

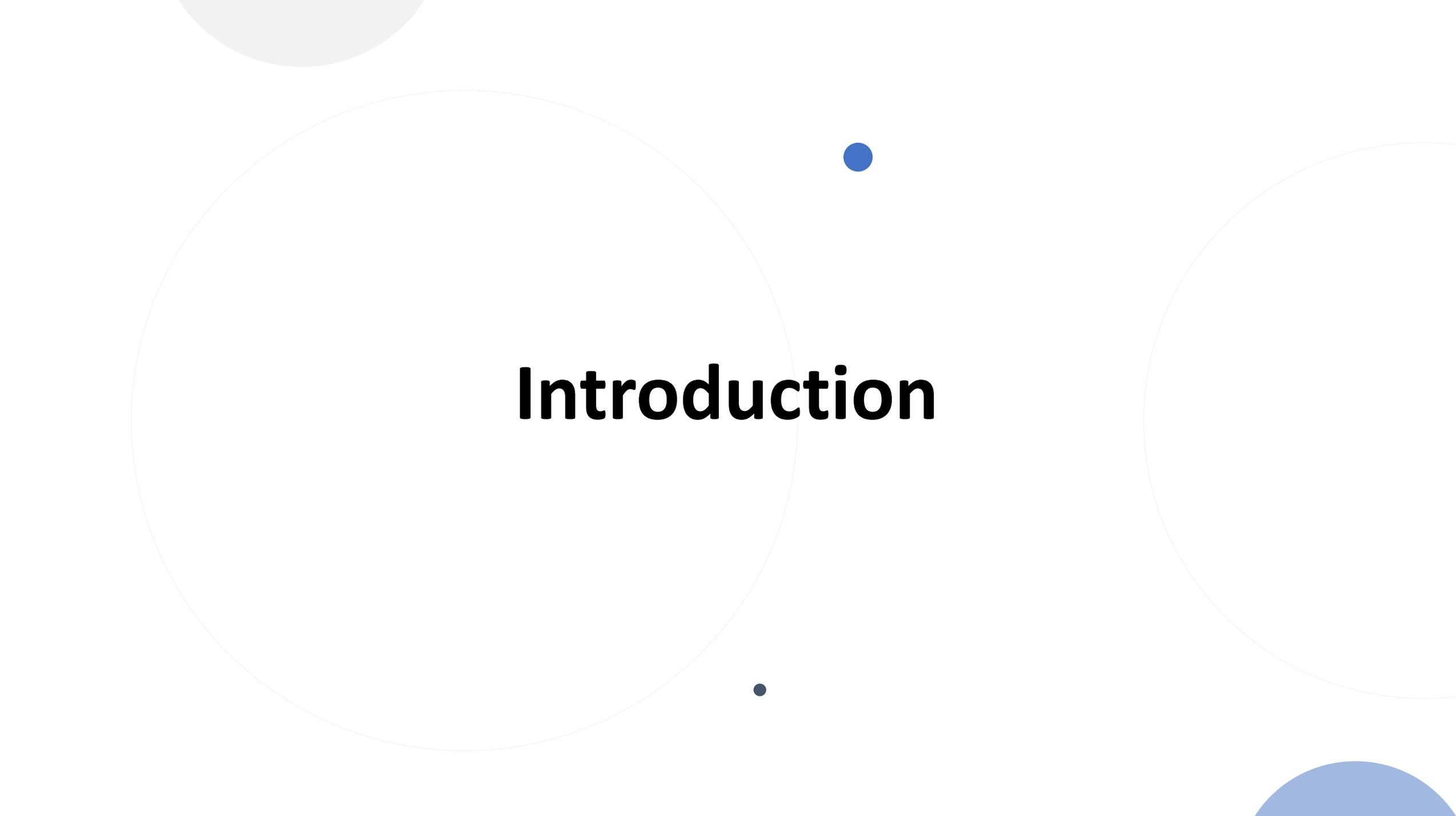
# 能量束縛嵌入式網路之資料更新最佳化

## **Energy-Constrained Data Freshness Optimization in Self-Powered Networked Embedded Systems**

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# Outline

- Introduction
- System Model
- Motivation
- Aol Optimization
- Performance
- Conclusion

The background features a white canvas with several decorative elements: a large light gray circle at the top left, a large light blue circle at the bottom right, a large white circle on the left side, and a large white circle on the right side. Two small solid circles are also present: a blue one in the upper right and a dark blue one in the lower center.

# Introduction

# Environmental Monitoring Networked Intermittent System

- Environmental monitoring
  - To characterize and monitoring the quality of the environment with the collected environmental monitoring data.
- Intermittent systems
  - Powered by ambient power source absorbed by energy harvesting devices without the batteries
- The freshness of the collected data is crucial.



# Energy harvested(EH) networked embedded systems (NESs)

- NESs, consisting of EH-based sensor nodes, EH-based sink nodes, and a central controller, are usually used for environmental monitoring applications.
- Age of information(AoI) is a key indicator to measure freshness of real-time data
- Multi-monitors have various output with different importance

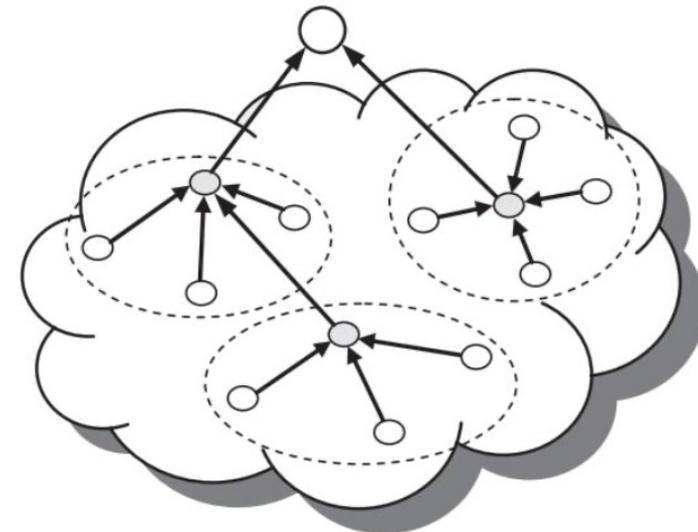
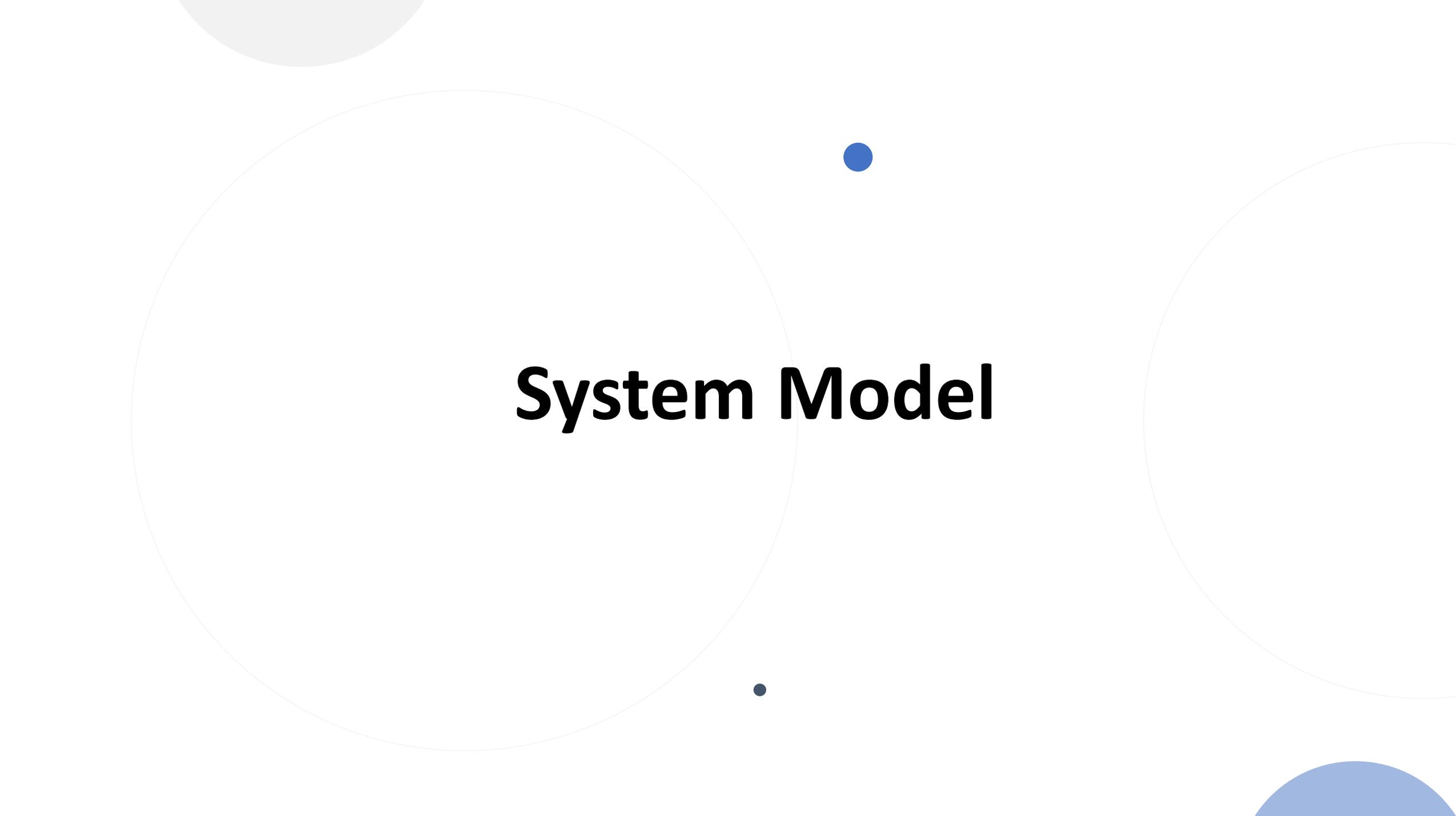
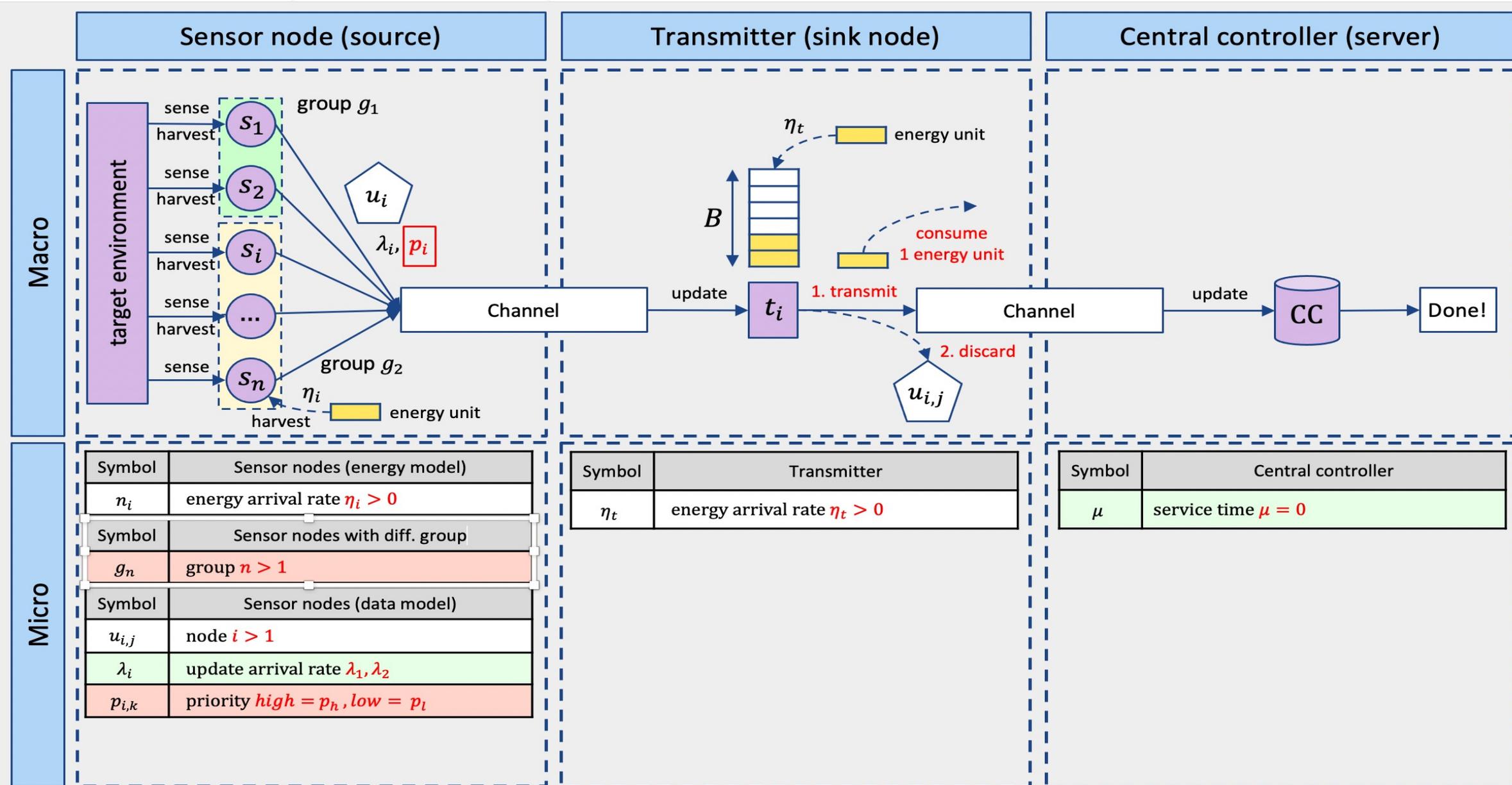


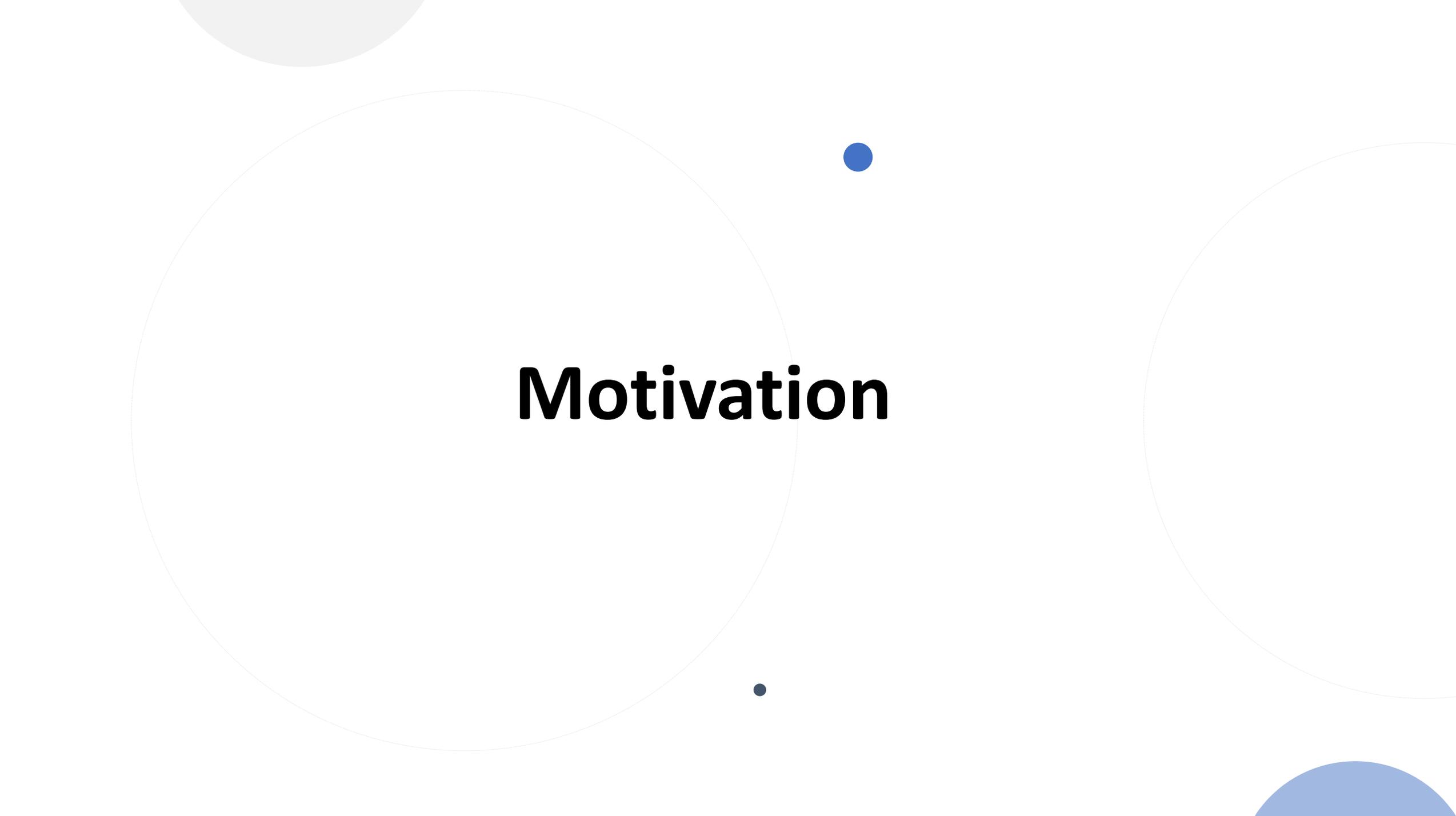
Fig. An overview of multi-hop networks

The background features a white canvas with several decorative elements: a large light gray circle at the top left, a large light gray circle on the right side, a solid blue circle at the top right, and a solid blue circle at the bottom right. Two small dark blue dots are positioned near the center, one above and one below the main text.

# **System Model**

# System Architecture



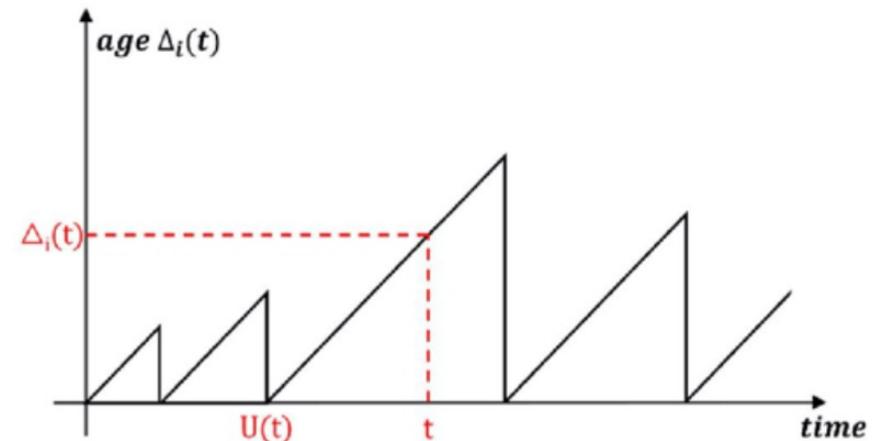
The background features a minimalist design with several overlapping circles and dots. A large, light gray circle is partially visible at the top left. A smaller, solid blue circle is positioned in the upper right quadrant. A large, thin-lined light gray circle is centered on the left side, containing the text. Another large, thin-lined light gray circle is on the right side. A small, solid dark blue dot is located in the lower right quadrant. A solid blue circle is partially visible at the bottom right corner.

# Motivation

# Characterizing Data Freshness with Age of Information (AoI)

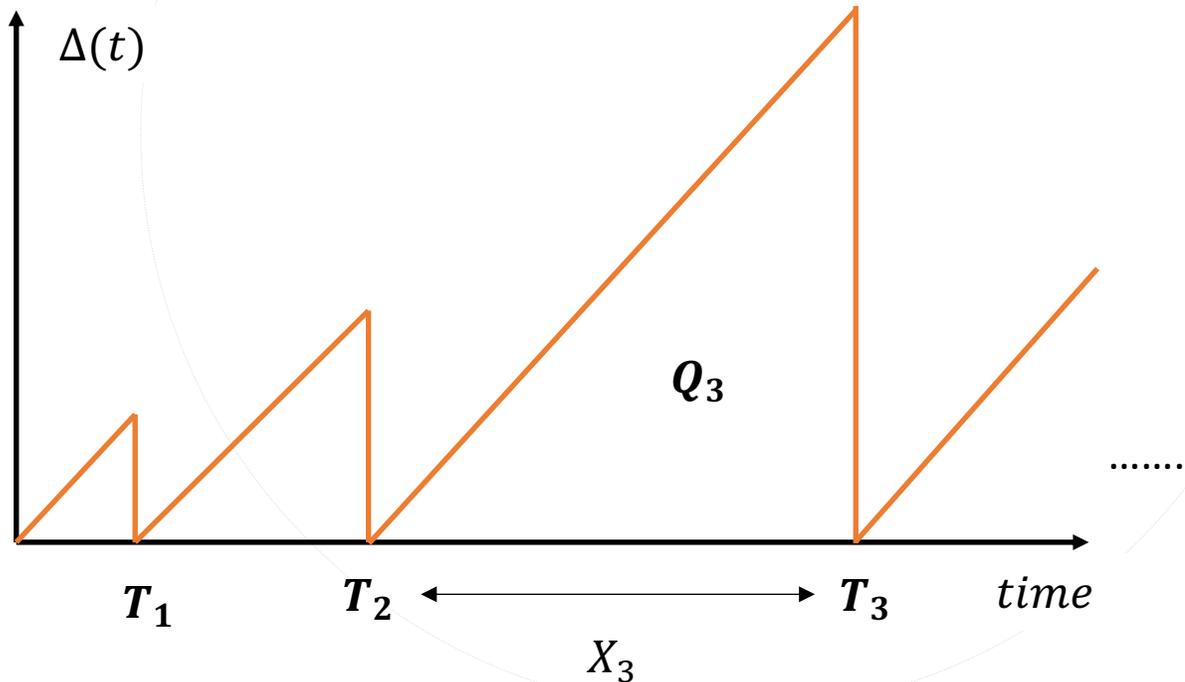
- The age of information (AoI) of a sensor node  $s_i$  at time  $t$ 
  - is defined as the difference between the current time and the timestamp of the latest received update  $U(t)$  :

$$AoI = \Delta_i(t) = t - U(t)$$



# Characterizing Data Freshness with Age of Information (Aol)

- The average Aol (A<sup>2</sup>ol) of a sensor node in the time interval [0,T] – can be seen as the sum of triangle areas (e.g.,  $Q_i$ ), divided by considered time interval (e.g., T)



General example of Aol

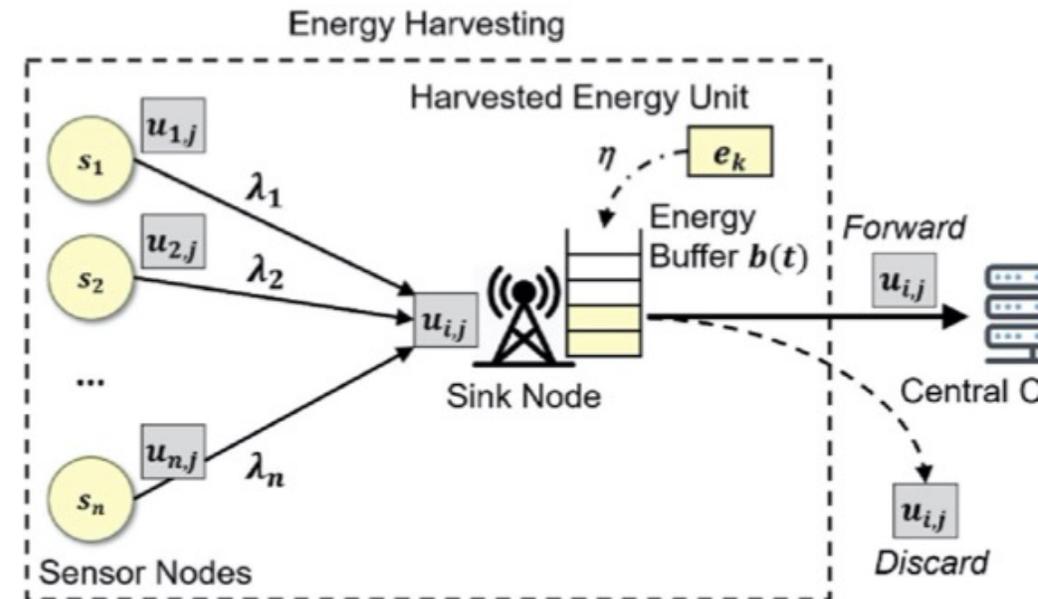
$$\text{average Aol of interval } [0,T] = \Delta_T = \frac{1}{T} \int_0^T \Delta(t) dt$$

$$= \frac{1}{T} \sum_i^n Q_i$$

$$(Q_i = \frac{1}{2} (X_i)^2) \longrightarrow \frac{1}{2T} \sum_i^n (X_i)^2$$

# Challenge

- The EH-based sink node has insufficient energy to forward all status updates from the sensor nodes to the central controller, i.e., only forward when the energy is available.
- The decision is challenging because the monitoring application requires multiple types of monitor data, each of which might have different importance to the system.
- Deciding which update can be forwarded or discarded to minimize the average Aol of all sensor nodes by developed strategy.

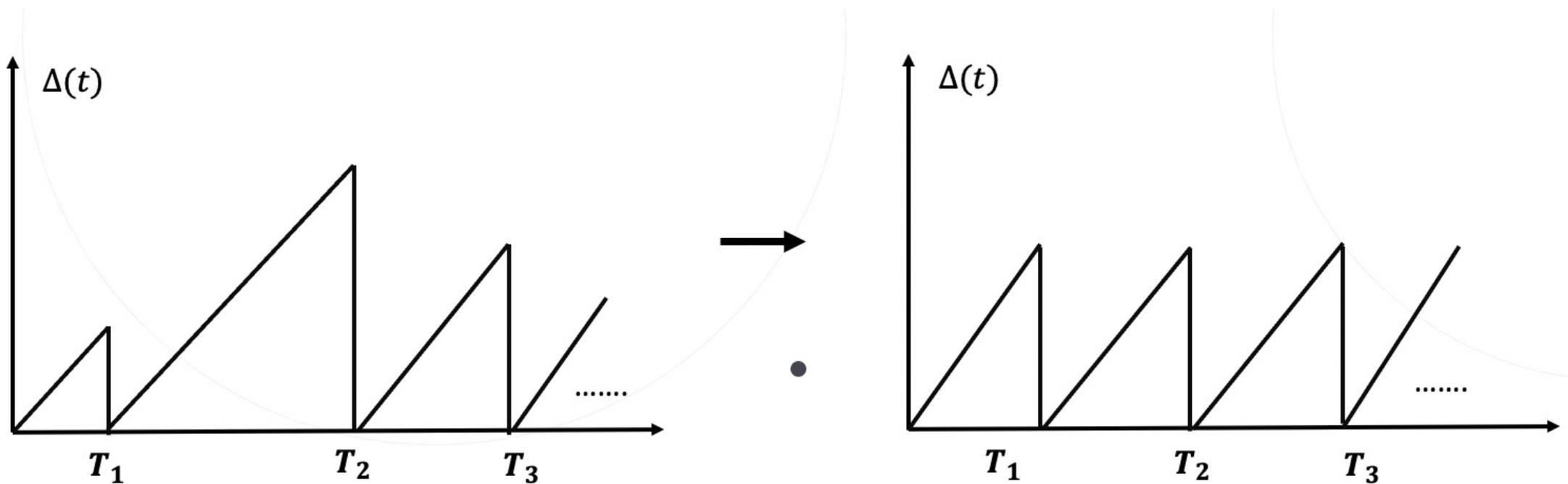


The slide features a white background with several decorative elements: a light gray circle in the top-left corner, a blue circle in the bottom-right corner, and two large, faint light gray circles that frame the central text. Two small blue dots are positioned above and below the text. The text 'Aol Optimization' is centered in a bold, black, sans-serif font.

# Aol Optimization

# Objective

- By Cauchy–Schwarz inequality, the sum of areas is minimum when each one is equal. Therefore, our objective is to find out a series of time (threshold) making the area **as uniform as possible**.

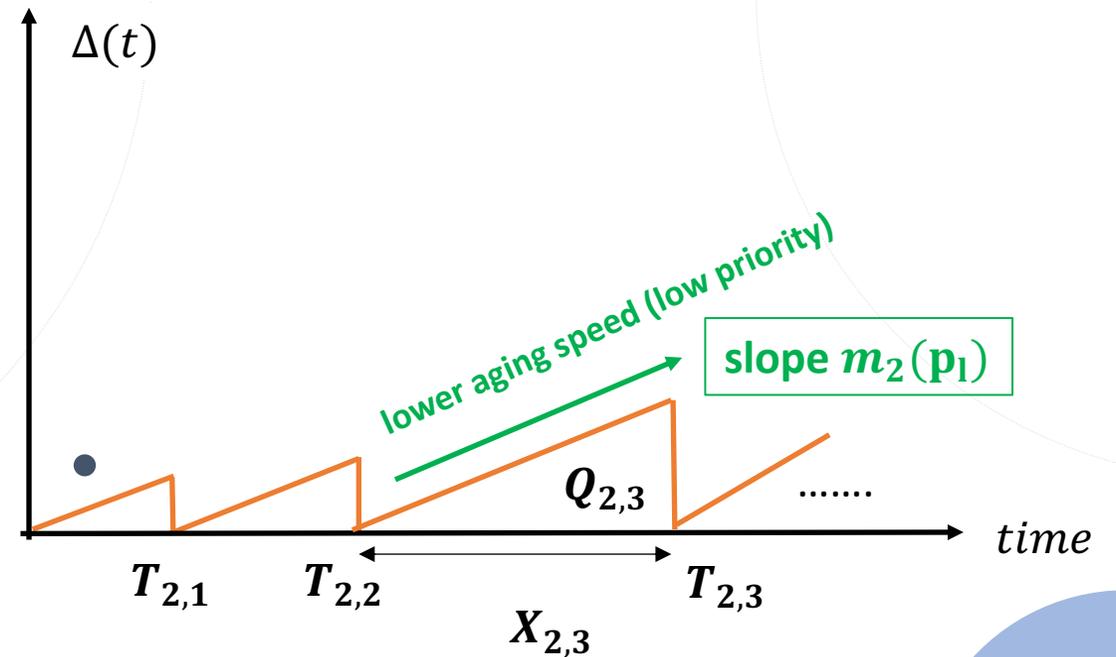
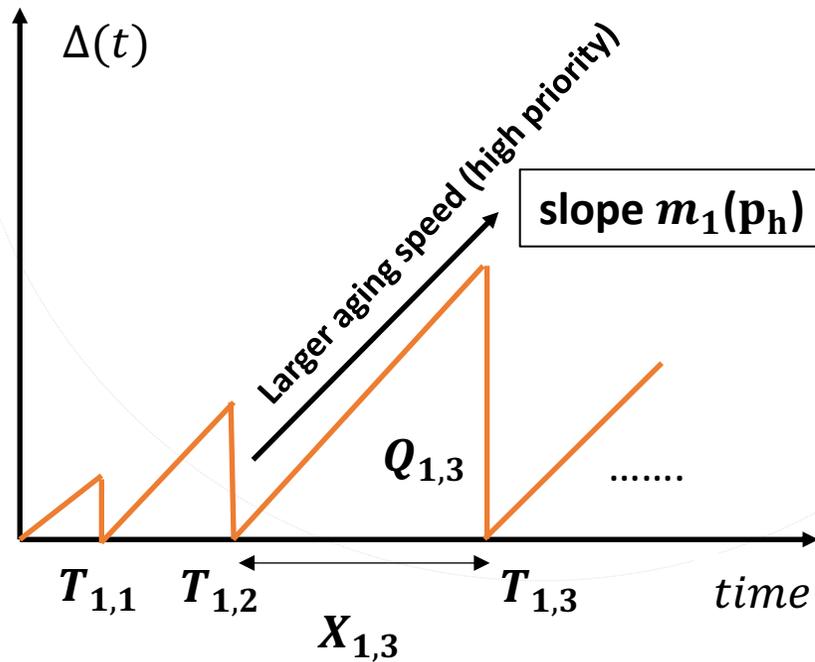


# Relationship between Priority & Aging rate

- With  $n$  nodes, the priority expresses as  $\alpha_1 p_1, \alpha_2 p_2, \dots, \alpha_n p_n$
- With two diff. priority data streams, the ratio of priority can be expressed by two parameters  $\rightarrow$  low : high =  $p_l : p_h$
- With two diff. priority data streams, the ratio of can also represent the aging rate of the data package, which is represented by the slope  $m_1, m_2$  on the graph.

# Definition of Aol with diff. priority

|           |   |
|-----------|---|
| $m_j$     | $j=1,2$ two diff. slope (aging rate)            |
| $T_{j,i}$ | time instant of update $u_i$ completing service |
| $X_{j,i}$ | time of update $u_i$ spent in the system        |
| $Q_{j,i}$ | Aol triangle area for time interval $X_{j,i}$   |



# Definition of Aol with diff. priority

$$m_j = \frac{\Delta y}{\Delta x}$$

$$= \frac{\Delta t}{X_{j,i}}$$

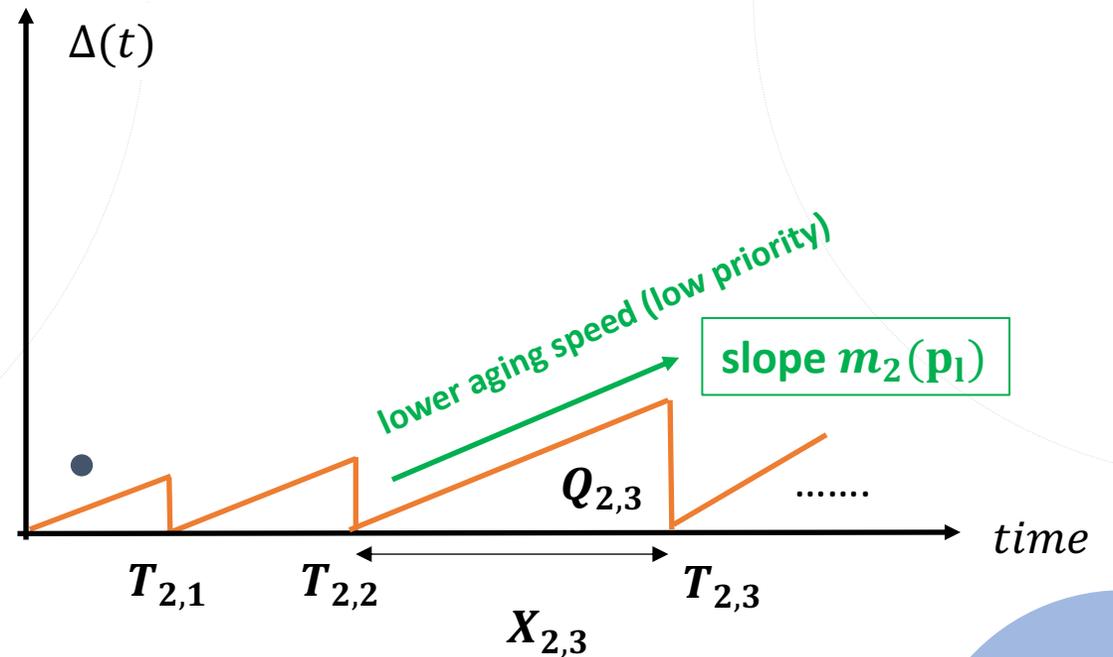
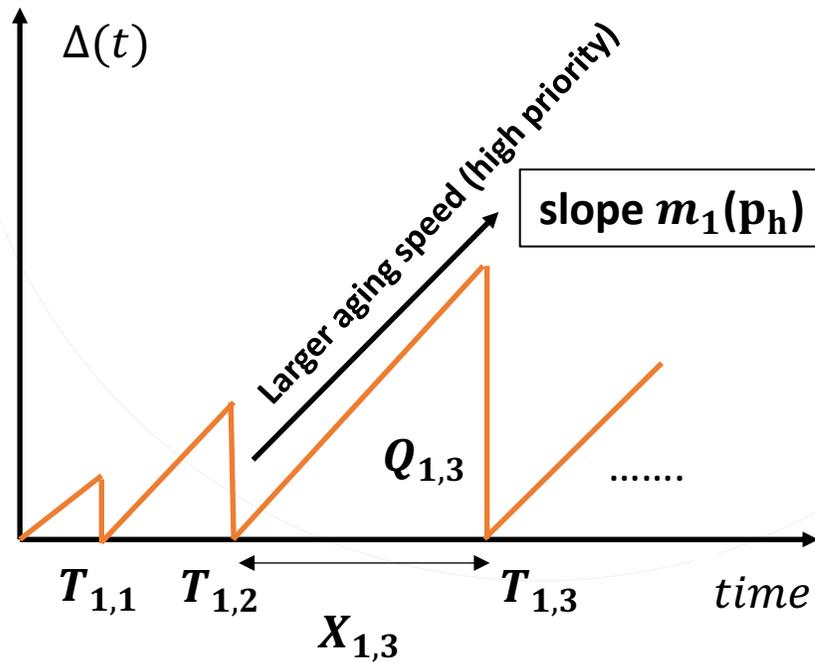
$$\Delta t = m_j * X_{j,i}$$

$$Q_{j,i} = \frac{1}{2} \text{ base} * \text{perpendicular height}$$

$$= \frac{1}{2} * X_{j,i} * \Delta t$$

$$= \frac{1}{2} * X_{j,i} * (m_j * X_{j,i})$$

$$= \frac{1}{2} m_j X_{j,i}^2$$



# Offline Solution

1. Given the energy arrival sequence  $(e_1, e_2, e_2 \dots)$ , the update arrival sequence  $(\mu_1, \mu_2, \mu_2 \dots)$ , and the priority of arrival updates  $(\alpha_1 p_1, \alpha_2 p_2, \dots, \alpha_n p_n)$
2. Because energy arrival rate  $\eta <$  update arrival rate  $\lambda$  ,  
total number of energy unit = total number of accepted updates

# Offline Solution

- The optimal solution means the area of each triangle is **equal**.

$$Q_{1,i} = Q_{2,i}$$

$$\frac{1}{2} m_1 X_{1,i}^2 = \frac{1}{2} m_2 X_{2,i}^2$$

$$m_1 X_{1,i}^2 = m_2 X_{2,i}^2$$

$$\rightarrow \frac{X_{1,i}}{X_{2,i}} = \sqrt{\frac{m_2}{m_1}}$$

In a time interval  $T$ , total number of energy unit is  $T * \eta$

Threshold for *node* $_j$ :

$$X_{1,i} = T * \frac{\# \text{ of nodes}}{T * \eta} * \sqrt{\frac{m_2}{m_1}}$$

$$= \frac{\# \text{ of nodes}}{\eta} * \sqrt{\frac{m_2}{m_1}}$$

$$X_{2,i} = T * \frac{\# \text{ of nodes}}{T * \eta} * \sqrt{\frac{m_1}{m_2}}$$

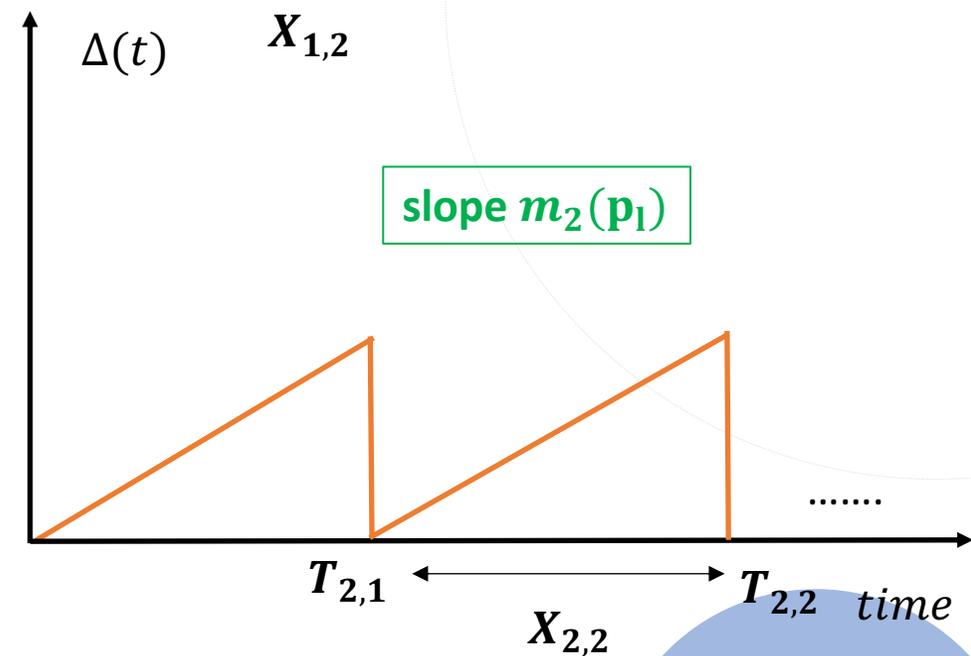
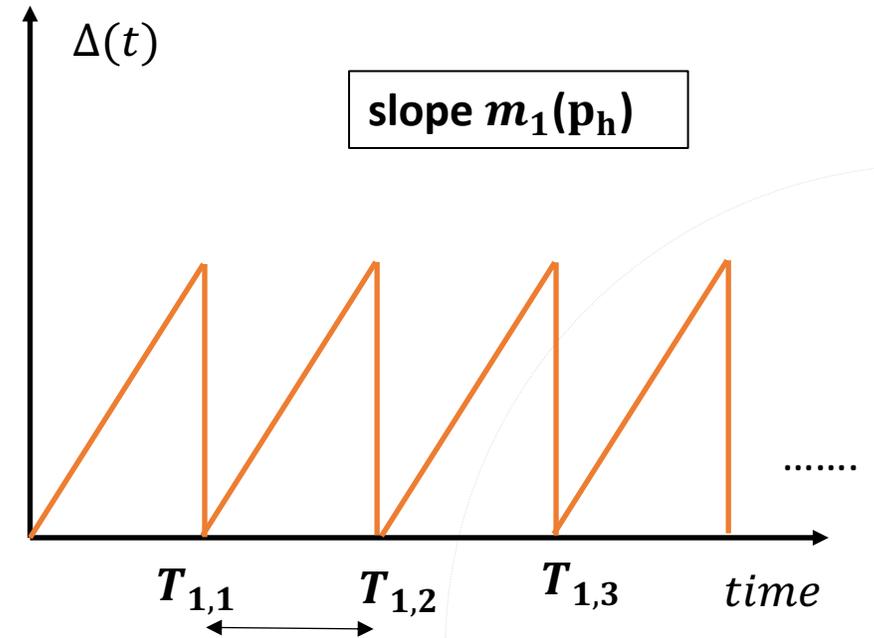
$$= \frac{\# \text{ of nodes}}{\eta} * \sqrt{\frac{m_1}{m_2}}$$

# Offline Solution

- By the given ratio of priority, transmitter decides whether to accept upcoming update based on threshold.

$$X_{1,2} = \frac{\# \text{ of nodes}}{\eta} * \sqrt{\frac{m_2}{m_1}}$$

$$X_{2,2} = \frac{\# \text{ of nodes}}{\eta} * \sqrt{\frac{m_1}{m_2}}$$



**While** True do

**if** Harvested energy arrives **then**

        b=b+1;

$i_t$  : elapsed time since last accept update

**end if**

**if** Update arrives **then**

**if**  $(b > 1) \cap ( i_t > \frac{\# \text{ of nodes}}{\eta} * \frac{1}{\sqrt{m_i} * \sum_{k=0}^N \sqrt{\frac{1}{m_k}}} )$  **then**

            accept update

**else if** (b=1)

            accept min(  $AoI_{[\Delta_t * \lambda_N]} + 1$  th update of each node )

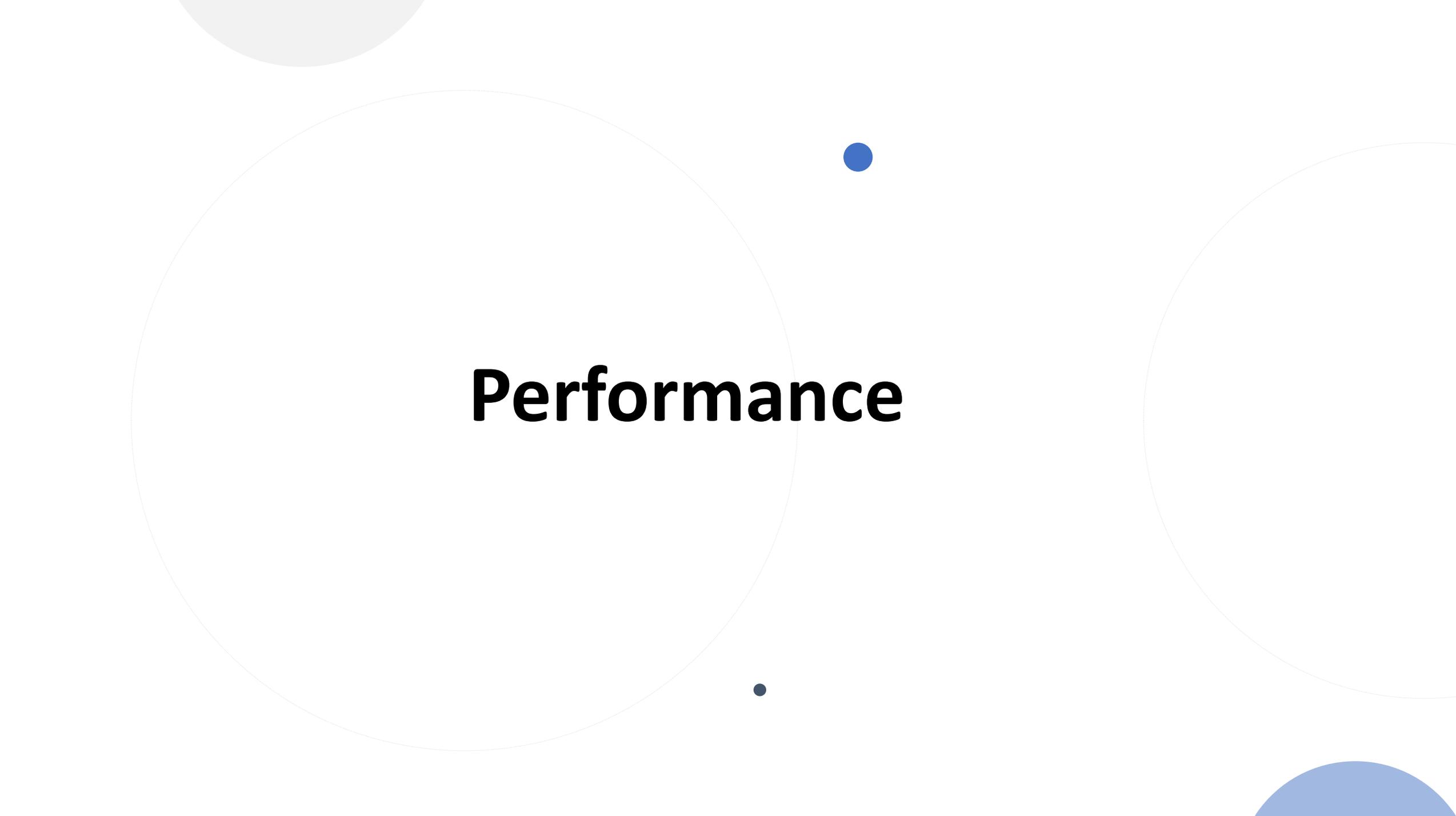
**else**

            discard update

**end if**

**end if**

**end while**

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# Performance

# Result

Parameter:

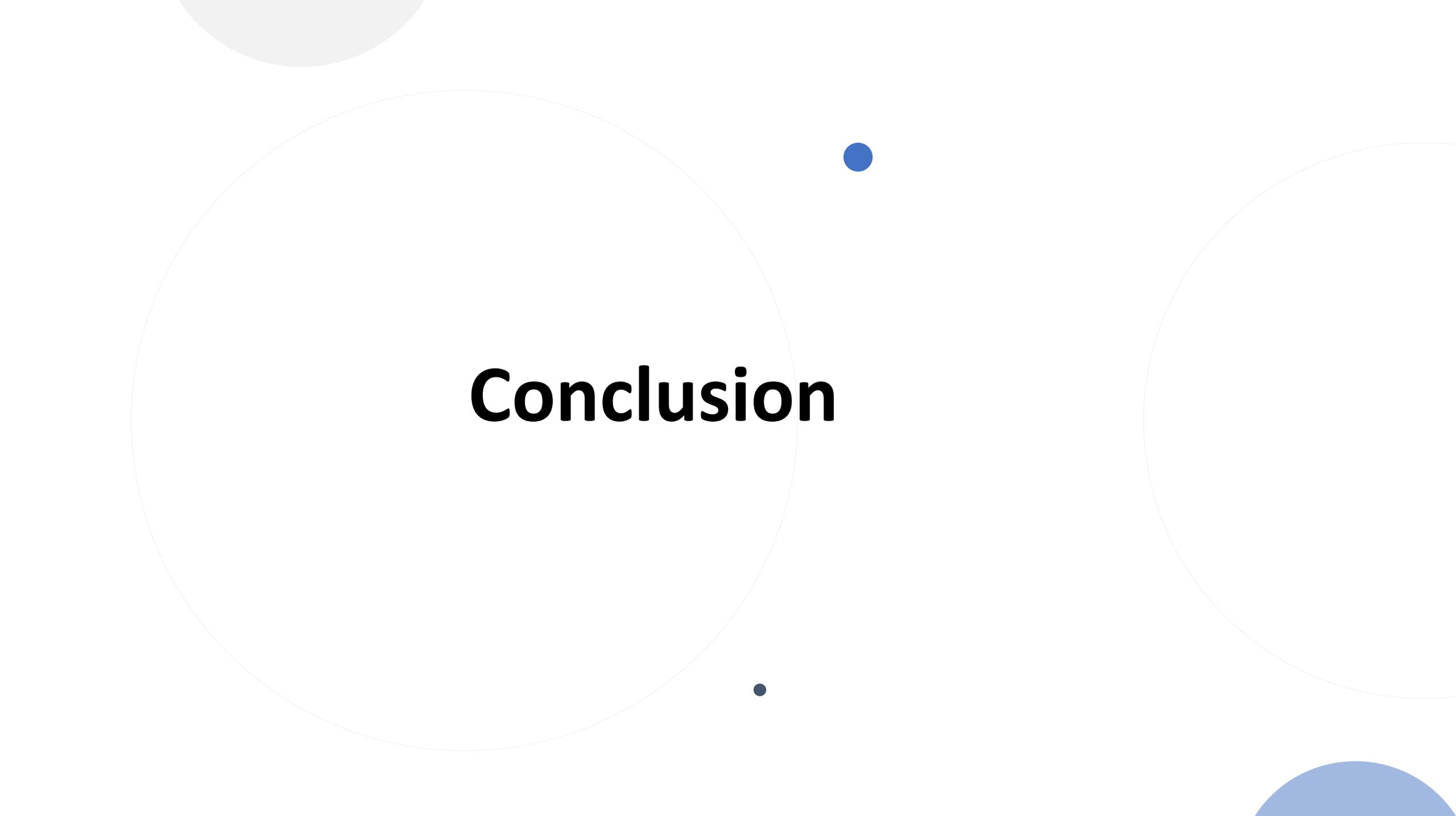
- # of source: 2
- Priority rate: 2:1
- Energy arrival rate: 4
- Update arrival rate: 5:3

|   | Average Aol |
|---|-------------|
| <b>Reference</b>                        | 0.97        |
| <b>Ours<br/>(with diff. thresholds)</b> | 30%: 0.29   |
|   | 20%: 0.28   |
|   | 10%: 0.11   |
|   | 5%: 0.10    |

if Update arrives then

if  $(b > 1) \cap (i_t \approx \frac{\# \text{ of nodes}}{\eta} * \frac{1}{\sqrt{m_i} * \sum_{k=0}^N \sqrt{\frac{1}{m_k}}})$  then

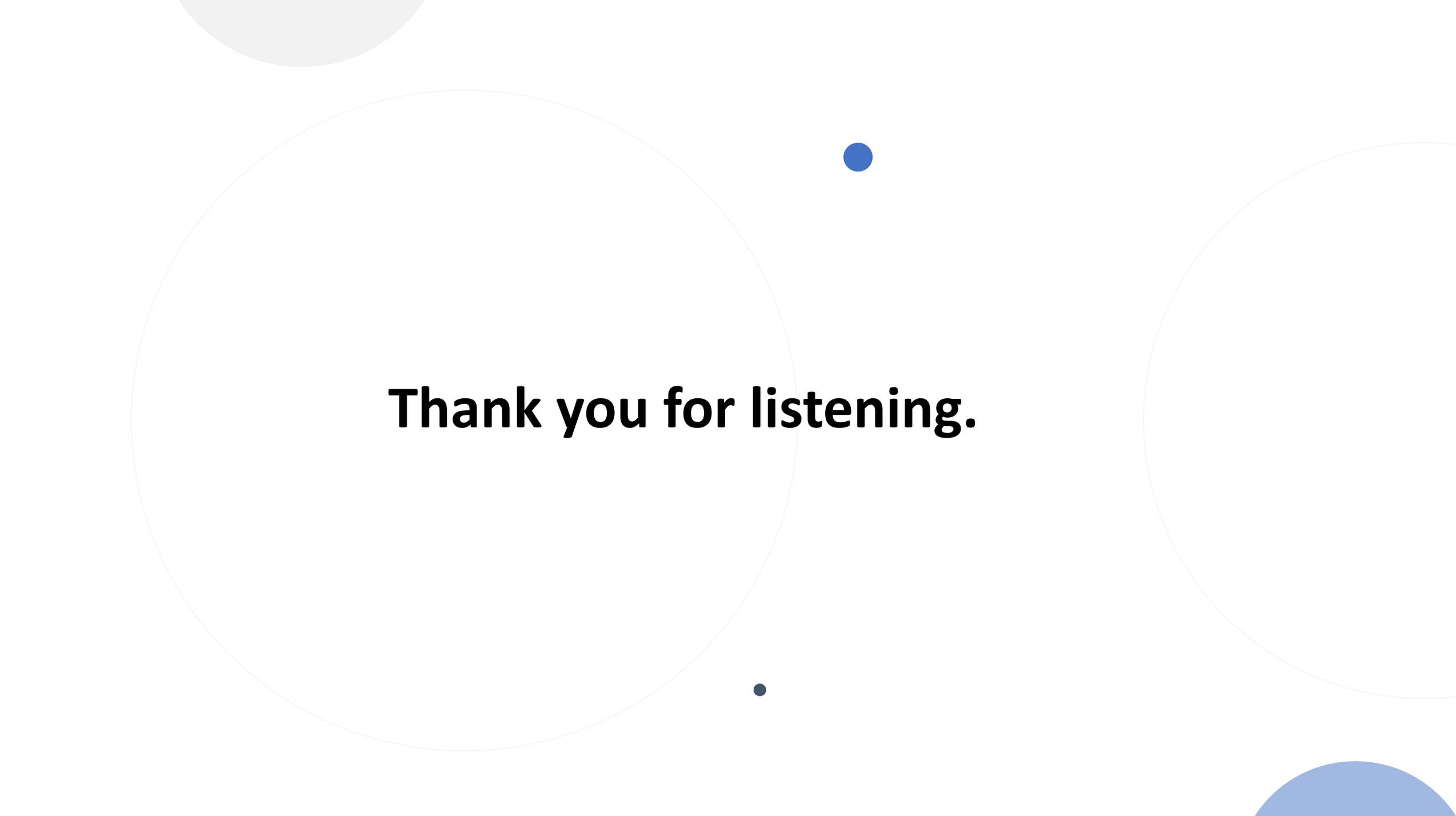
accept update

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# Conclusion

# Conclusion

- In response to the characteristics of NES, we propose a solution to optimize data freshness
- According to the formula of average Aol, we can greatly increase data freshness of NIS by effective decision strategy

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**Thank you for listening.**