Age-of-Information: Definition, Analysis, and Applications

Igor Kadota

IEOR6706 Queueing Networks, November 10, 2020

Outline

1. Introduction:
   - Age-of-Information and Applications

2. Theoretical Results: scheduling policies with performance guarantees
   - Using Renewal Theory, Stochastic Dominance, RMAB framework, and others.

3. System Deployment: validation in real operating scenarios
   - Using Software Defined Radios

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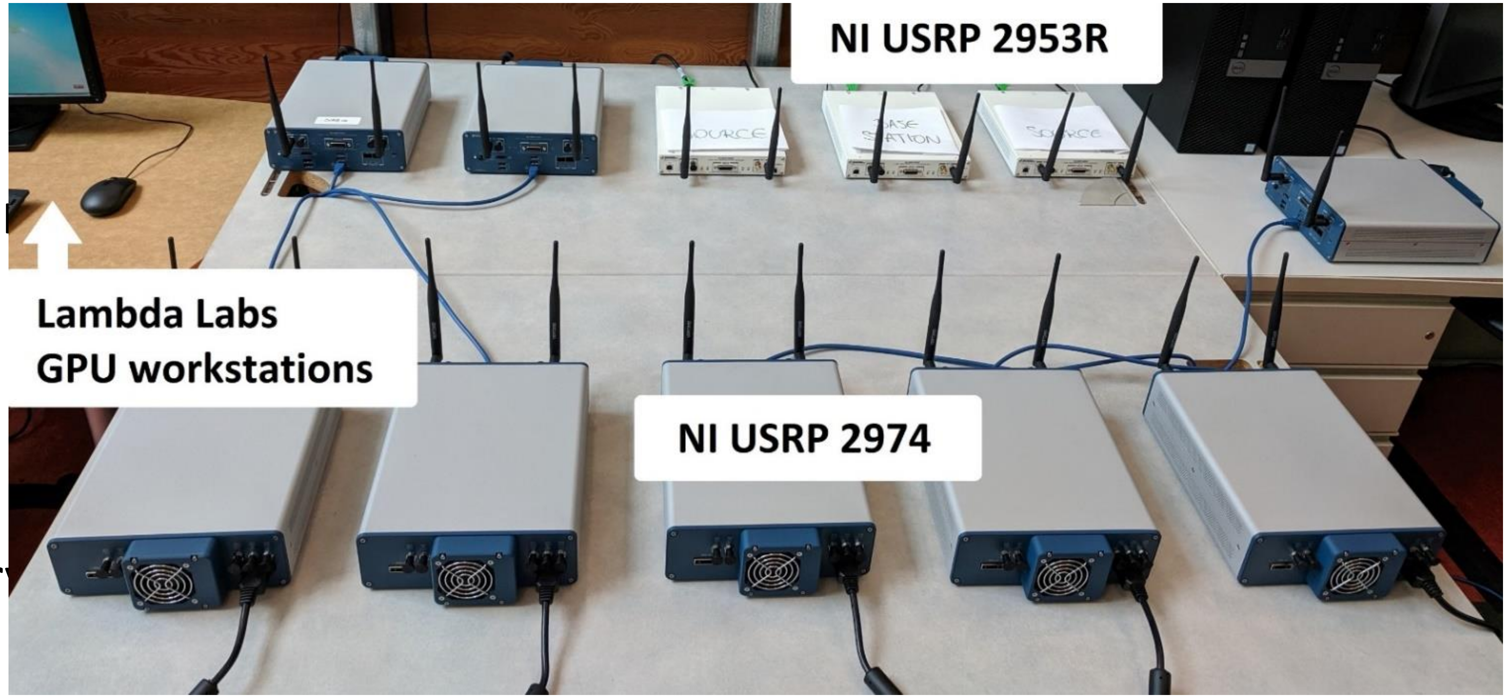
   - Age-of-Information ar



2. <u>Theoretical Results</u>:
   - Using Renewal Theor

3. <u>System Deployment</u>: validation in real operating scenarios
   - Using Software Defined Radios

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2. Theoretical Results: scheduling policies with performance guarantees
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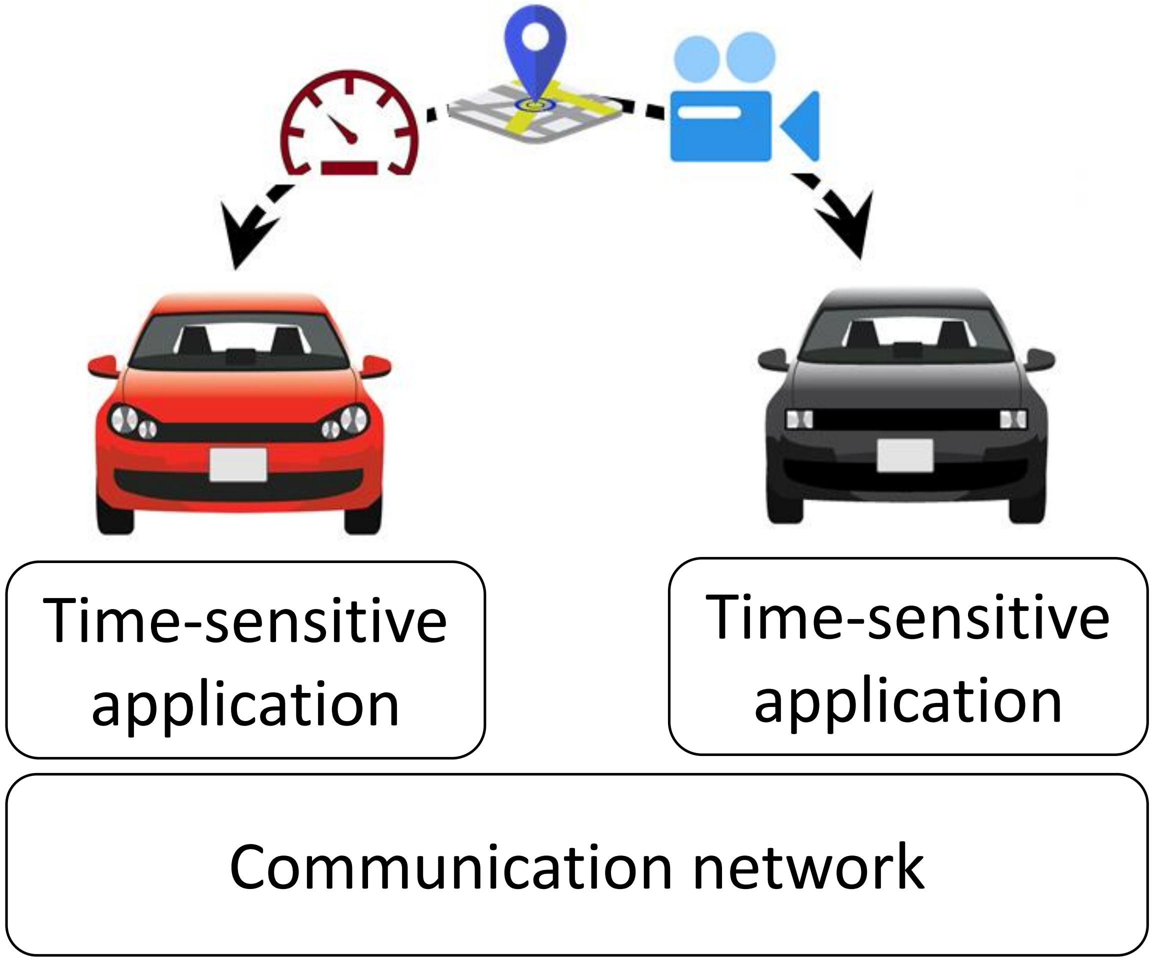
Sharing time-sensitive information



Emerging applications:

- Autonomous vehicles (ITS)
- Swarm of drones
- Smart factory (Industry 4.0)
- Large-scale Monitoring System
- Shared Augmented Reality
- Immersive Gaming
- Distributed Computation (SGD)

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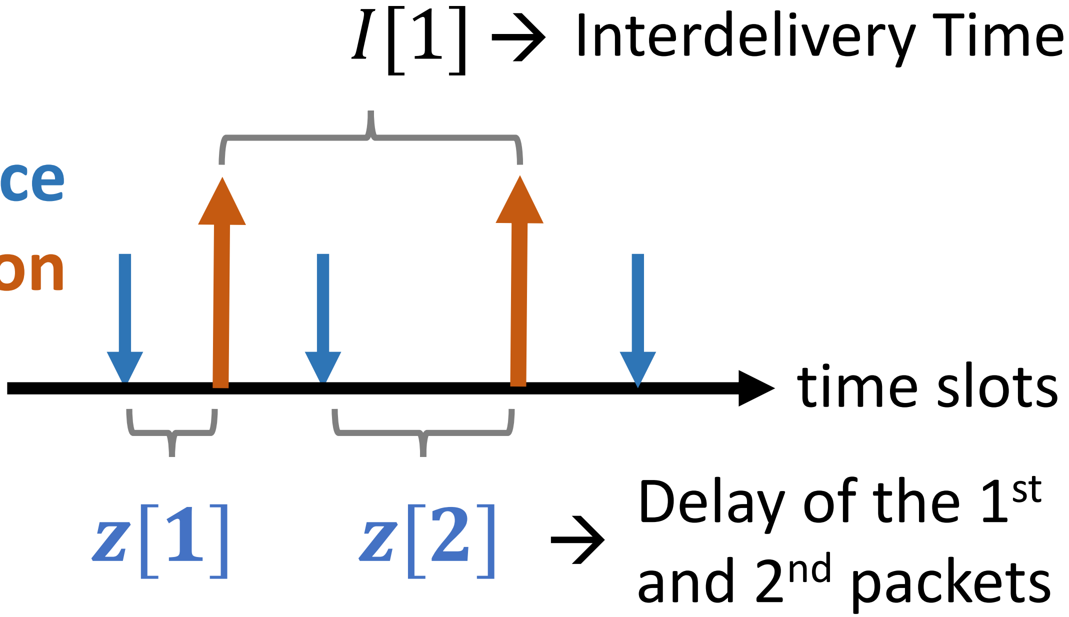
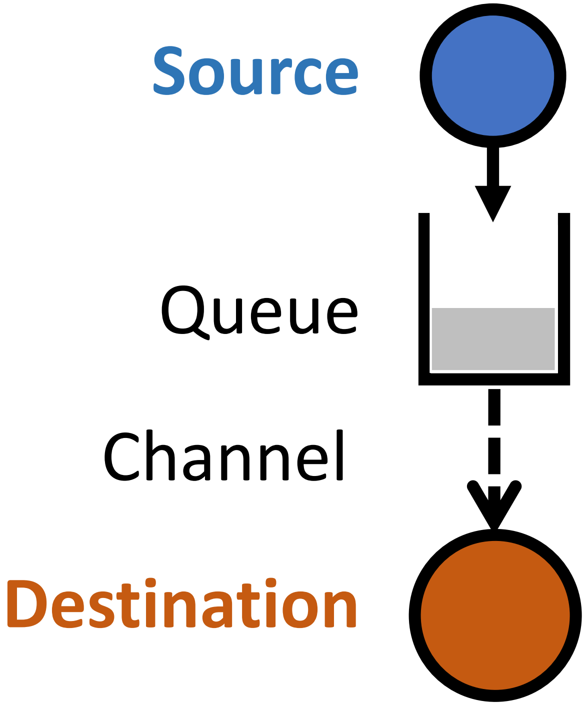
Age-of-Information (AoI)

Packet generation at the source

Delivery of packets to the destination



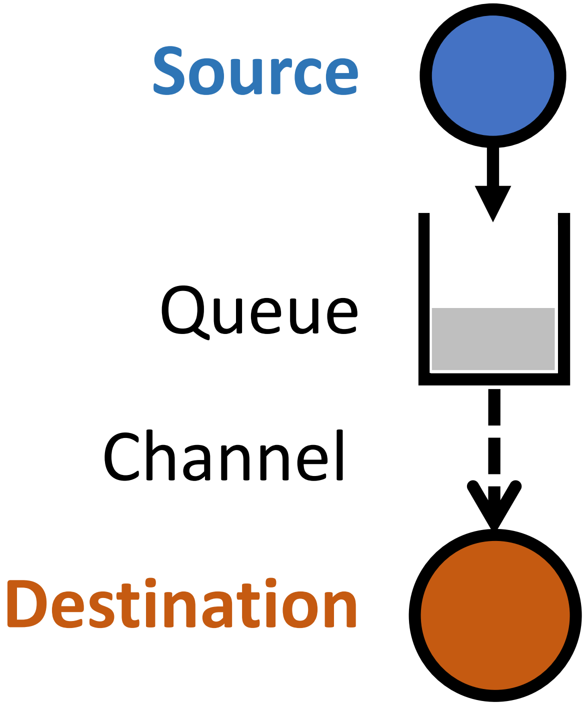


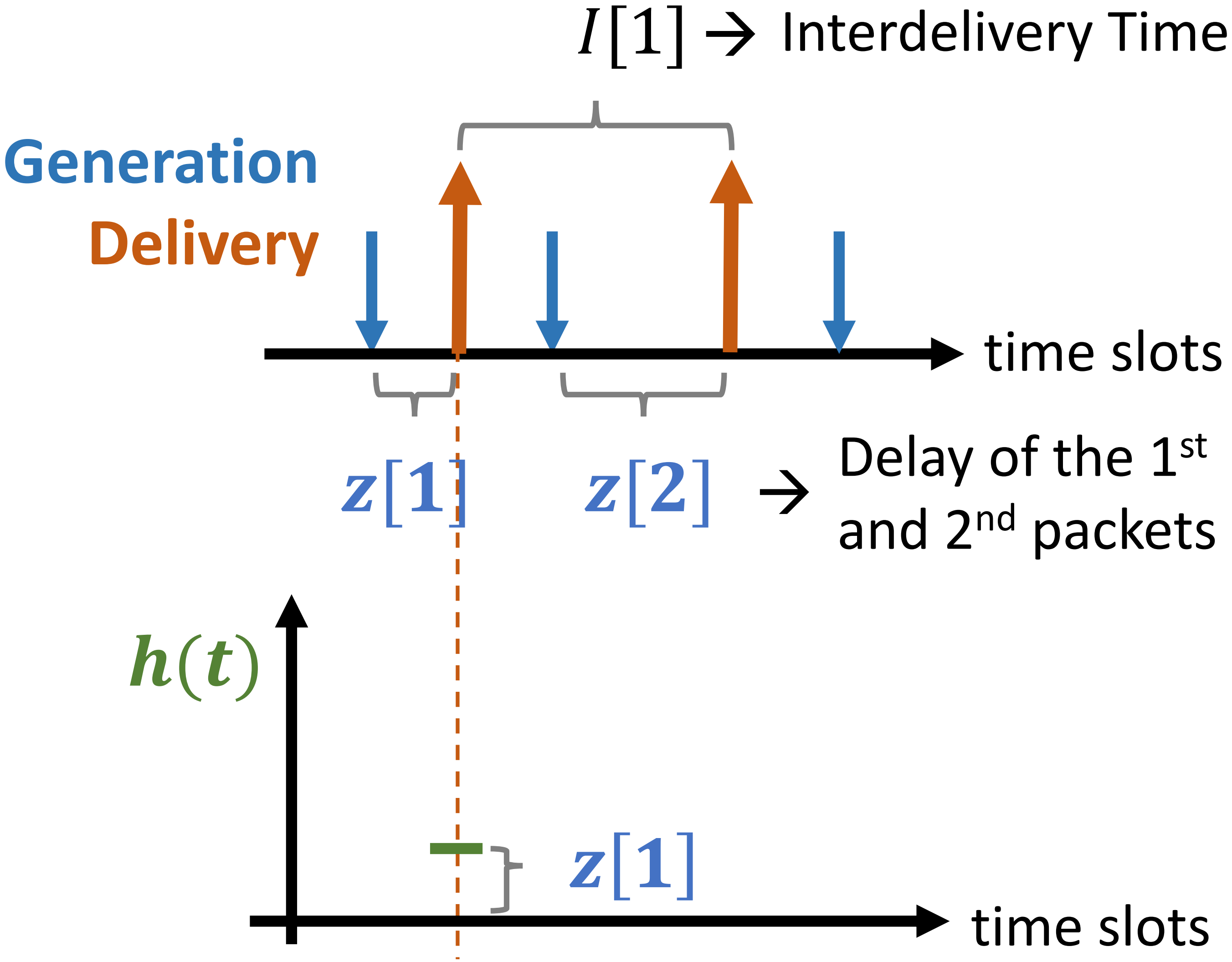
How old is the information at the destination?

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

Age-of-Information (AoI)

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





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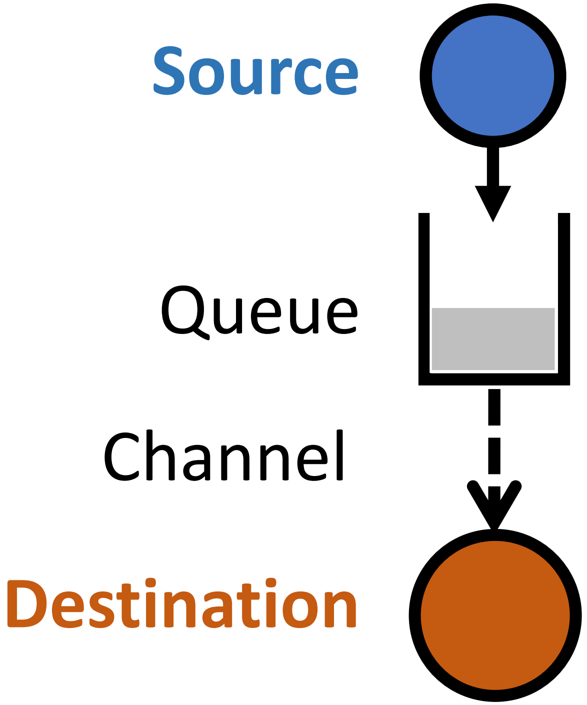

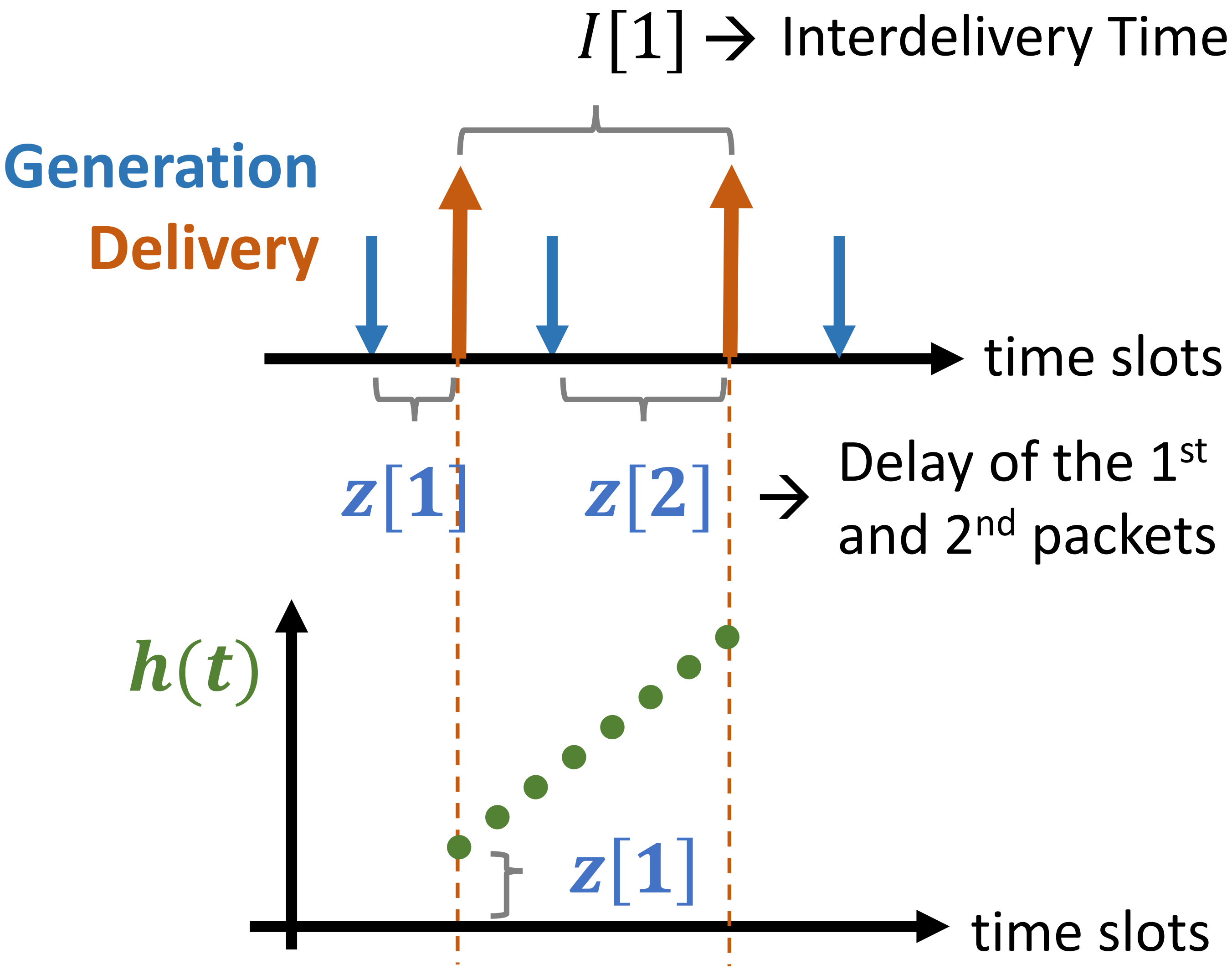

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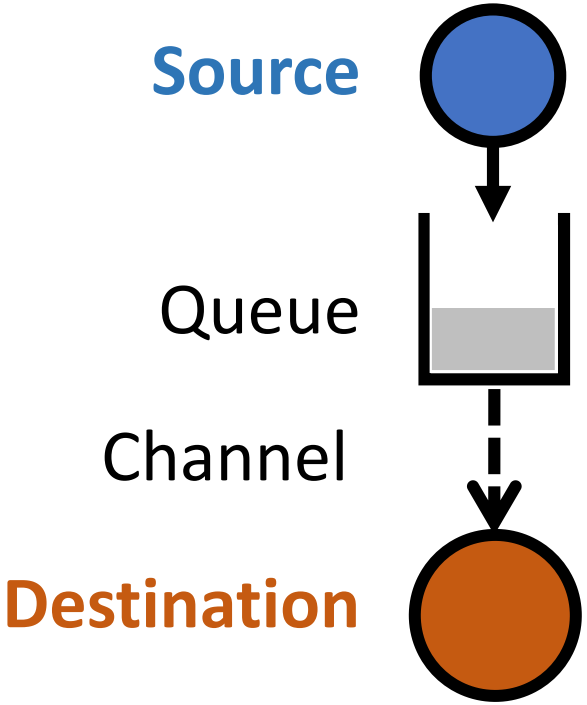

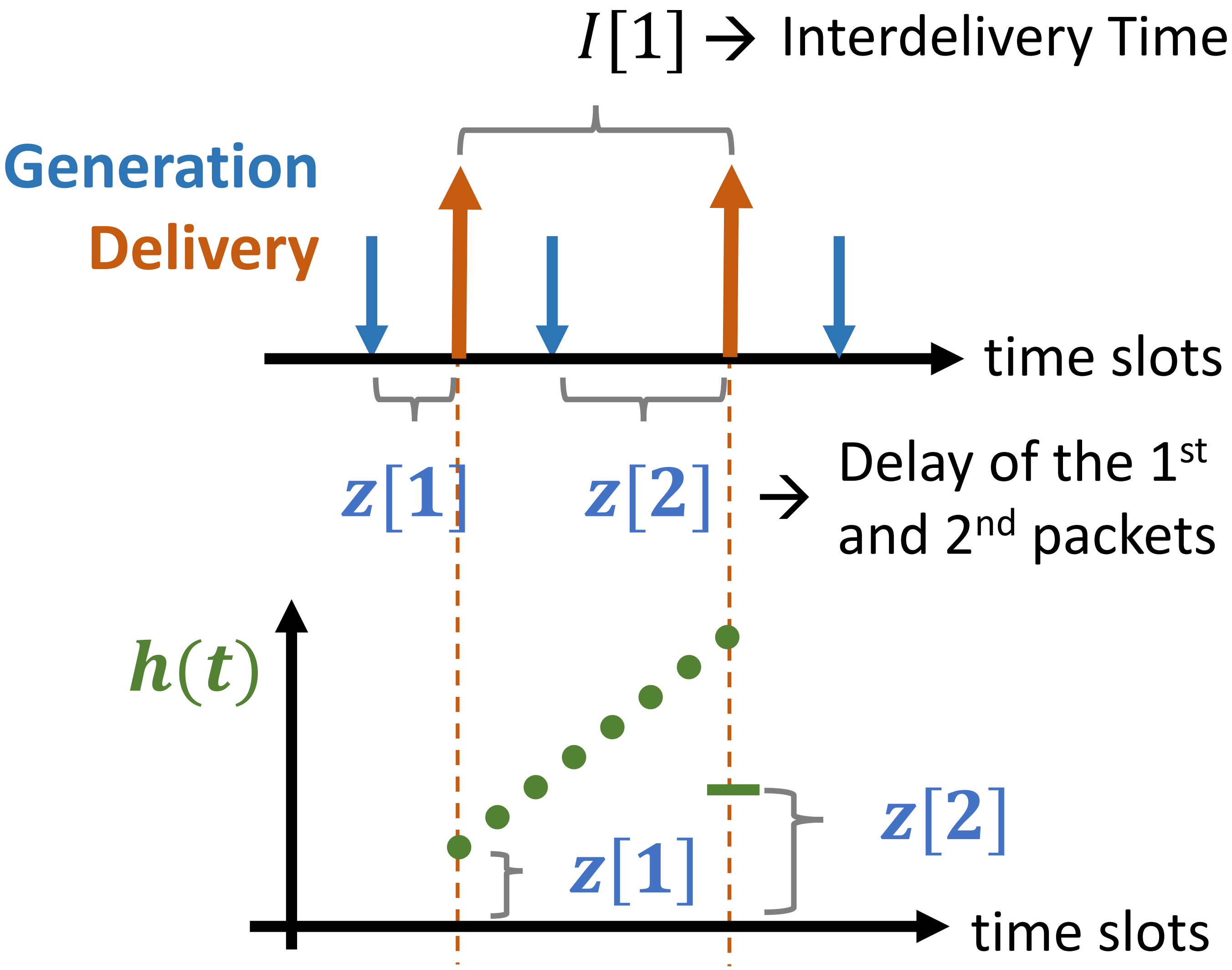

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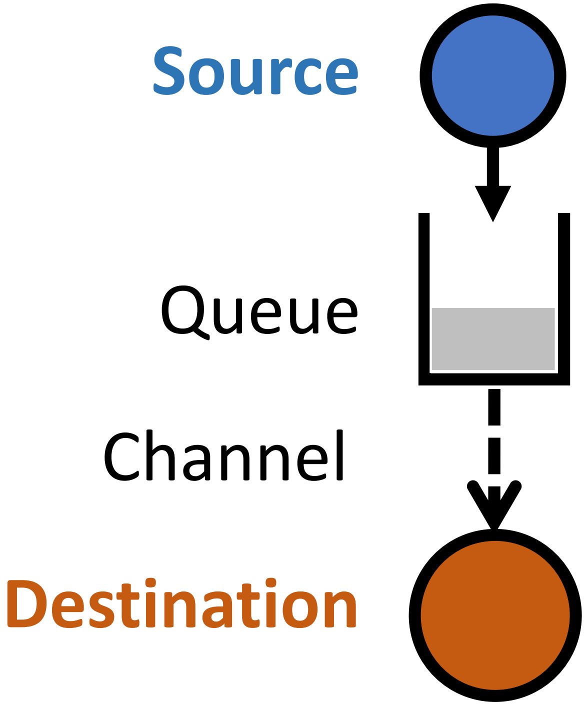

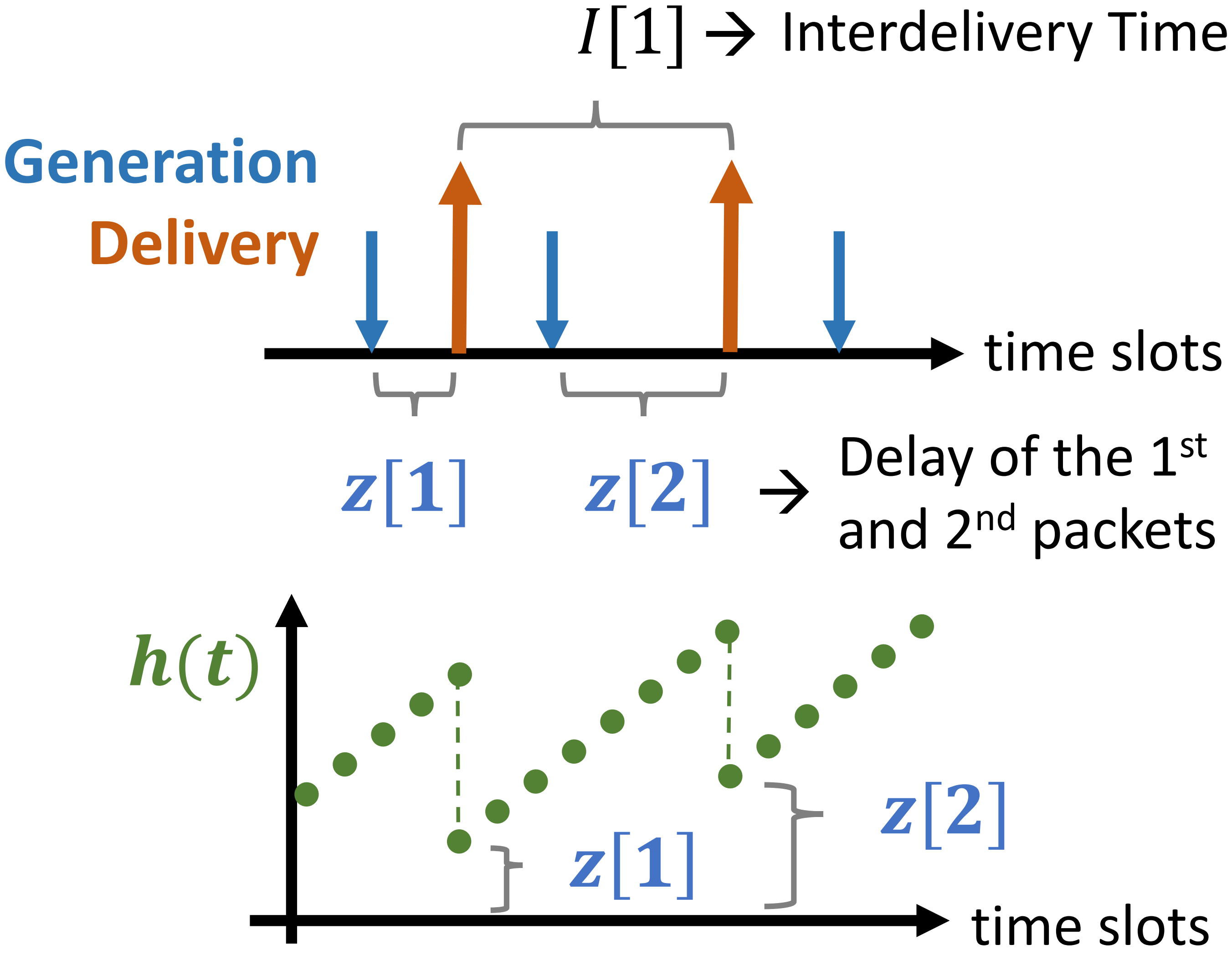

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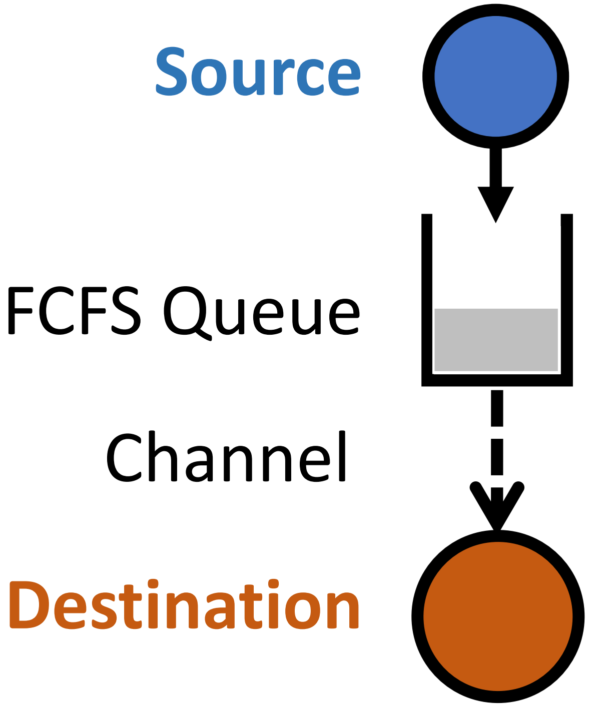
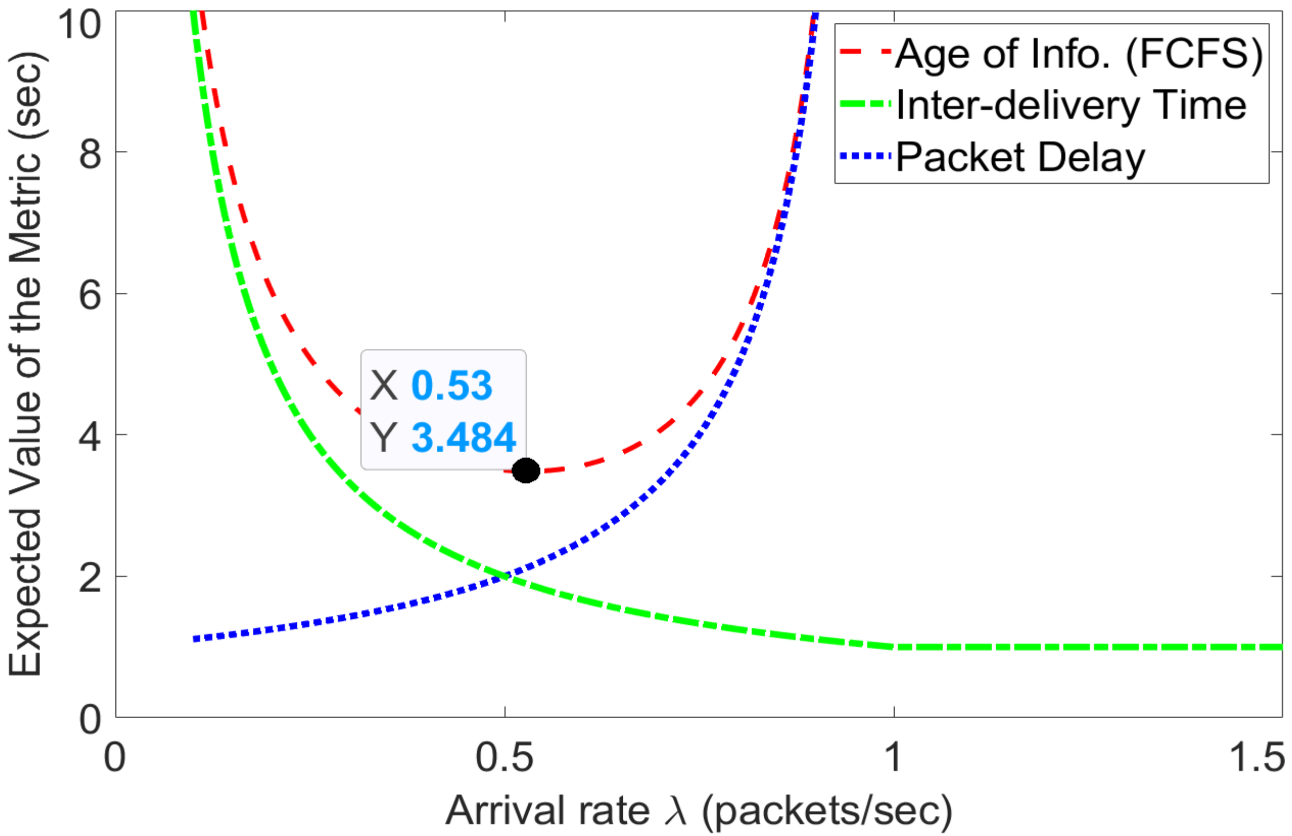
AoI, Delay, and Interdelivery time

<u>Example</u>: M/M/1 queue using FCFS discipline

Controllable arrival rate λ and fixed service rate $\mu = 1$ packet per second.





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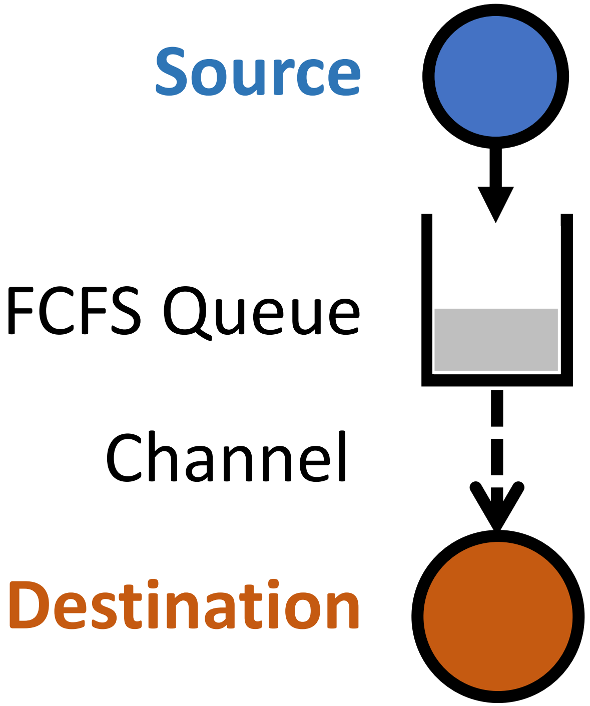
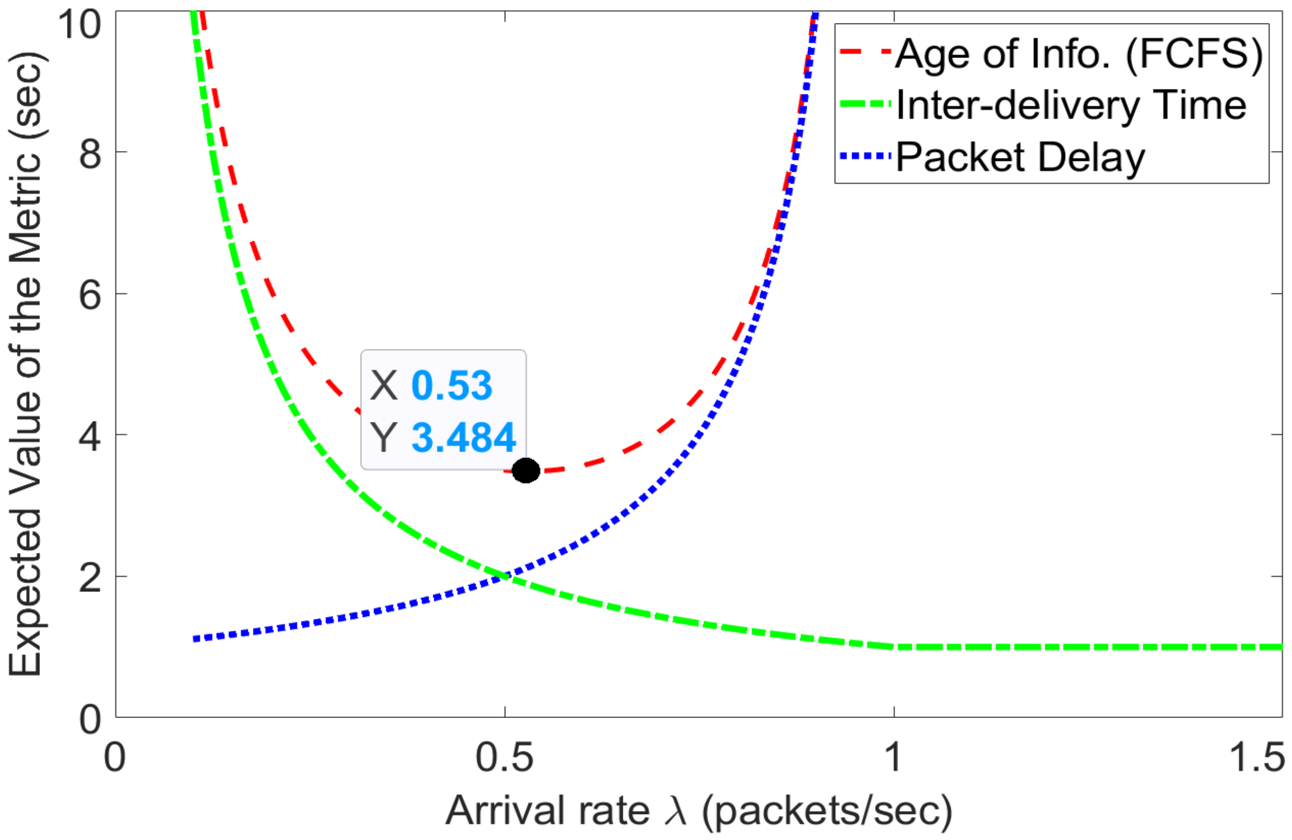
AoI, Delay, and Interdelivery time

$$\lim_{T\to\infty}\frac{1}{T}\int_{t=0}^{T} h(t)dt = \mathbb{E}[h(t)] = \frac{1}{\lambda}+\frac{1}{\mu}+\frac{\lambda^2}{\mu-\lambda}$$





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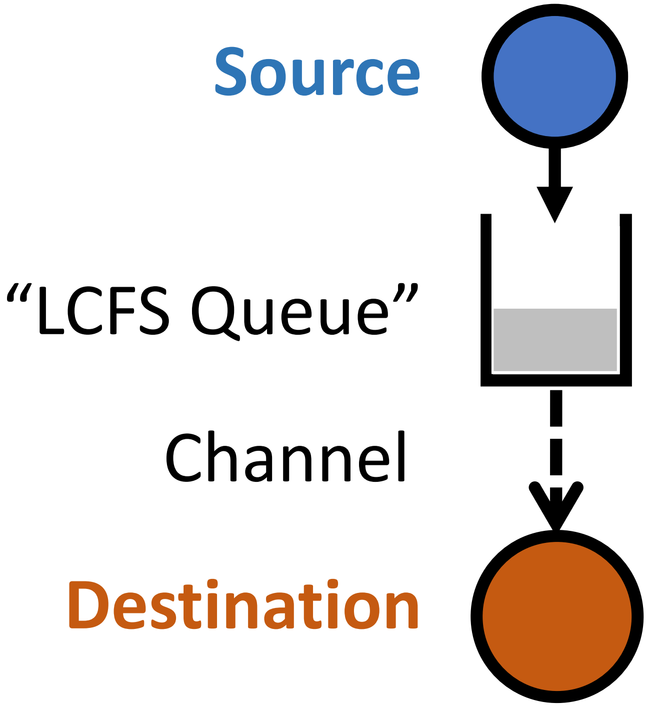
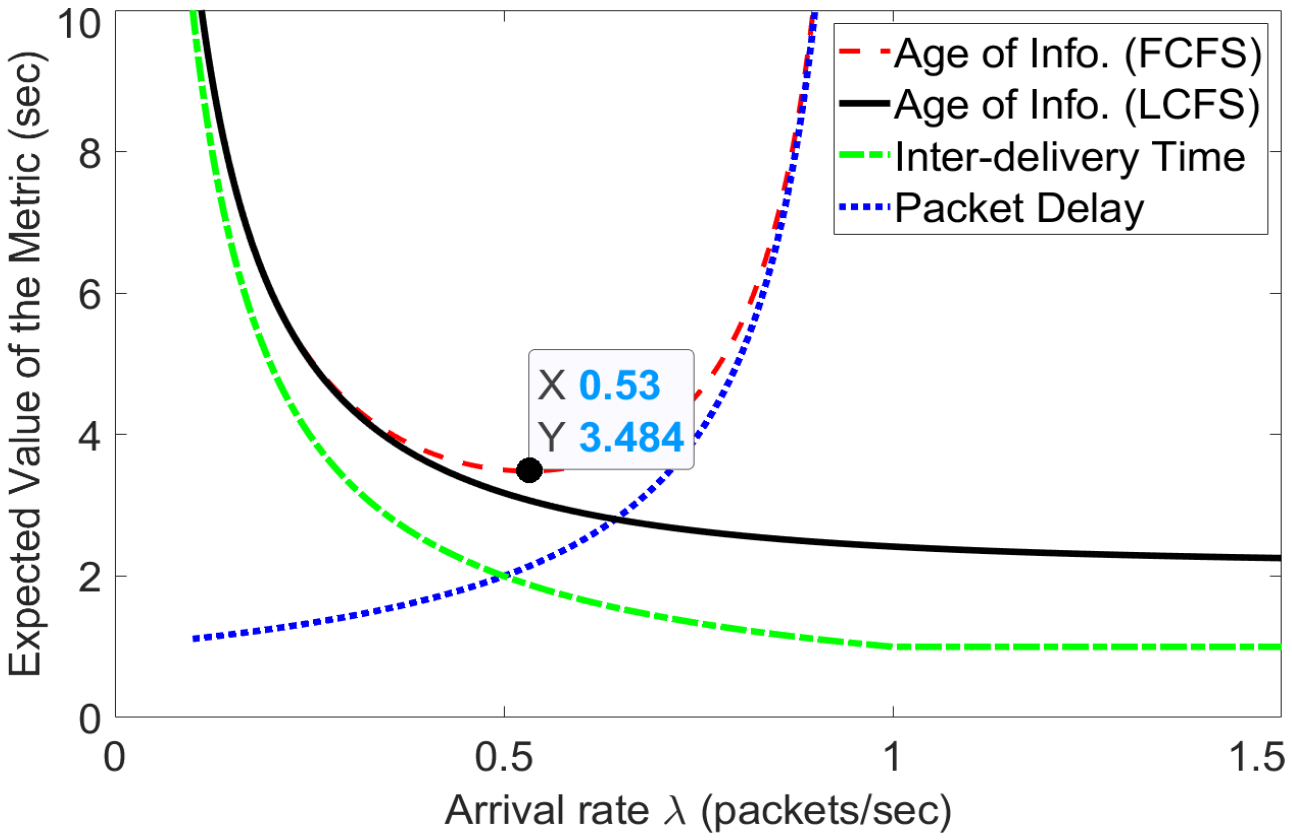
AoI, Delay, and Interdelivery time

Example: M/M/1/2* queue

Controllable arrival rate λ and fixed service rate $\mu = 1$ packet per second.





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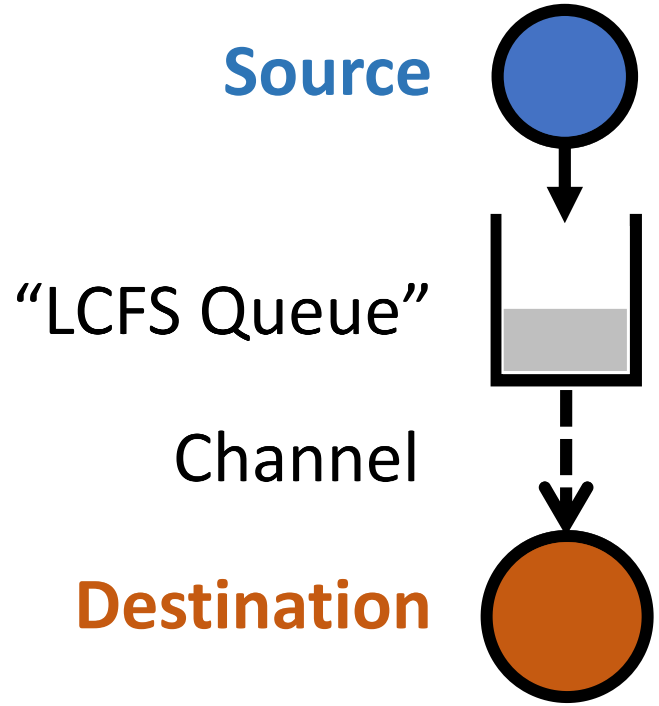
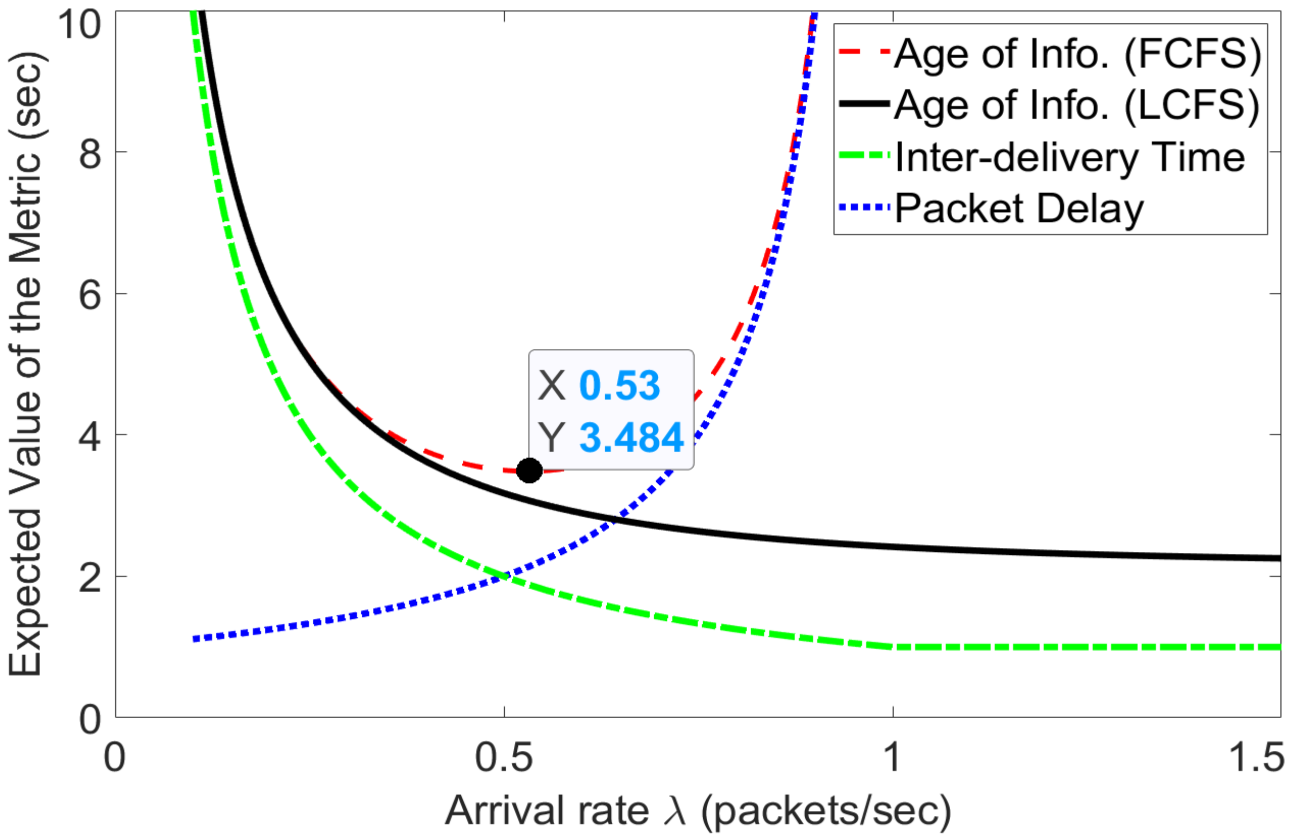
AoI, Delay, and Interdelivery time

$$\lim_{T\to\infty}\frac{1}{T}\int_{t=0}^{T} h(t)dt = \mathbb{E}[h(t)] = \frac{1}{\lambda}+\frac{2}{\mu}+\frac{\lambda}{(\lambda+\mu)^2}+\frac{1}{\lambda+\mu}-\frac{2(\lambda+\mu)}{\lambda+\lambda\mu+\mu^2}$$





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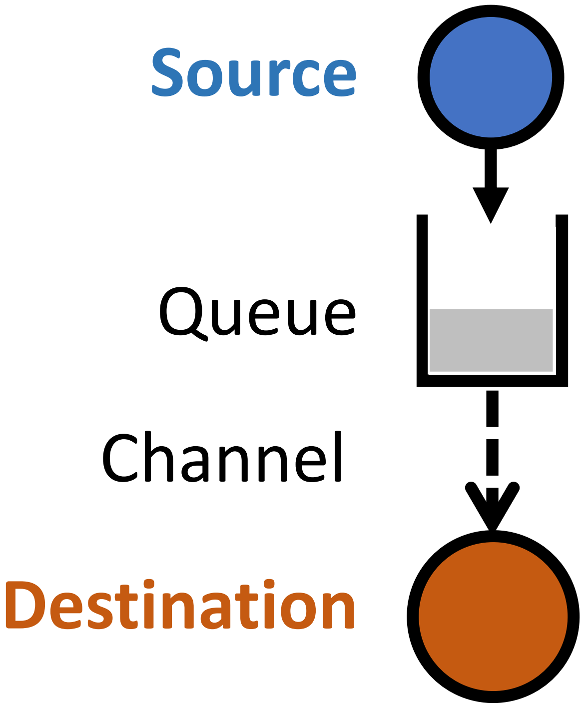
Age-of-Information (AoI)

Interesting problems in <u>single queue systems</u>:

- When to transmit data when sources harvest energy?
- Which is the best queueing discipline? Preemption? No preemption?
- Should we retransmit packets? Should we encode packets?



Please refer to http://webhome.auburn.edu/~yzs0078/AoI.html for references

Age-of-Information (AoI)

Other broad classes of interesting problems:

- Wireless Communication Networks
- Caching Systems
- Networked Control Systems
- UAV-assisted Status Updates

- Systems Research… only a handful of papers…
- Operations Research… nothing in the literature yet…

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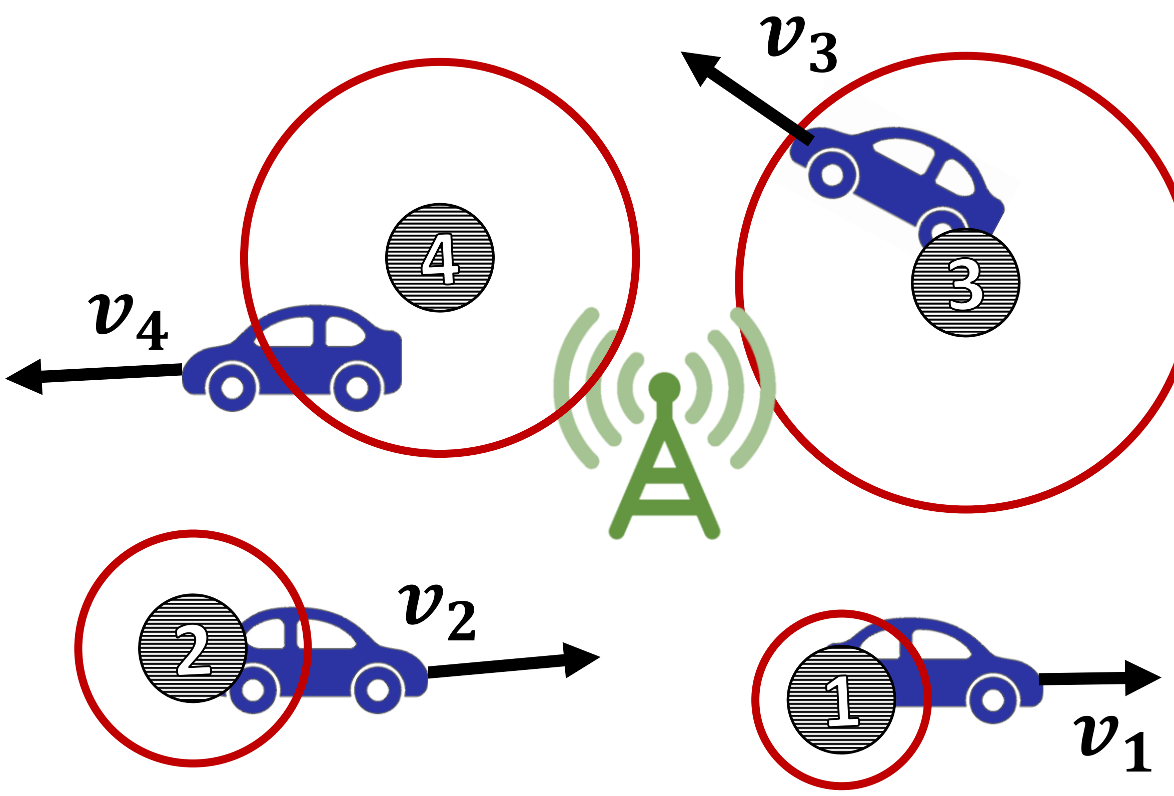
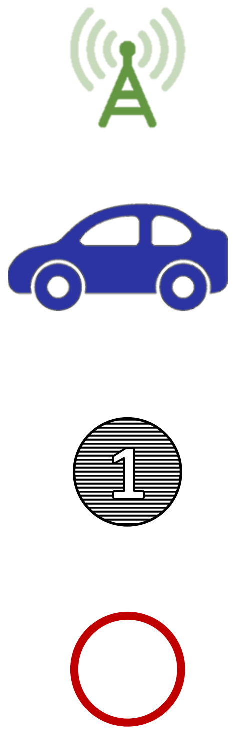
Monitoring system



Legend



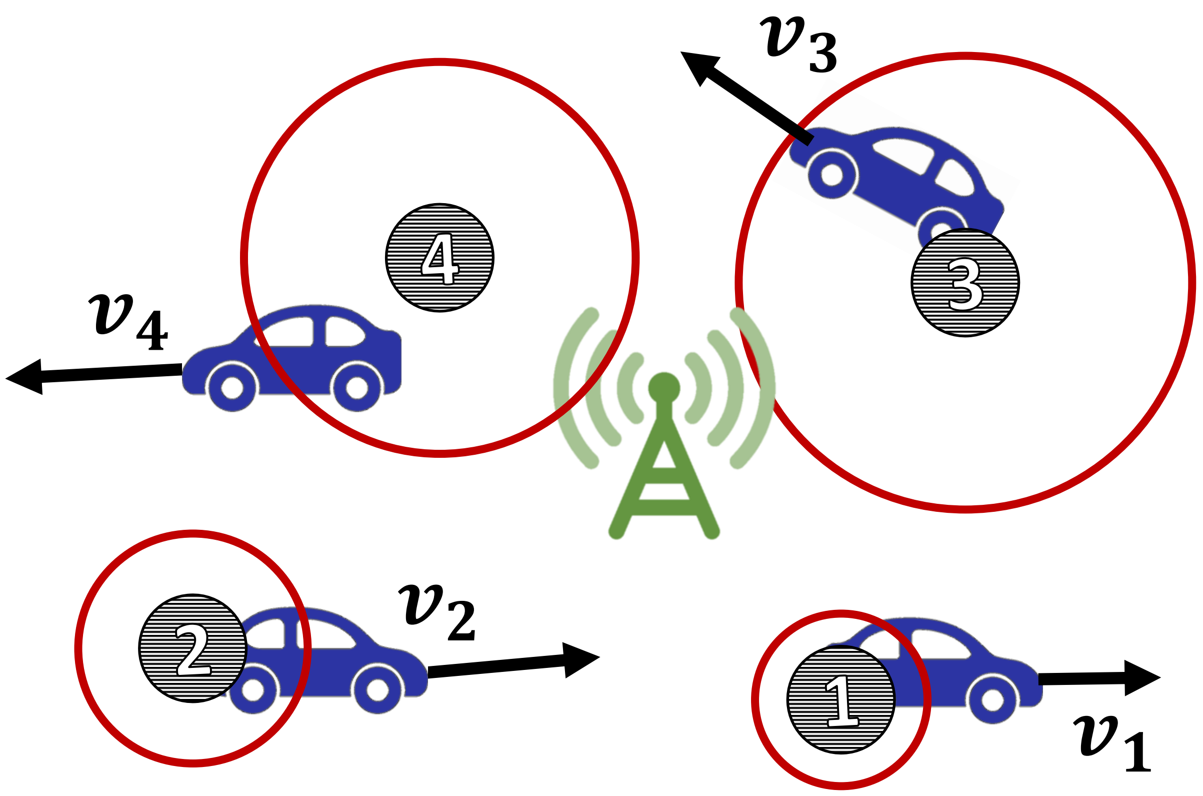
wireless base station

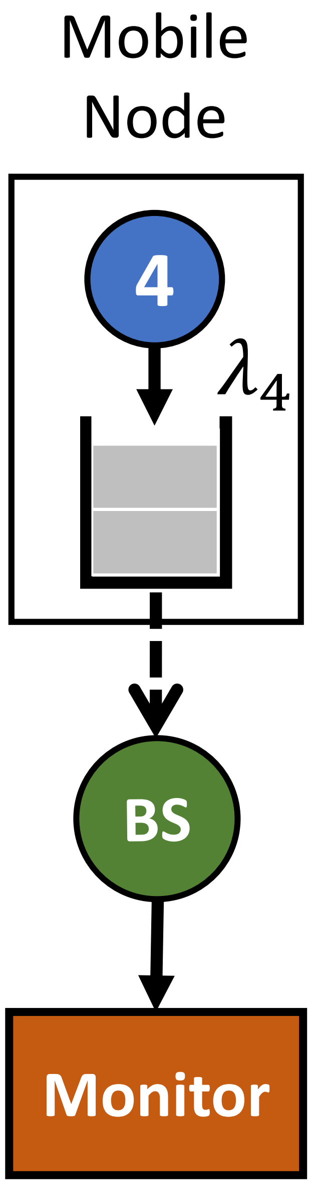
current position of nodes (cars, drones, robots, …)

last known position (from last packet received)

position uncertainty

Monitoring system





Time-sensitive information (GPS and IMU)

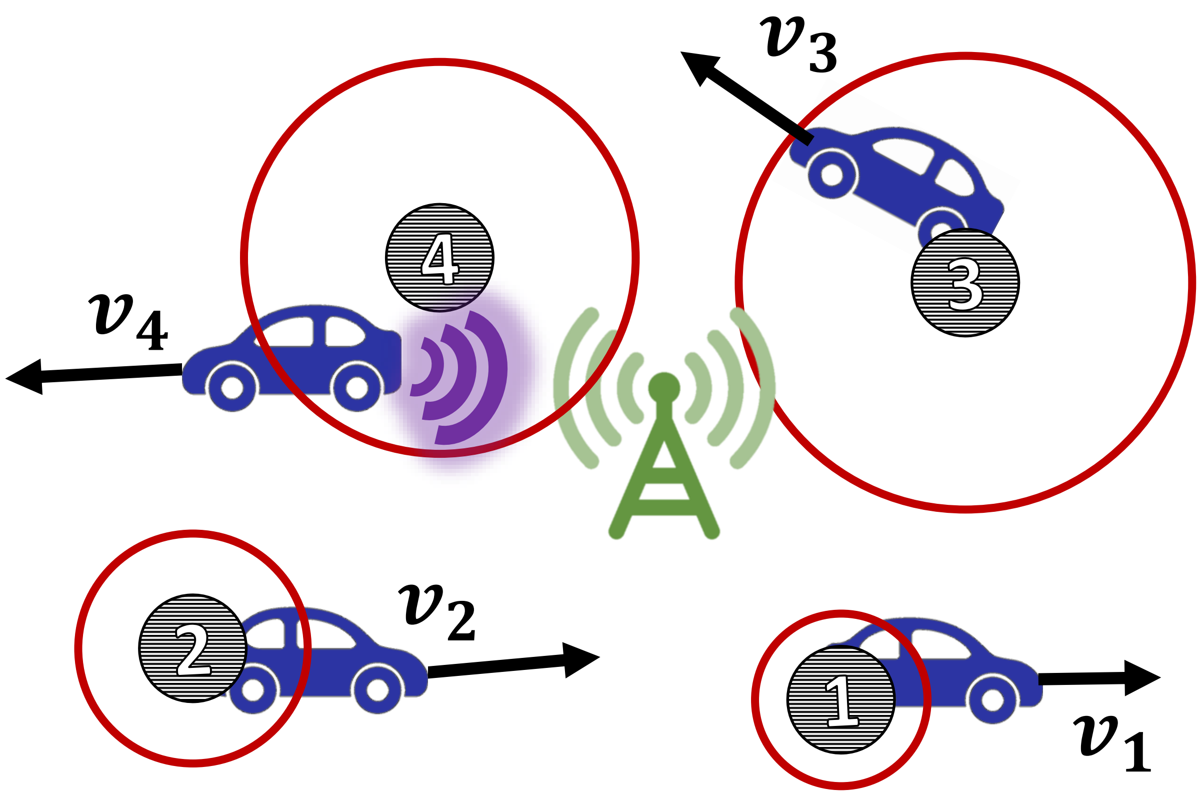
Queueing

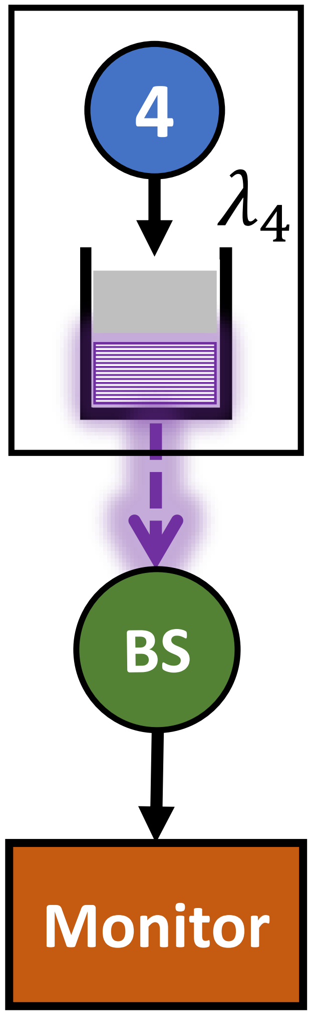
Channel Access

Wireless Base Station

Keeps track of the information

Monitoring system





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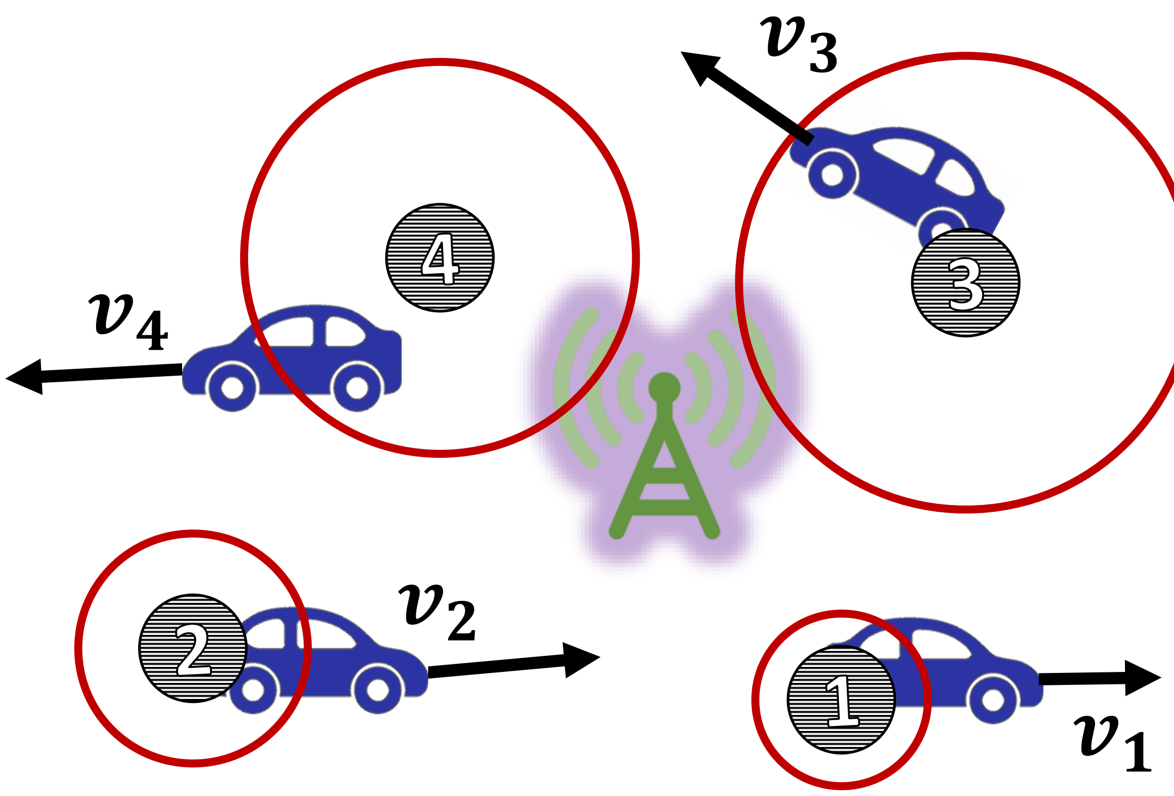
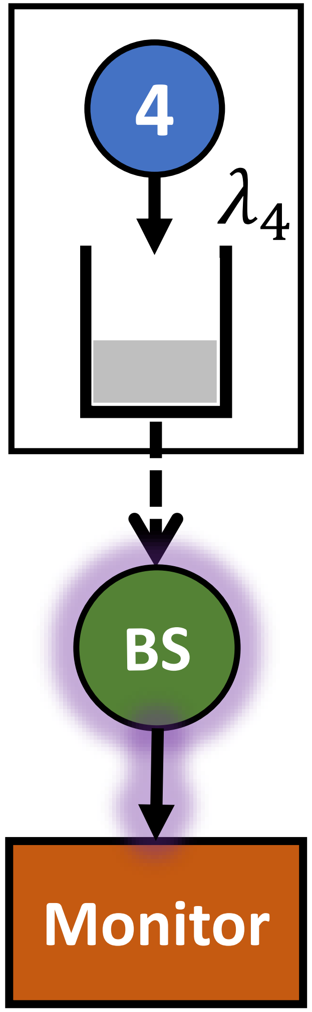


Mobile Node



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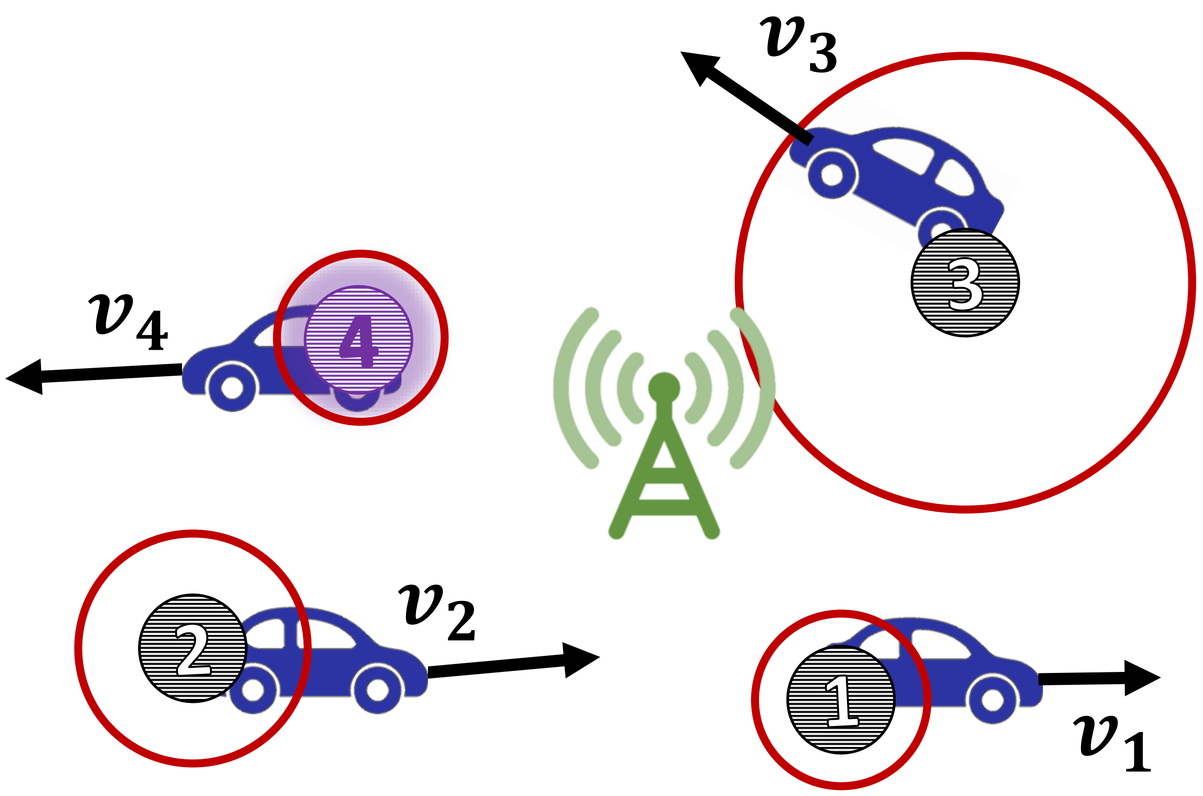

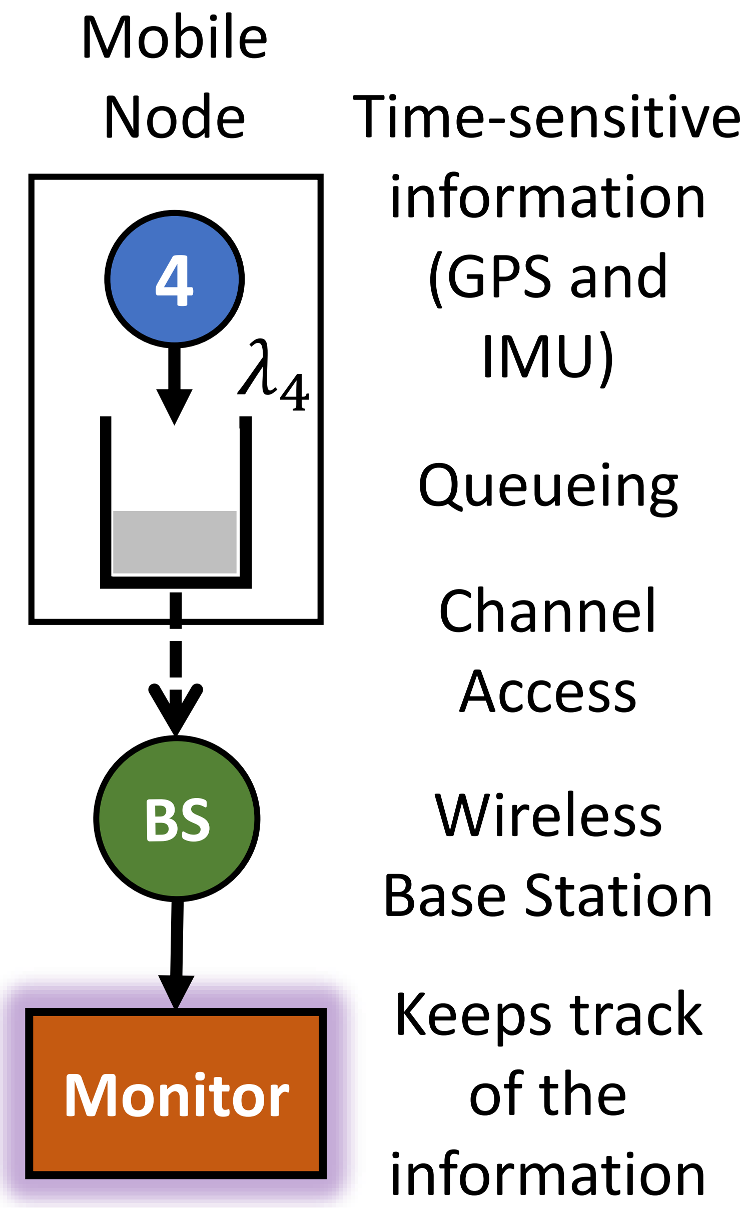

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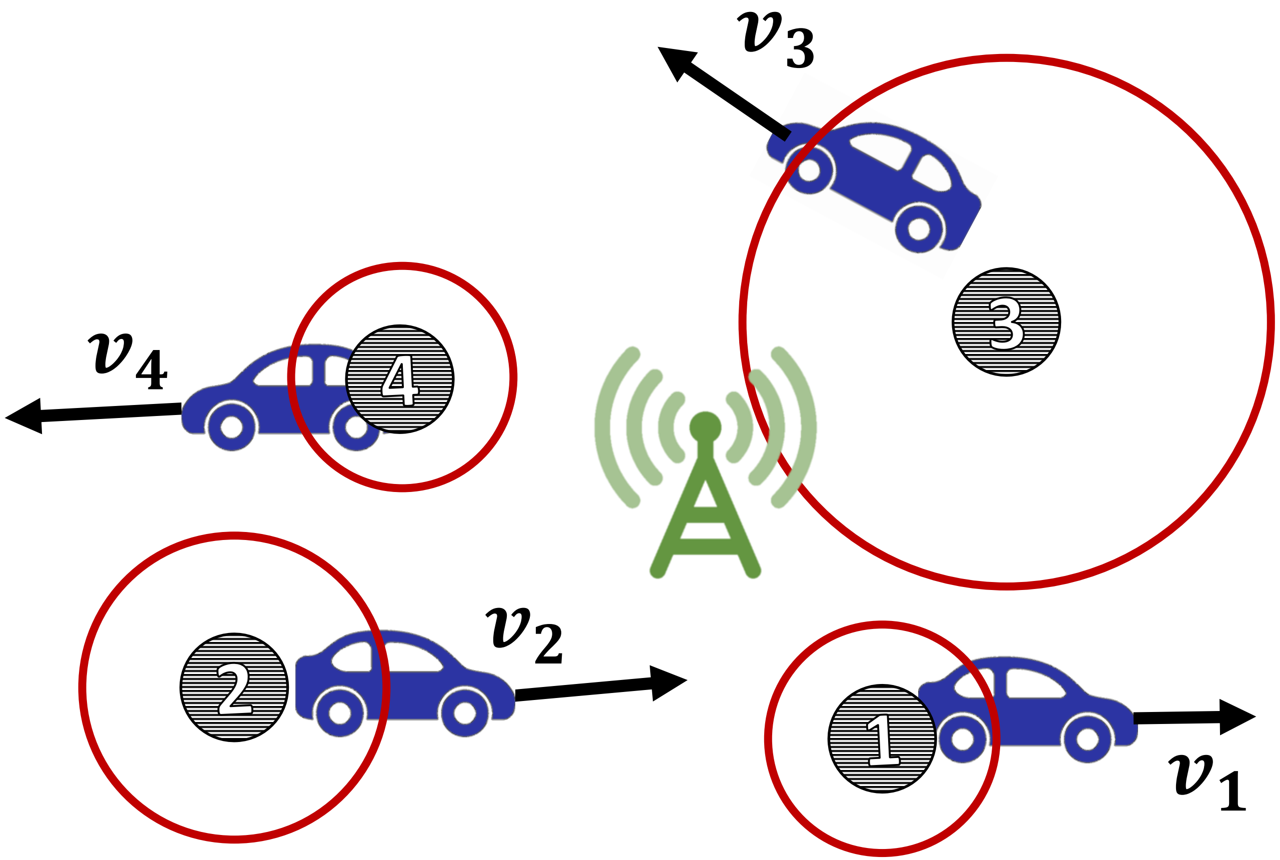

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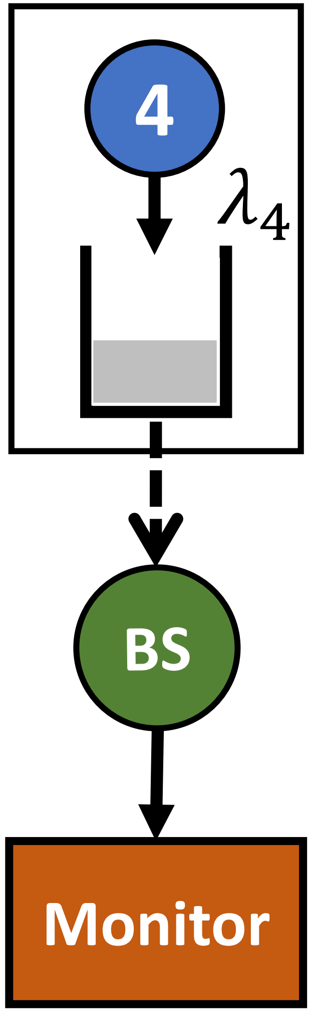

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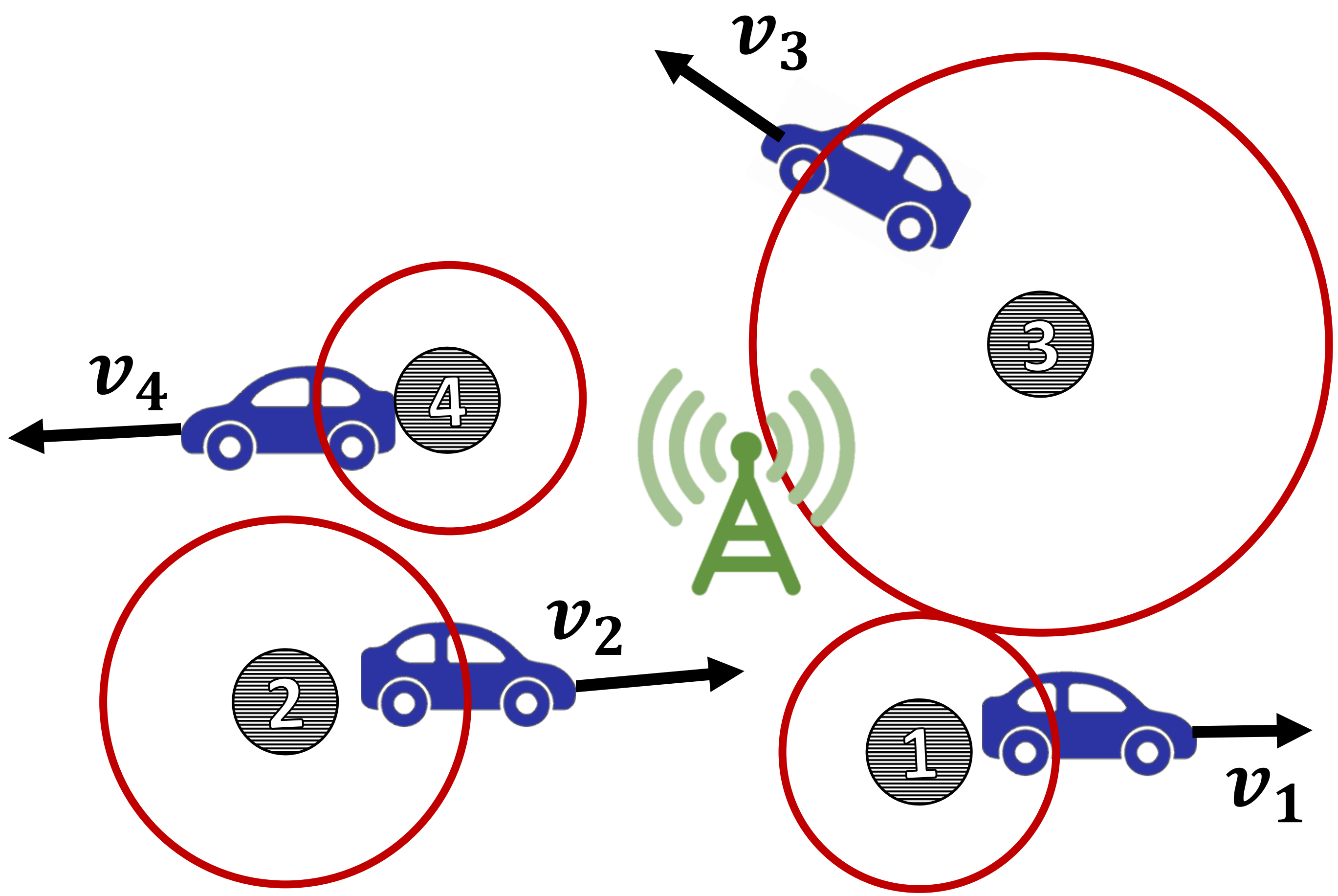

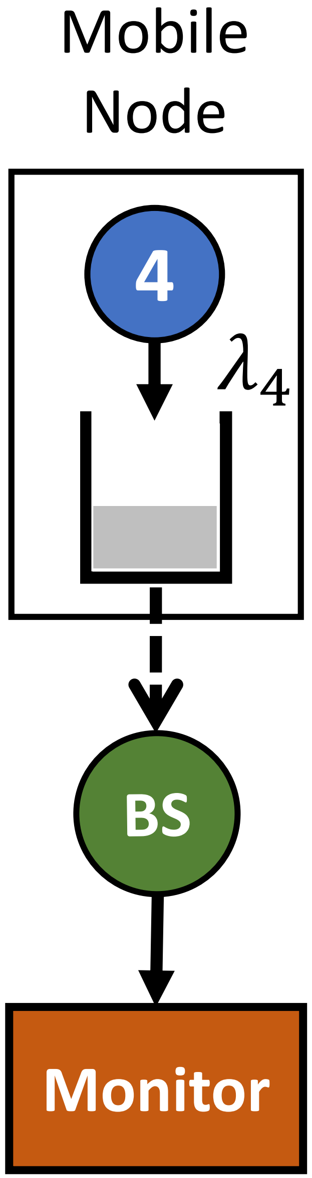

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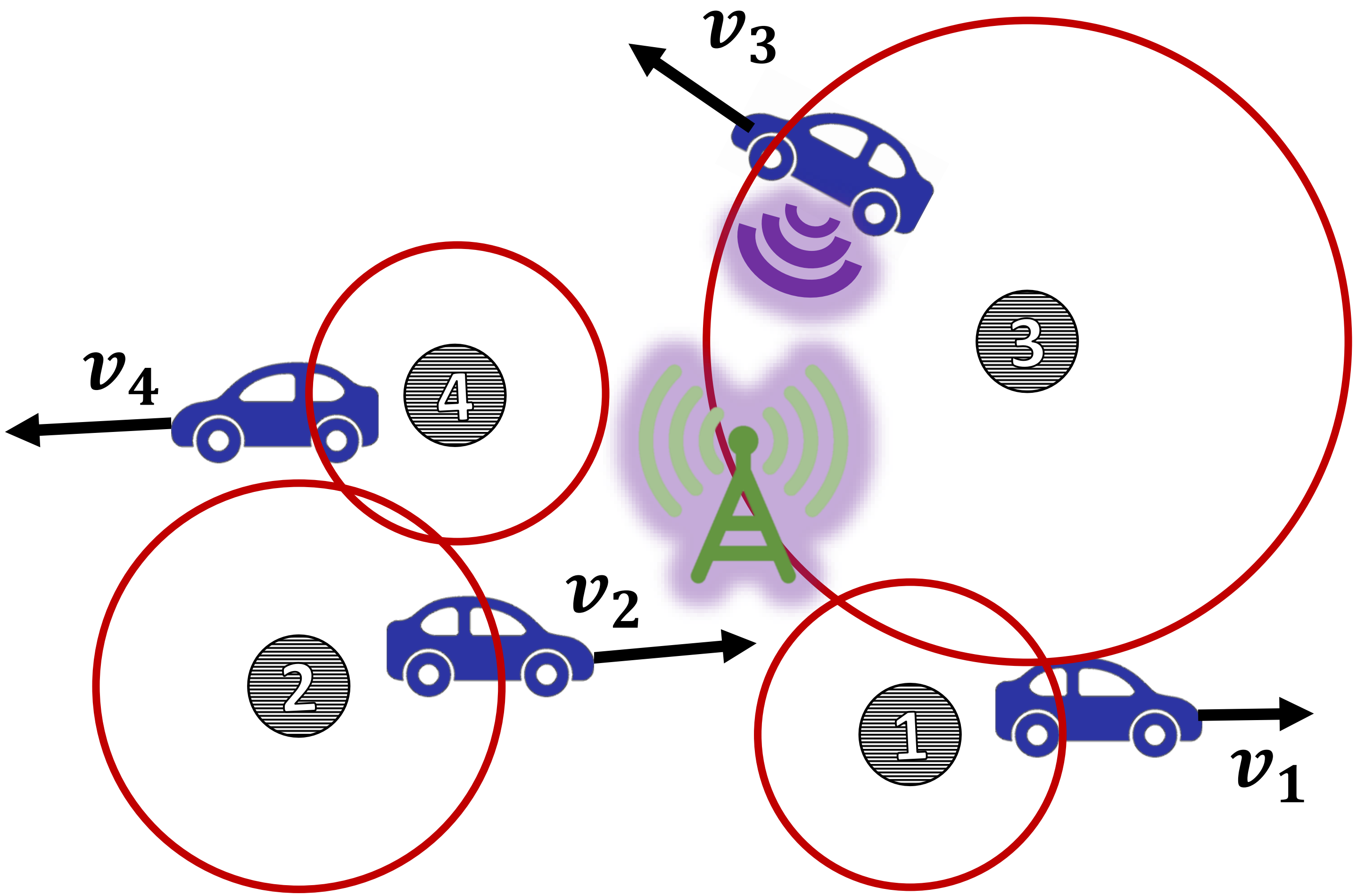

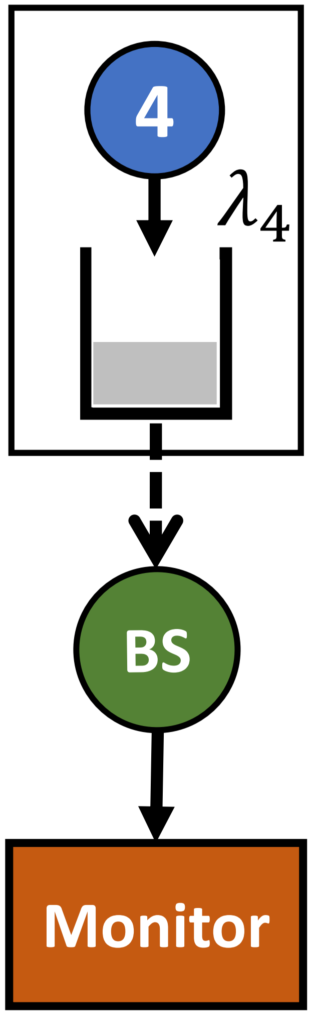

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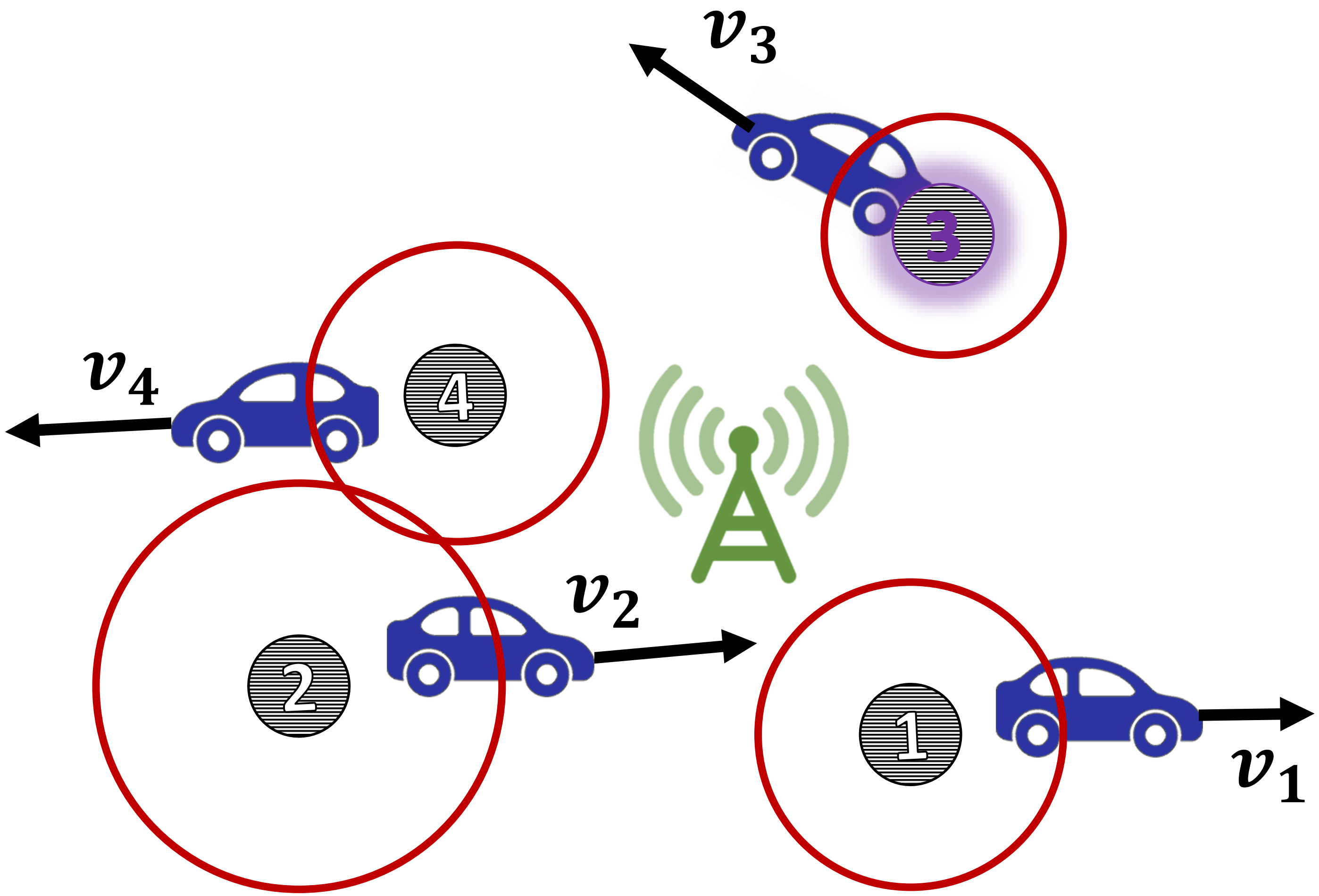

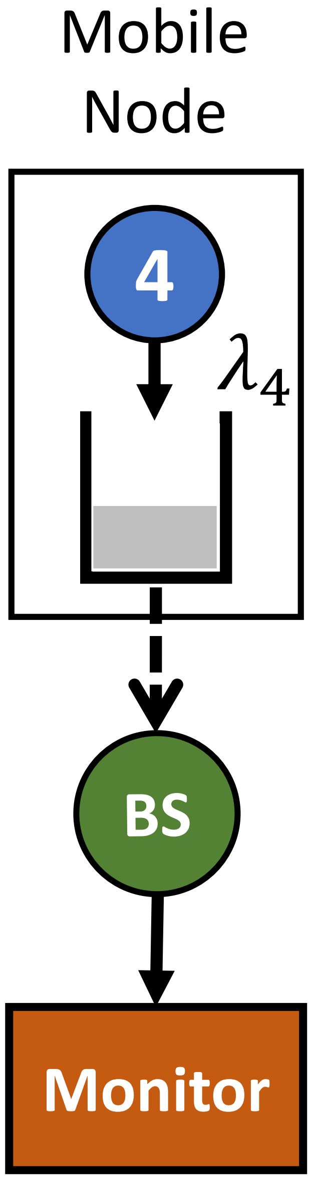

Time-sensitive information (GPS and IMU)

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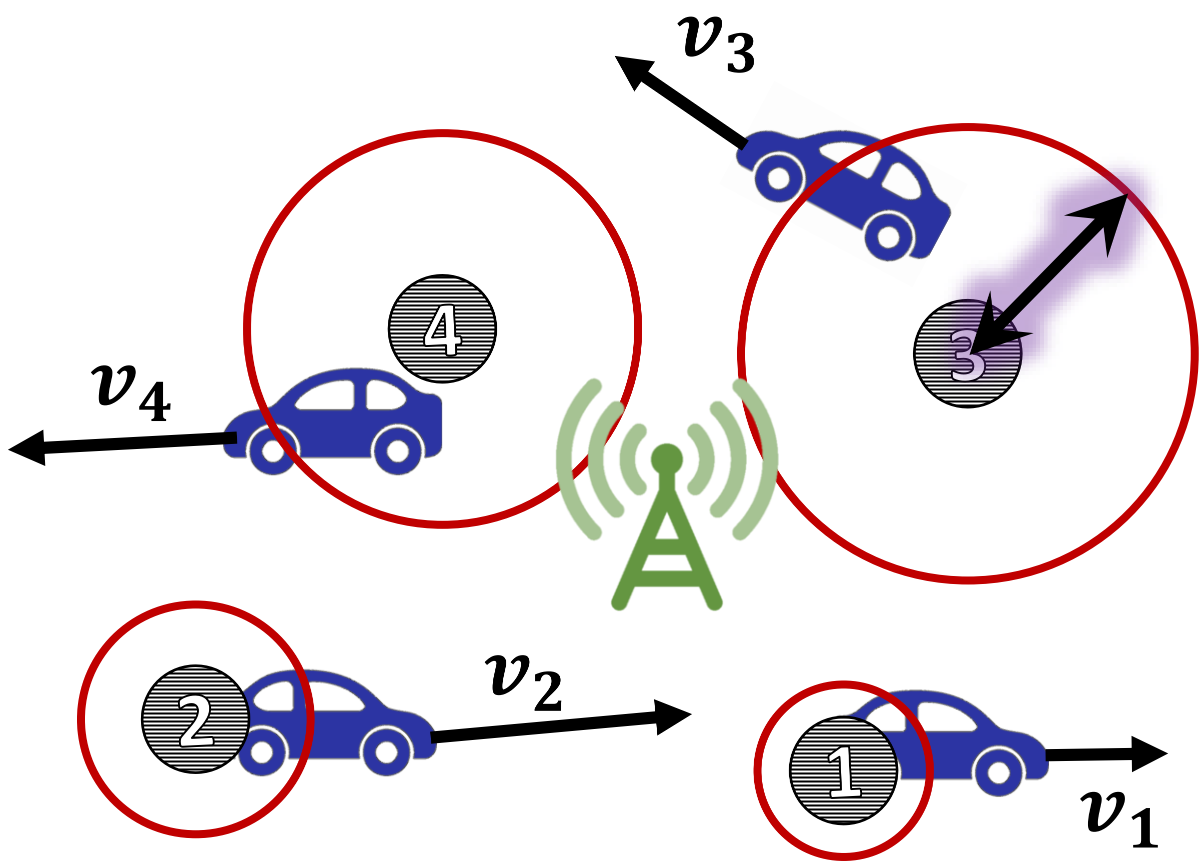
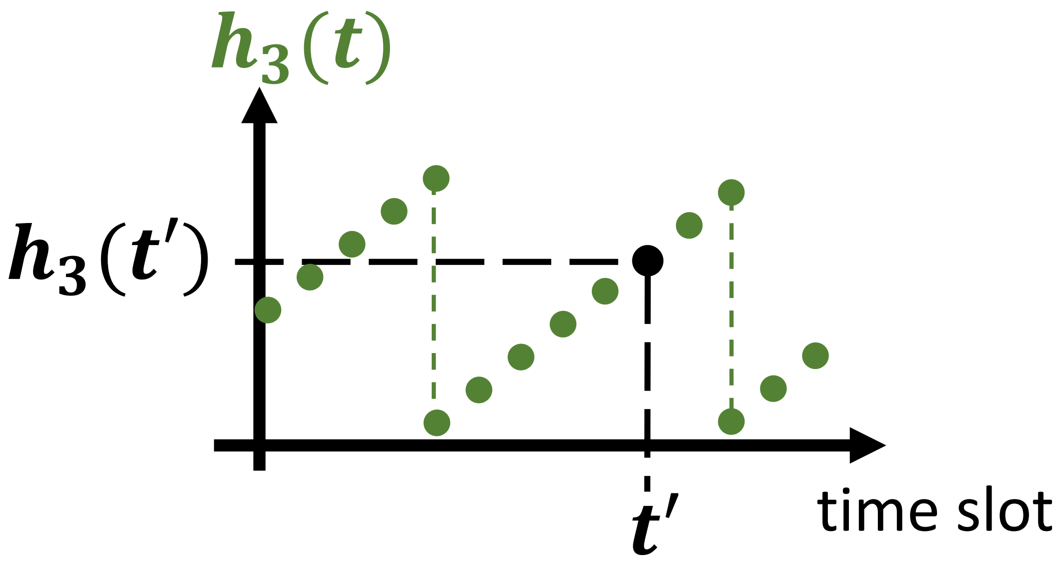
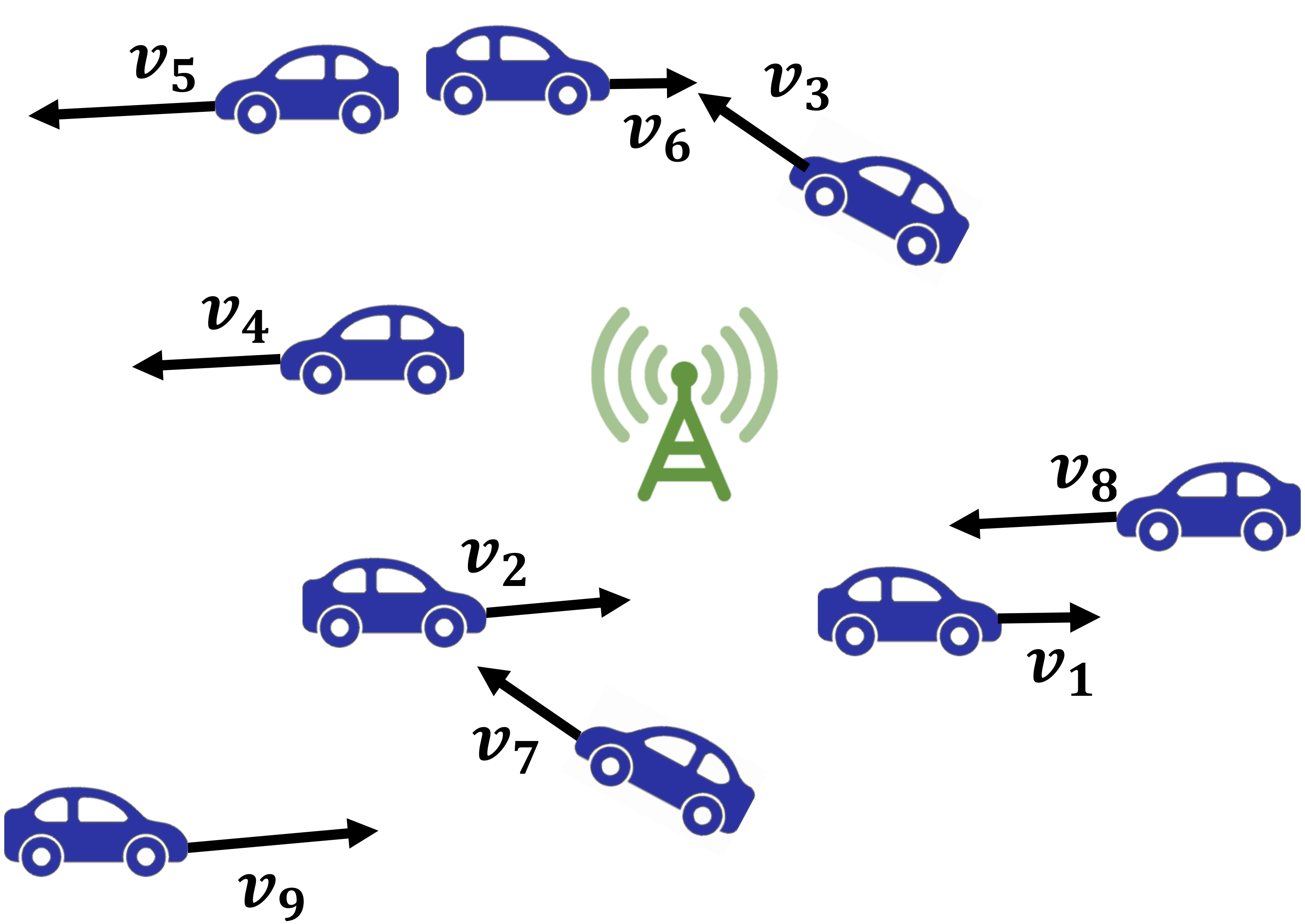
Age-of-Information and Position Uncertainty

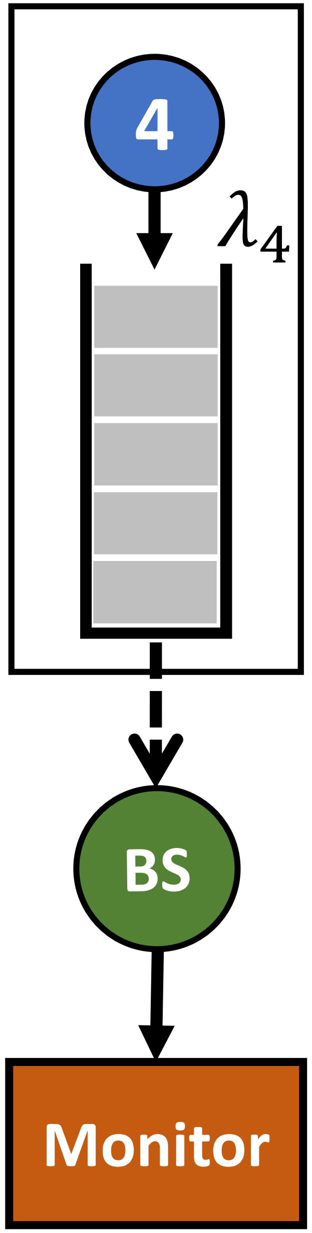


Position uncertainty of node 3 at slot t' is given by the **radius** $v_3 h_3(t')$



Large-scale system using **WiFresh**





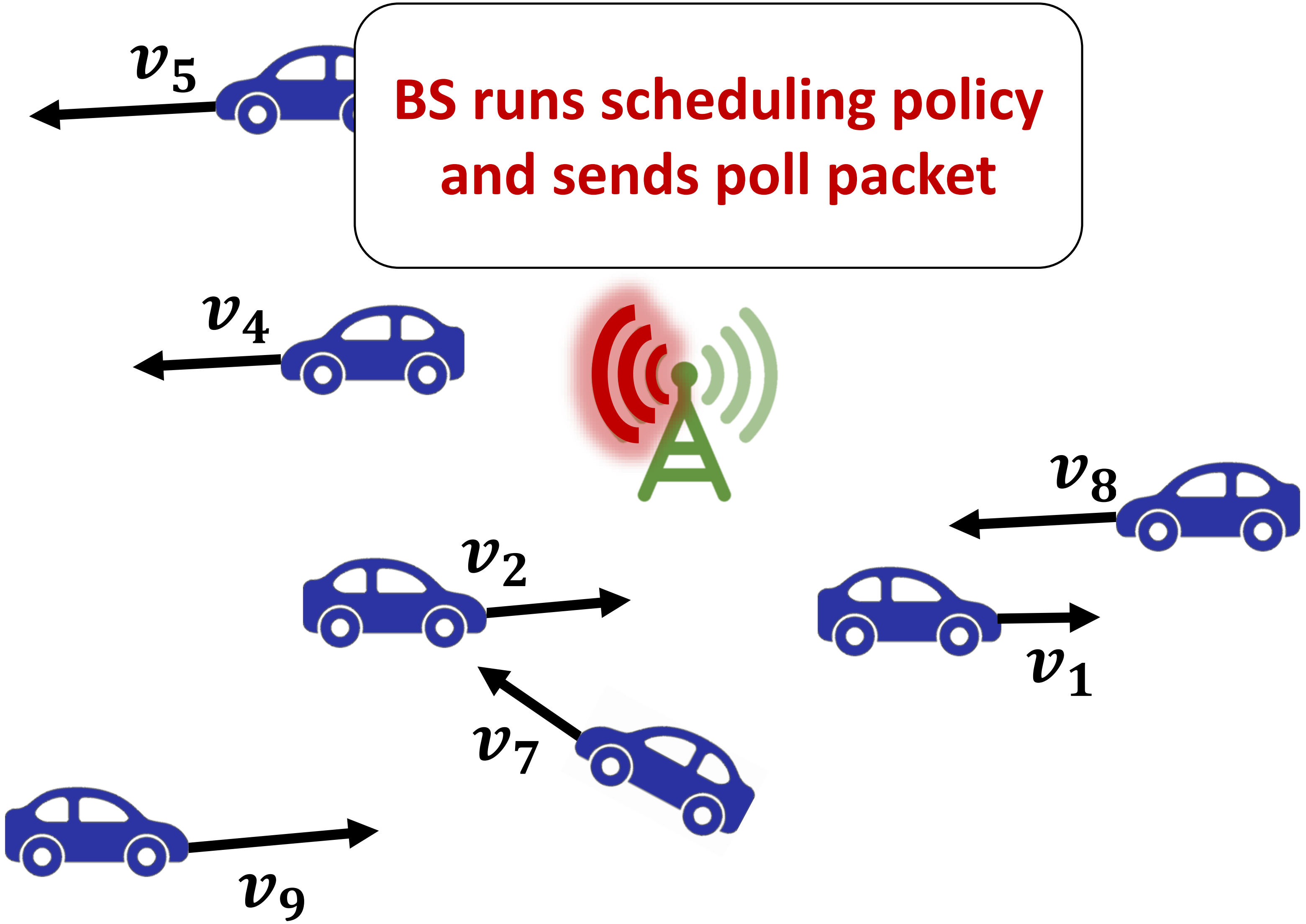
Time-sensitive information (GPS and IMU)

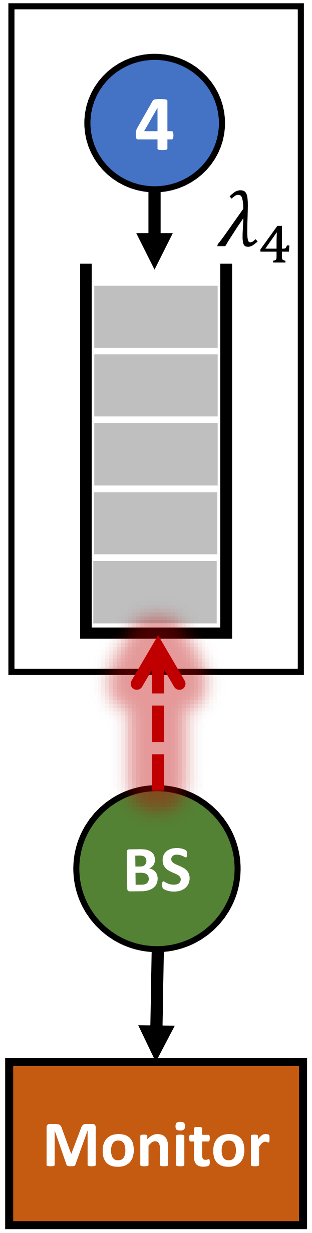
LCFS queue

Wireless Base Station **schedules transmissions**

Keeps track of the information

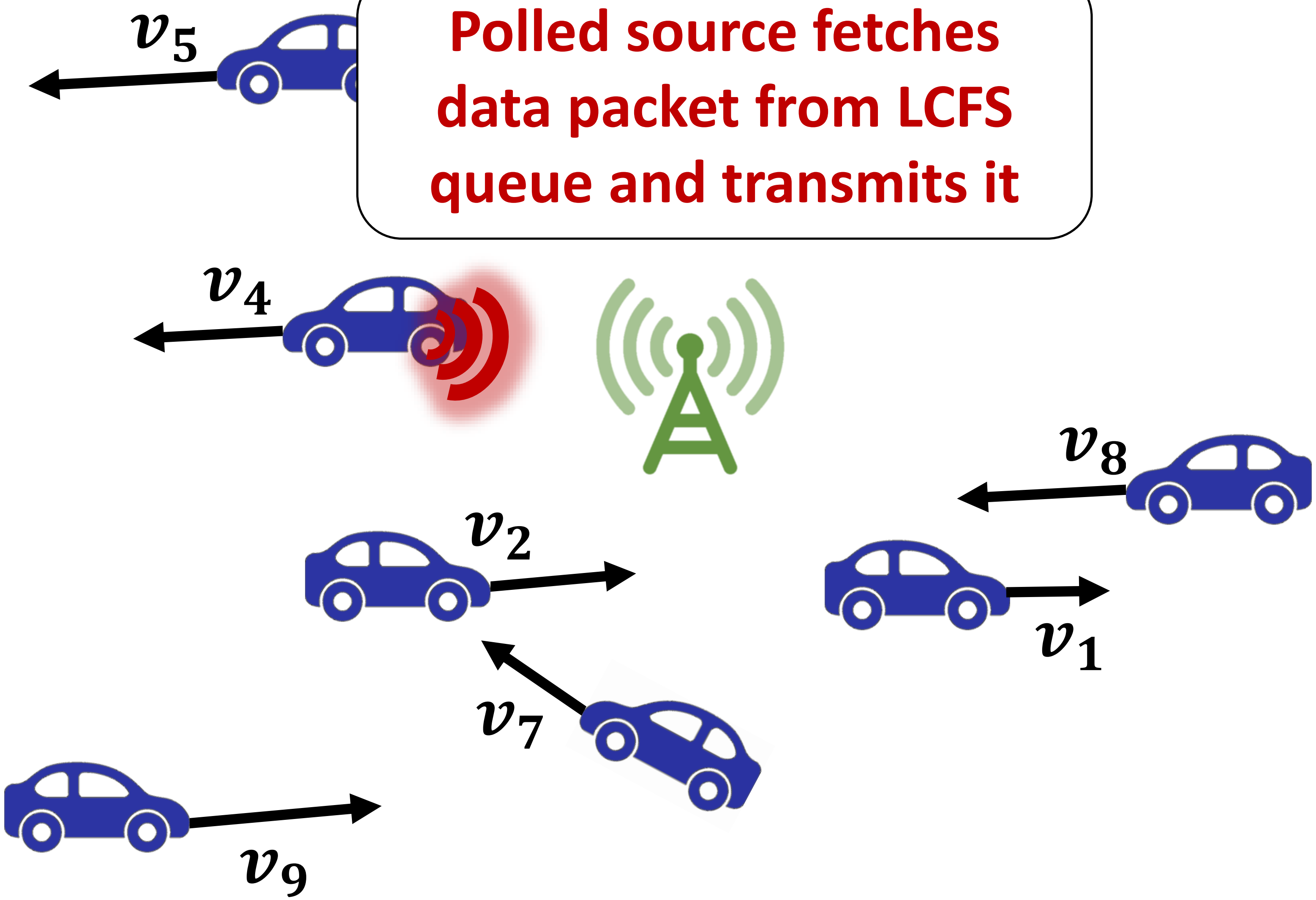
Large-scale system using WiFresh

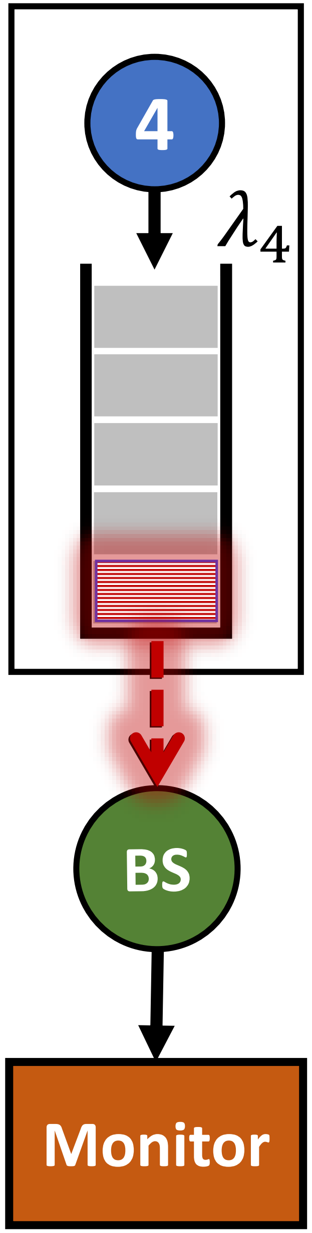




Large-scale system using WiFresh

Polled source fetches data packet from LCFS queue and transmits it





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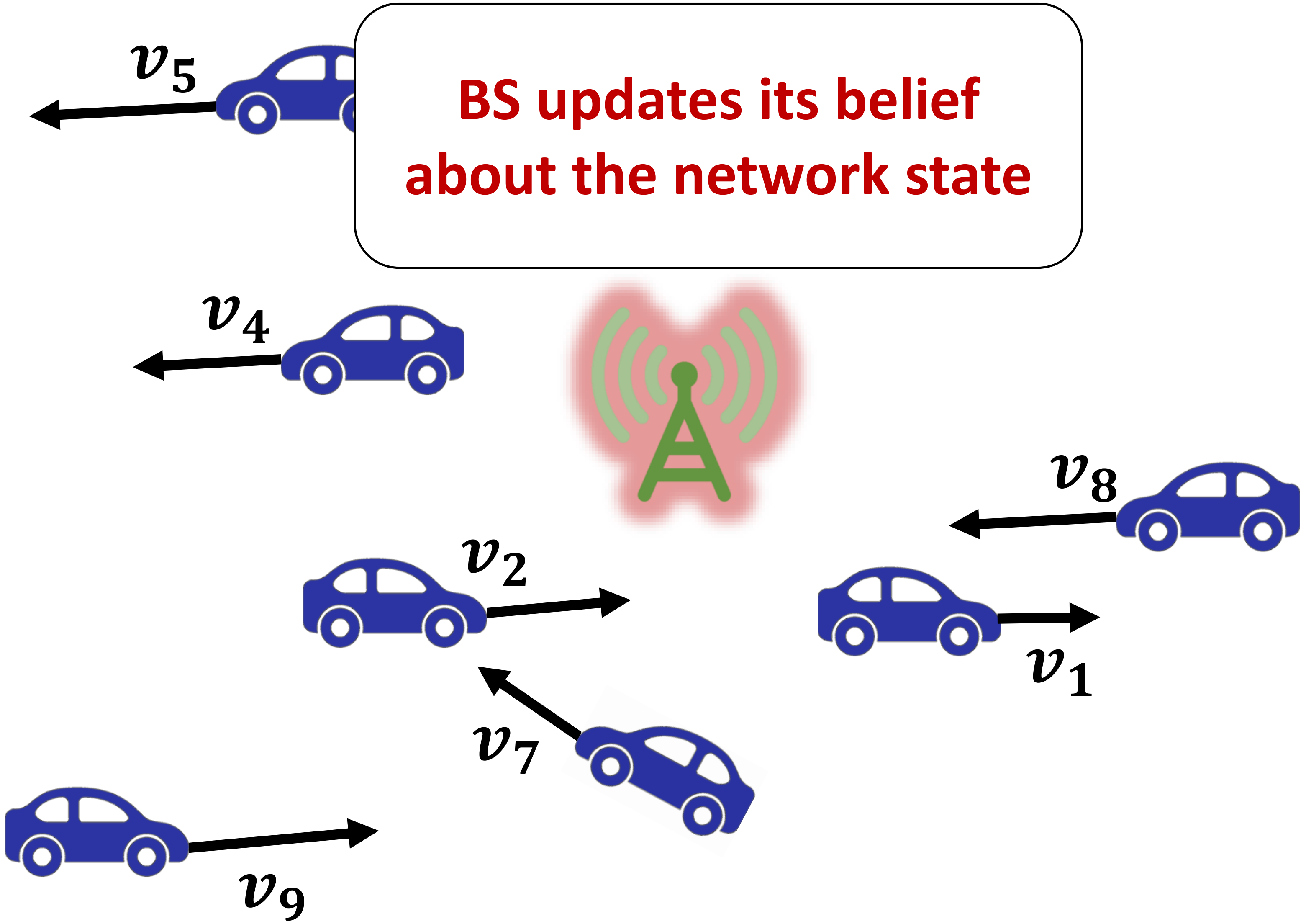

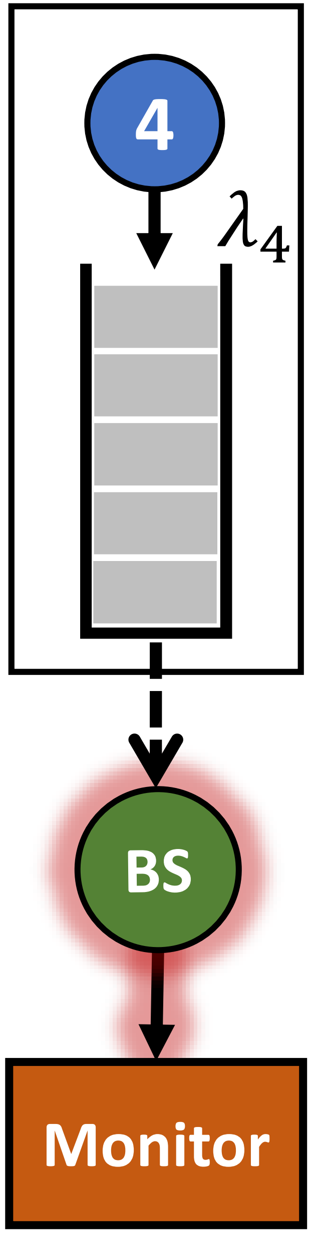

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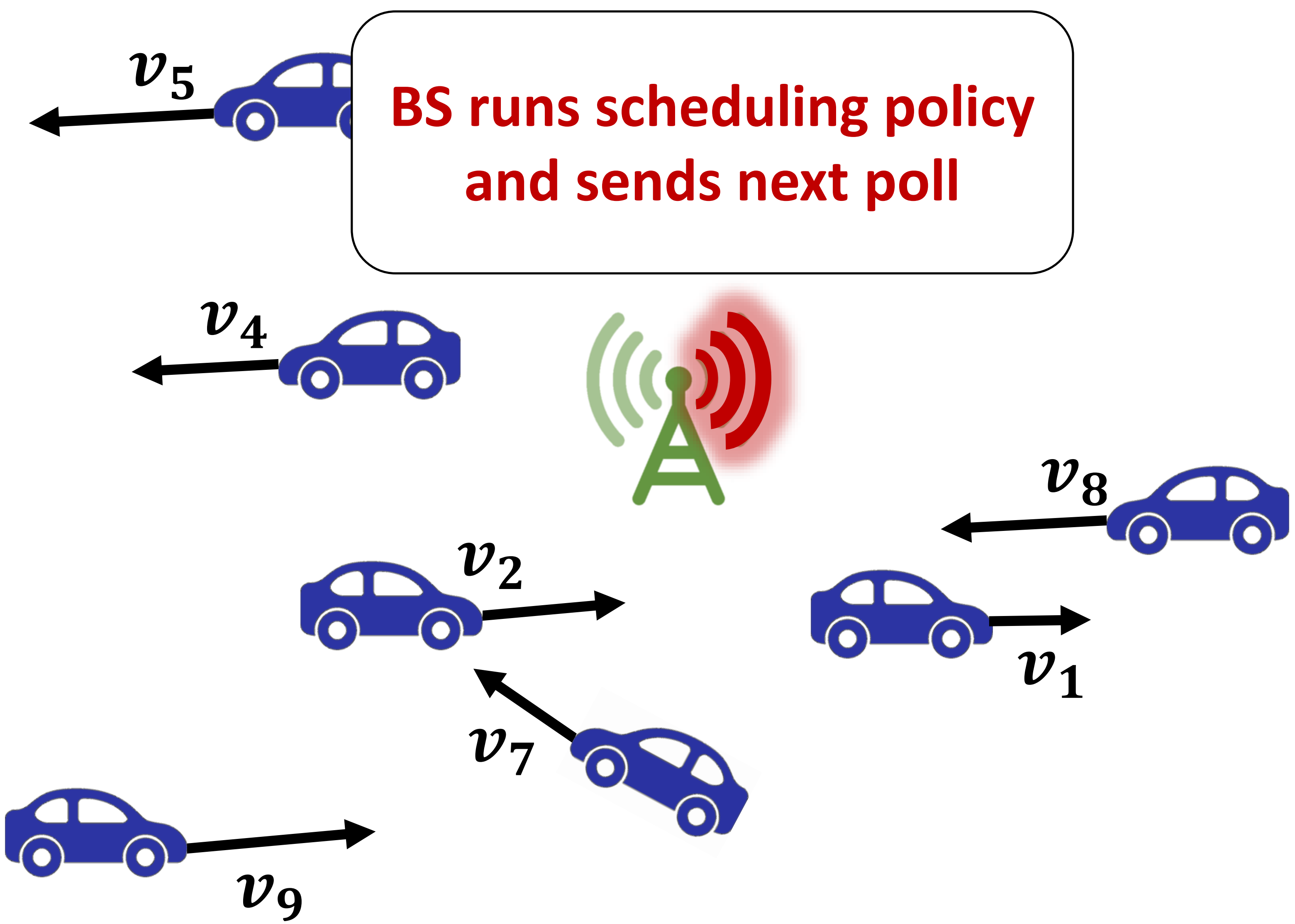

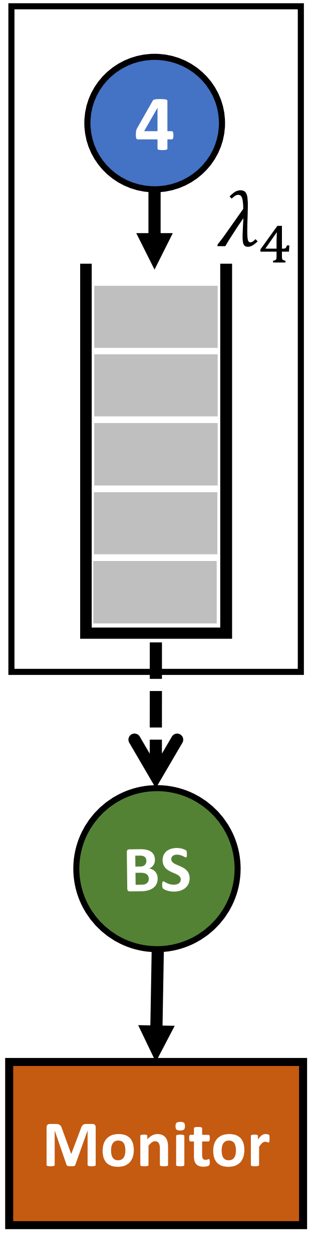

Time-sensitive information (GPS and IMU)

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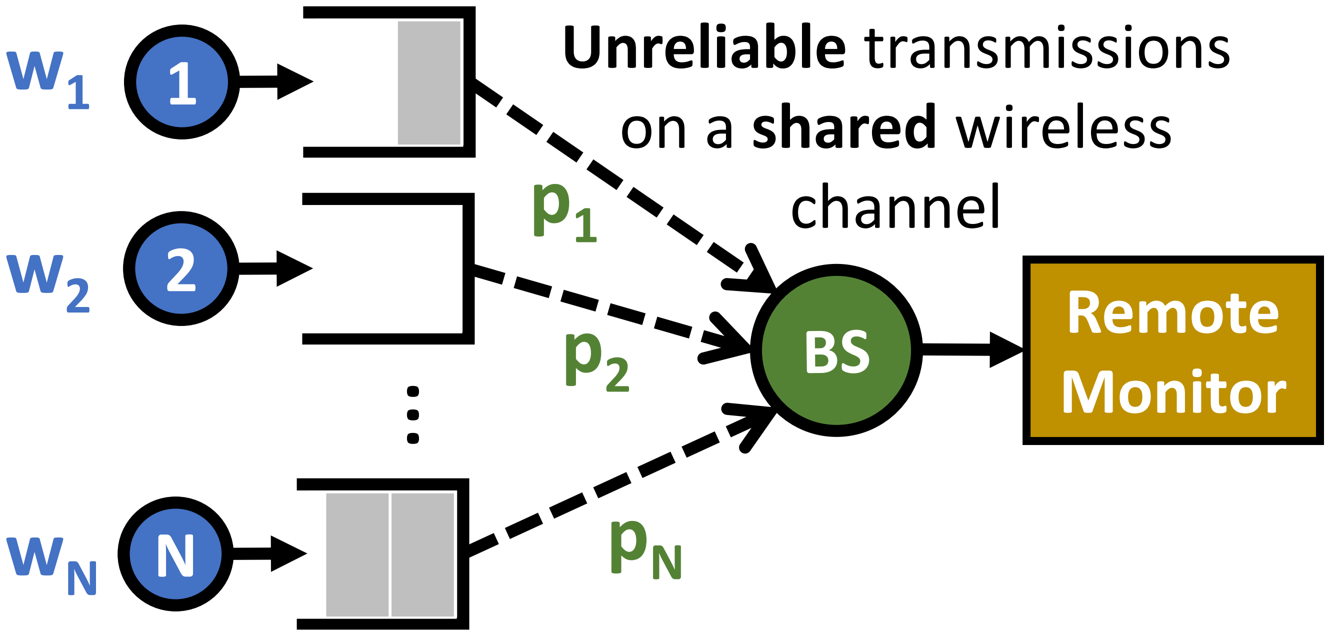
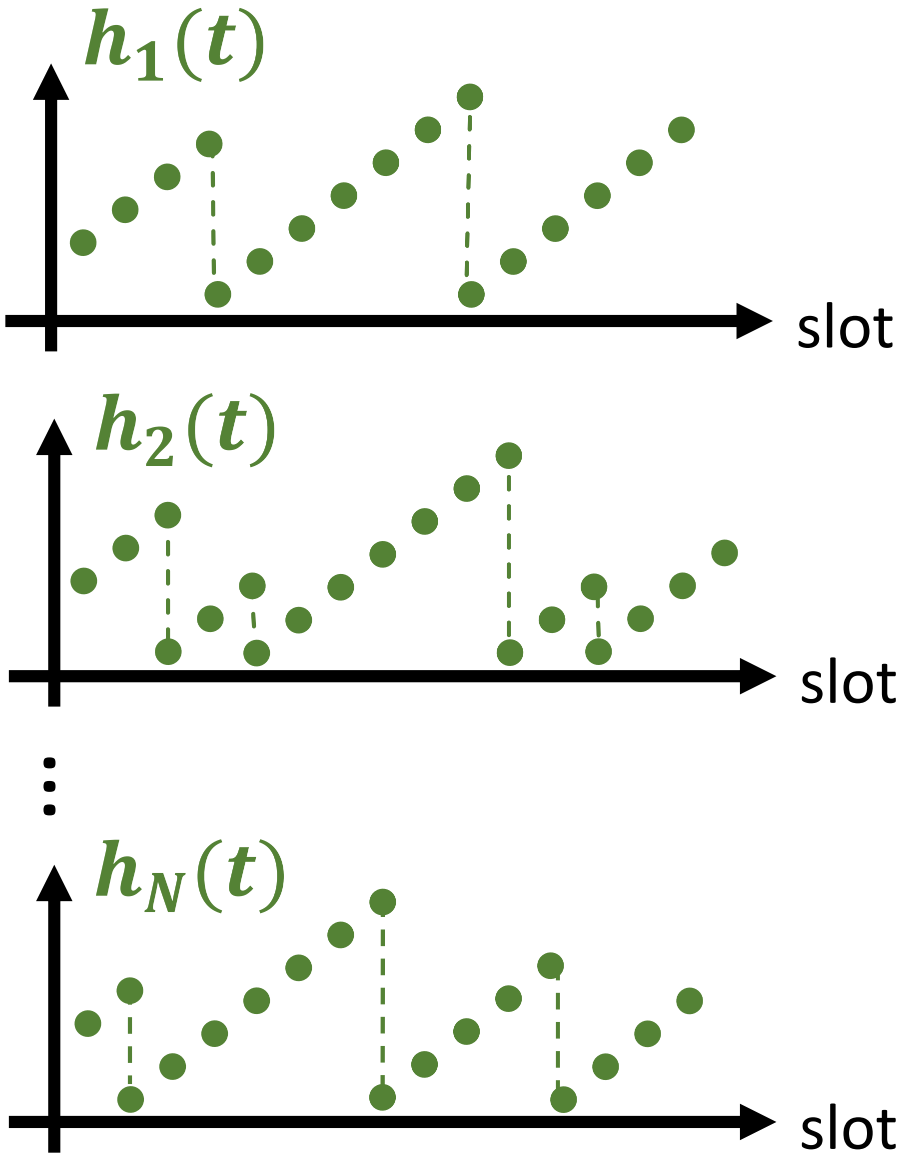
Network Model

Simplest model:
On-demand packet generation and LCFS queues





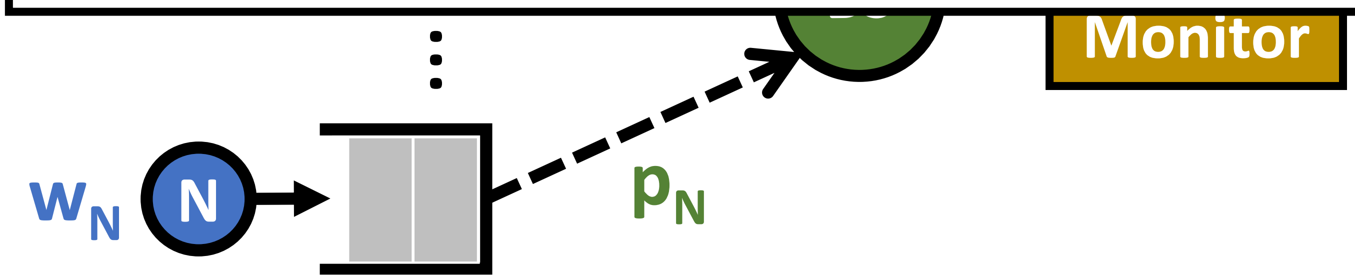
Weight $w_i > 0$ represents **priority** of source i

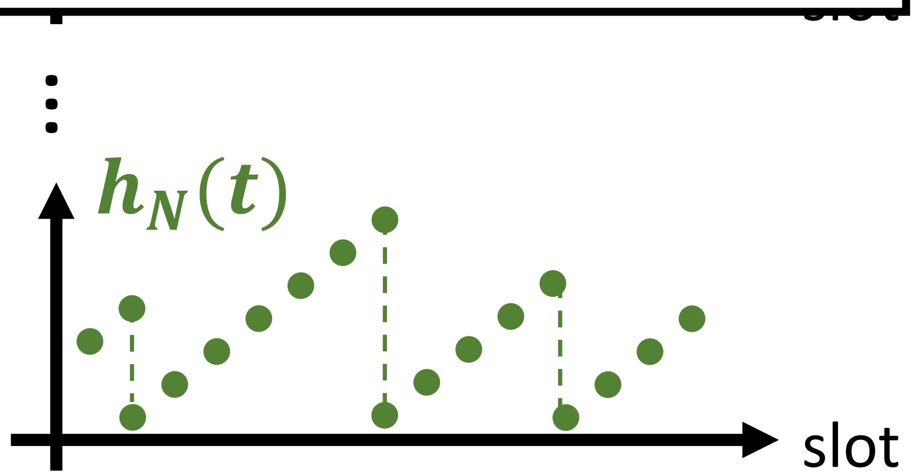
Probability $p_i \in (0,1]$ represents **quality of the link**

Network Model - Objective Function

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

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





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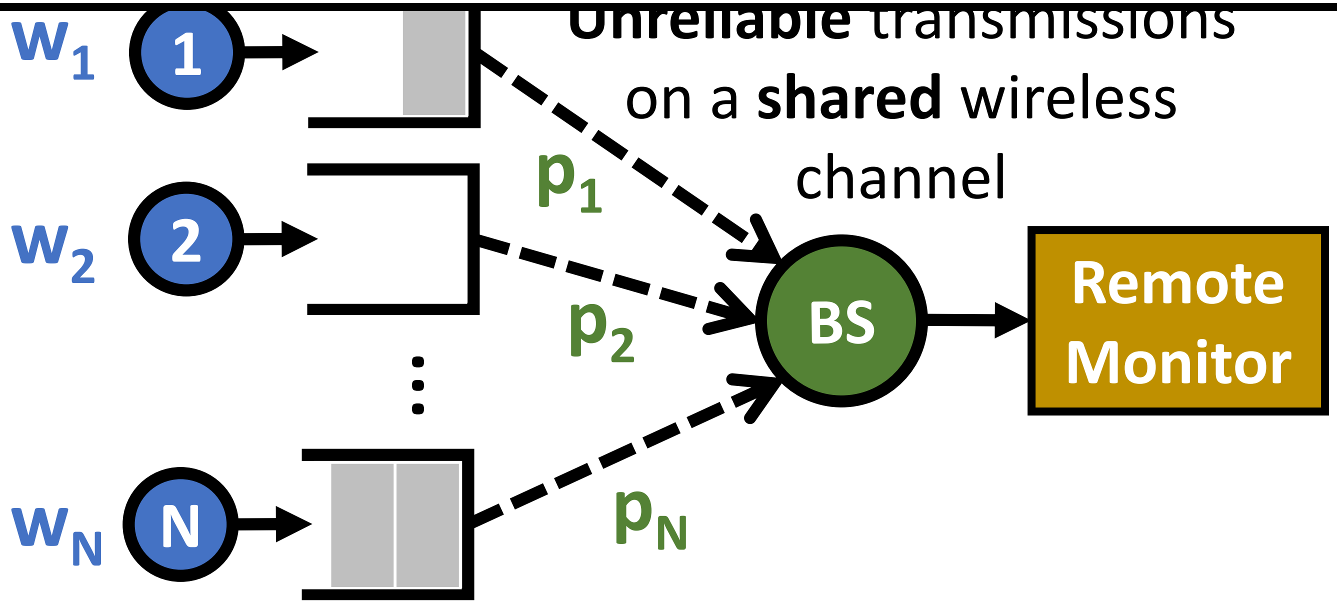
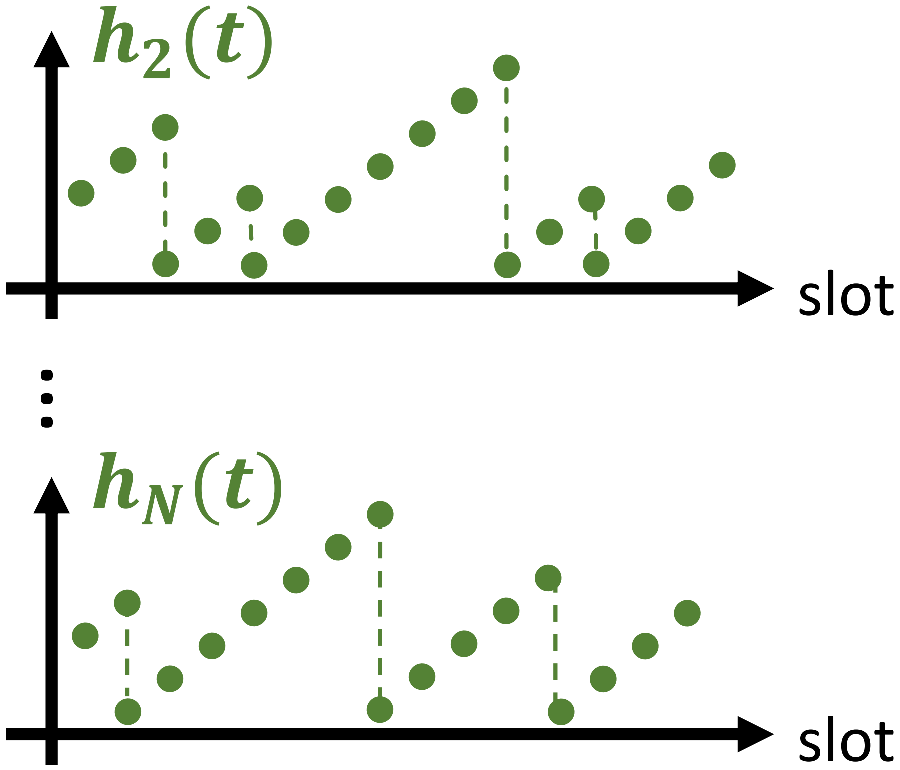
Summary of Theoretical Results

Model:

On-demand packet generation and LCFS queues. Packets are <u>always fresh</u>.





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

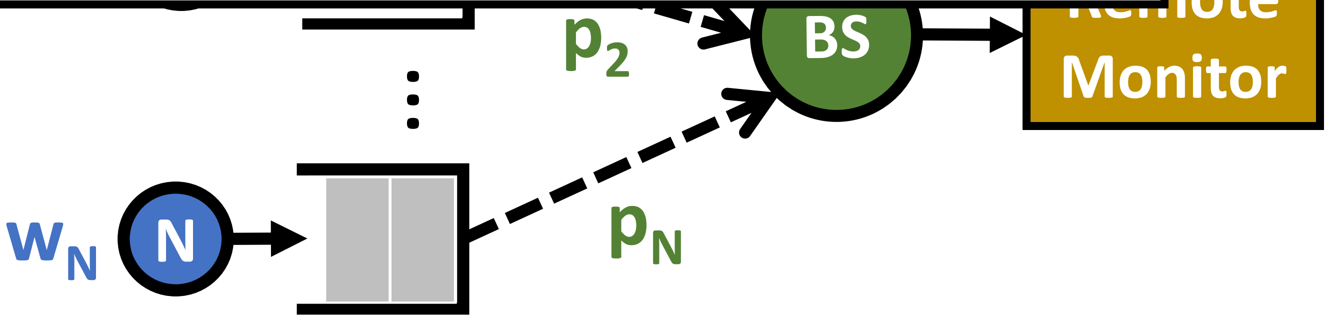
Probability $p_i \in (0,1]$ represents **quality of the link**

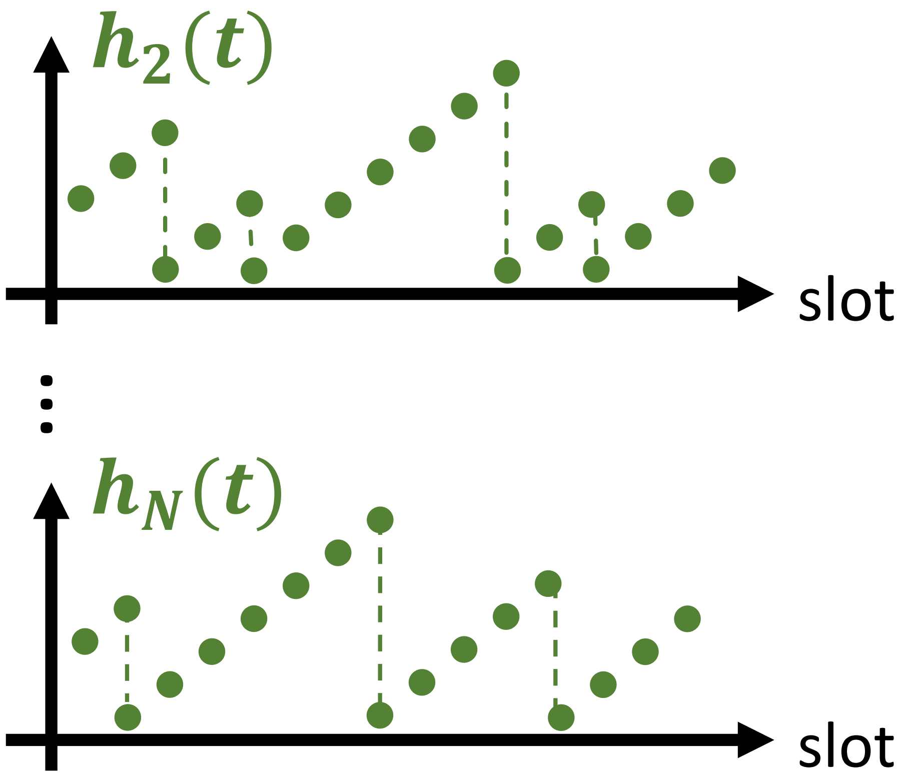
Summary of Theoretical Results

Model:

On-demand packet generation and LCFS queues. Packets are <u>always fresh</u>.

Dynamic Programming to <u>compute</u> the AoI-optimal policy





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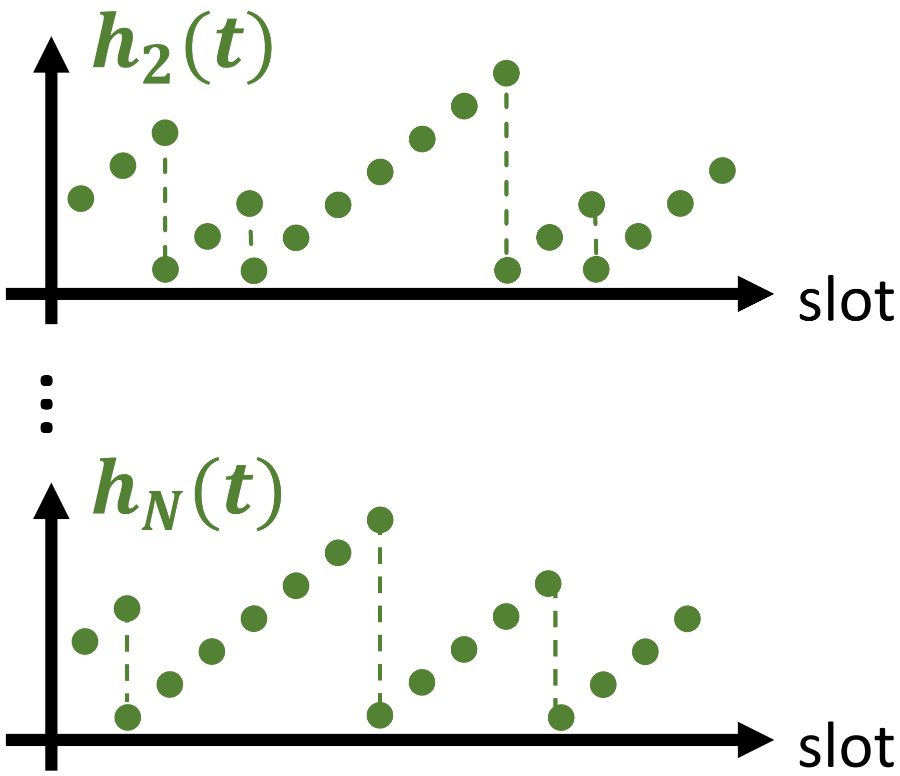

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Lower Bound: for any given network with (N, w_i, p_i): $\lim_{T\to\infty} \mathbb{E}[J_T^\pi] \geq L_B$

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 Guarantees

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

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

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

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

Summary of results for this model

Scheduling Policy	Decision in slot t	Performance Guarantee
Greedy	highest $h_i(t)$	optimal when symmetric
Randomized	node i w.p. $\propto \sqrt{w_i/p_i}$	2-optimal
Age-Based Max-Weight	highest $w_i p_i h_i^2(t)$	2-optimal
Whittle's Index	highest $w_i p_i h_i^2(t) + w_i p_i h_i(t)[\,2/p_i - 1\,]$	8-optimal

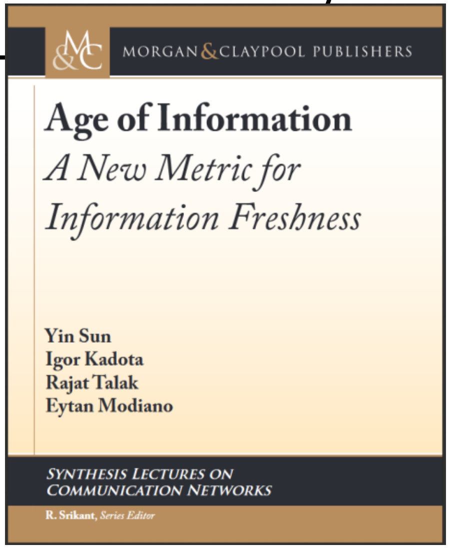
- For symmetric networks: **Whittle's** $\equiv$ **Max-Weight** $\equiv$ **Greedy** (all are optimal)

Extensions

In this presentation:

- Minimize EWSAoI
- LCFS queue
- Sources generating packets on-demand

[Book’19]



Sources generating packets periodically

[IEEE Allerton’16] [IEEE/ACM ToN’18]

Minimize EWSAoI subject to throughput constraints

[IEEE INFOCOM’18 best paper award]
[IEEE/ACM ToN’19]

- Sources generating packets stochastically
- Analysis for different queueing disciplines

[ACM MobiHoc’19 best paper finalist]
[IEEE TMC’20]

Outline

1. Introduction:
   - Age-of-Information and Applications

2. Theoretical Results: scheduling policies with performance guarantees
   - Using Renewal Theory, Stochastic Dominance, RMAB framework, and others.

3. System Deployment: validation in real operating scenarios
   - Using Software Defined Radios

WiFresh - Implementation

CPU: System initialization, configuration, and creating log files.

information exchange

FPGA: Clock-Driven (10MHz) code for generating packets, accessing the wireless channel, and managing time.

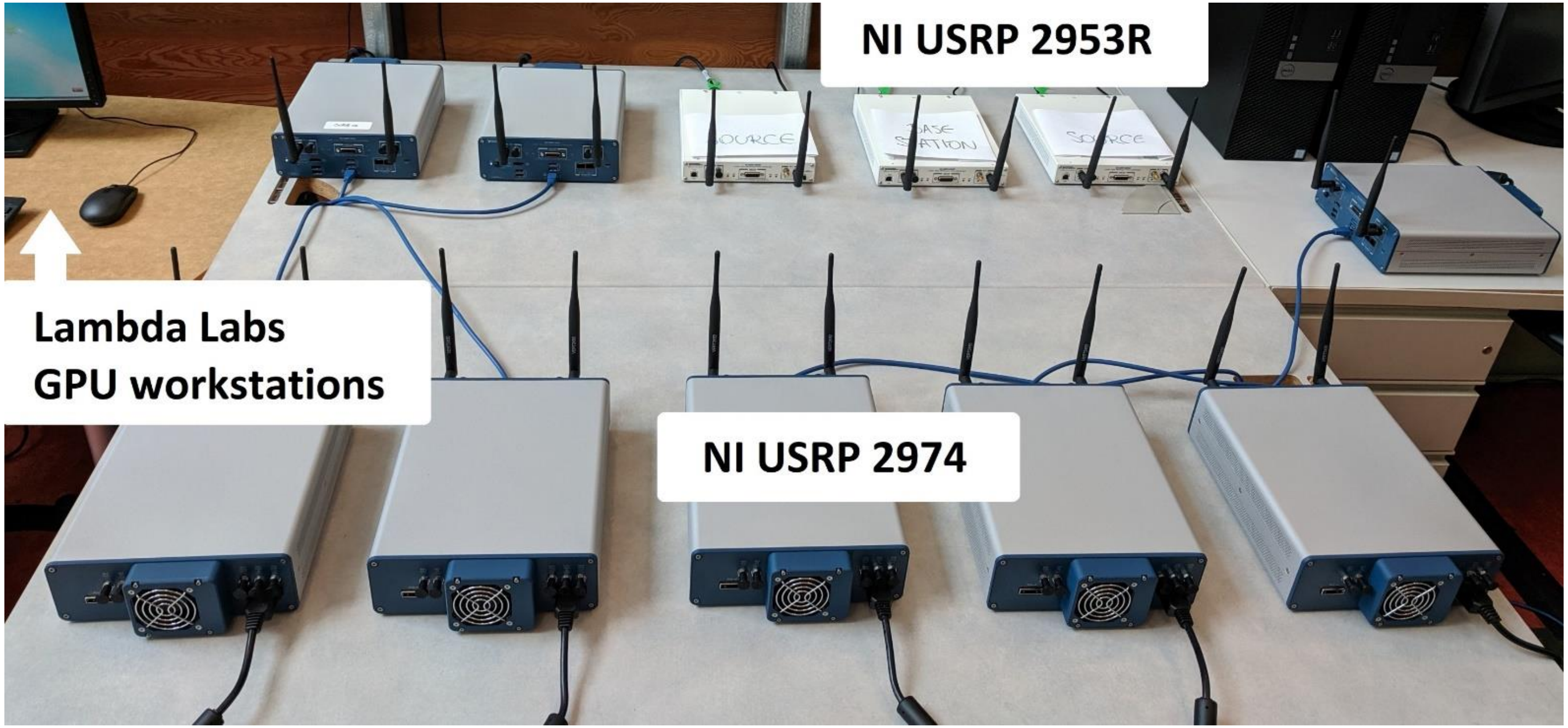
Software Defined Radio
NI USRP 2974

New functions at the FPGA:

- Polling with Max-Weight
- LCFS queue
- Time-stamp processing
- Estimating parameters

WiFresh - Video

- Ten sources generating packets of 150 bytes with frequency of $\lambda = 3k$ packets per second.



Base
Station

Outline

Thank you!!

contact: igor.kadota@columbia.edu

webpage.: http://www.igorkadota.com

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