW policy selects, in each decision time t, the source $i^*(t)$ with highest value of

$$\mathcal{J}(i,t) = w_i(t)\,\hat{p}_i(t)\hat{h}_i^2(t)$$



Generates time-sensitive information

LCFS queue

Wireless Access Point **schedules transmissions**

Keeps track of the information

Implementations (It takes a village…)

WiFresh in a SDR testbed

Source	Access Point	Server
APP	APP	APP
TRA	TRA	TRA
NET	NET	NET
MAC	**MAC**	MAC
PHY	**PHY**	PHY

WiSwarm in a drone testbed

Source	Access Point	Server
APP		**APP**
TRA		TRA
NET	NET	NET
MAC	**MAC**	**MAC**
PHY	**PHY**	**PHY**

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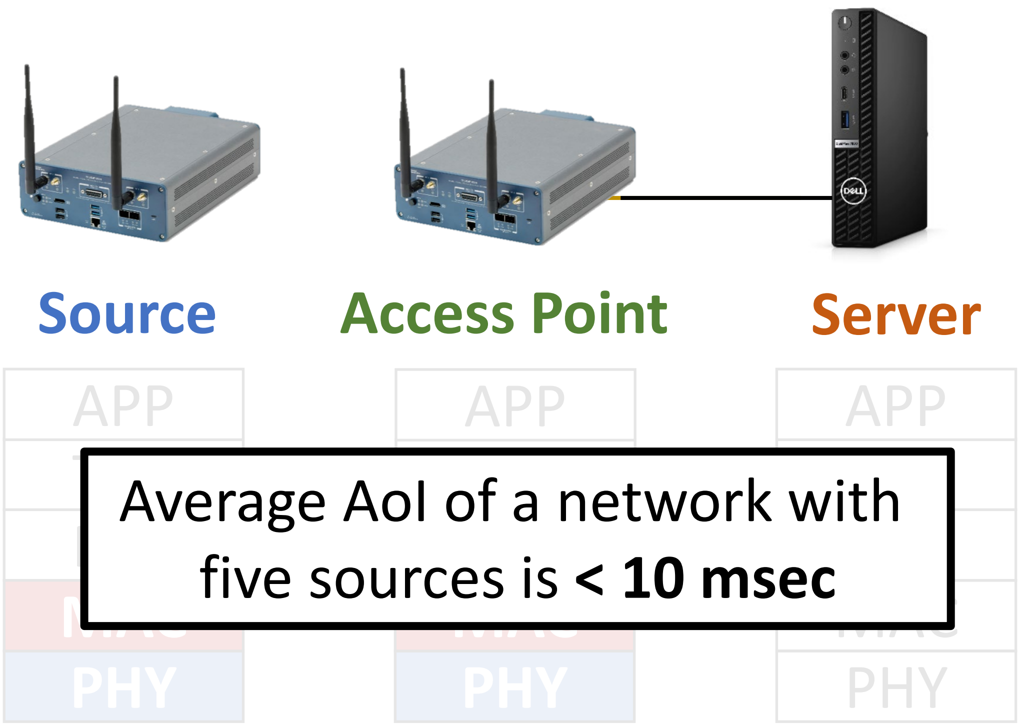
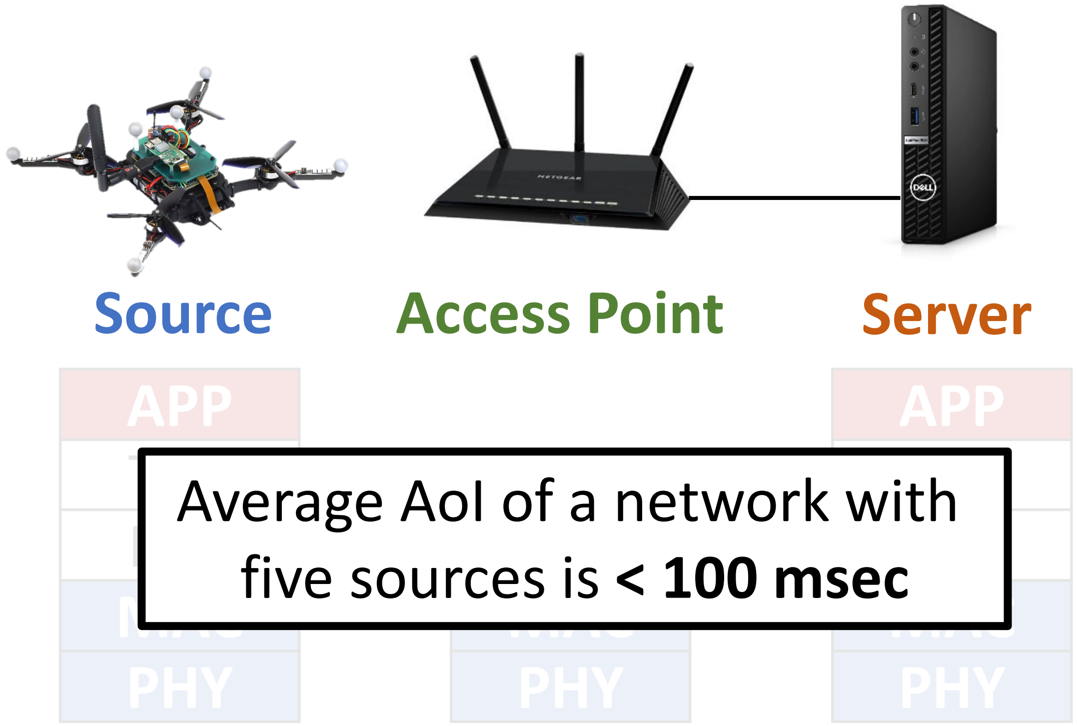


Average AoI of a network with five sources is **< 10 msec**

WiSwarm in a drone testbed



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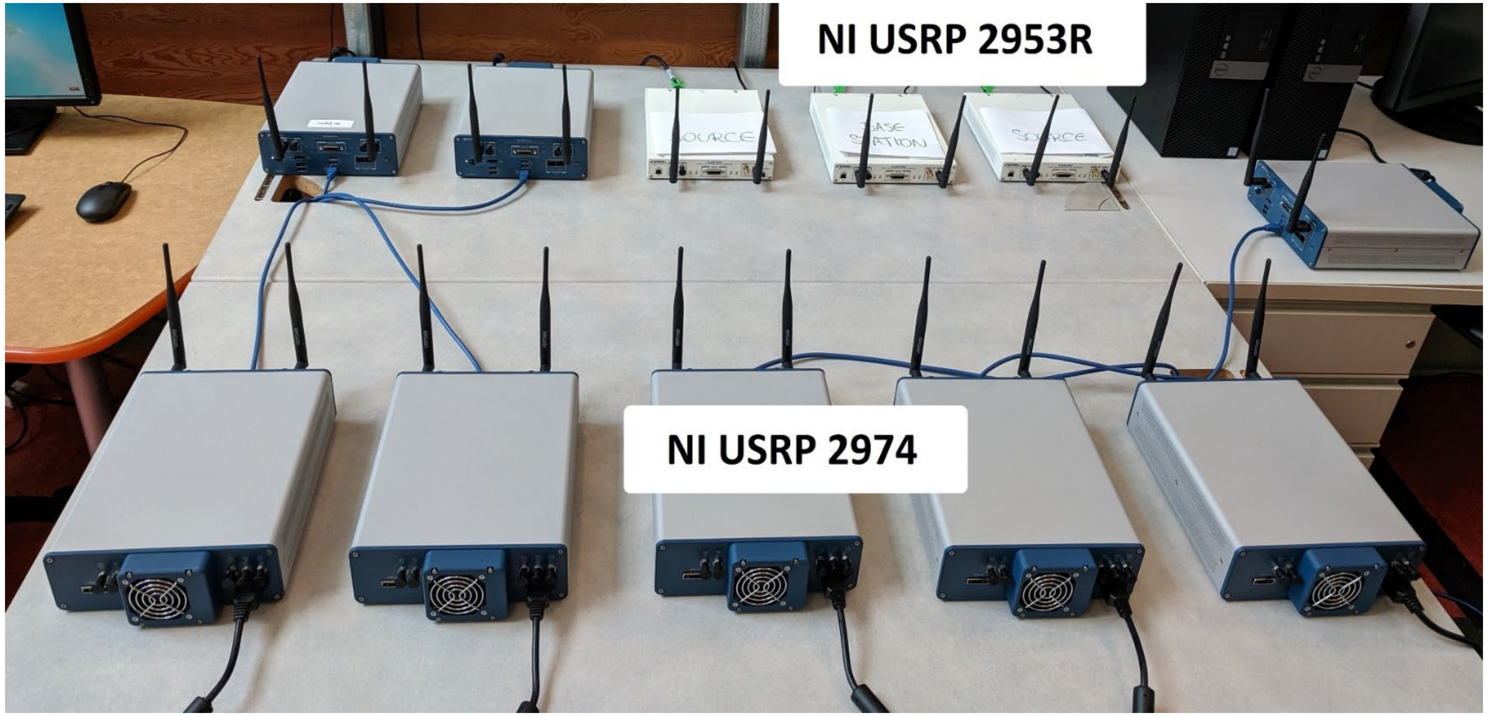
Implementation Challenges

- **Complexity:** Microsecond time-scale scheduling decisions achieved by implementing WiFresh at the MAC layer using FPGAs and hardware-level programming.

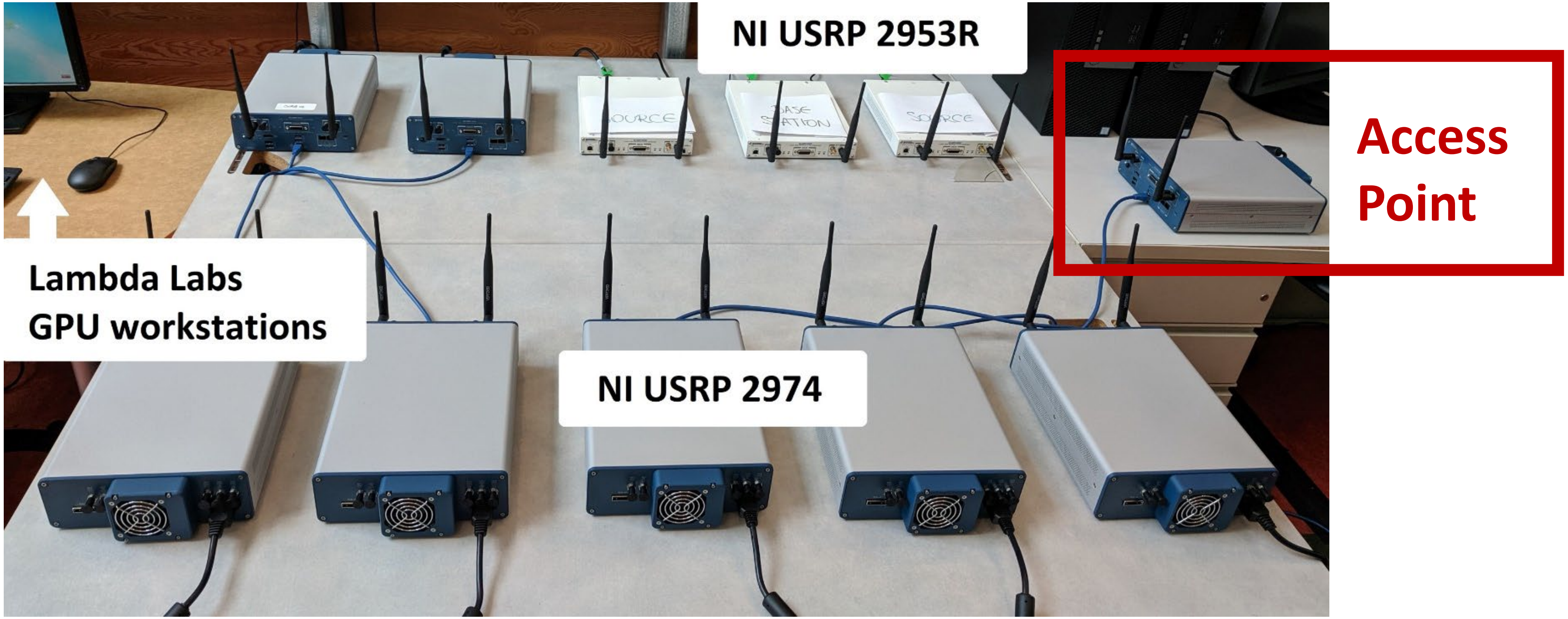
- **From Theory to Practice:**
  Clock Synchronization
  Estimation of Parameters
  Packet Fragmentation

- **Barrier to adoption:**
  Alternative implementation (WiSwarm) that can be easily integrated into applications already run over WiFi



WiFresh: Measurements

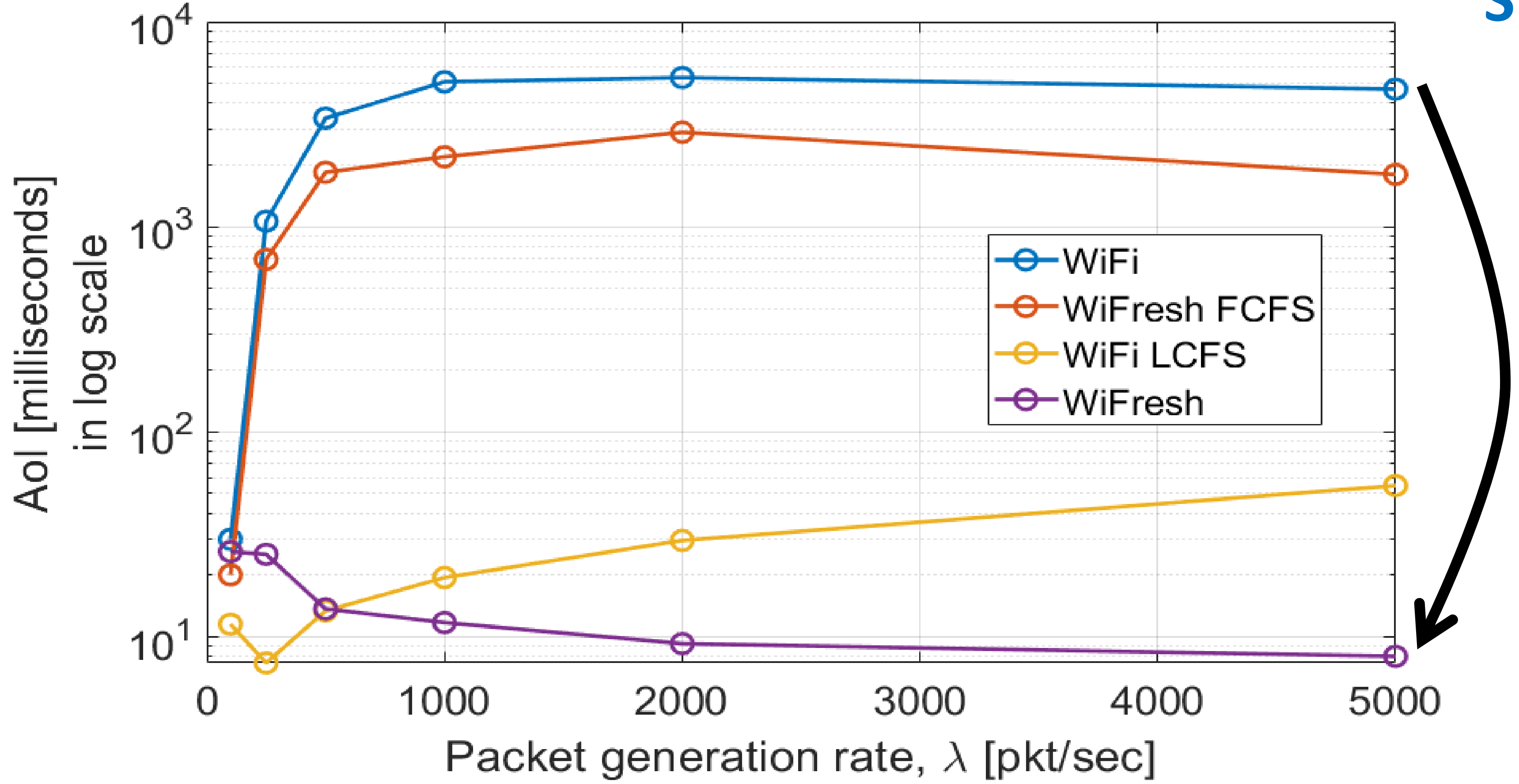
- Ten SDRs generating packets of 150 bytes with frequency λ packets per sec.



WiFresh: Measurements

- Ten SDRs generating packets of 150 bytes with frequency λ packets per sec.
- We measure the EWSAoI of the following communication systems:
  1) **WiFresh**;
  2) **Standard WiFi**
  3) **WiFresh FCFS**; and
  4) **WiFi LCFS**.
- Each experiment runs for a total of 10 minutes.

WiFresh: Measurements



Standard WiFi

AoI ~ 5 secs

Pos Uncert. ~ 5 m

x 586 improv.

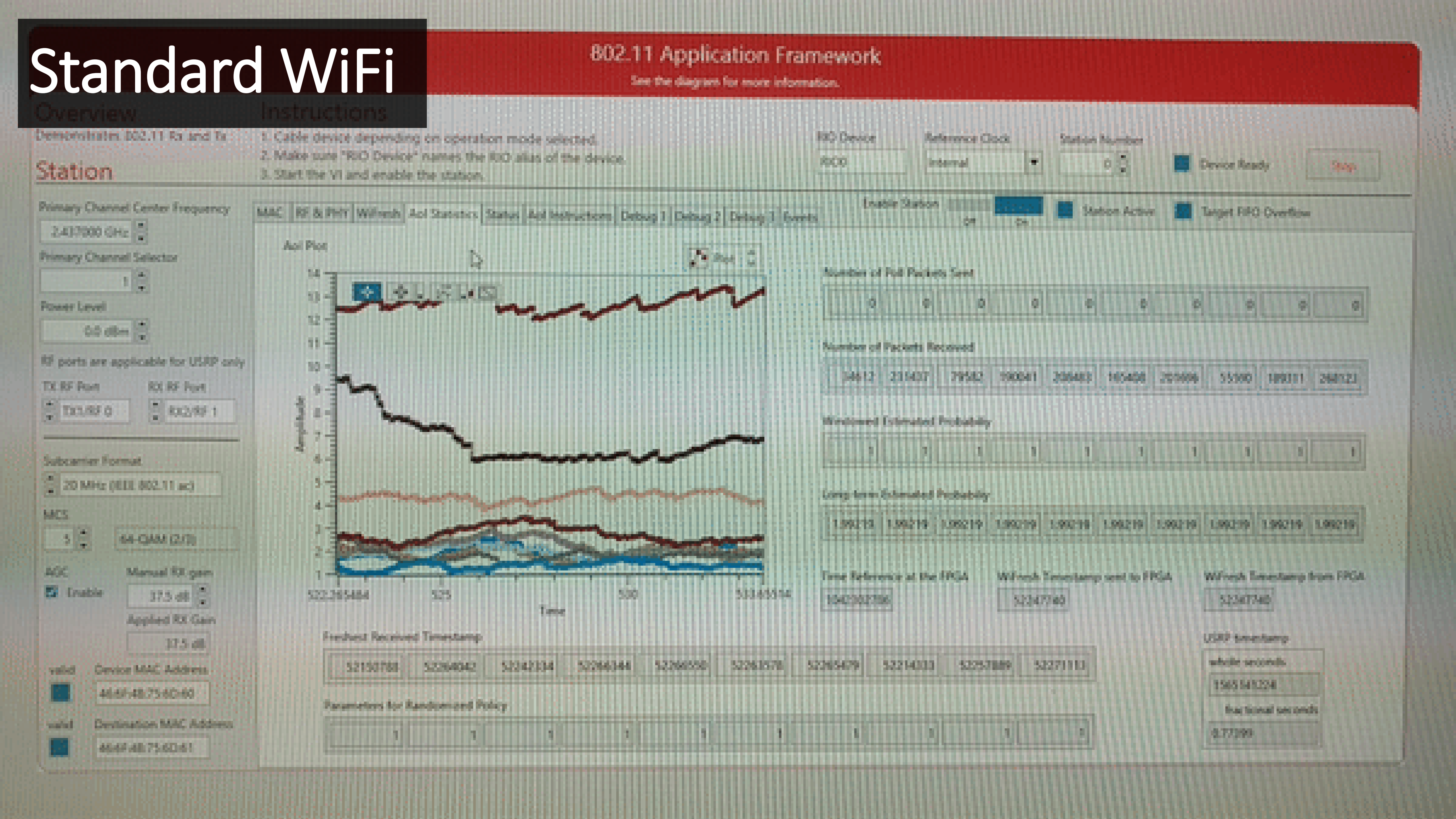
WiFresh

AoI ~ 10 msecs

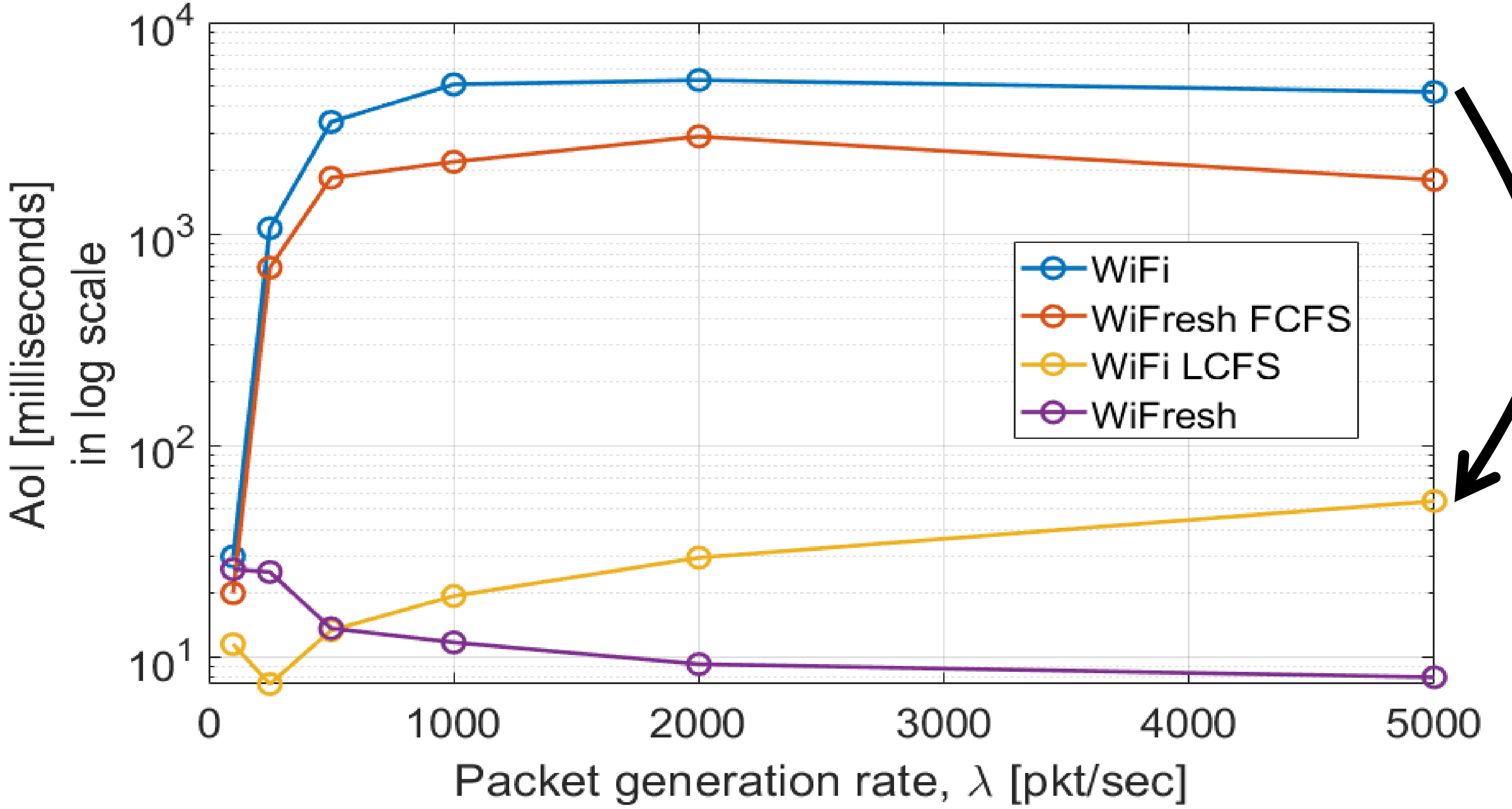
Pos Uncert. ~ 1 cm

WiFresh

Standard WiFi



WiFresh: Measurements



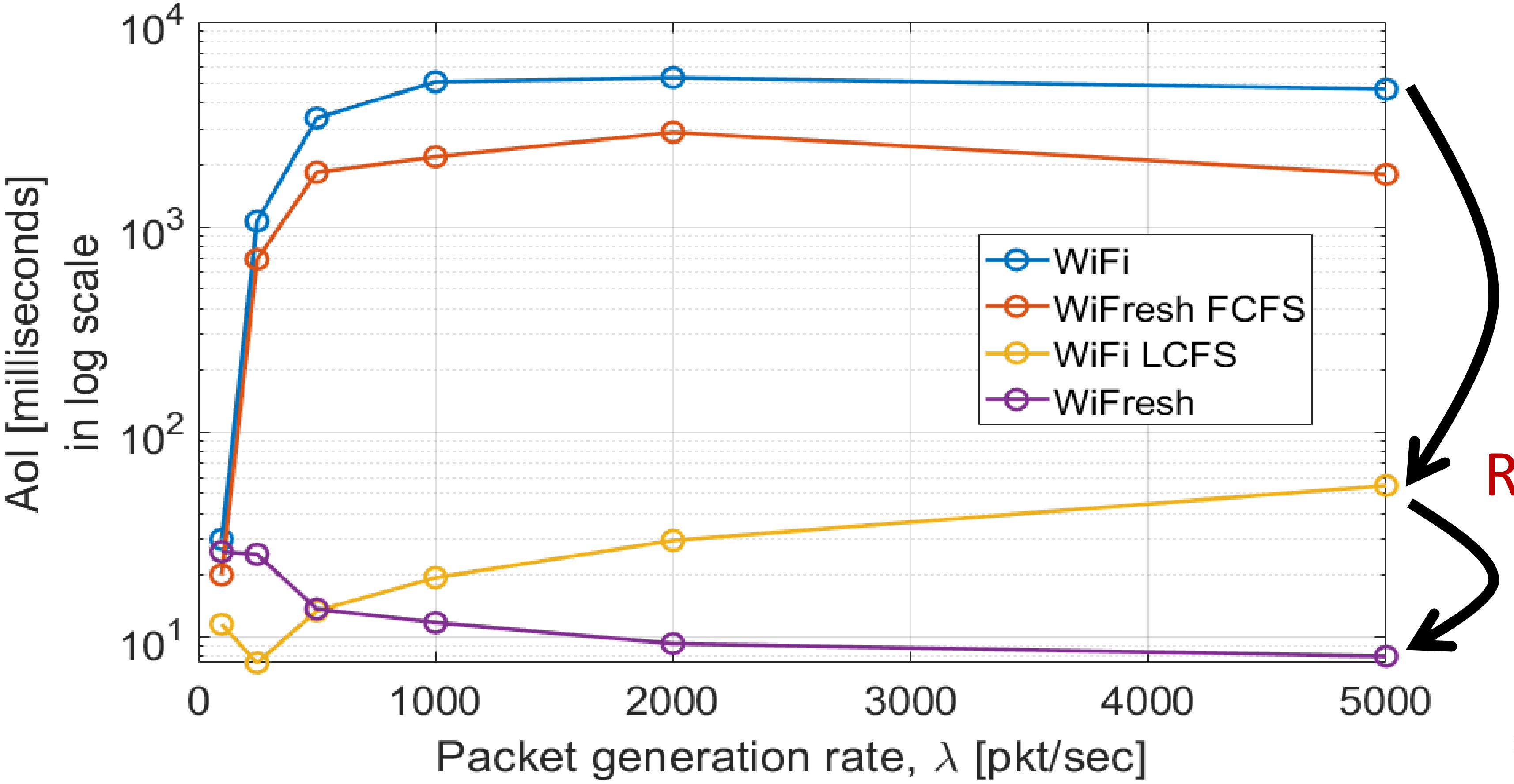
Standard WiFi =

Rand Access FCFS

x 85 improv.

Rand Access LCFS

WiFresh: Measurements



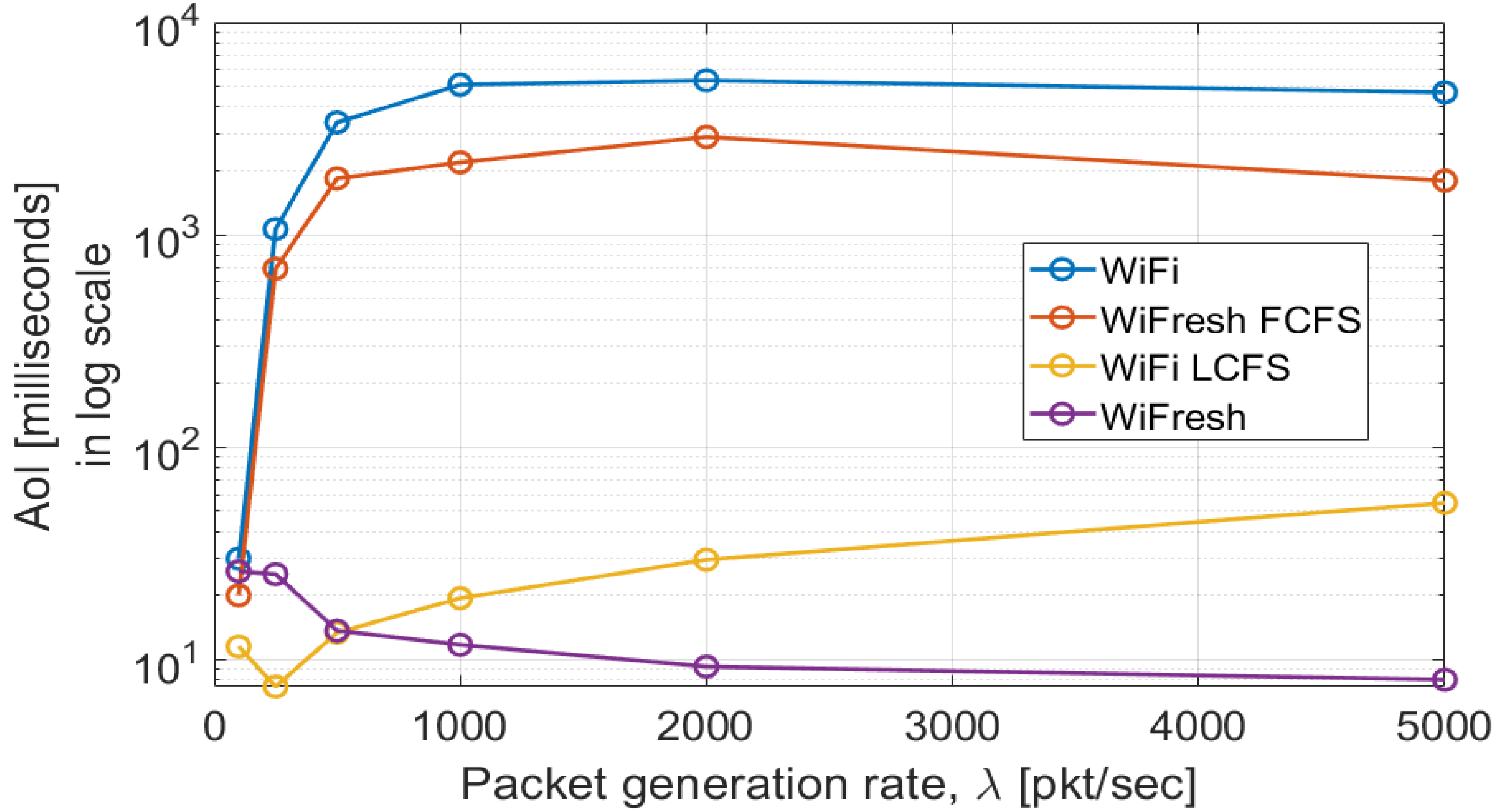
x 85 improv.

Rand Access LCFS

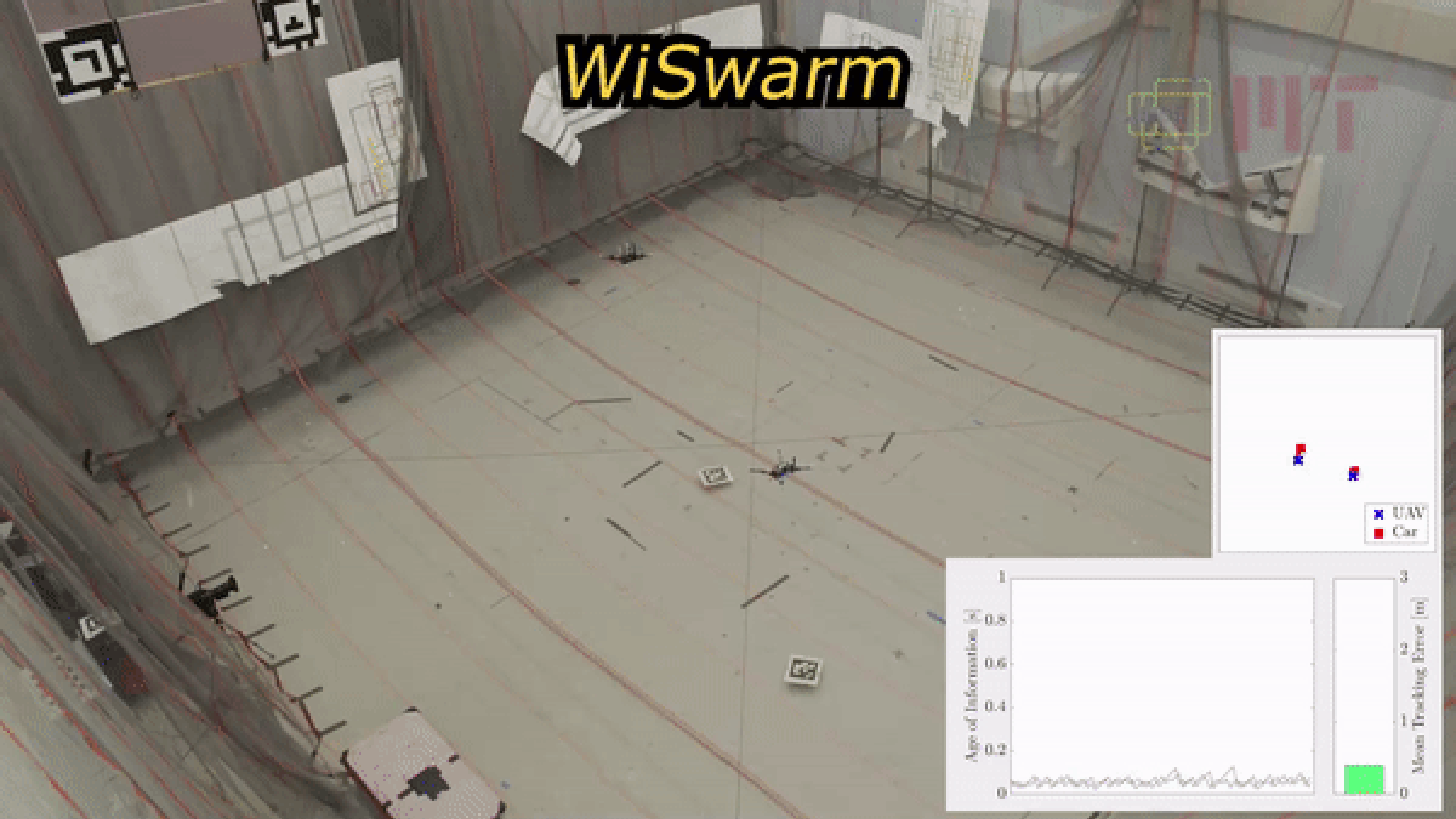
x 7 improv.

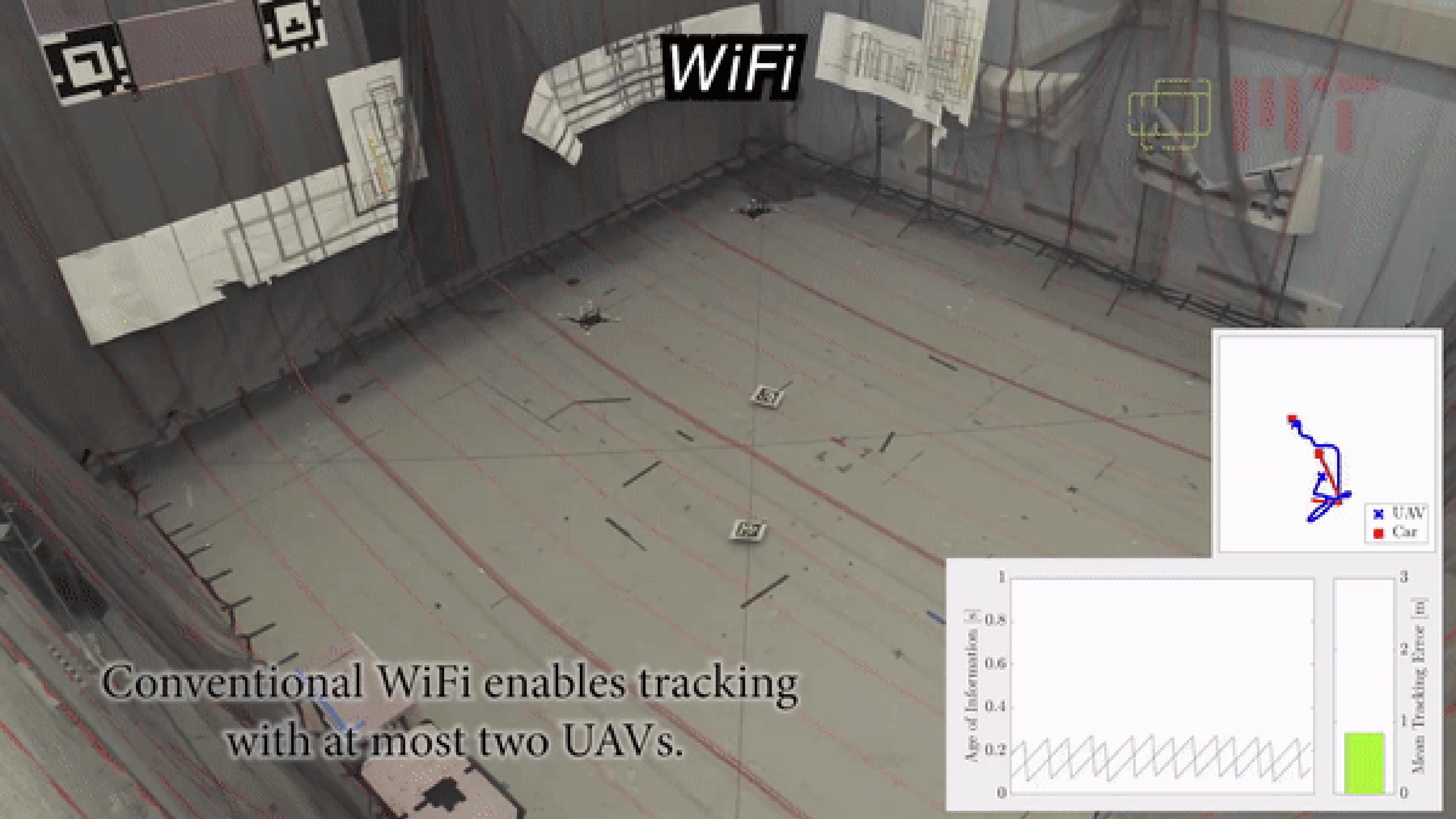
Max Weight LCFS
= **WiFresh**

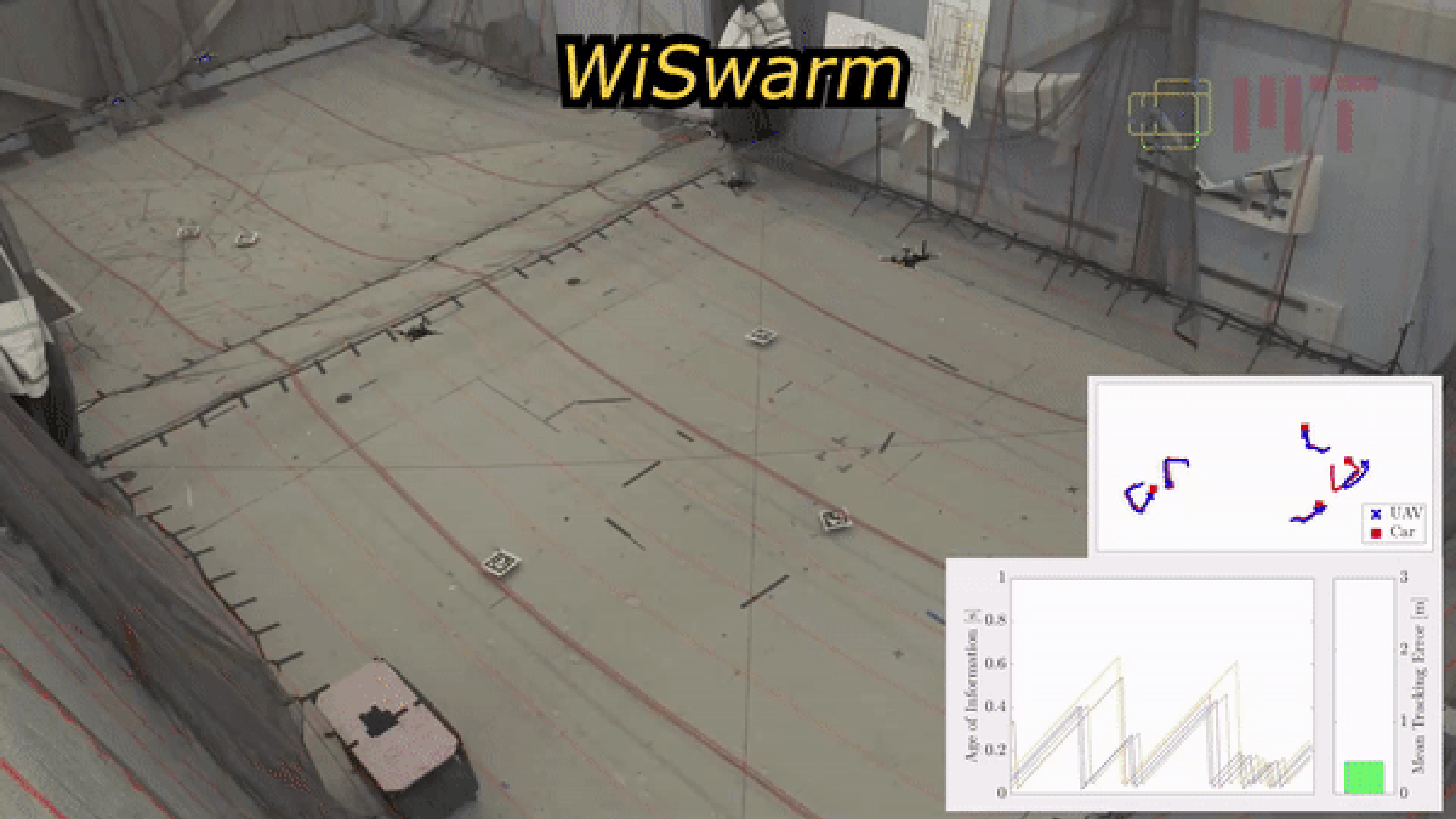
WiFresh: Measurements



WiFresh is the **only** in which a higher λ always leads to fresher info. at the destination


WiSwarm
UAV
Car
Age of Information [s]
Mean Tracking Error [m]


WiFi
Conventional WiFi enables tracking with at most two UAVs.
UAV
Car
Age of Information [s]
Mean Tracking Error [m]
0
0.2
0.4
0.6
0.8
1
2
3


WiSwarm
UAV
Car
Age of Information [s]
Mean Tracking Error [m]
0
0.2
0.4
0.6
0.8
1
0
1
2
3

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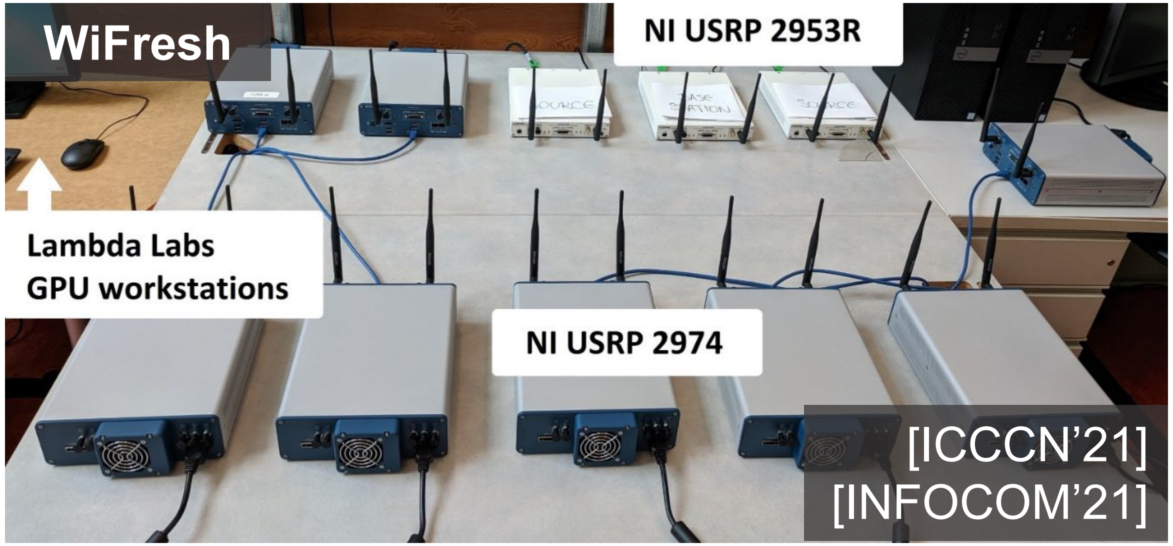
  - Theoretical Results: Lower Bound and Scheduling Policies

- **System Implementation in a SDR Testbed and Flight Tests with Drones**



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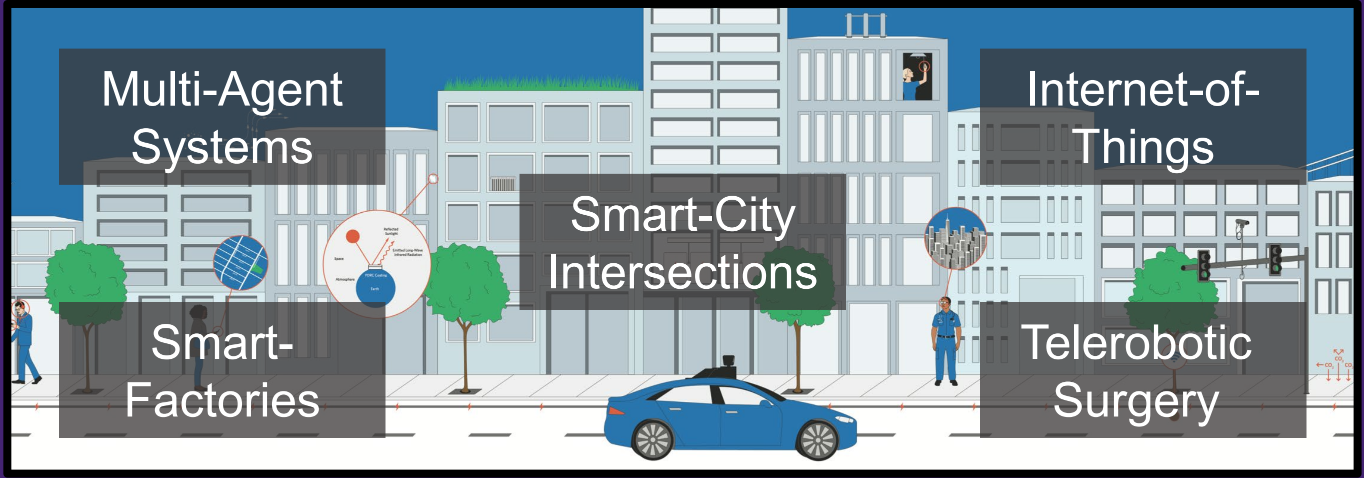
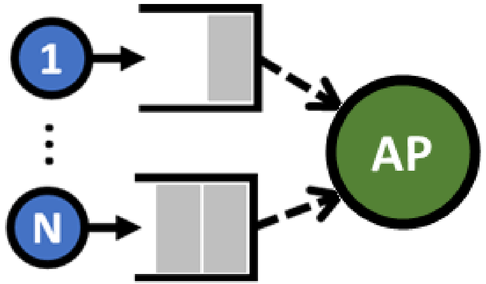
Future Applications

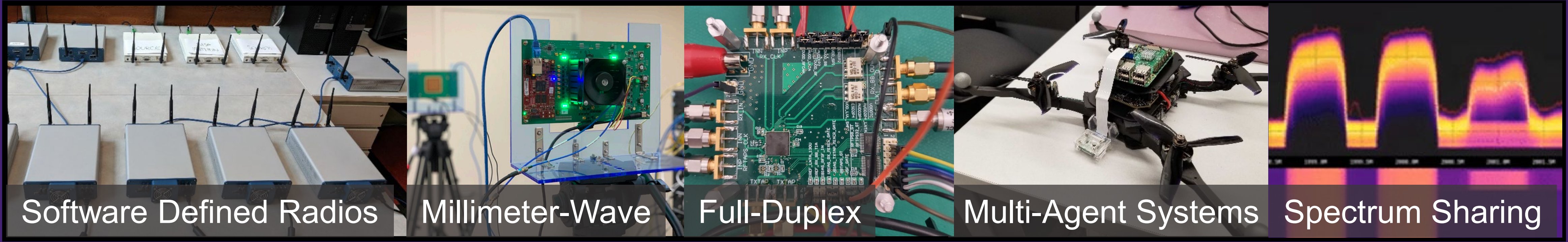


Rigorous Theory



Multi-Armed Bandits
Markov Decision Process
Lyapunov Optimization
Dynamic Programming

Next-Gen Technology



Supplemental Slides

Lower Bound

Lower Bound

Lemma:

$$\lim_{T\to\infty} J_T^{\pi} \triangleq \lim_{T\to\infty} \frac{1}{TN}\sum_{t=1}^{T}\sum_{i=1}^{N} \boldsymbol{w_i h_i(t)} \geq \frac{1}{2N}\sum_{i=1}^{N} \boldsymbol{w_i}\bar{\mathbb{M}}[\boldsymbol{I_i}] + \frac{1}{2N}\sum_{i=1}^{N}\boldsymbol{w_i}, \text{wp1}$$

<u>Proof outline</u>:

$$\sum_{i=1}^{N} \boldsymbol{w_i}\bar{\mathbb{M}}[\boldsymbol{I_i}] = \lim_{T\to\infty}\sum_{i=1}^{N}\boldsymbol{w_i}\frac{\sum_{m=1}^{D_i(T)} I_i^{\pi}[m]}{D_i(T)} \approx \lim_{T\to\infty} T\sum_{i=1}^{N}\frac{\boldsymbol{w_i}}{D_i(T)} \geq$$

$$\geq \lim_{T\to\infty}\sum_{i=1}^{N}\Upsilon_i(T)\sum_{i=1}^{N}\frac{\boldsymbol{w_i}}{D_i(T)} \geq \lim_{T\to\infty}\left(\sum_{i=1}^{N}\sqrt{\frac{\Upsilon_i(T)\,\boldsymbol{w_i}}{D_i(T)}}\right)^2 = \left(\sum_{i=1}^{N}\sqrt{\frac{\boldsymbol{w_i}}{\boldsymbol{p_i}}}\right)^2$$

Optimal Randomized Policy

Stationary Randomized Policies

- For fixed and positive w_i and p_i. Consider the optimization problem below:

$$\min_{\mu_i, \forall i} \left\{ \frac{1}{N} \sum_{i=1}^{N} \frac{w_i}{\mu_i p_i} \right\} \quad s.t. \sum_{i=1}^{N} \mu_i \leq 1$$

- The Cauchy-Schwarz Inequality (below) holds with **equality** when:

$$\left(\sum_{i=1}^{N} \sqrt{\frac{w_i}{p_i}} \right)^2 \leq \left(\sum_{i=1}^{N} \mu_i \right) \left(\sum_{i=1}^{N} \frac{w_i}{\mu_i p_i} \right)$$

$$\mu_i^* = \frac{\sqrt{w_i / p_i}}{\sum_{j=1}^{N} \sqrt{w_j / p_j}}, \forall \boldsymbol{i}$$