Age of Information: A new metric proposed for measuring data freshness

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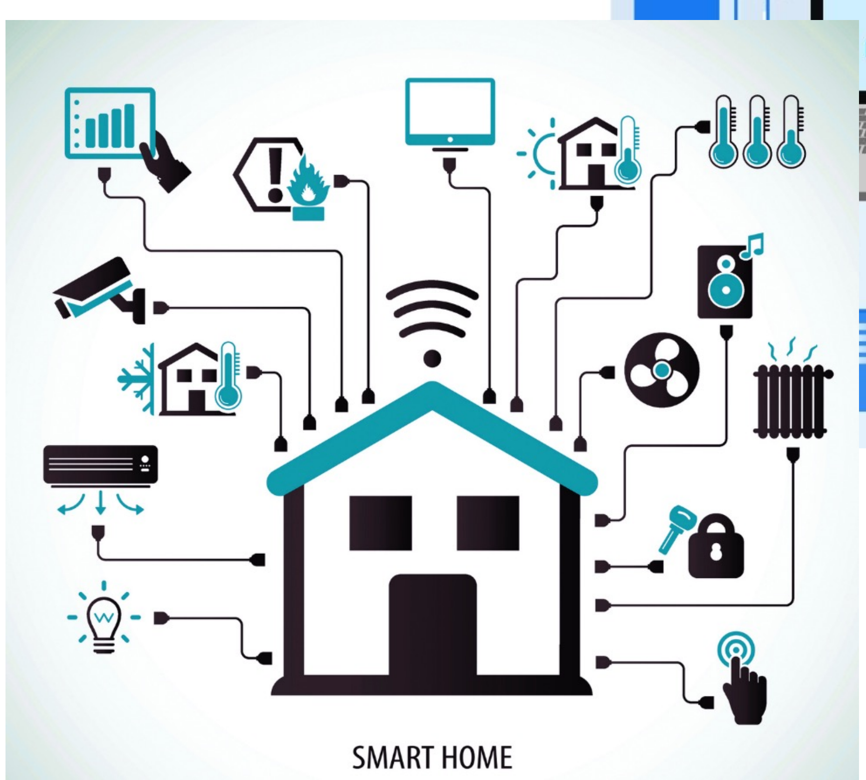
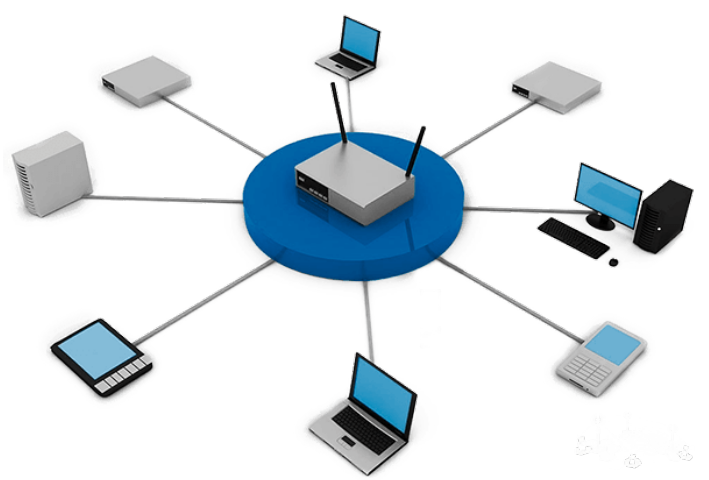
Data Freshness

- **Timely updates are essential in emerging applications of CPS/IoT**

Smart Plant



Smart Home



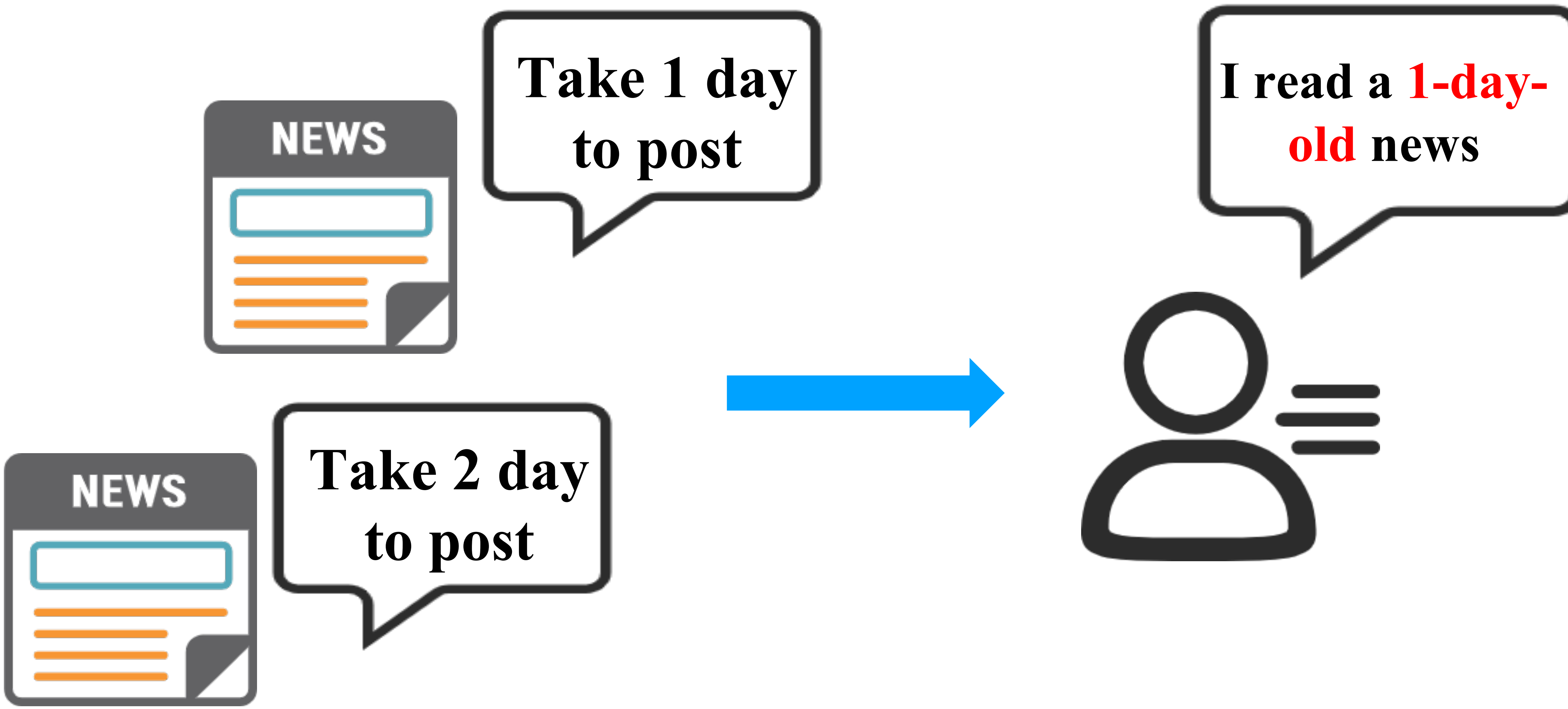
Data freshness in WSN

| Traditional Metrics

- **Limitation when describing “freshness”**
  - Throughput——Network perspective
    Rate of message delivery over network.
    Inappropriate
  - Delay——Data Packet perspective
    Time for data traveling across the network
    Ambiguous

Age of Information

- **News Delivery Example**



Delay

AoI

Age of Information

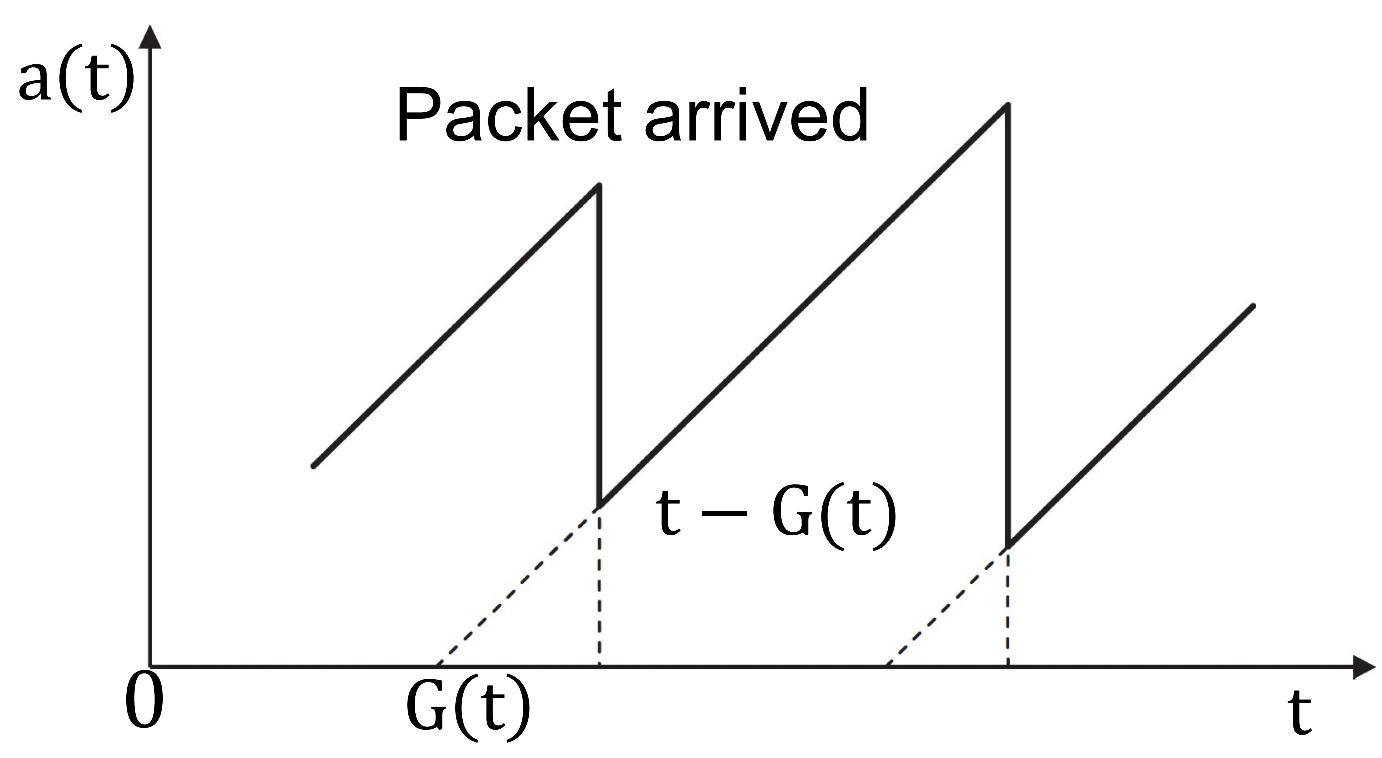
- **Definition**

The time elapsed since the generation time of the latest arrival packet.

$G(t)$: Generation time of the latest data

$a(t)$: AoI at the time t

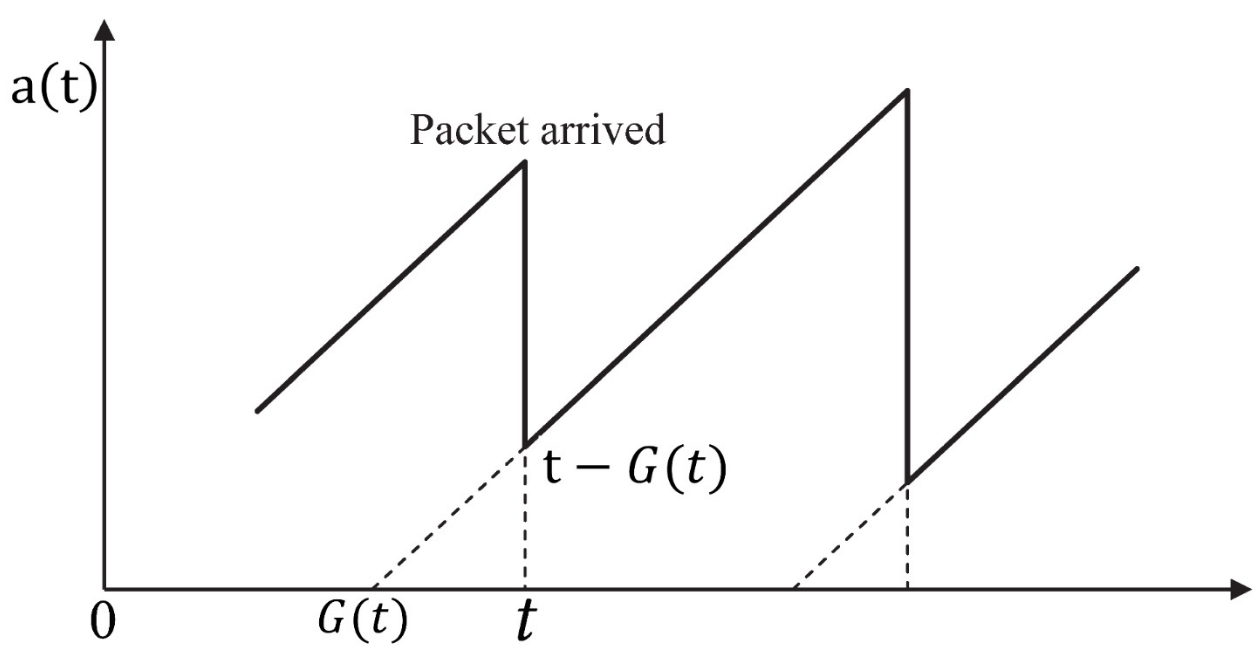
$$a(t) = t - G(t)$$



Age of Information

- **AoI Variation**

$$a(t) = \begin{cases} a(t-1)+1, & \text{No new packet arrived;} \\ t - G(t), & \text{Received a new packet generated at } G(t). \end{cases}$$



Aggregated AoI

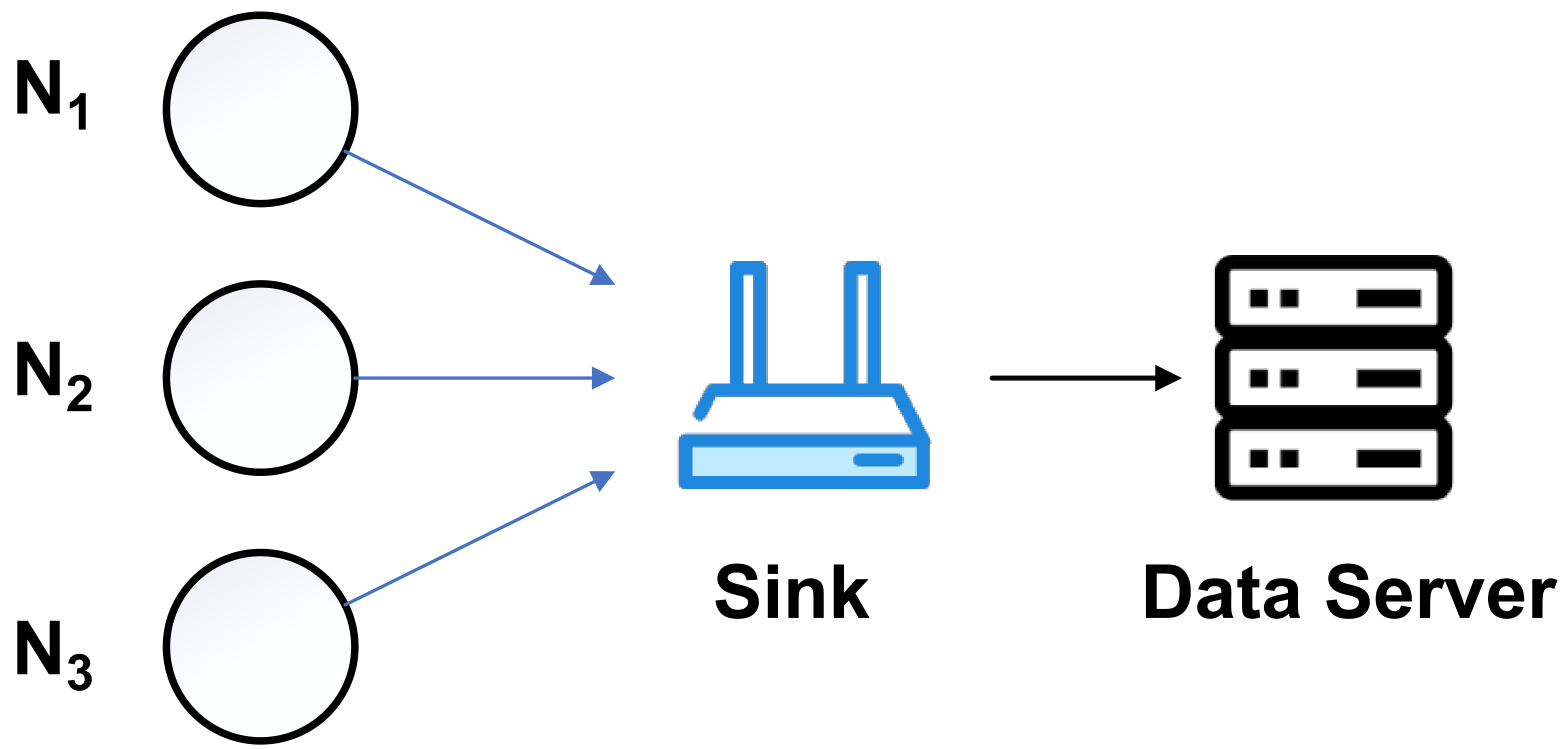
$$\Delta A_{d_l} = \int_0^T a_{d_l}(t)dt$$

Time-averaged AoI

$$A_{d_l} = \frac{1}{T}\int_0^T a_{d_l}(t)dt$$

Age of Information

- **Data Transmission Example**



RR with cycle of 4	N_1	N_2	N_3		N_1	N_2	N_3		N_1	N_2	N_3
RR with cycle of 2	N_1		N_2		N_3		N_1		N_2		N_3

Age of Information

- **AoI and Delay Comparisons**

TABLE I
AoI VARIATION IN PERIODIC REQUEST WITH THE REQUEST CYCLE OF 2

Slot / Node	1	**2**	3	**4**	5	**6**	7	**8**	9	**10**	**Comparison Metrics**
N_1	1	**1**	2	**3**	4	**5**	6	**1**	2	**3**	–
N_2	1	**2**	3	**1**	2	**3**	4	**5**	6	**1**	–
N_3	1	**2**	3	**4**	5	**1**	2	**3**	4	**5**	–
Transmission Delay	–	**2**	–	**2**	–	**2**	–	**2**	–	**2**	**Long-term Delay: 2**
AoI Variations	3	5	8	8	11	9	12	9	12	9	**Accumulative AoI: 8.6**

TABLE II
AoI VARIATION IN PERIODIC REQUEST WITH THE REQUEST CYCLE OF 4

Slot / Node	1	2	3	**4**	5	6	7	**8**	9	10	**Comparison Metrics**
N_1	1	2	3	**3**	4	5	6	**3**	4	5	–
N_2	1	2	3	**2**	3	4	5	**2**	3	4	–
N_3	1	2	3	**1**	2	3	4	**1**	2	3	–
Transmission Delay	–	–	–	**9**	–	–	–	**9**	–	–	**Long-term Delay: 9**
AoI Variations	3	6	9	6	9	12	15	6	9	12	**Accumulative AoI: 8.7**

Existing Work

- Special network topologies
- Interference-free link sets
- Flexible routing
- … …

Multi-hop

Applications scenario

- Interference and throughput
- Energy consuming
- Broadcast network
- Moving collection agents
- … …

Single-hop

- Generation rate control
- Queuing packet management
- Scheduling policies
- … …

Instant AoI Optimization in IoT Networks with Packet Combination

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Outline

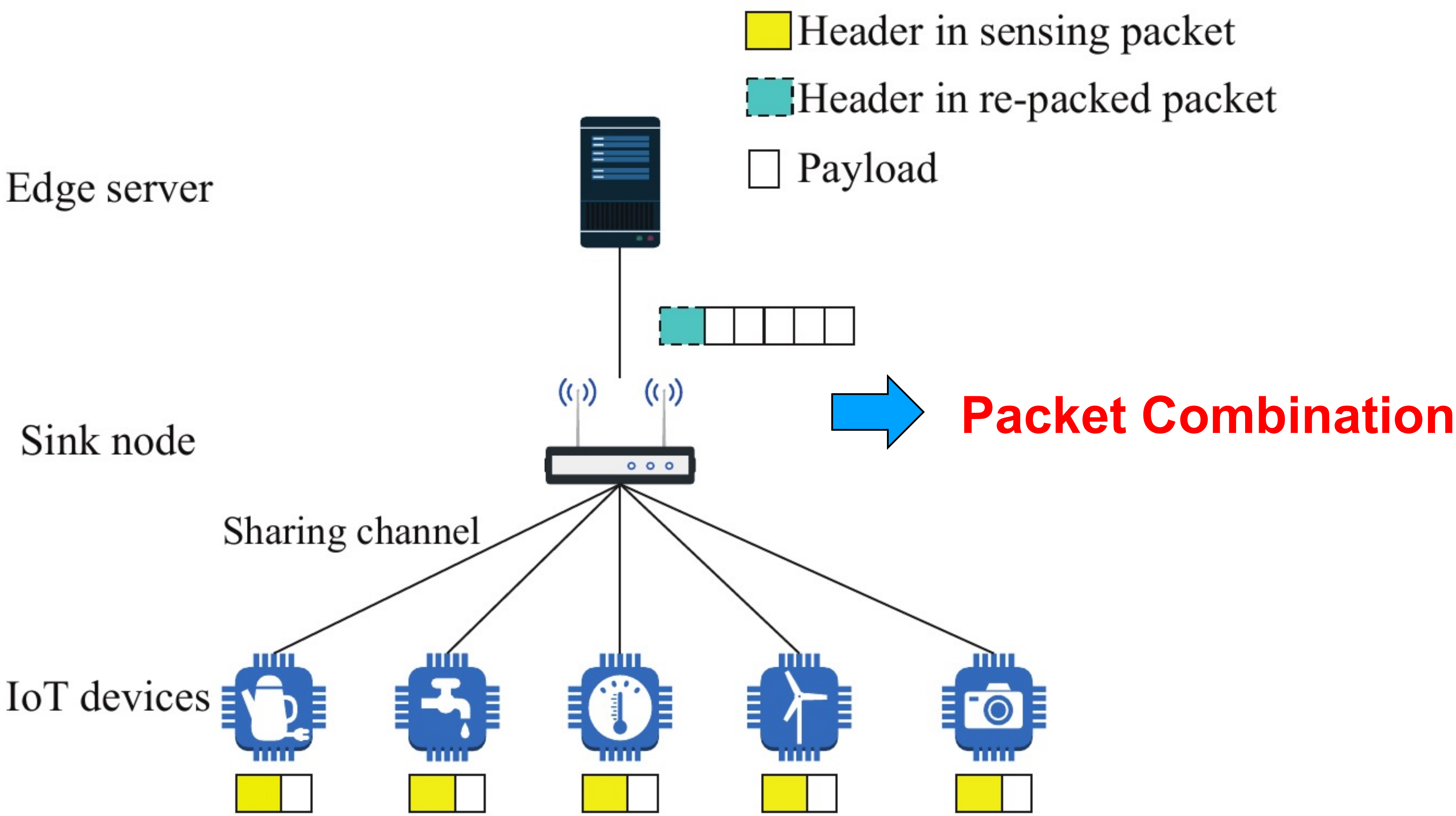
Network Model
- IoT Networks
- Packet Combination

New Metric
- Instant AoI

Request Modes
- Periodic Request
- Proactive Request

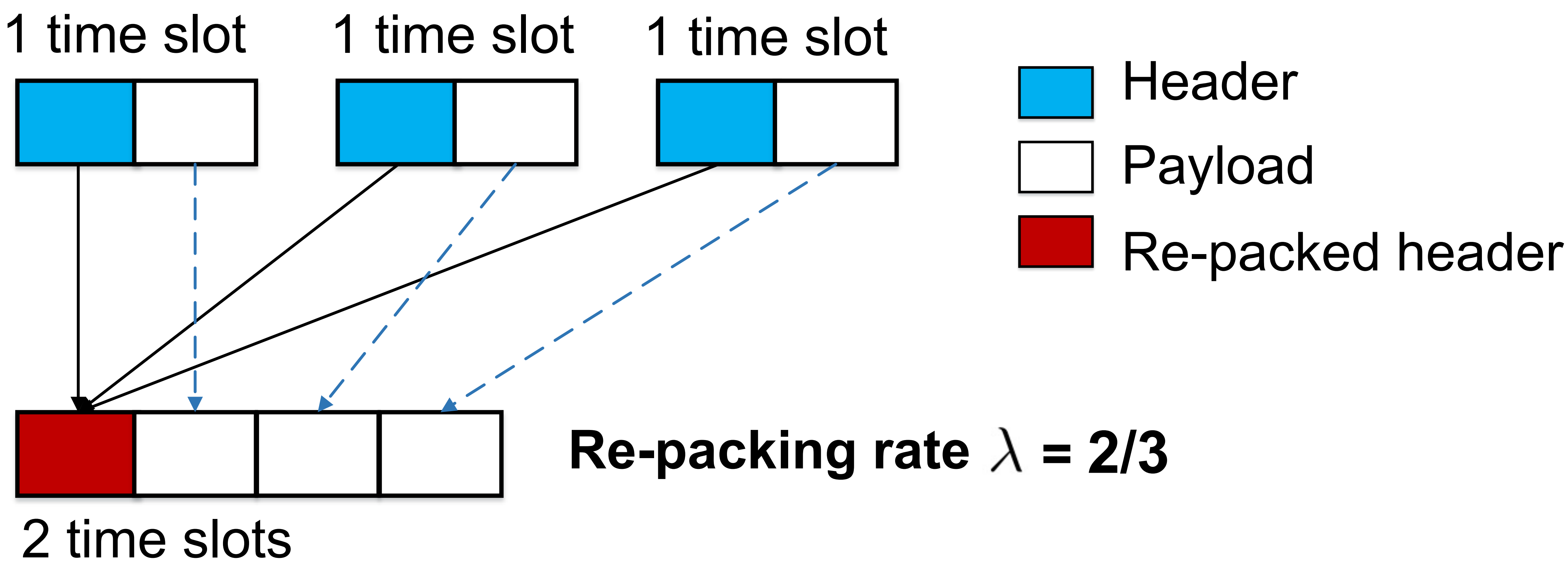
IoT Application

- **Packet Aggregation in the IoT Network**



Packet Combination

- **Re-packing Rate and Transmission Time**



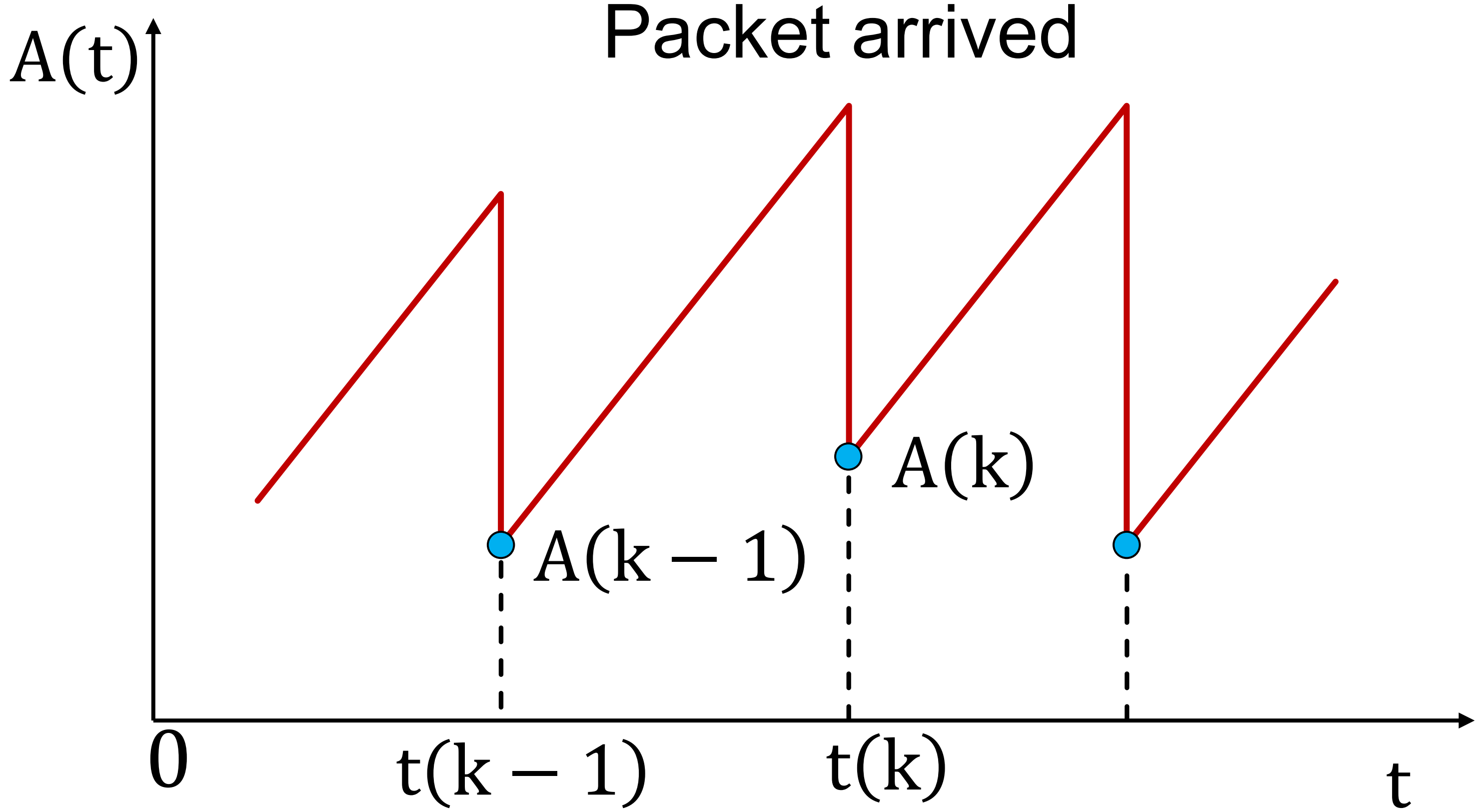
Re-packing rate λ = 2/3

Time slot for transmitting L packets: $\lceil \lambda L \rceil = 3$

Instant AoI

- **AoI at Packet Delivered Time Point**

Instant AoI $\bar{A}(k) = A\big(t(k)\big)$



Time-averaged AoI

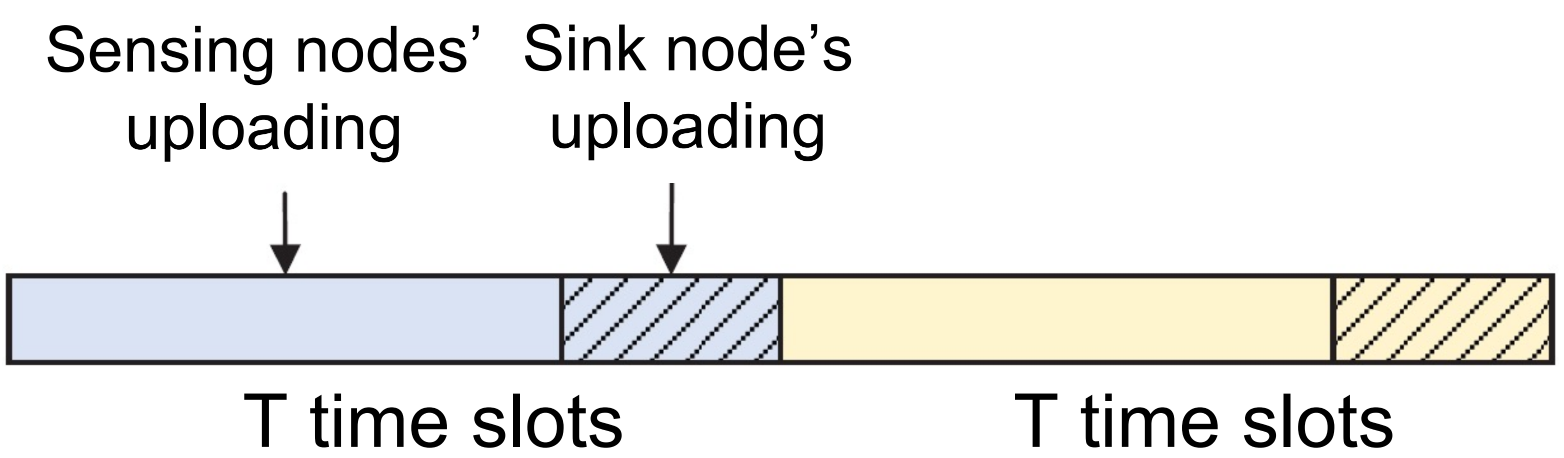
$$\tilde{A} = \lim_{T\to\infty} \frac{1}{T} \sum_{t=1}^{T} A(t)$$

Long-term Instant AoI

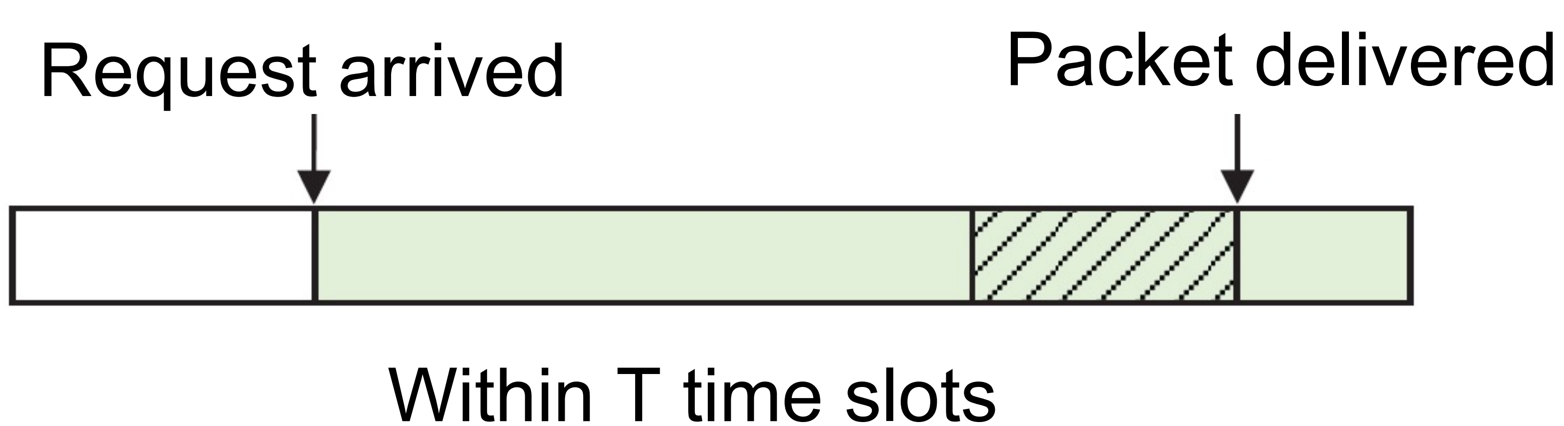
$$\bar{A} = \lim_{K\to\infty} \frac{1}{K} \sum_{k=1}^{K} A(k)$$

Request Modes

- **Periodic Request: Arrived in every T time slot**



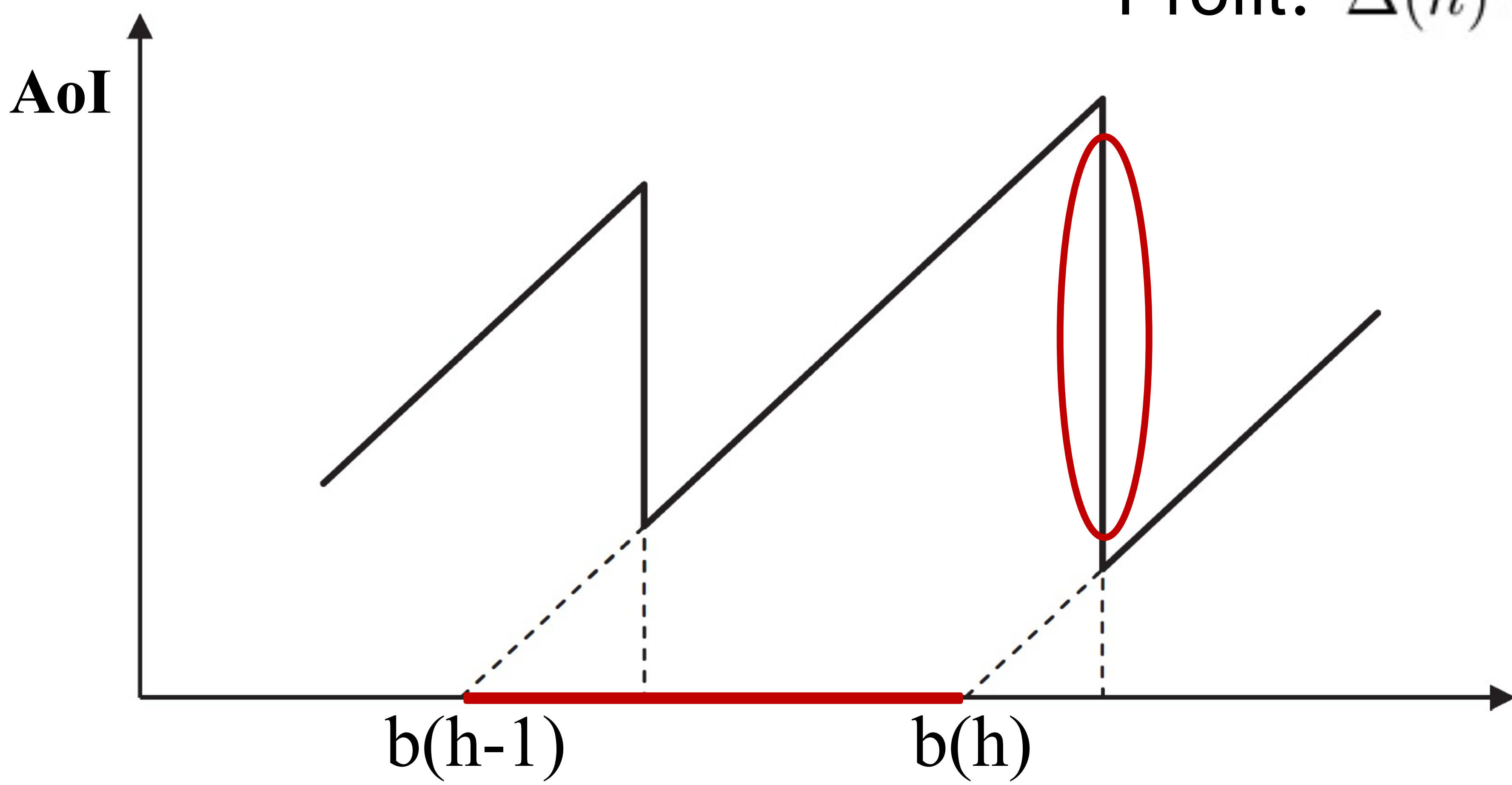
- **Proactive Request: Arrived arbitrarily**



Periodic Request

- **AoI Profit: The Value of decreased AoI**

Profit：$\Delta(h) = b(h) - b(h-1)$



Time interval between the two packets uploading

Periodic Request

- **Instant AoI Calculation**

Instant AoI at H-th cycle

$$\bar{A}^E(H) = \boxed{\bar{A}^E(0)} + \frac{1}{|\mathcal{N}|}\sum_{h=1}^{H}\Big(\boxed{|\mathcal{N}|\cdot T} - \sum_{n\in\mathcal{V}(h)}\boxed{\Delta_n(h)}\Big)$$

Initial AoI **Increased AoI** **AoI Profit**

Long-term Instant AoI

Latest uploading time slot

$$\bar{A}^E = \bar{A}^E(0) + \frac{H+1}{2}T - \boxed{\lim_{H\to\infty}\frac{1}{H}\frac{1}{|\mathcal{N}|}\sum_{h=1}^{H}\sum_{n\in\mathcal{N}}\tilde{b}_n(h)}$$

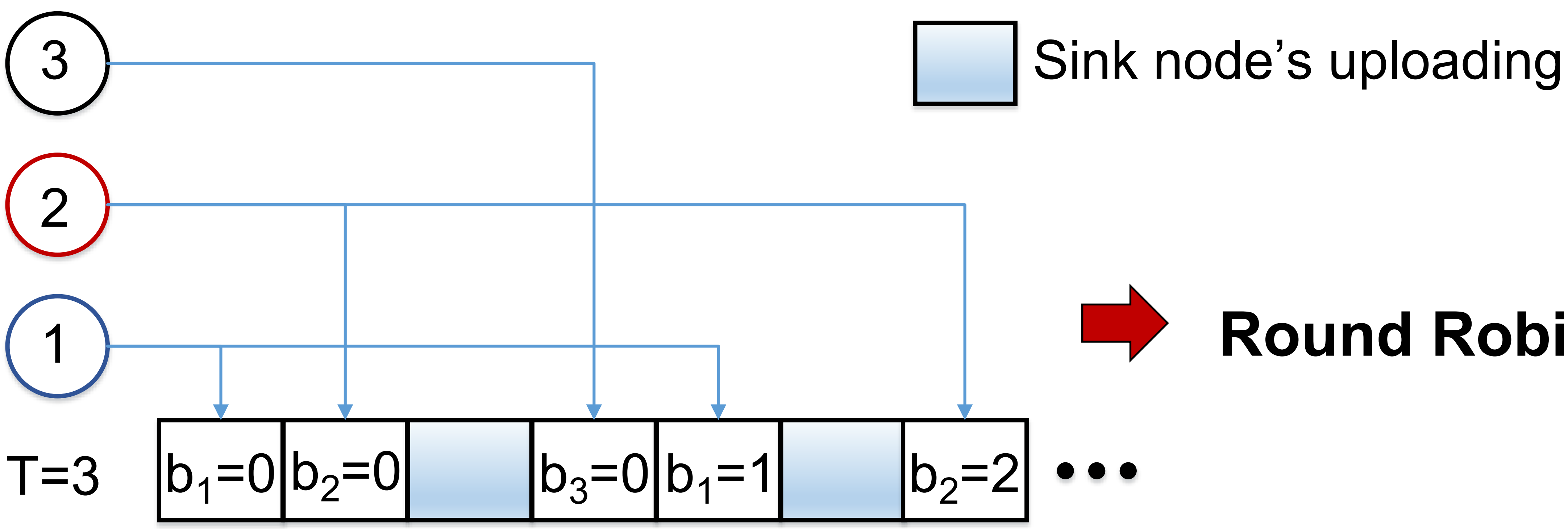
Scheduling parameter

Periodic Request

- **Instant AoI Optimization**

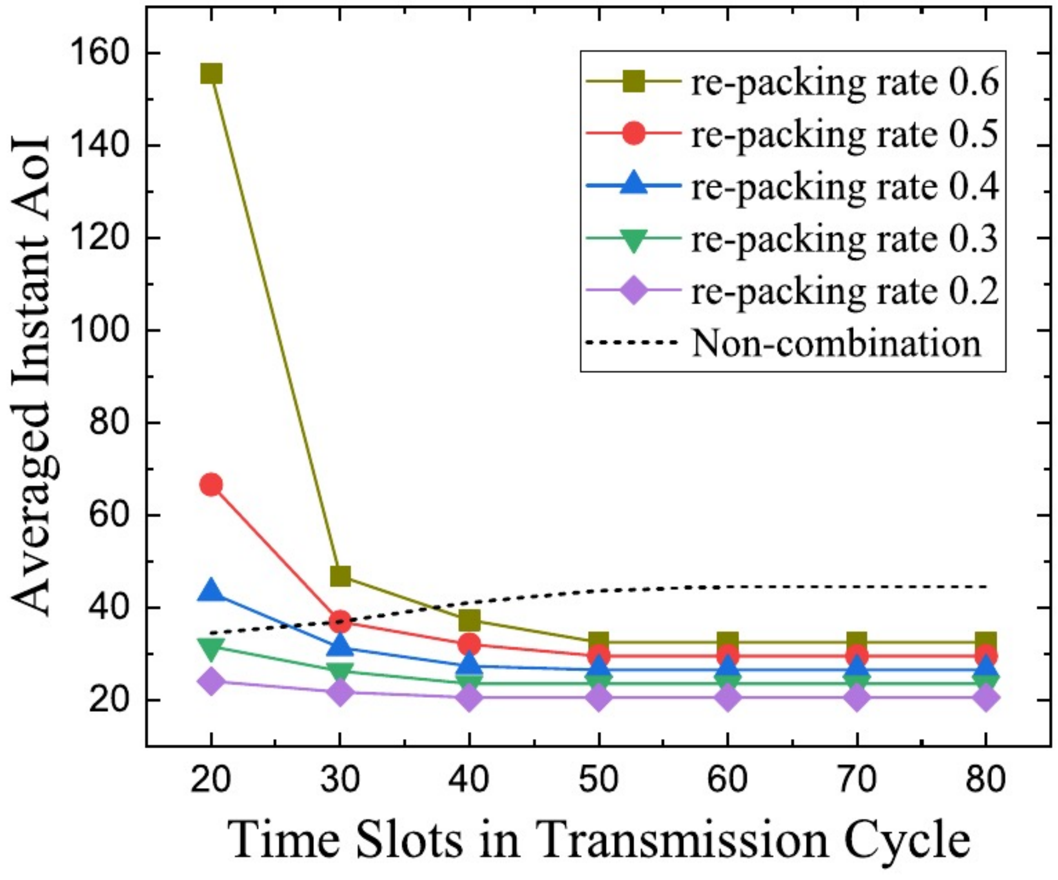
$$\text{OPT-1} \quad \max \sum_{h=1}^{H} \sum_{n \in \mathcal{N}} \tilde{b}_n(h)$$
$$s.t.\ \text{Constraints: } \tilde{b}_n(h) \le hT$$

In a time slot, the node with minimum index uploads its new packet

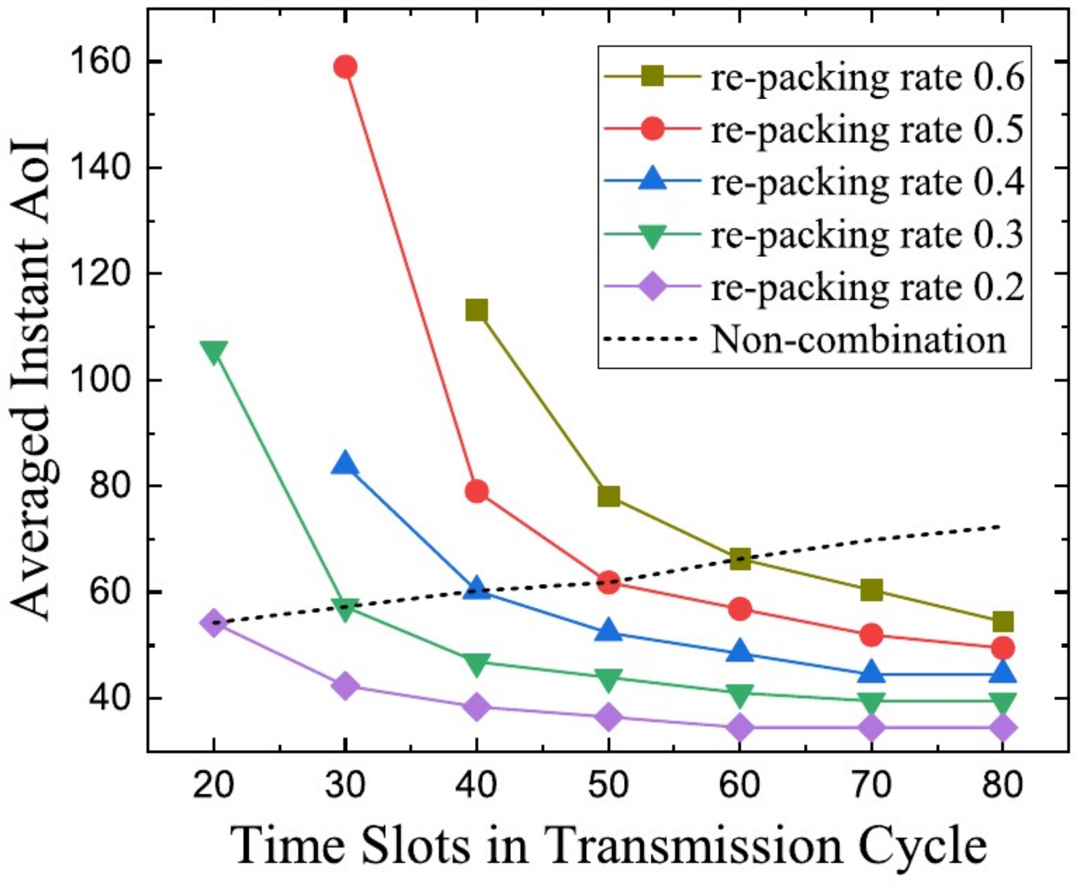


Round Robin

Numerical Results



30 Sensing Nodes



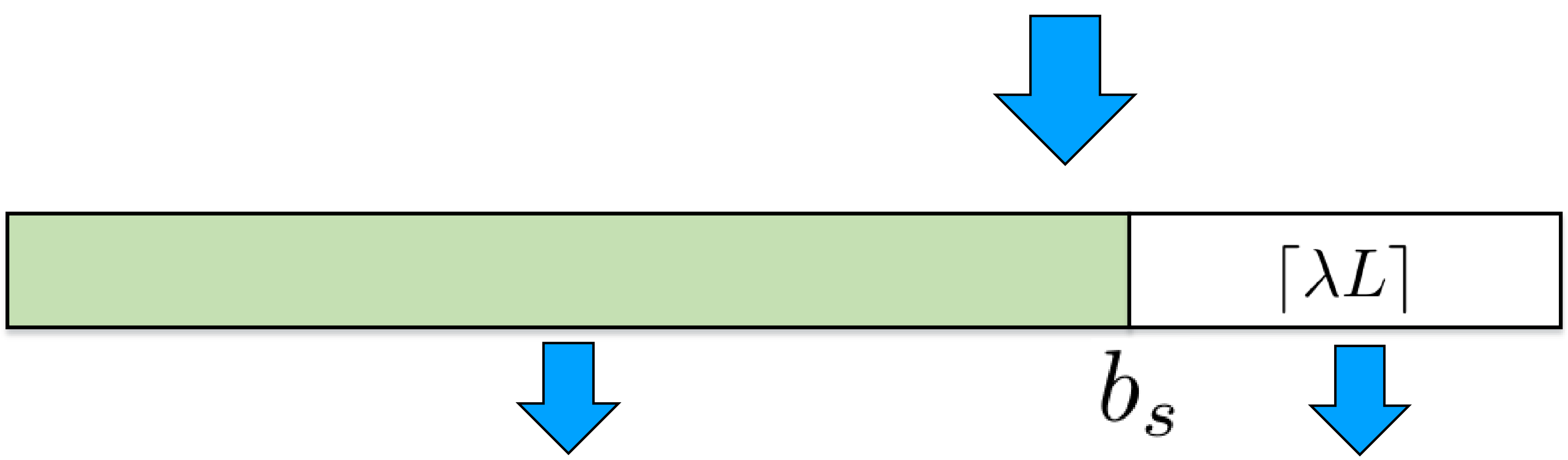
50 Sensing Nodes

| Proactive Request

- **Instant AoI Calculation**

$$A^E = \frac{1}{|\mathcal{N}|}\Big(\sum_{n\in\mathcal{N}} \big(\boxed{A_n^E(0)} + \boxed{b_s + \lceil \lambda L \rceil - 1}\big) - \boxed{\sum_{n\in\mathcal{V}} \Delta_n} \Big)$$

Initial AoI **Increased AoI** **AoI Profit**



Sensing node uploading Combined packet uploading

Proactive Request

- **Instant AoI Optimization**

$$A^E = \frac{1}{|\mathcal{N}|}\Big(\sum_{n\in\mathcal{N}}\big(A_n^E(0) + b_s + \lceil \lambda L \rceil - 1\big) - \sum_{n\in\mathcal{V}} \Delta_n\Big)$$

L packets from sensing nodes

$$A^E = \frac{1}{|\mathcal{N}|}\Big(\boxed{f(L)} - \frac{(L+1)}{2}L + |\mathcal{N}|(L + \lceil \lambda L \rceil)\Big)$$

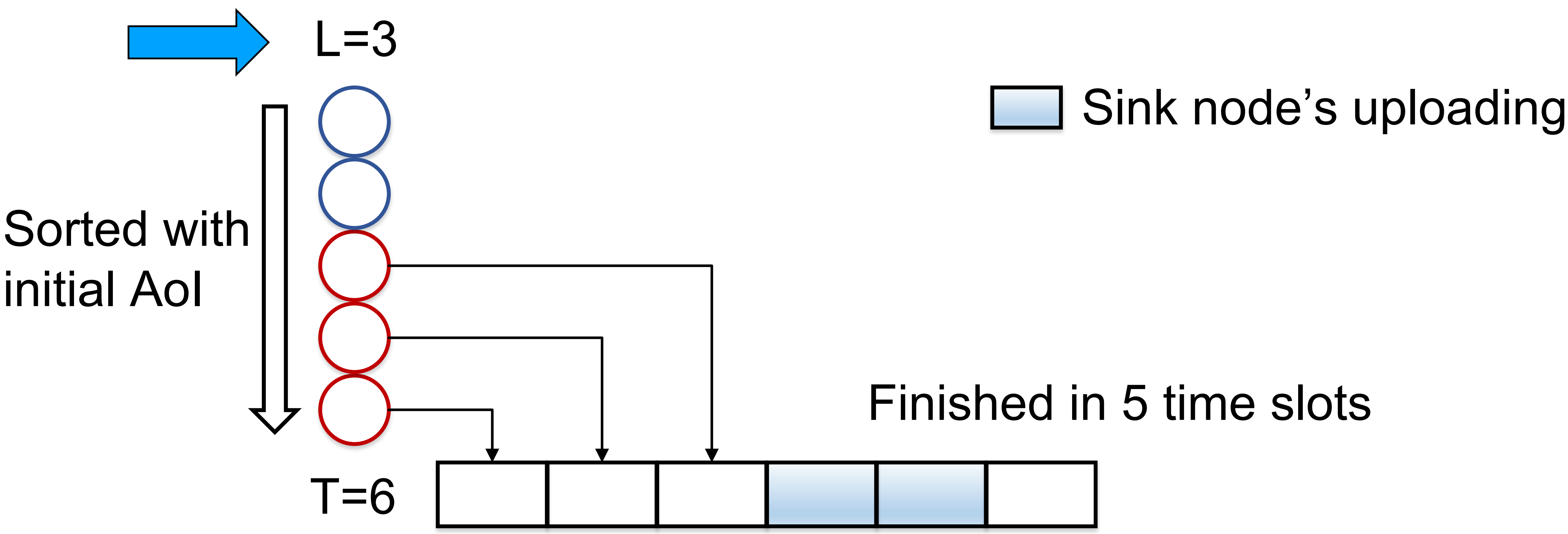
L Minimum Initial AoIs

Proactive Request

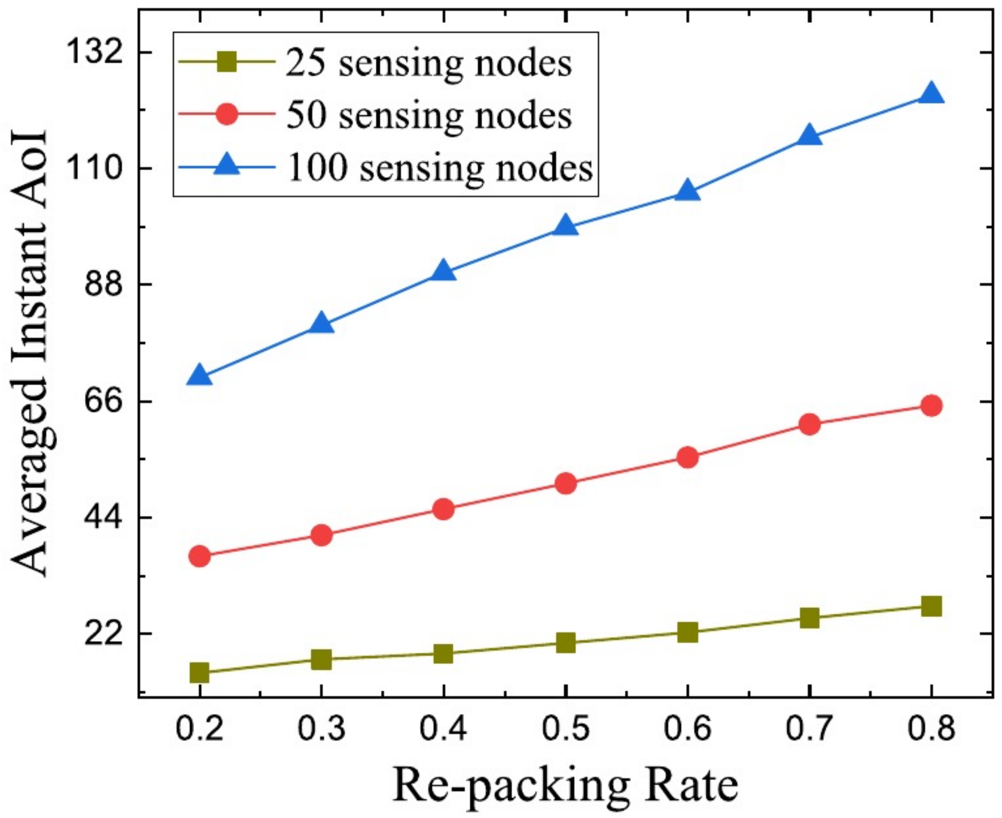
- **Instant AoI Optimization**

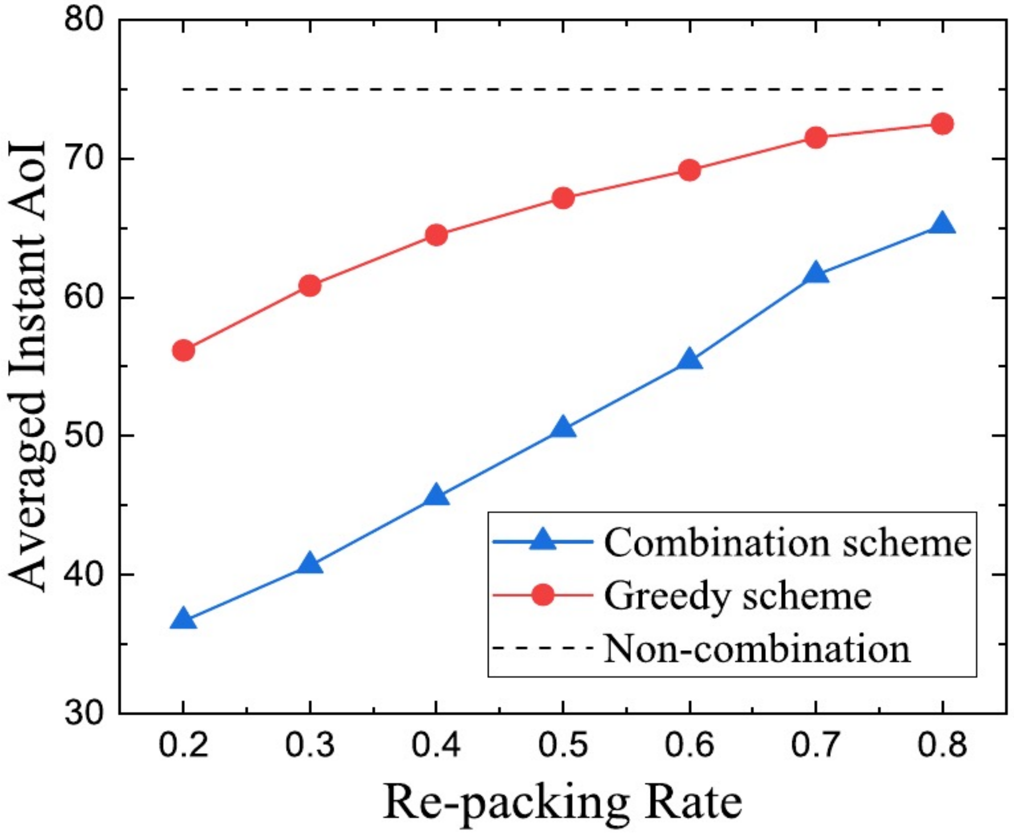
Iteratively calculating the optimal Instant AoI under different **L** values

$$A^E = \frac{1}{|\mathcal{N}|}\left(f(L) - \frac{(L+1)}{2}L + |\mathcal{N}|(L + \lceil \lambda L \rceil)\right)$$



| Numerical Results





Comparison under different sensing node counts and re-packing rates

Comparison with non-combination and greedy combination schemes

AoI and Throughput Tradeoffs in Routing-aware Multi-hop Wireless Network

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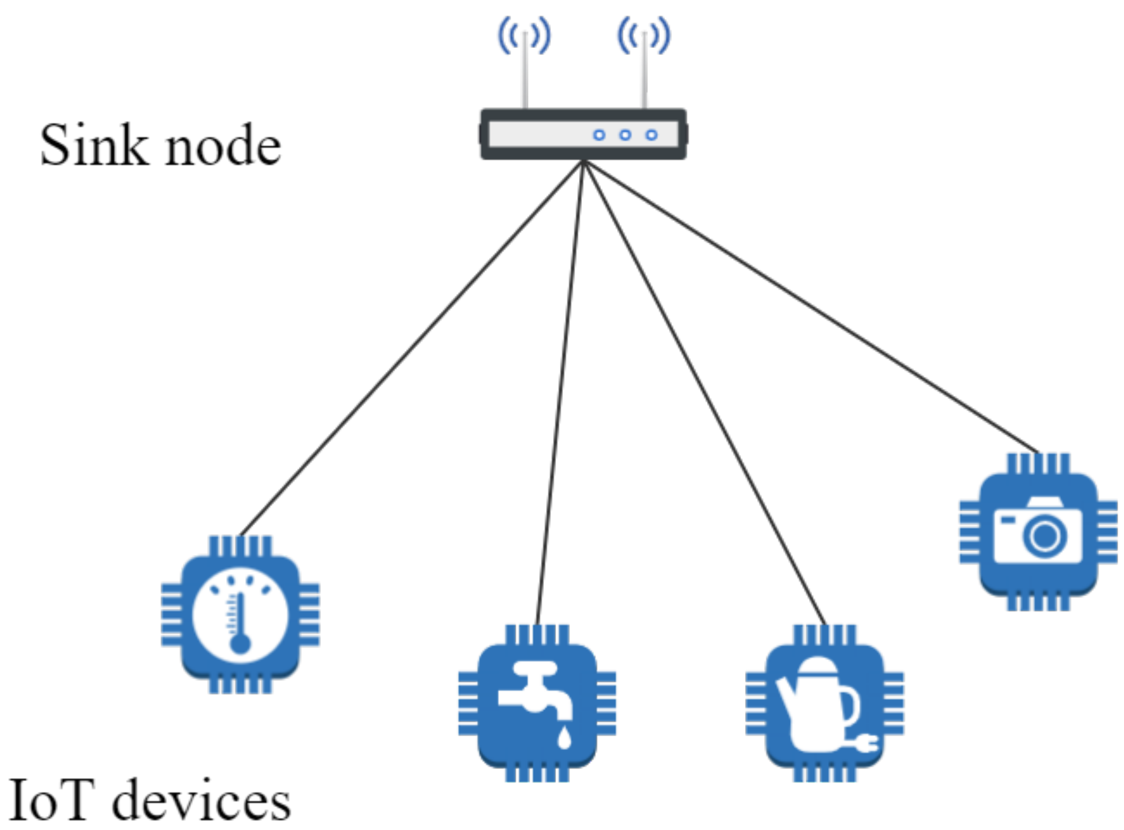
Motivation

- **AoI and Throughput Tradeoffs**

Smart Home : Plenty of smart devices deployed to gather information

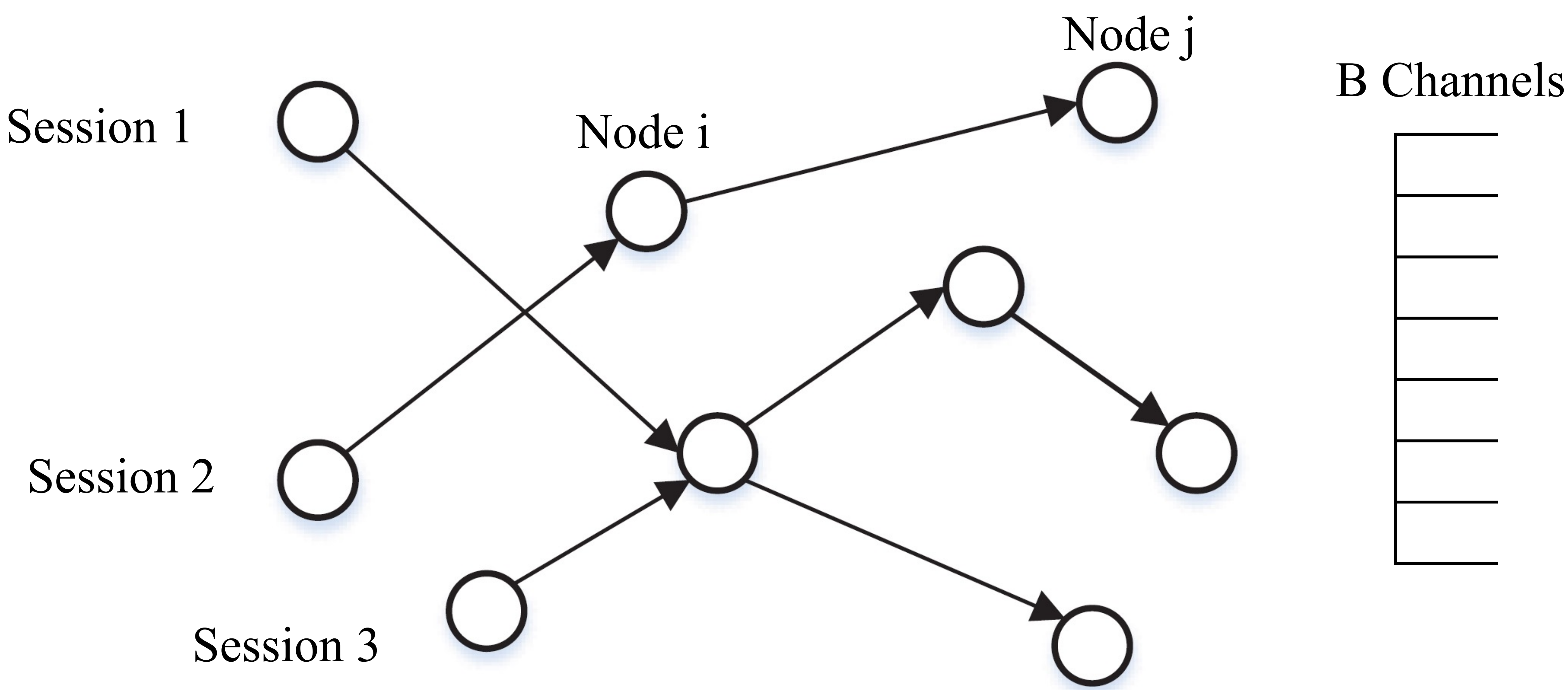


Lower AoI: timely responses for urgent events

High throughput: massive data uploads

Network Modeling

- **OFDM-based Multi-hop Wireless Networks**



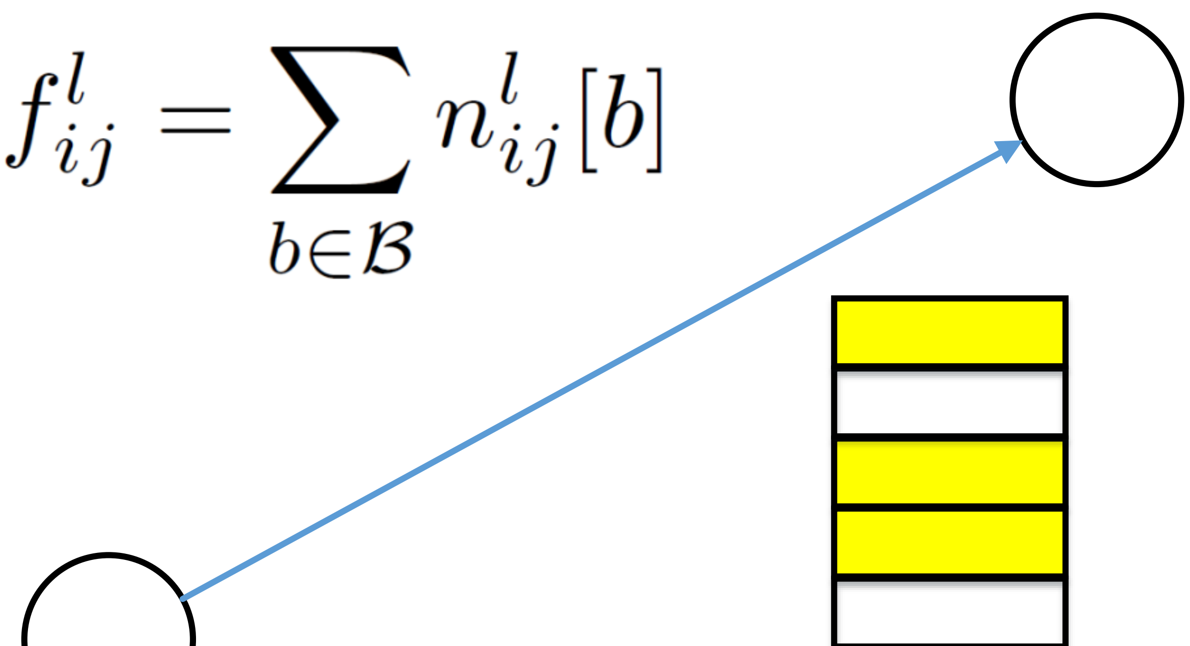
$$n_{ij}^{l}[b] = \begin{cases} 1, & \text{if the link } (i,j) \text{ is activated in channel } b \\ & \text{for sesssion } l, \\ 0, & \text{otherwise.} \end{cases}$$

Network Modeling

- **Link Activation and Frequency**

Frequency

$$f_{ij}^l = \sum_{b \in \mathcal{B}} n_{ij}^l[b]$$



Activation Indicator

$$z_{ij}^l = \begin{cases} 1, & \text{if } f_{ij}^l \geq 1, \\ 0, & \text{otherwise.} \end{cases}$$

Network Modeling

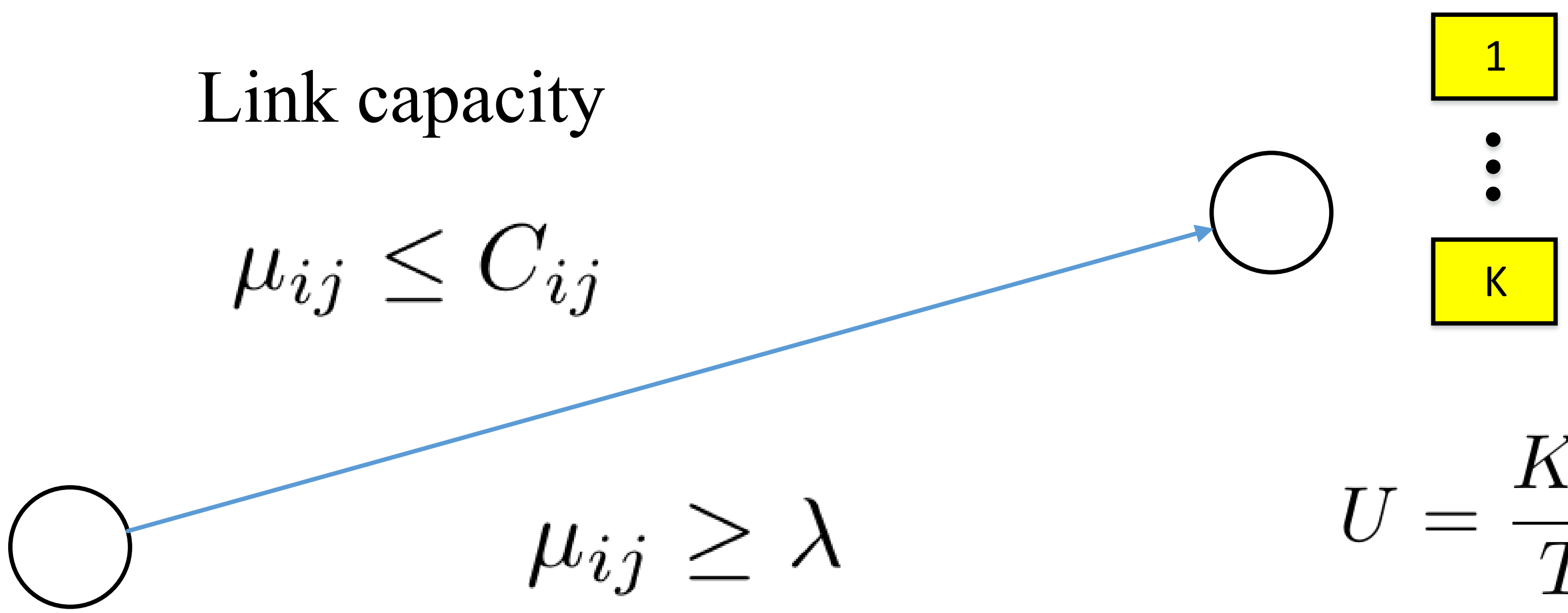
- **Transmission and Throughput**

Generation rate at source: λ

Transmission rate at link (i, j): μ_{ij}

Link capacity

$$\mu_{ij} \leq C_{ij}$$



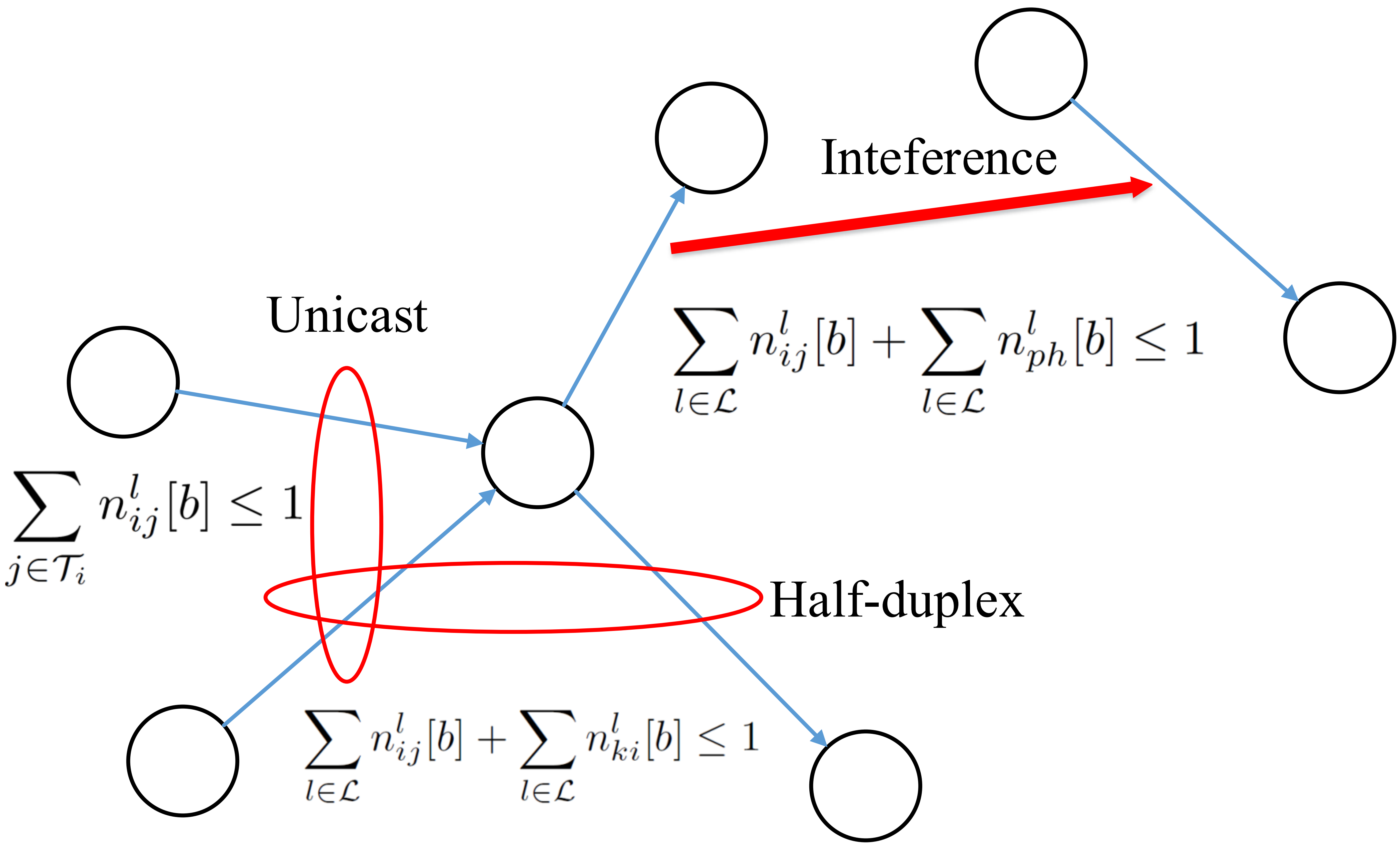
$$\mu_{ij} \geq \lambda$$

$$U = \frac{Kd}{T} = \lambda d$$

Throughput: U

Interfernce Modeling

- **Three Types of Interference**

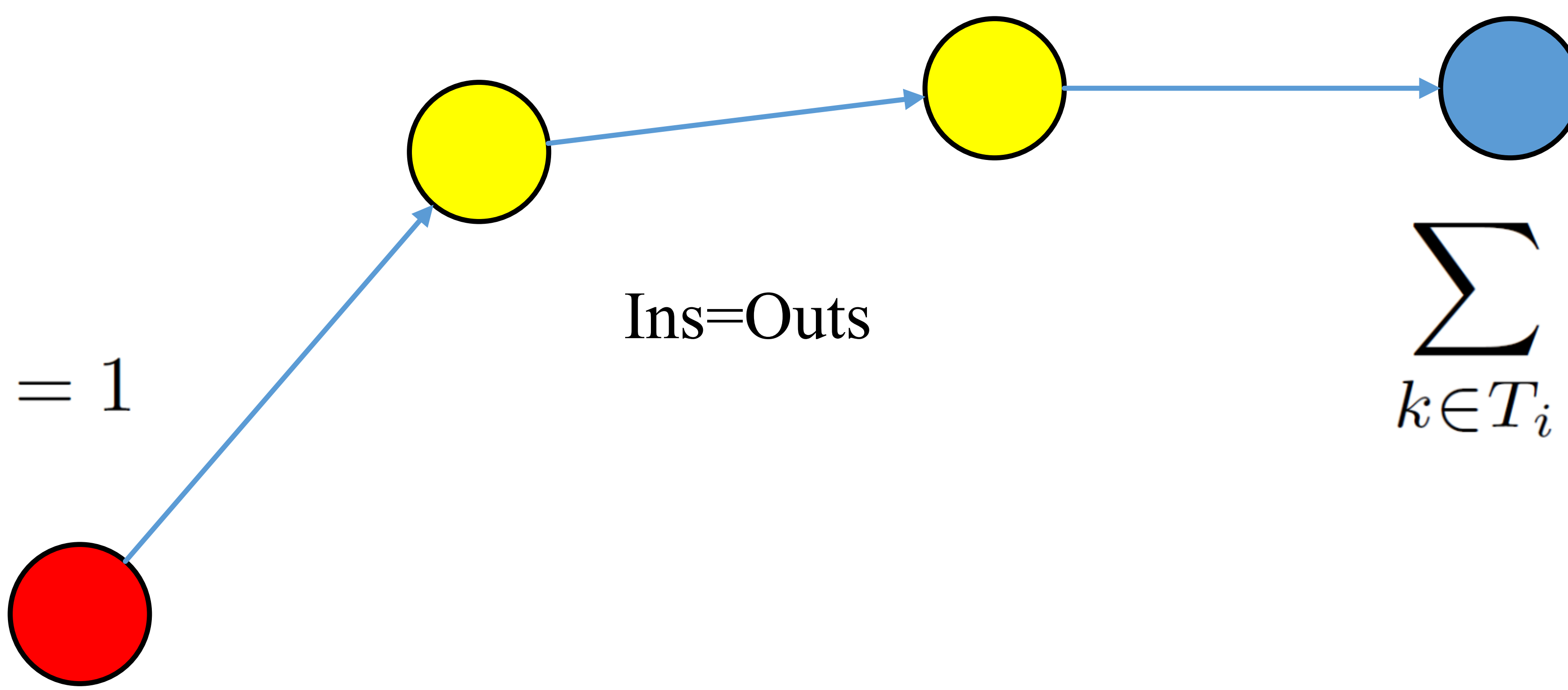


Flexible Routing Modeling

- **Routing Models of three nodes**

$$\sum_{j\in\mathcal{T}_i, j\neq s_l} z^l_{ij} = \sum_{k\in\mathcal{T}_i, k\neq d_l} z^l_{ki}$$

One input link



Ins=Outs

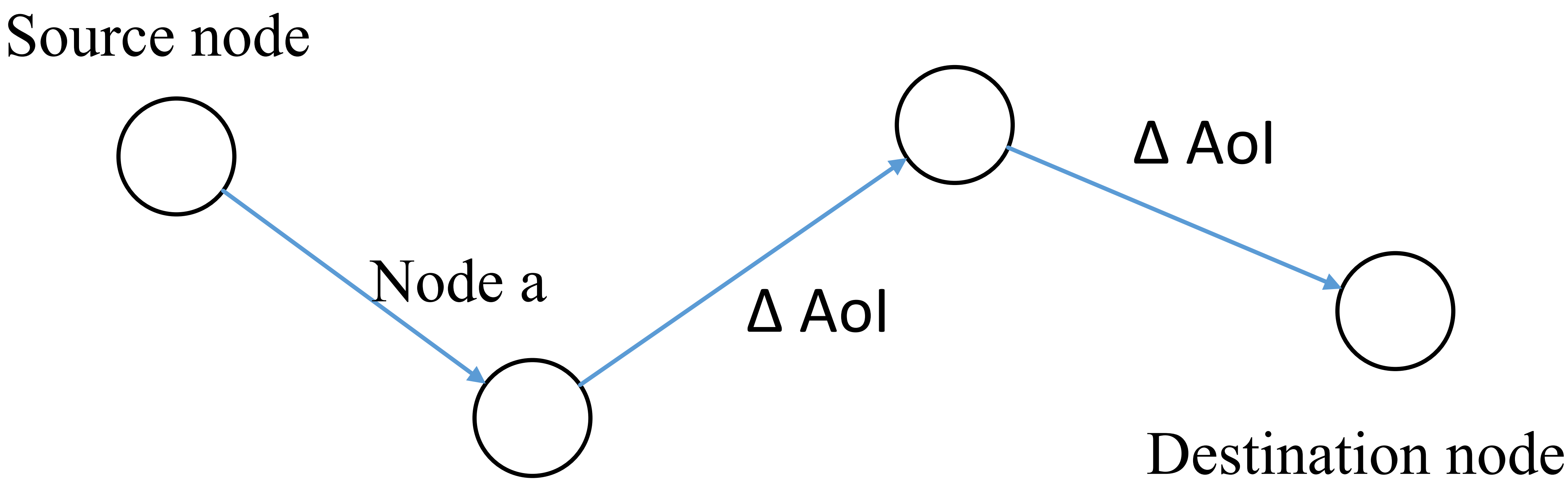
$$\sum_{k\in T_i} z^l_{ki} = 1$$

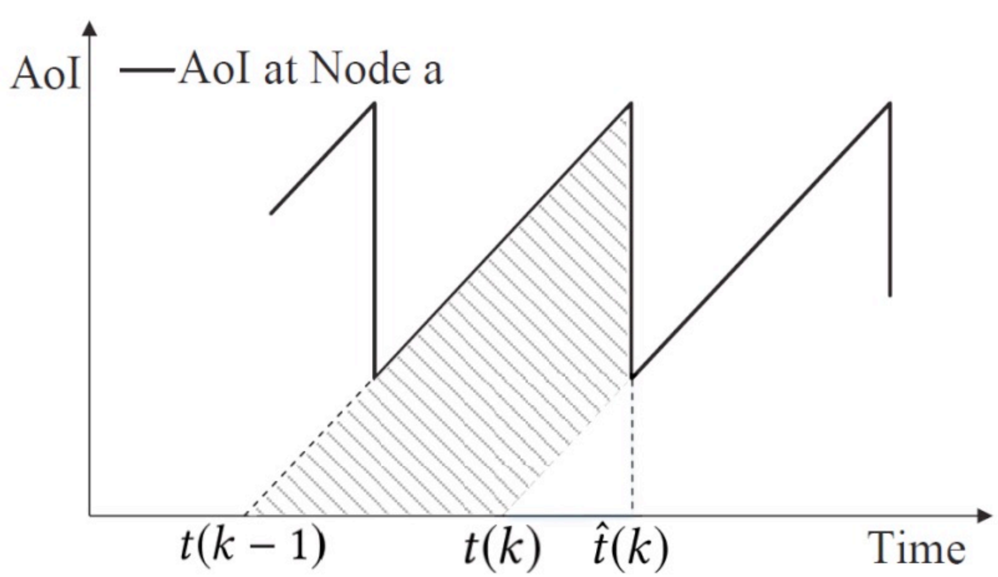
$$\sum_{j\in\mathcal{T}_i} z^l_{ij} = 1$$

One output link

|AoI Calculation

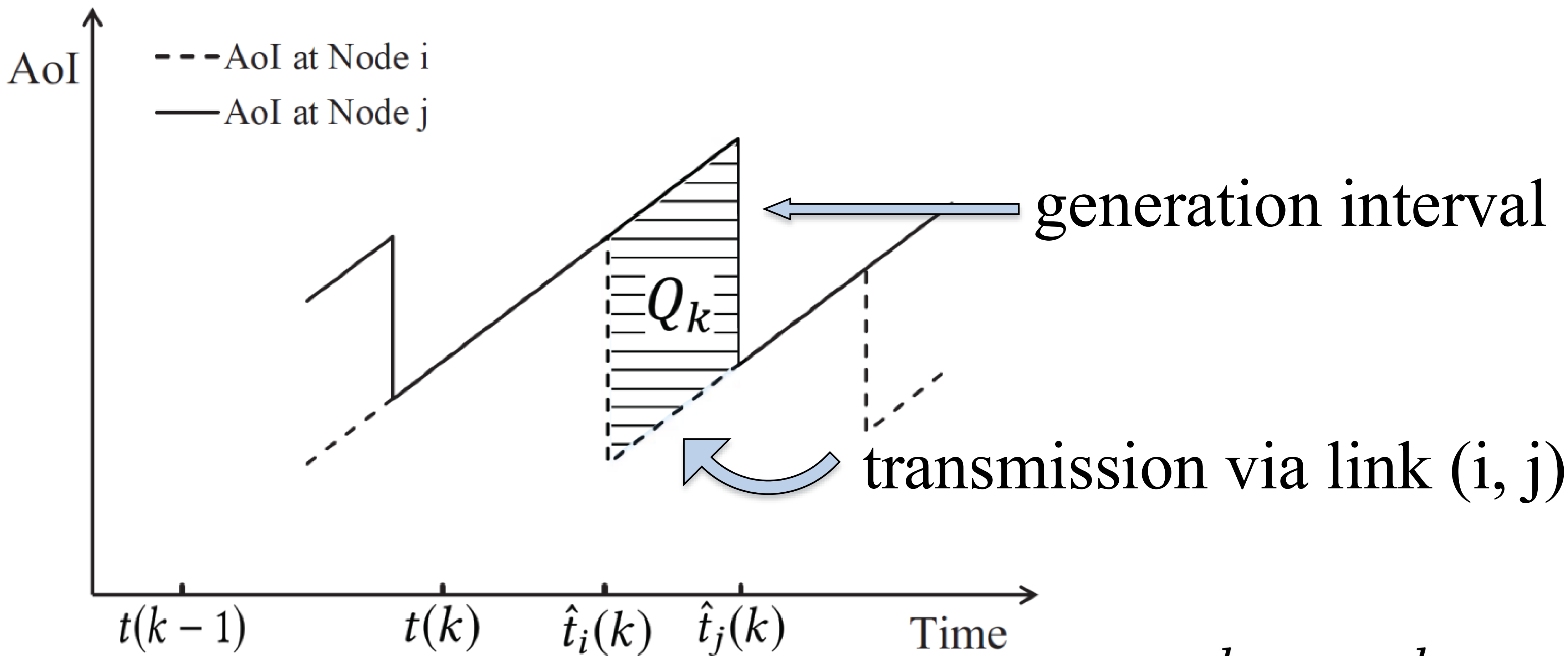
- **Accumulated Trapezoid Areas**





|AoI Calculation

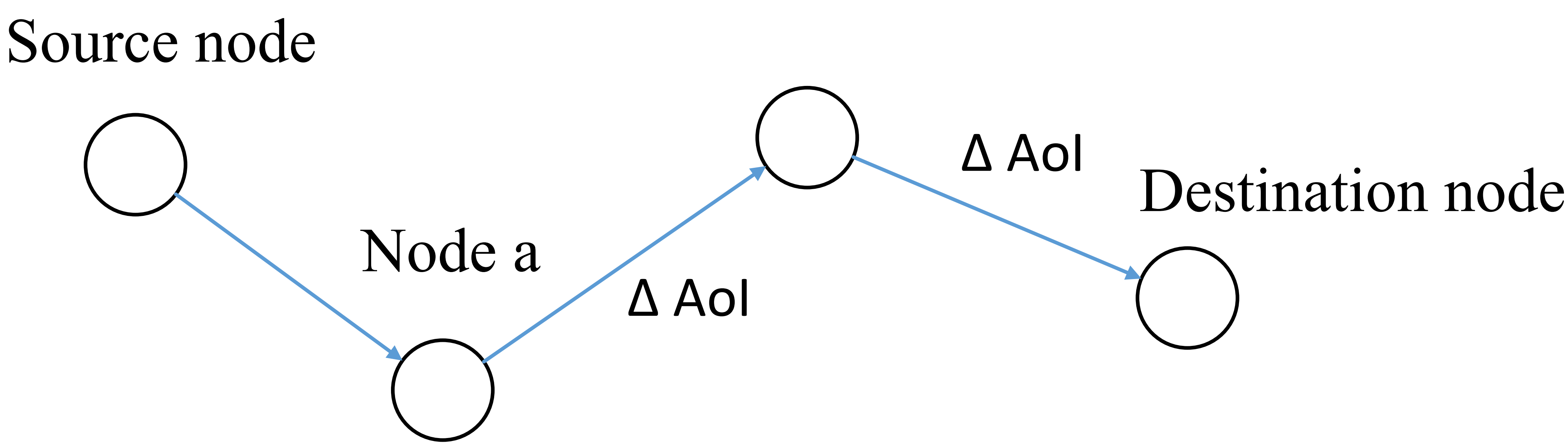
- **AoI Variations at Two Consecutive Nodes**

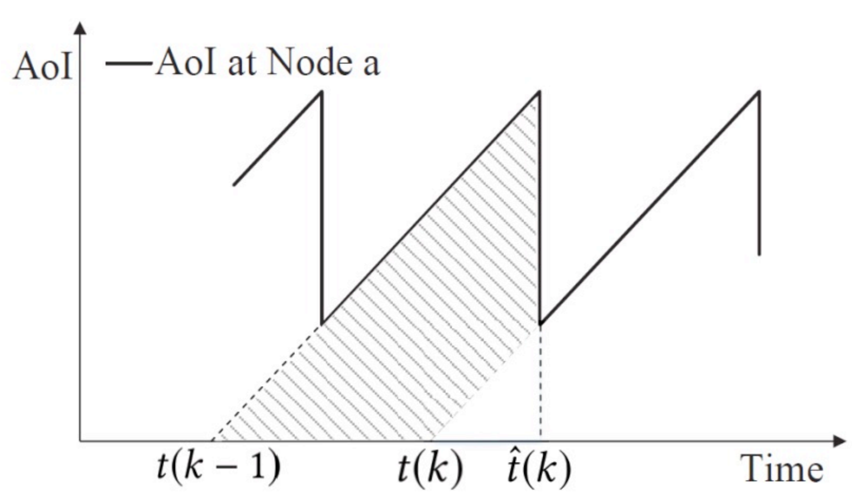


$$A_j^l = A_i^l + \frac{d}{\mu_{ij}}$$

|AoI Calculation

- **AoI at Destination Node**





$$A_{d_l} = \frac{1}{2\lambda^l} + \sum_{i \neq d_l, z_{ij}^l = 1} \frac{d}{\mu_{ij}}$$

|Multi-objective Problem

- **Minimize time-averaged AoI**

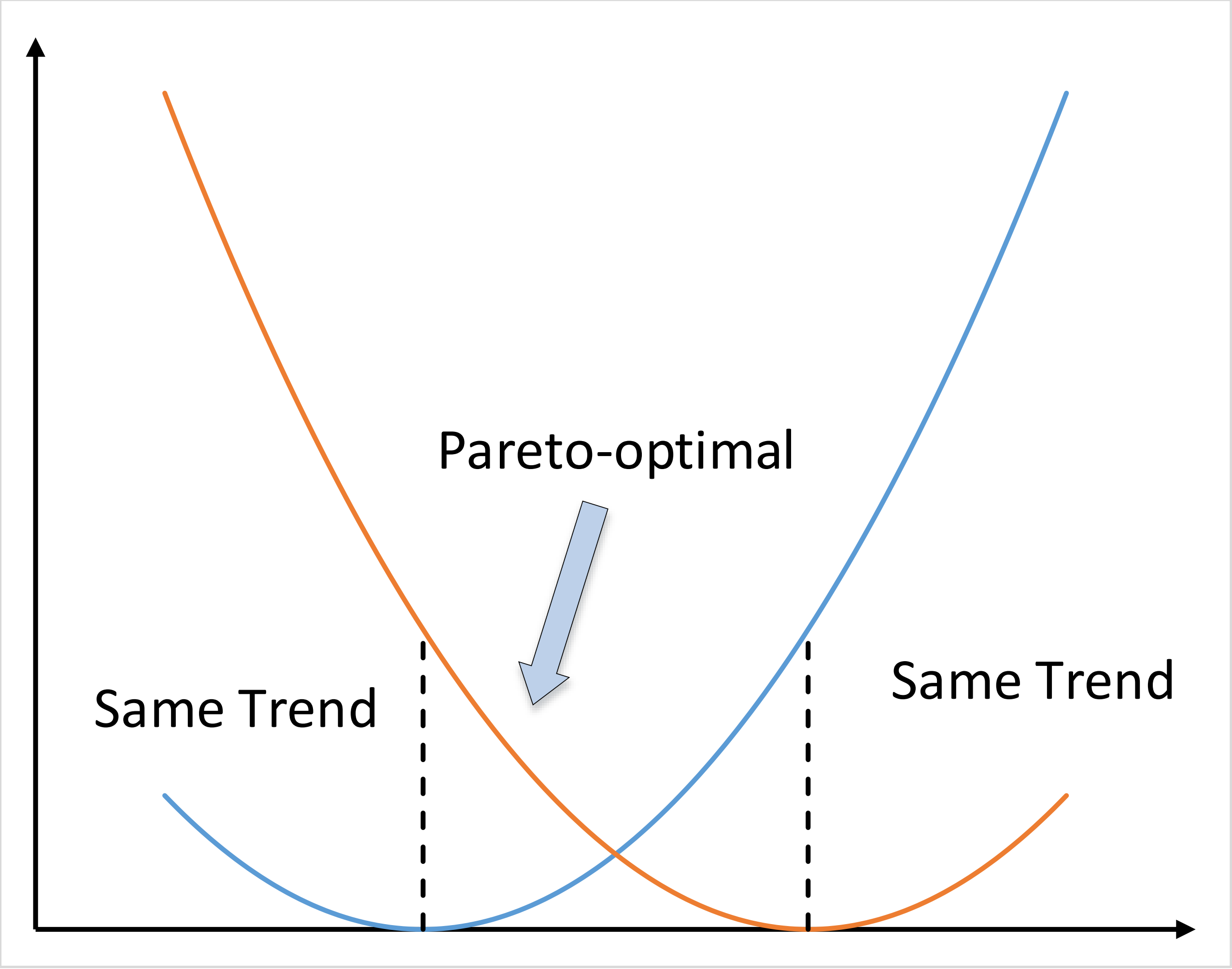
$$A_{ave} = \sum_{l \in \mathcal{L}} \frac{1}{2\lambda^l} + \sum_{i \in \mathcal{N}} \sum_{\substack{j \in \mathcal{T}_i \\ z_{ij}^l = 1}} \frac{p^l}{\mu_{ij}}$$

- **Maximize Throughput**

$$U_{\min} \leq U^l$$

Pareto-optimal

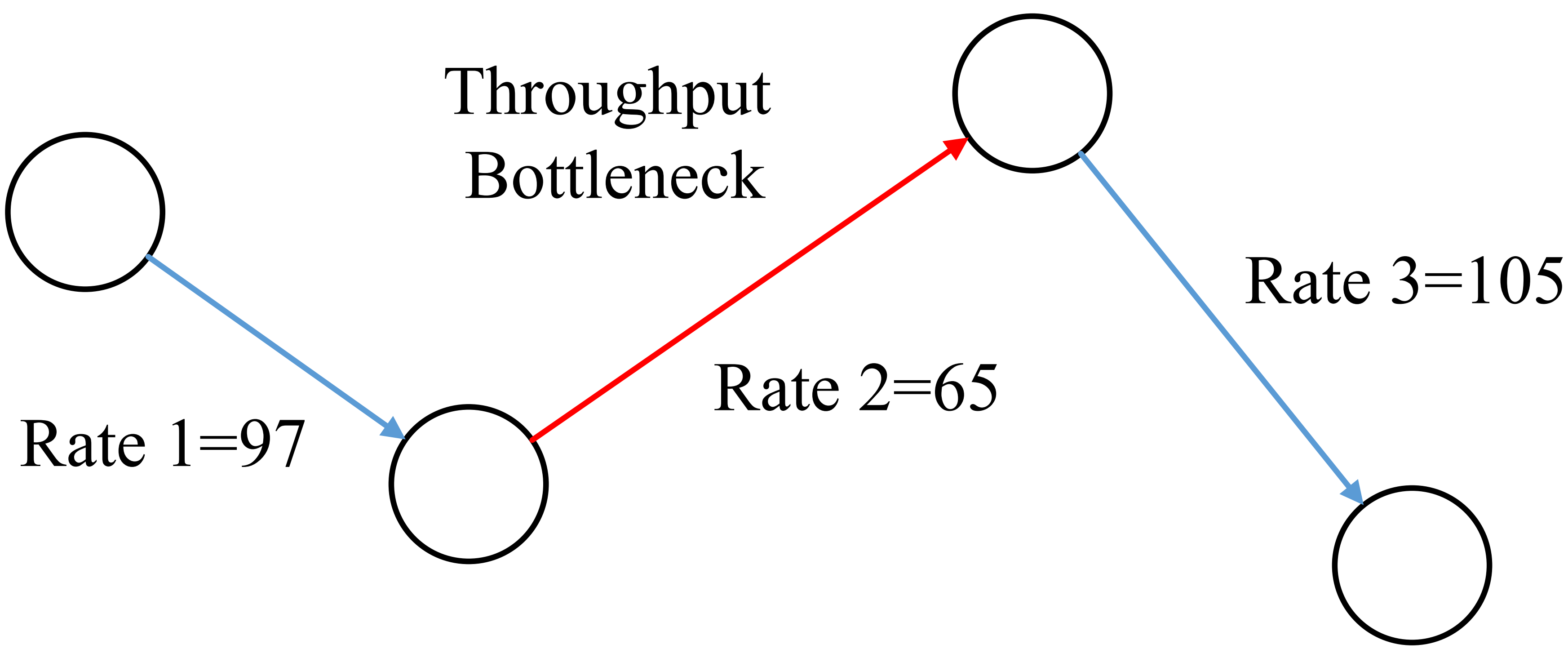
- **Minimizing Two Objectives**



Cannot make one individual metric better without making others worse

Local Optimal Throughput

- A scheduling including routing and channel allocation for optimizing AoI



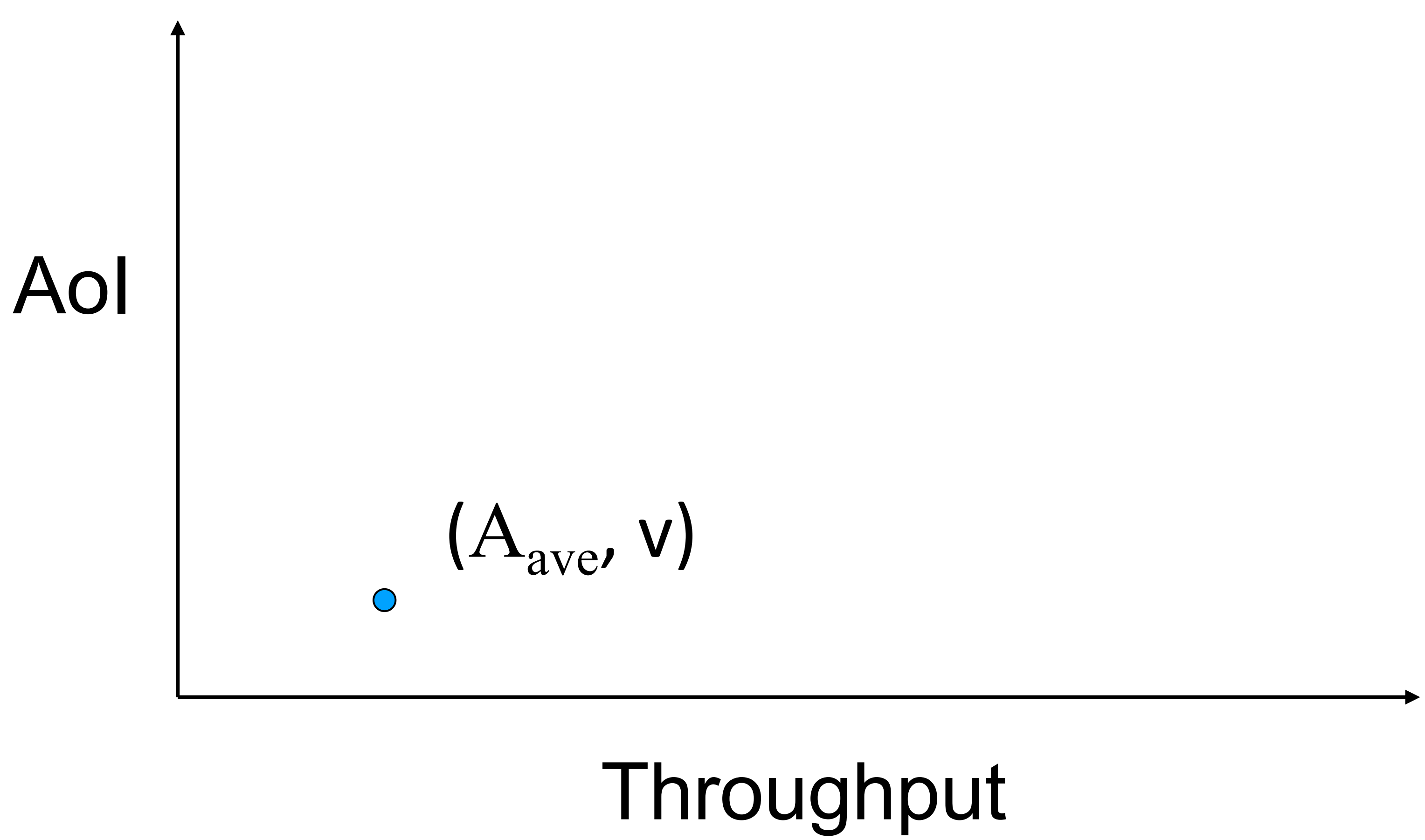
Maximum Throughput achieved as the bottleneck rate

Algorithm Design

1. Solve the optimization problem that merely minimizing the AoI

Get the global minimum AoI: A_{ave}

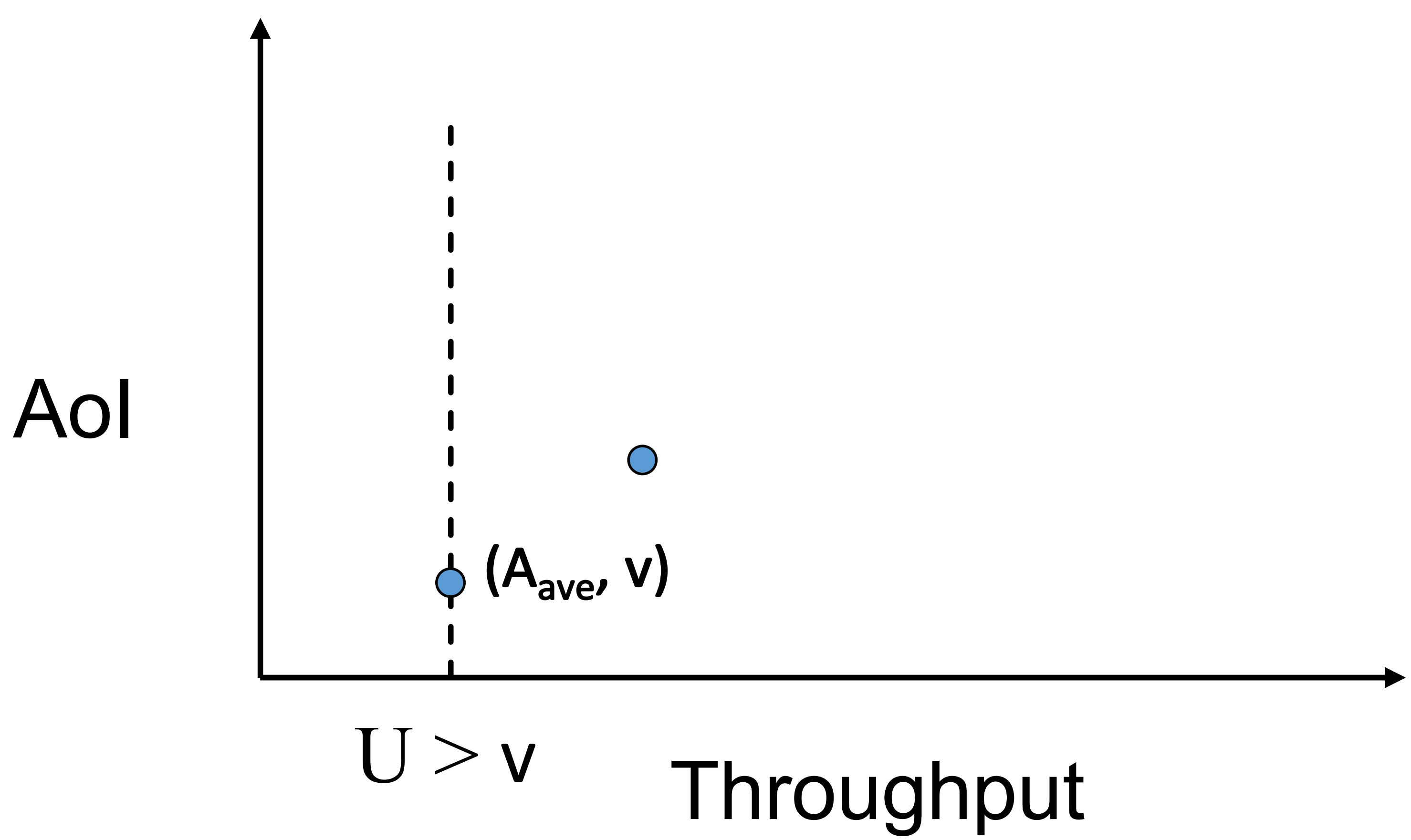
Get the local maximum throughput: v



Algorithm Design

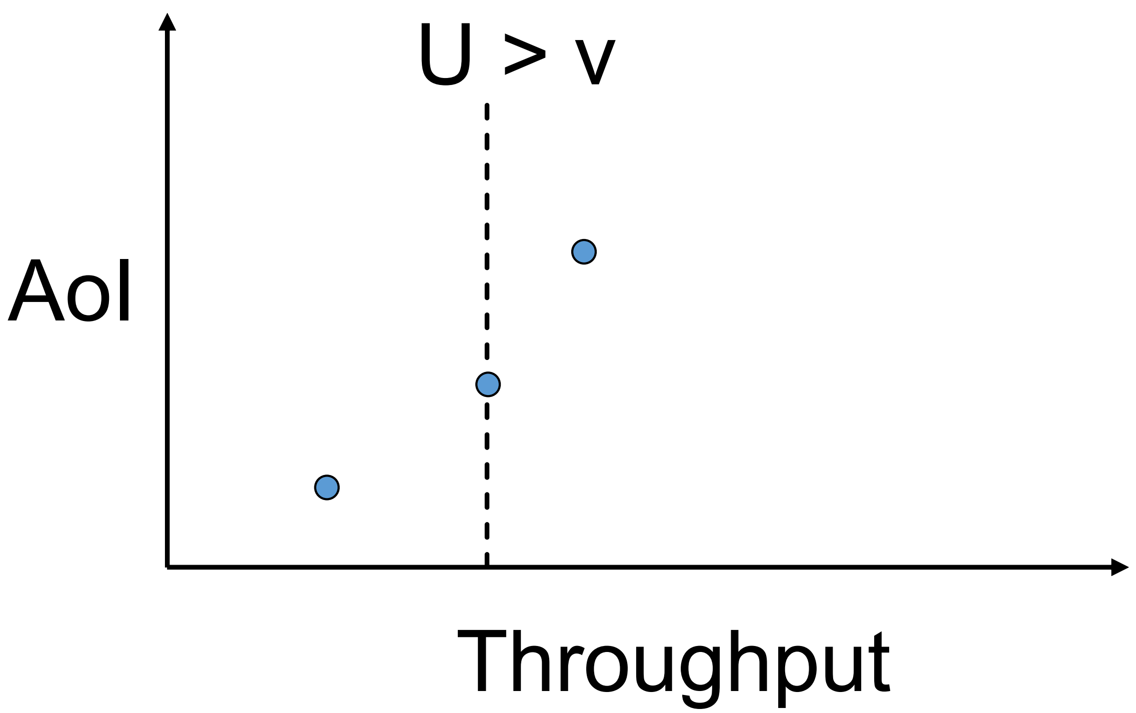
2. Add a throughput constraint to construct AoI optimization problem

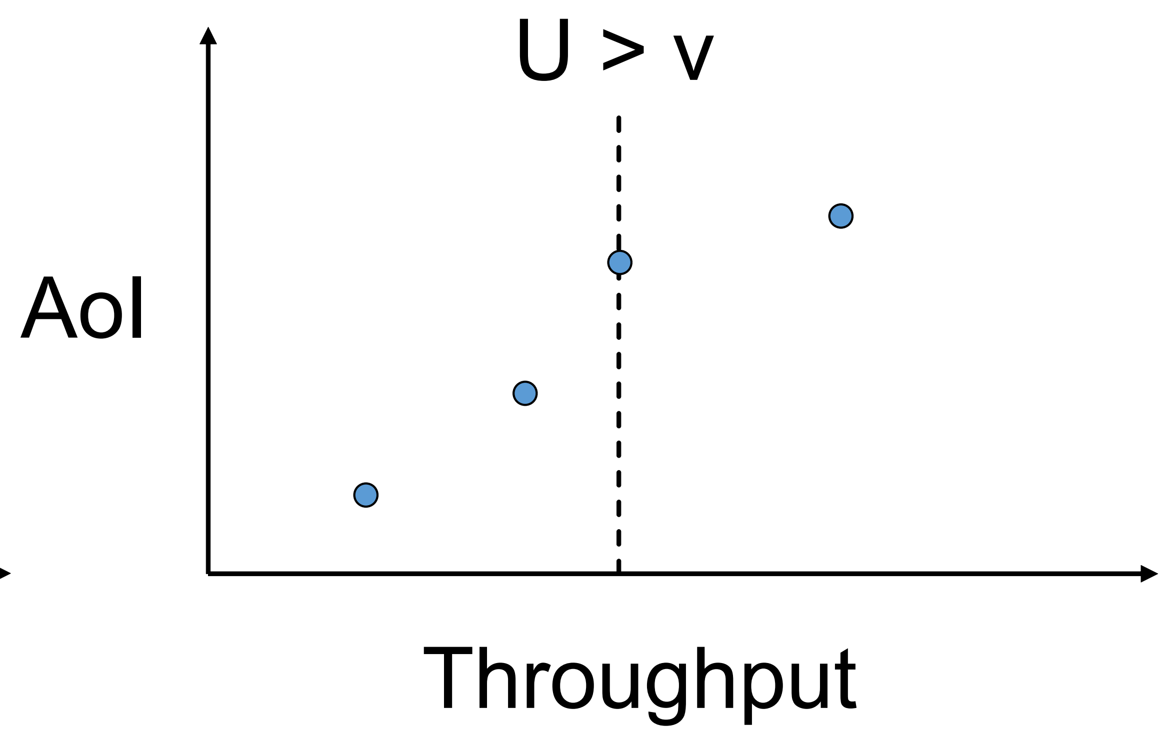
$$\min\ A_{ave} \qquad\qquad \min\ A_{ave}$$
$$\max\ U_{\min} \qquad\qquad s.t.\ \text{Throughput constraint: } U_{\min} > v$$



Algorithm Design

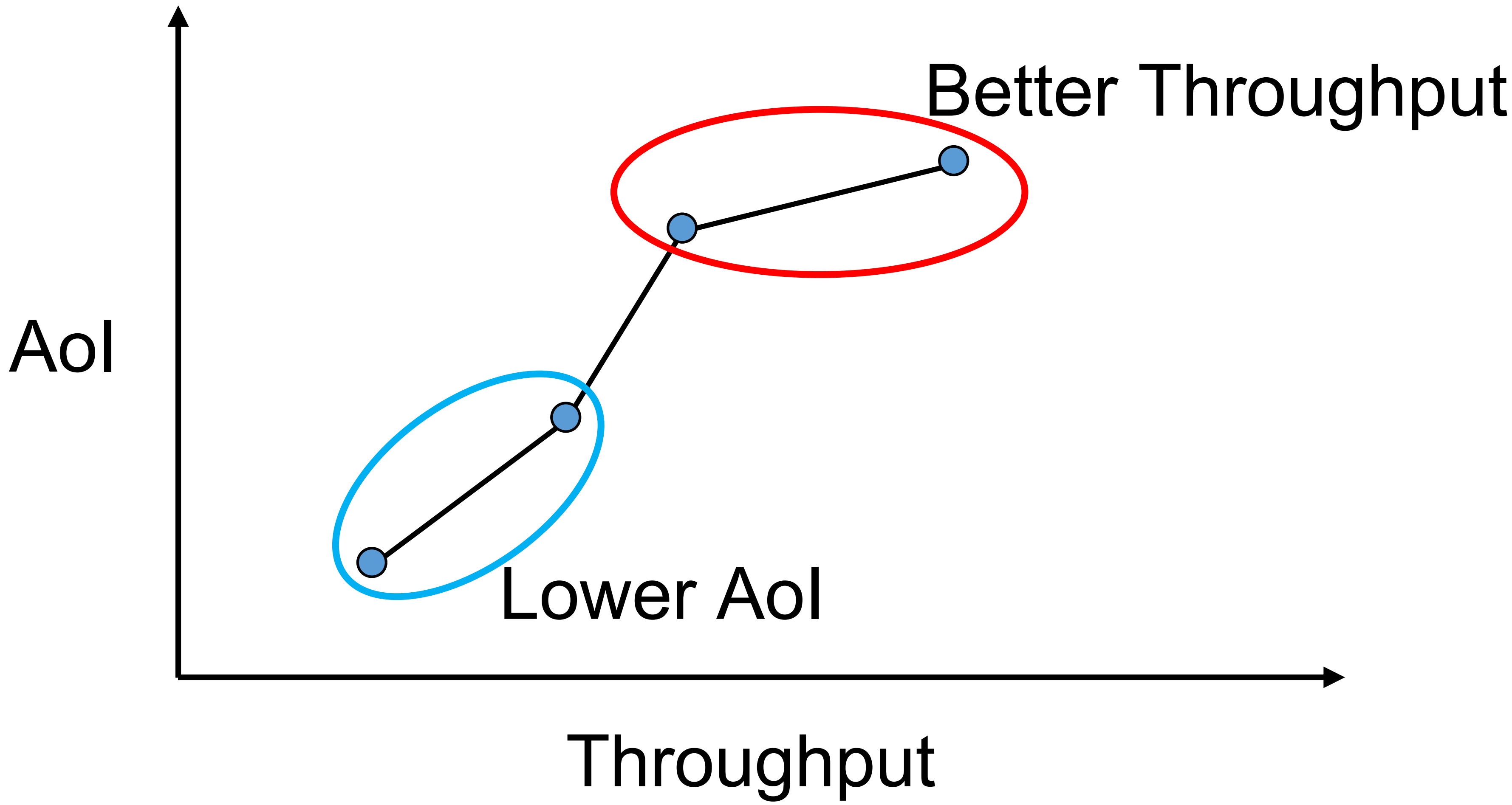
3. Repeat the step 2 until no feasible solutions





Pareto-optimal Curve

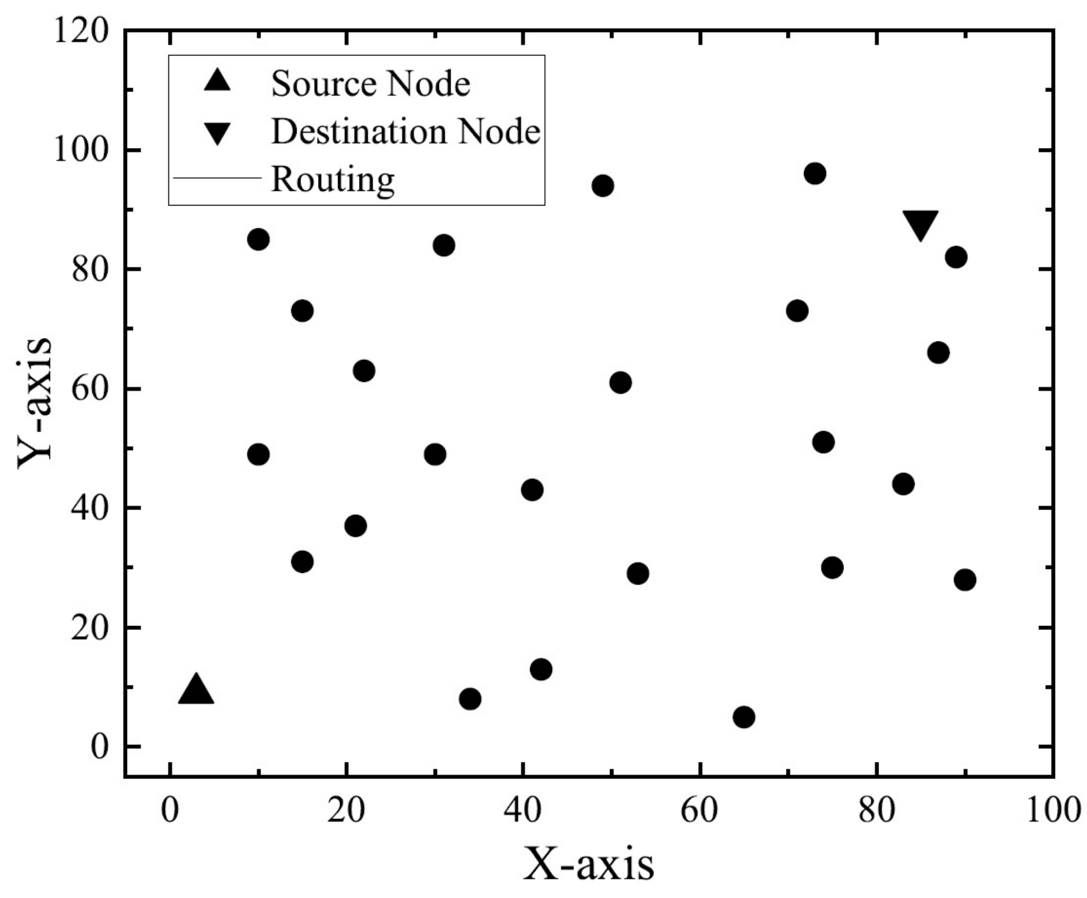
- **Obtain all Pareto-optimal points**

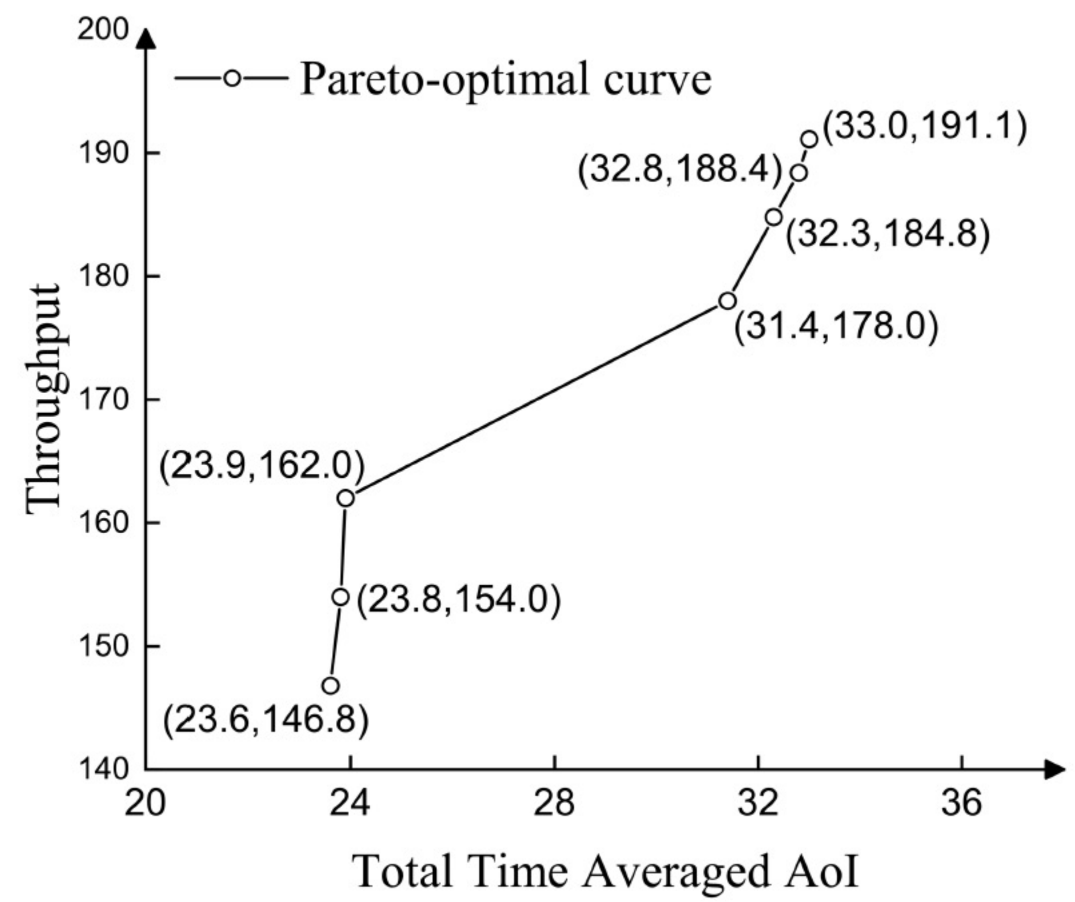


We prove that all Pareto-optimal points can be found

| Simulation Results

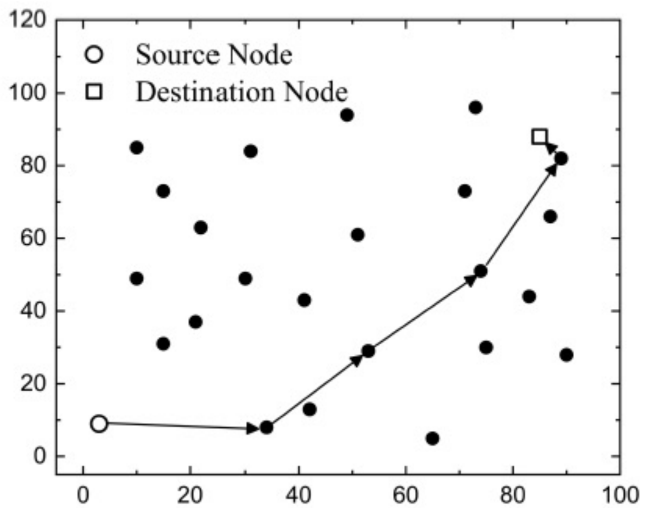
Randomly generate a 25-node network.



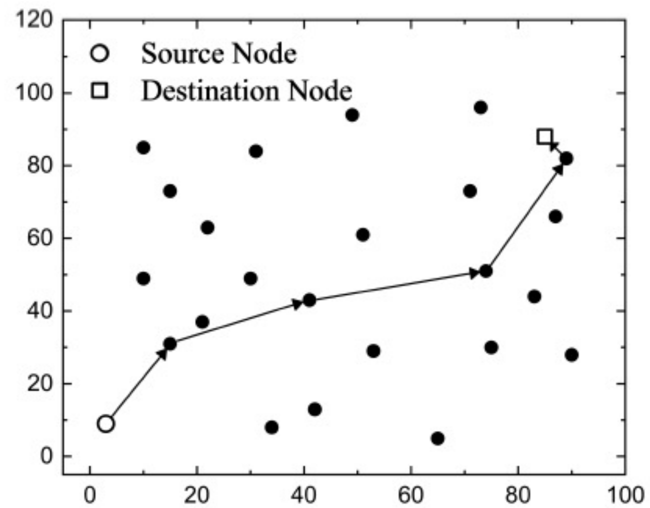


Simulation Results

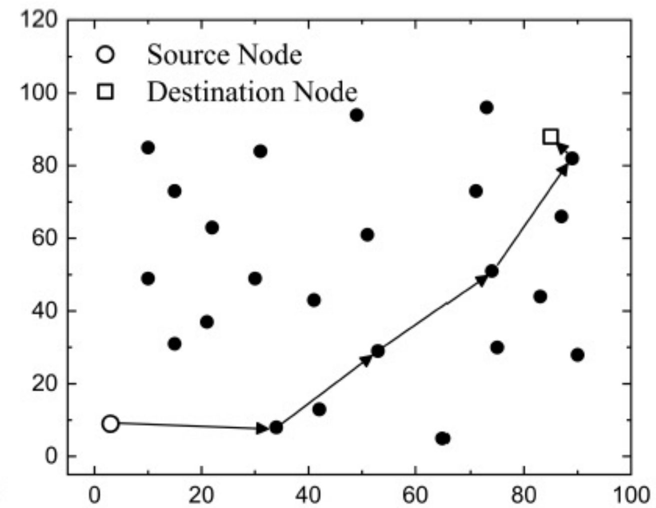
Routing Variations



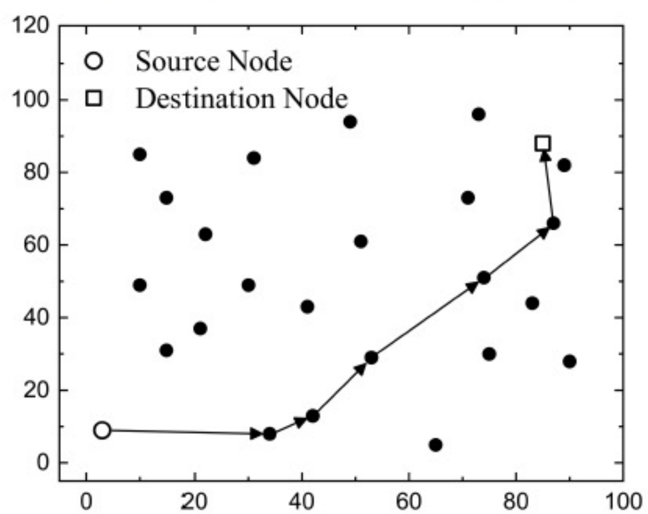
(a) The route for OPT-AoI with throughput constraint v=0 in the 1st iteration.



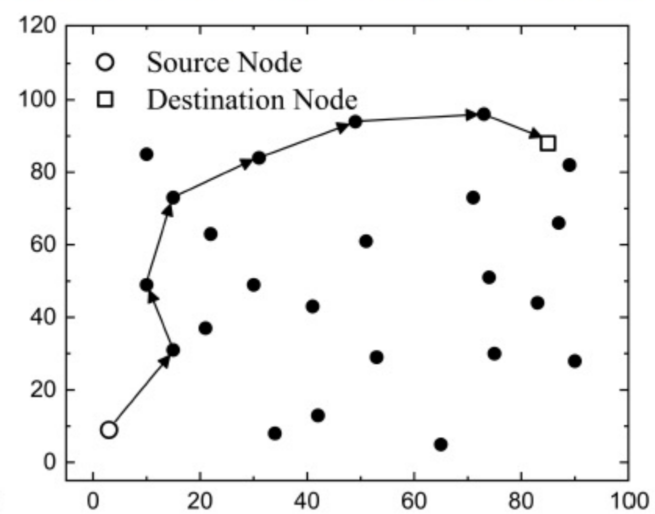
(b) The route for OPT-AoI with throughput constraint v=146.8 in the 2nd iteration.



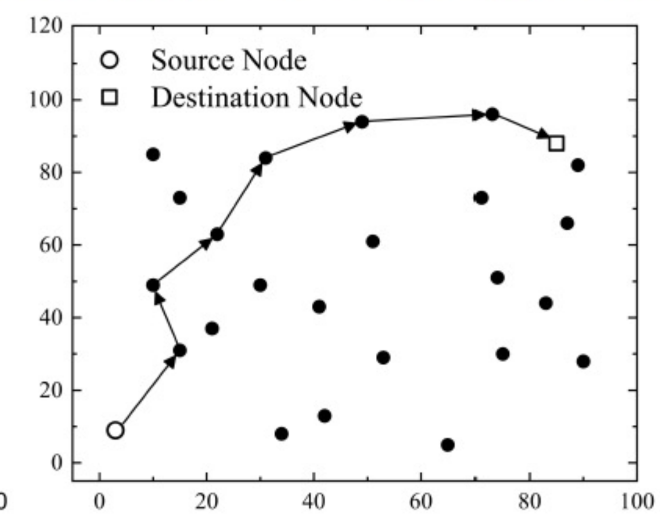
(c) The route for OPT-AoI with throughput constraint v=154.0 in the 3th iteration.



(d) The route for OPT-AoI with throughput constraint v=162.0 in the 4th iteration.

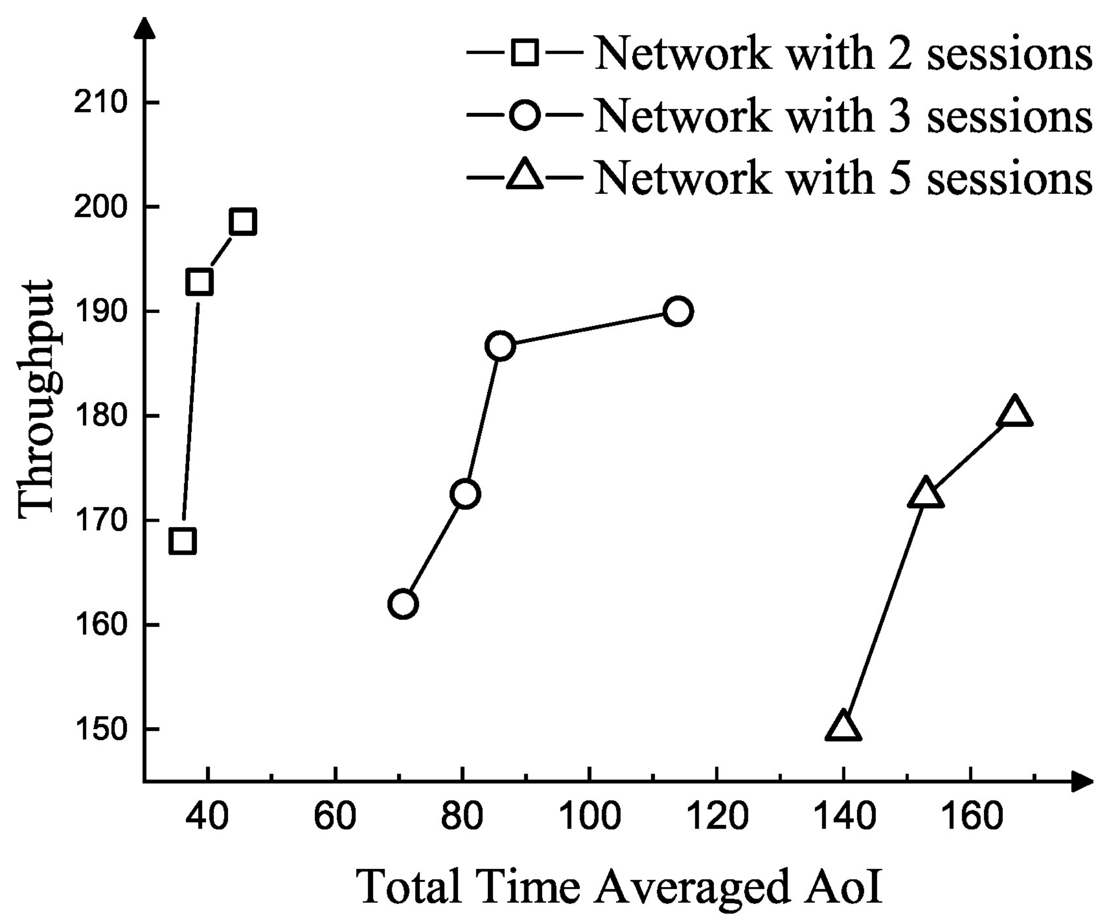


(e) The route for OPT-AoI with throughput constraint v=178.0 in the 5th iteration.

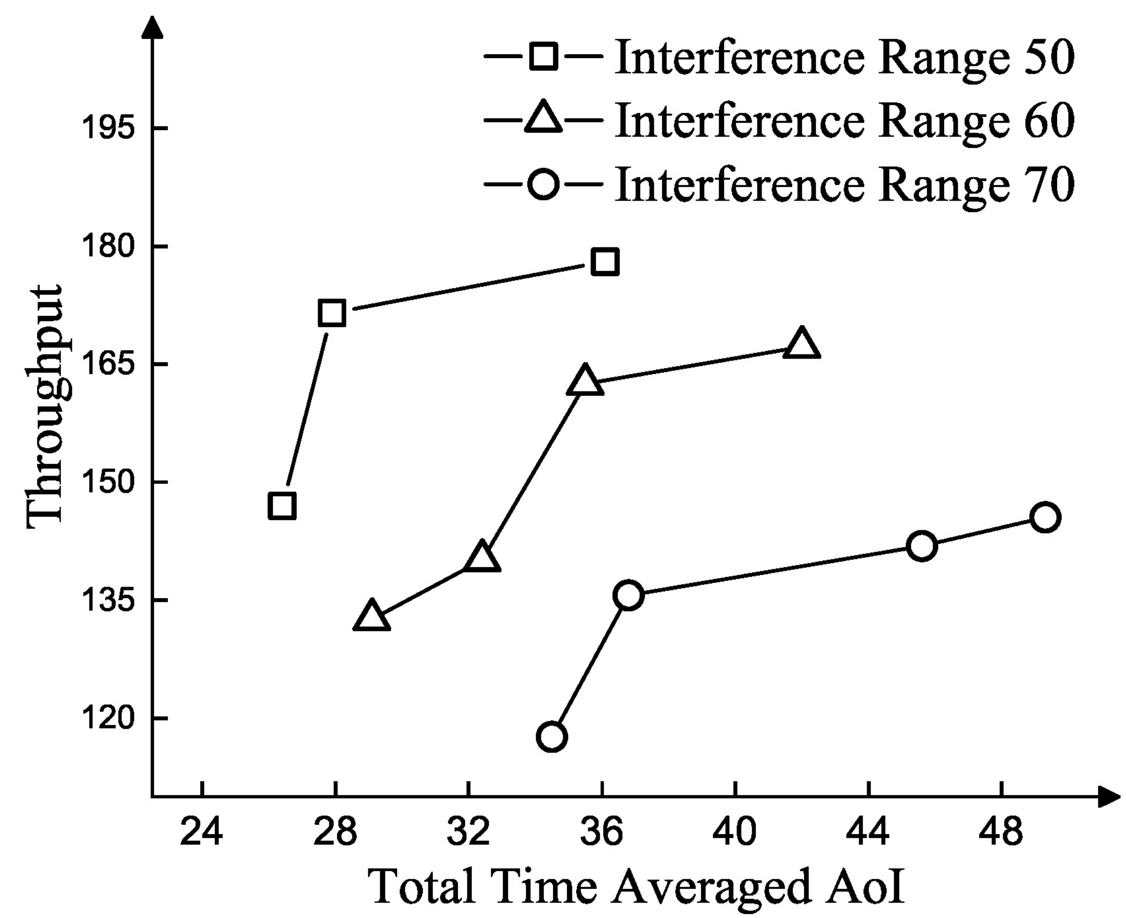


(f) The route for OPT-AoI with throughput constraint v=184.8 in the 6th iteration.

Simulation Results



Different number of sessions



Different interference ranges

Thank You

Q&A