

# AGE OF INFORMATION (AOI) A TOOL FOR DESIGNING TIME-CRITICAL NETWORKS

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Nikolaos Pappas, Linköping University  
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# Outline

- **Part I: Fundamentals**
  - Introduction
  - Definition of Age of Information
  - Age of Information Metrics
  - Goal-oriented communications
- **Part II: Hands-on in Wireless Channels**
  - Aol calculation
  - Average Aol
  - Average PAol

# Introduction

## Case 1

Generation Time  $>$  Packet delay



## Case 2

Generation Time  $<$  Packet delay



# Introduction

- Related metrics (**not sufficient**)
  - Packet delay
  - Inter-delivery time



Information Freshness

Source



Link

Receiver



Source



Link

Receiver



# Information Freshness

Source

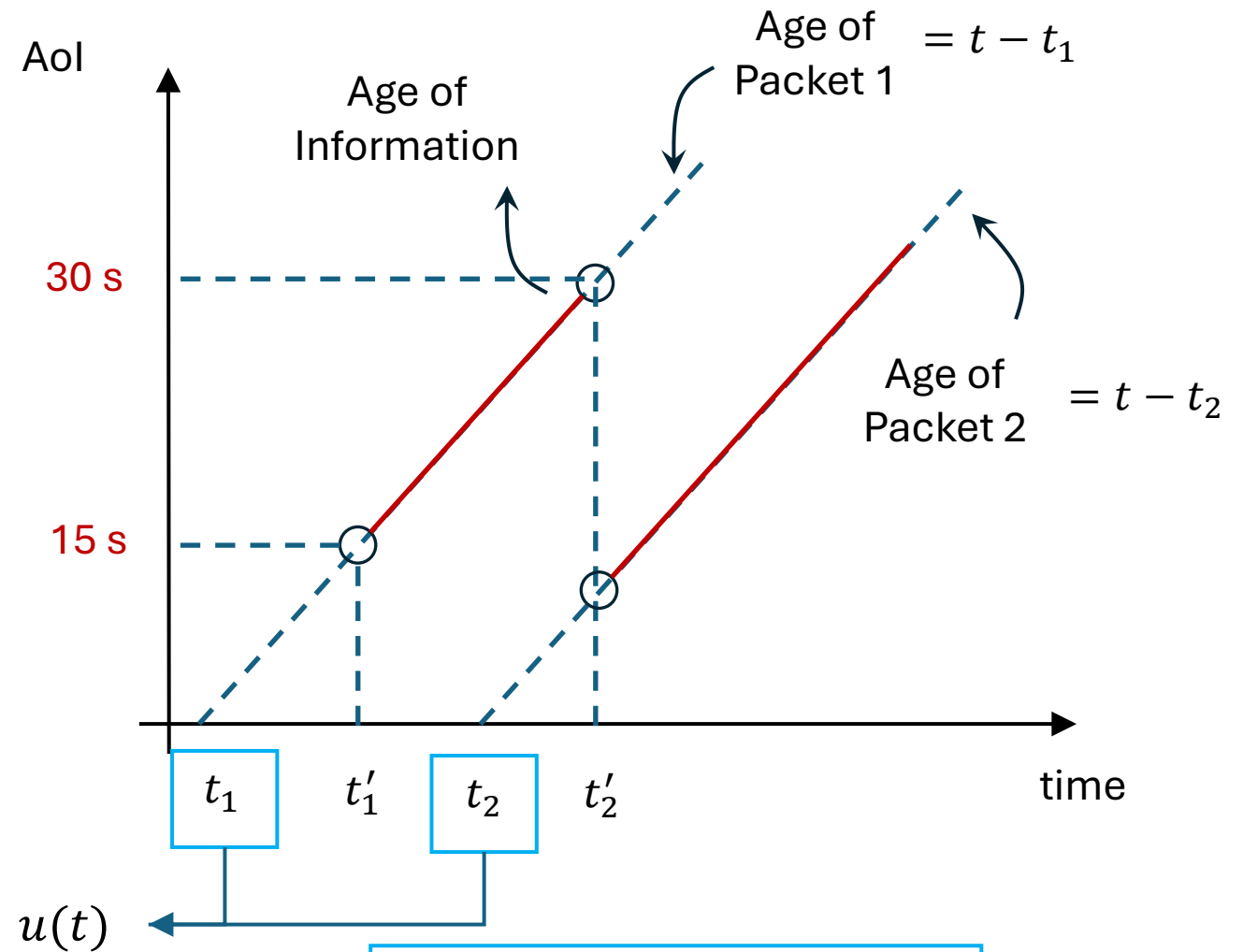
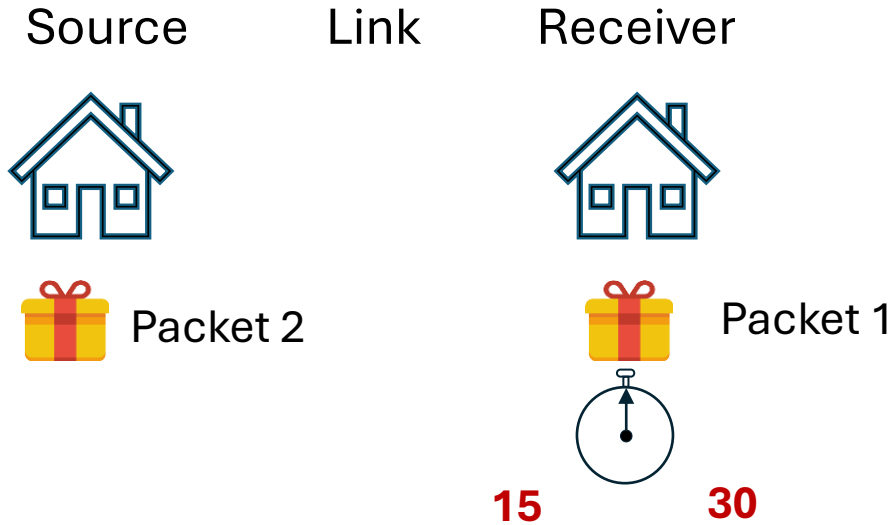


Link

Receiver



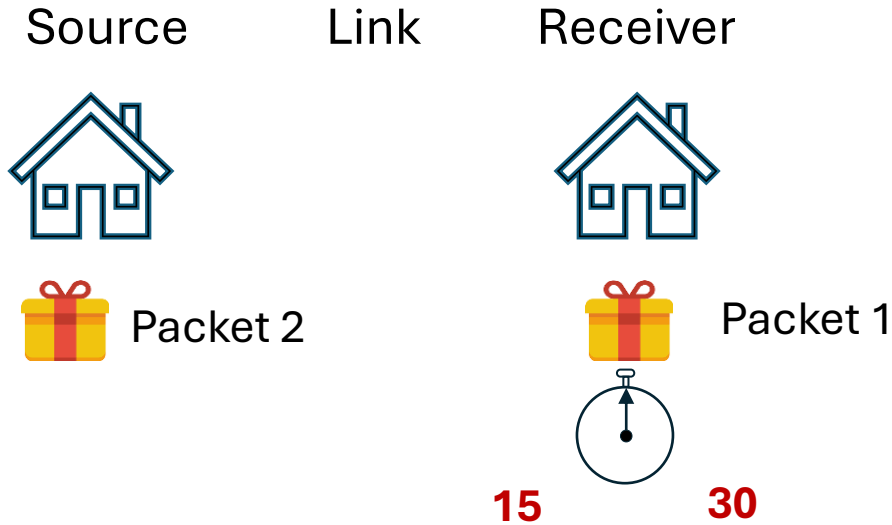
# Information Freshness



Definition

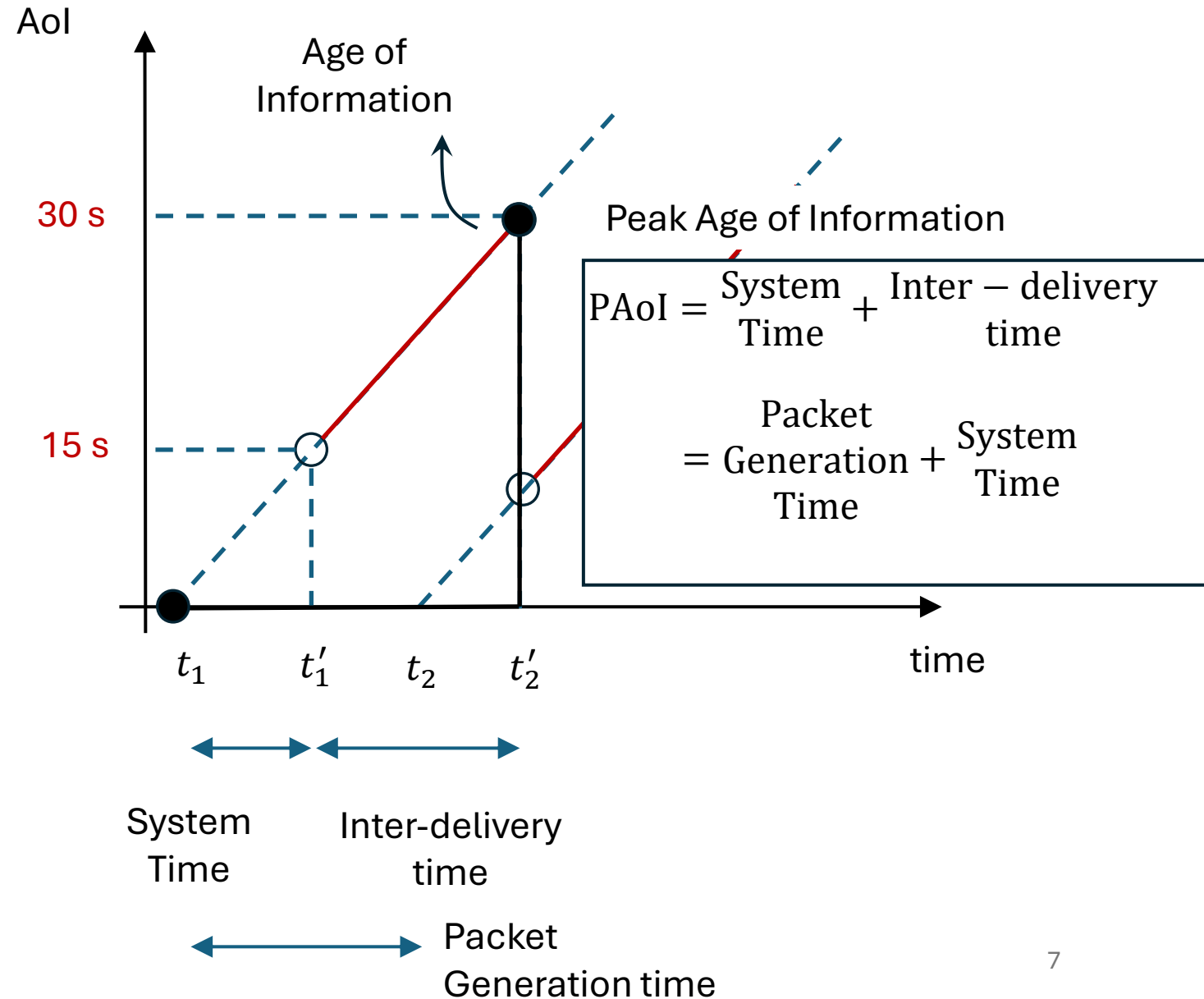
$$\text{AoI} = t - u(t)$$

# Information Freshness



## Definition

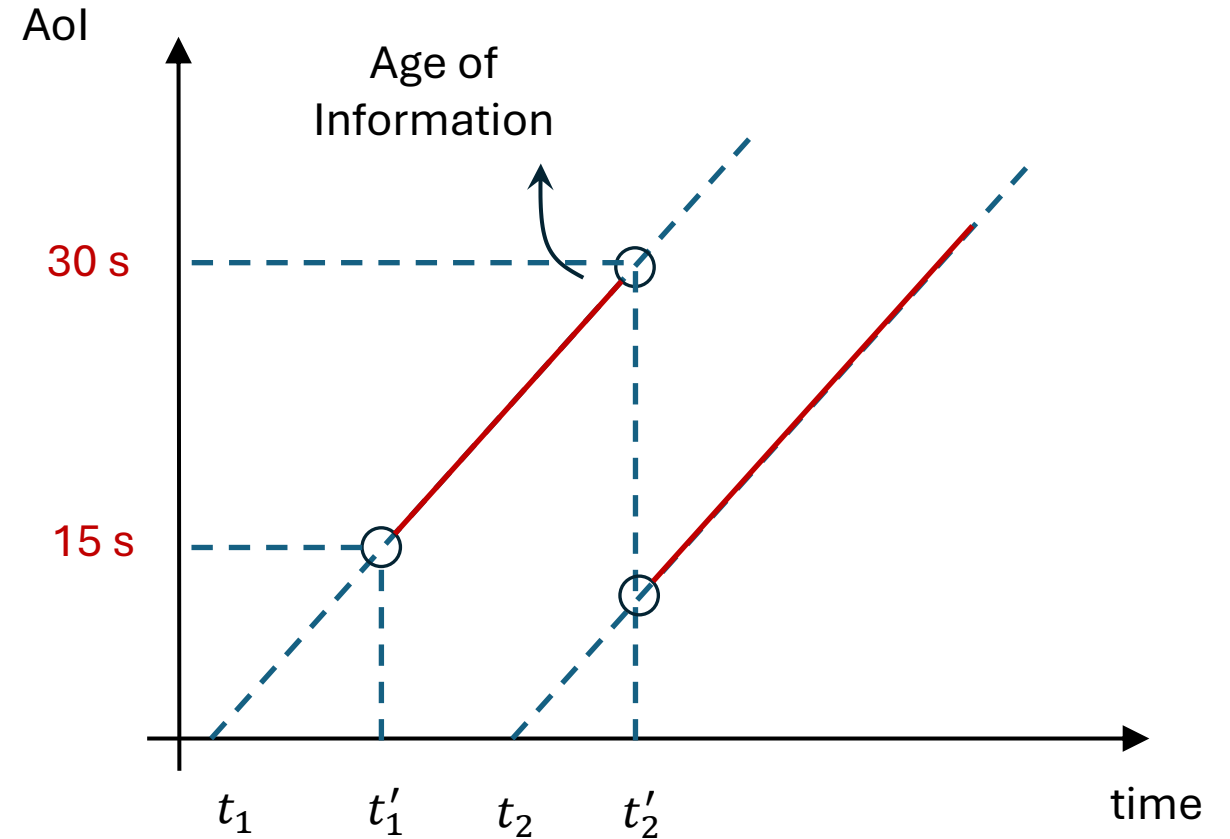
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# Information Freshness

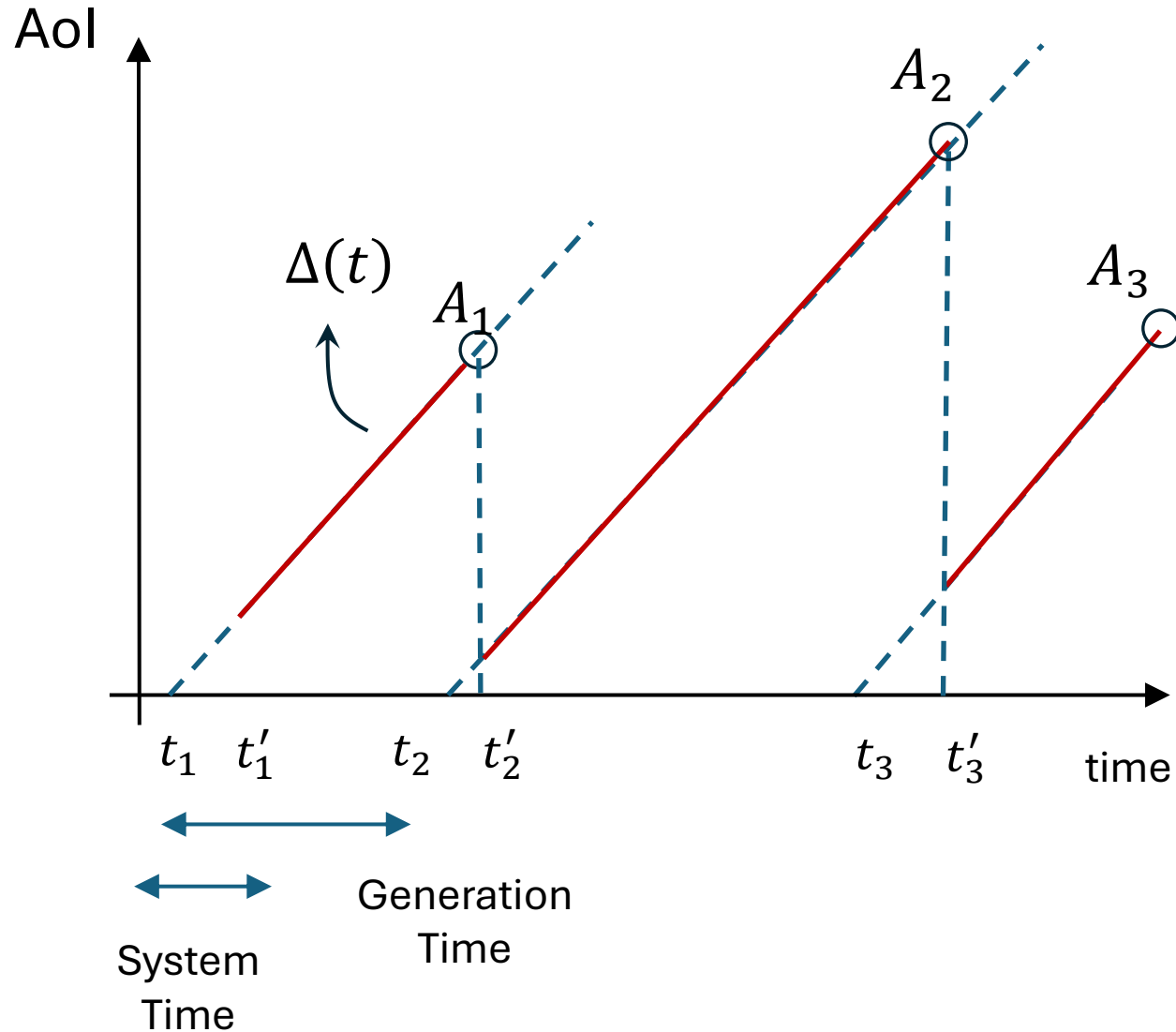
## Remarks

- Aol is an end-to-end metric.
- Aol captures the timeliness of information.
- Aol accounts for System Time, Inter-delivery time, and Generation time, all-together.





# Aol metrics



## Average AoI

$$\Delta = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T \Delta(t) dt \quad (1)$$

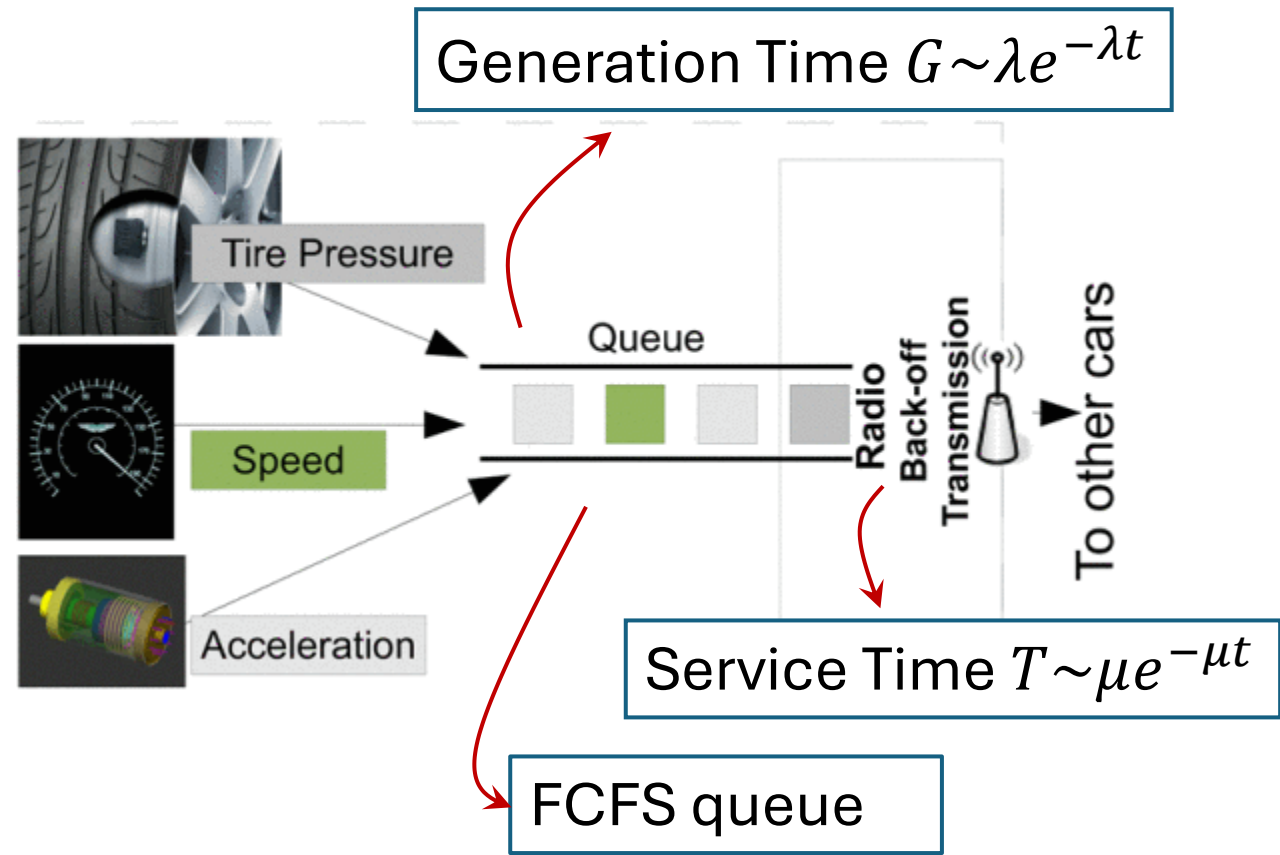
$$= \lambda \left( E[GT] + \frac{E[G^2]}{2} \right), \quad \lambda = \lim_{T \rightarrow \infty} \frac{N(T)}{T}$$

## Average PAoI

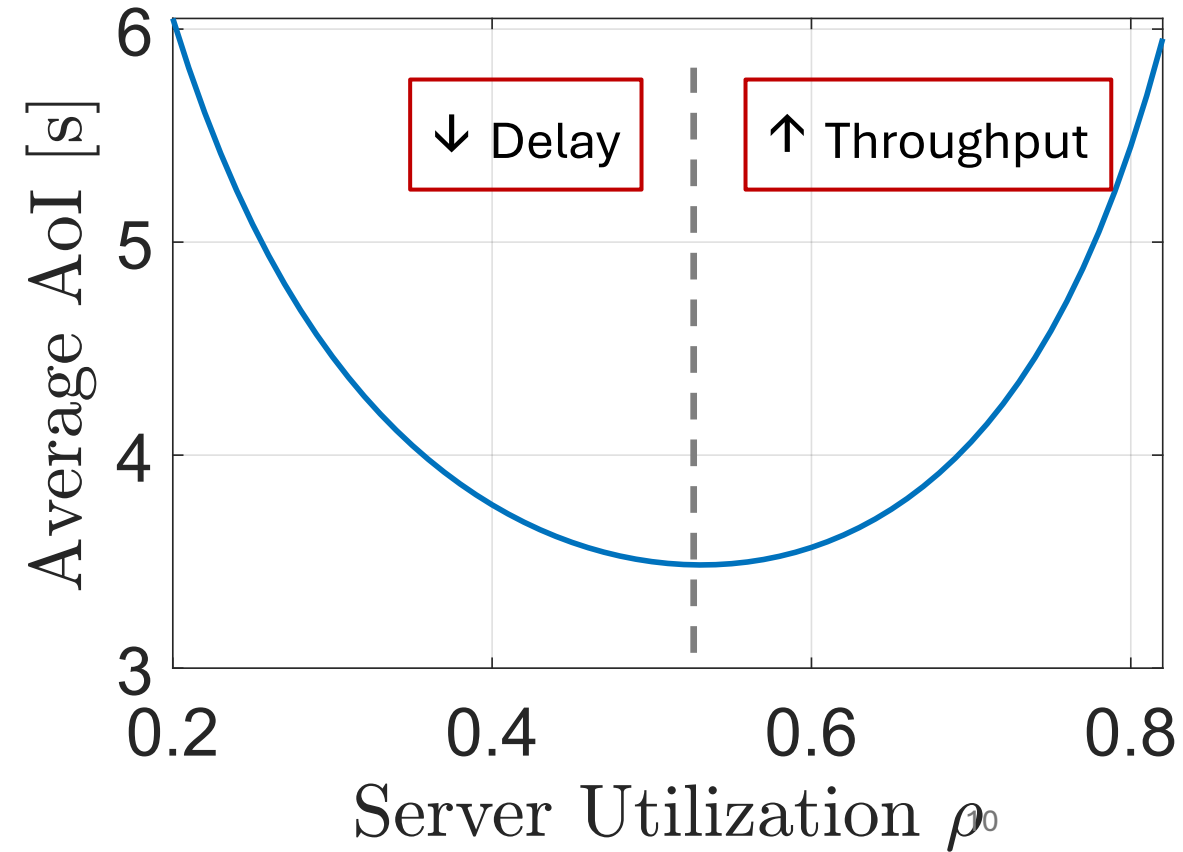
$$\Delta^{(p)} = E[A_i] \quad (2)$$

$$= E[G] + E[T]$$

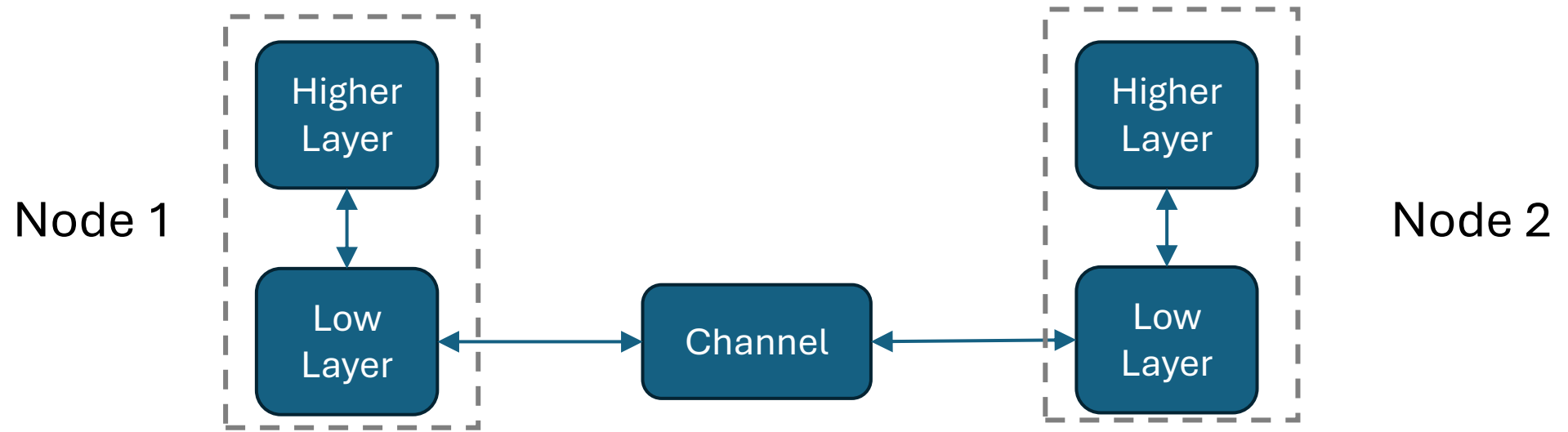
# Average AoI metric: FCFS queue



$$\Delta = \frac{1}{\mu} \left( 1 + \frac{1}{\rho} + \frac{\rho^2}{1 - \rho} \right), \rho = \frac{\lambda}{\mu} \quad (1)$$



# Remarks on the Aol metrics



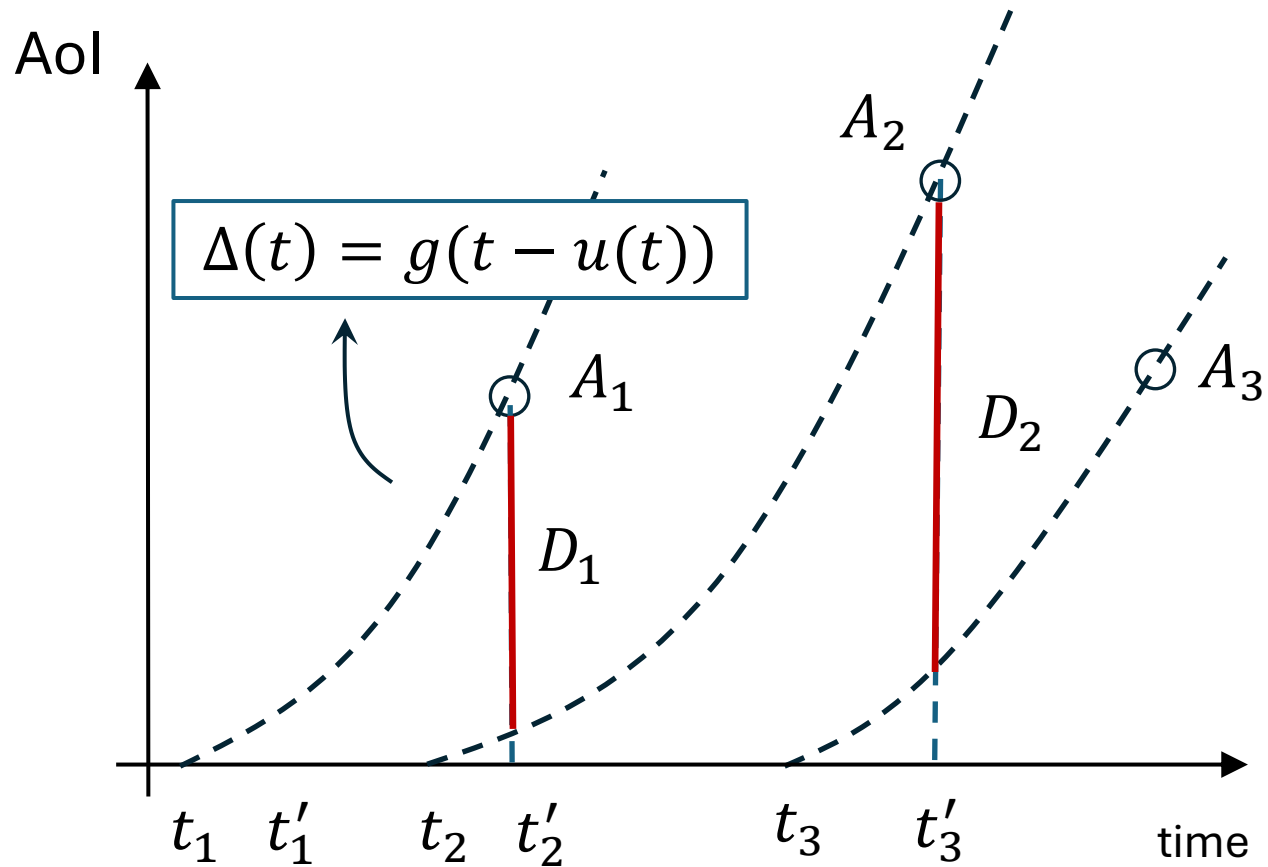
## Statistical Framework

- Tacit distinction:
  - Data communication systems
  - Information update systems.
- Freshness as a balance between delay and throughput.

## Shannon Model

- Instantaneous decoding.
- Zero latency
- Data agnostic
- Data is always available

# Non linear Aol-metrics



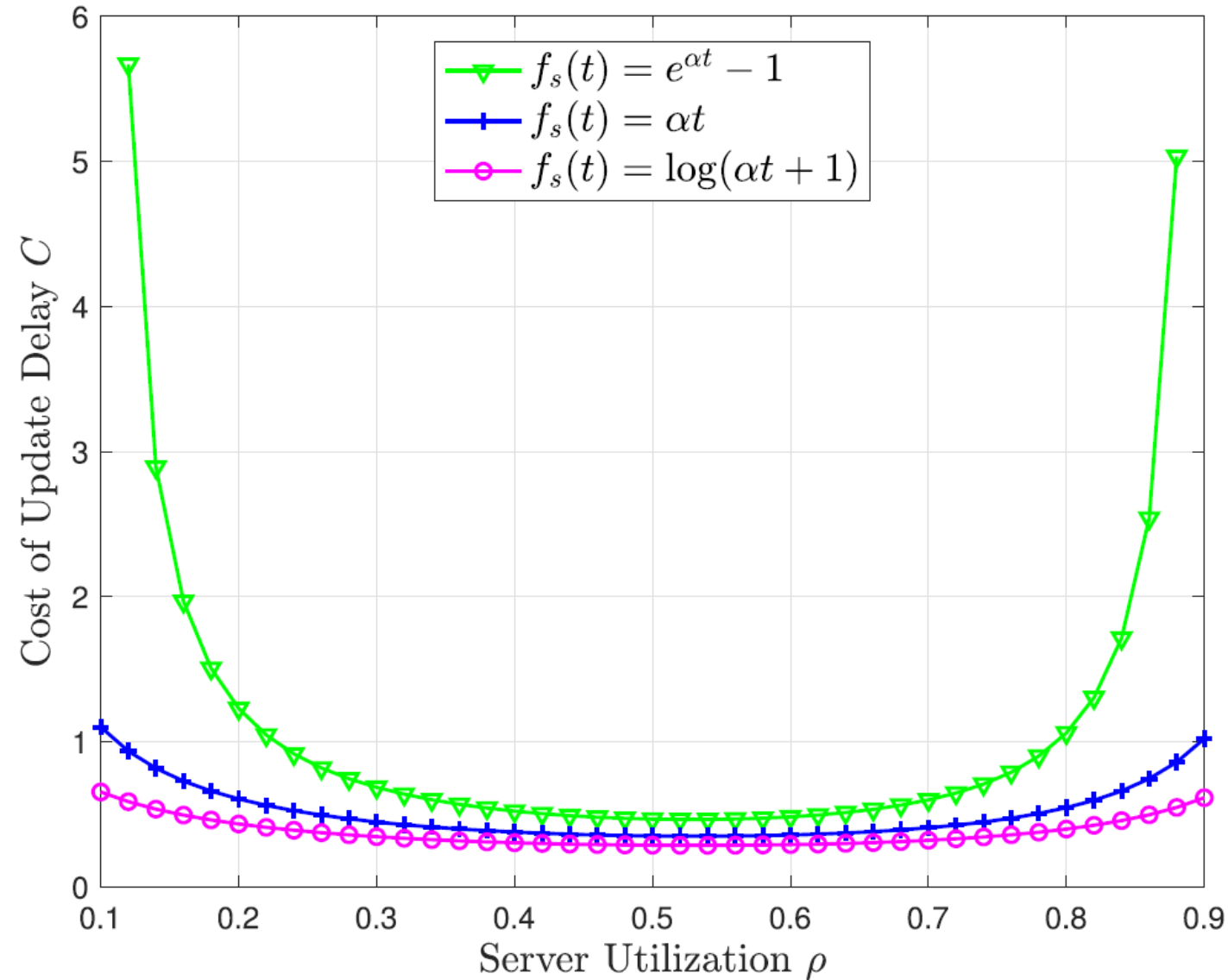
- Cost of Update Delay

$$g(t) = \begin{cases} \alpha t \\ e^{\alpha t} - 1 \\ \log(\alpha t + 1) \end{cases}$$

- Value of Information Update

$$V = E \left[ \frac{D_i}{A_i} \right]$$

# Non linear Aol-metrics



- Cost of Update Delay

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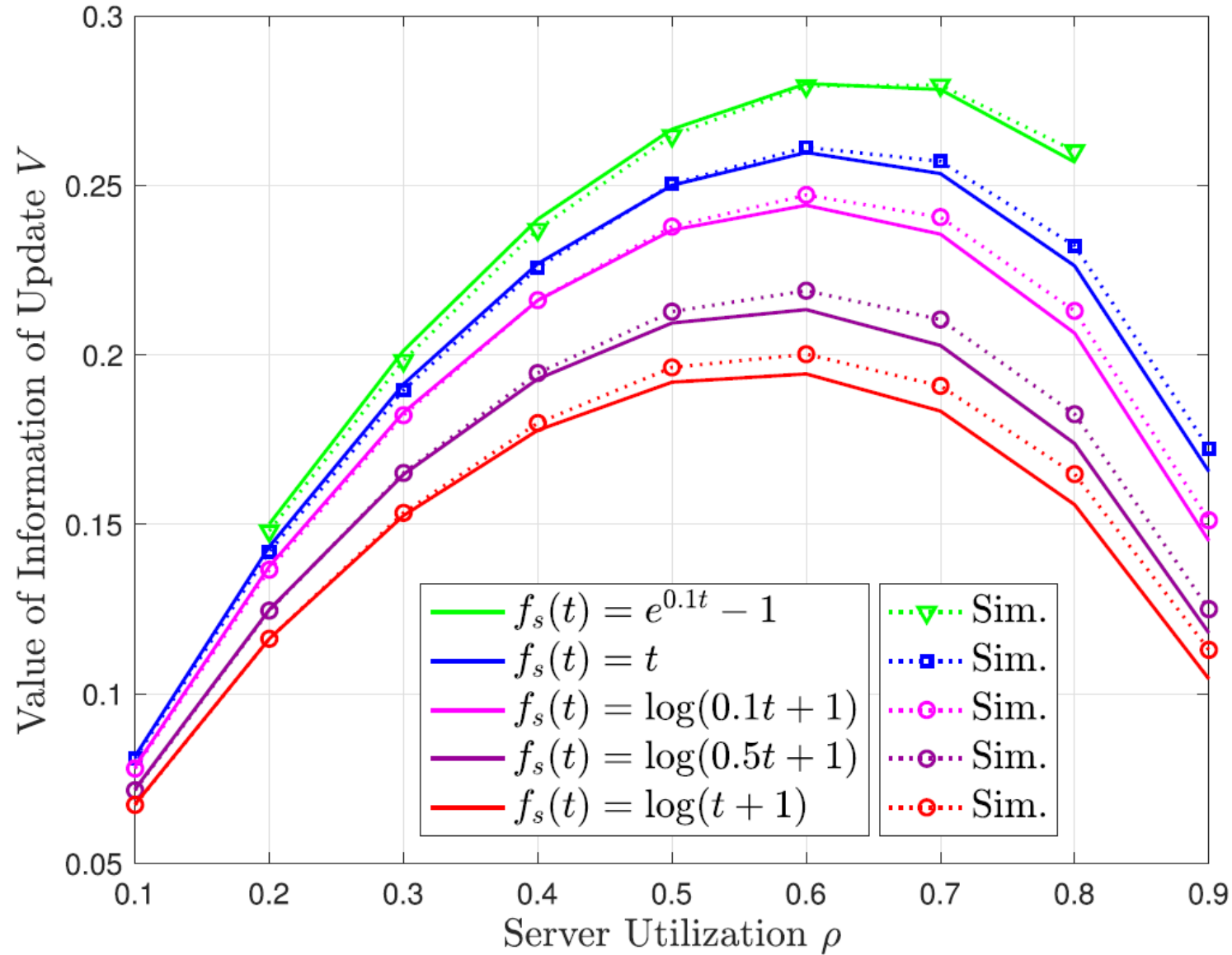
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[1] A. Kosta, N. Pappas, A. Ephremides, and V. Angelakis, "Age and value of information: Non-linear age case", IEEE ISIT 2017.

[2] A. Kosta, N. Pappas, A. Ephremides, and V. Angelakis, "The cost of delay in status updates and their value: Non-linear ageing", IEEE Trans. Comm., 2020.

# Non linear Aol-metrics



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# Goal Oriented Communications

- Communicate with a specific goal.
- Semantics (Pragmatic)
  - Utility to achieve a goal.
- Information Attributes
  - Innate (objective): freshness, precision
  - Contextual (goal): timeliness (deadline), completeness.
- Policy
  - Generate and communicate based on the goal.

# Fault Detection and autonomous maintenance

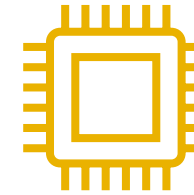
Remote  
Monitor



on/off  
channel



Sensor



- Pull-based communication model

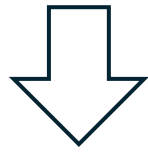
- Sensor State:  
healthy or faulty
- Slotted time

**Challenge:** Optimally decide, at the beginning of a time slot, whether to probe or not the sensor.



# Fault Detection and autonomous maintenance

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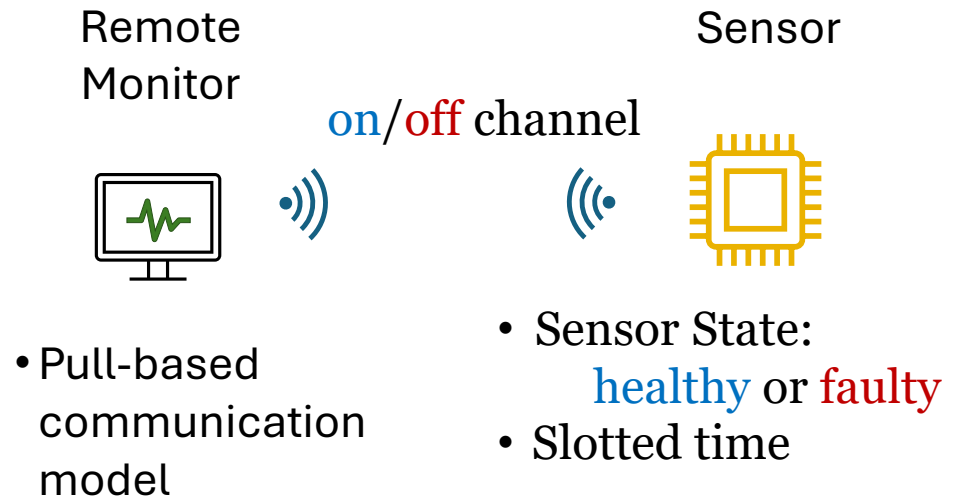


## Procedure

Minimize the total accumulated cost over a finite time horizon.

**Transition cost** is a function of

- Agent's confidence about the sensor and links status
- Staleness of the status updates
- Cost associated with the probing action.

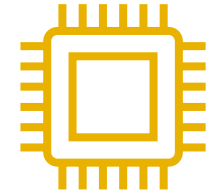


# Fault Detection and autonomous maintenance

Remote  
Monitor



Sensor



on/off  
channel

- Sensor State:  
healthy or faulty
- Slotted time

## Transition cost

- Agent's confidence:
  - Entropy of reported status
- Staleness of the status updates
  - Age of Information
- Cost associated to probing request
  - Ratio of resources per probing/resources per transmission

Value of Information

$$V = \lambda_1 H + \lambda_2 \times \text{average AoI}$$

Transition cost

$$g = c + V$$

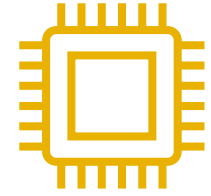
# Fault Detection and autonomous maintenance

Remote Monitor



on/off  
channel

Sensor



Dynamic program

$$J(x_t) = \min_{a \in \{0,1\}} \left[ g_t + \sum_{z,s,i} \underbrace{p_t^i}_{\text{Probability of System States}} \underbrace{p_{is}}_{\text{Probability of Observations}} r_s(a, z) J(x_{t+1}) \right]$$

Transition cost

Observations

Actions

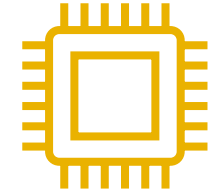
- Sensor State: **healthy** or **faulty**
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# Fault Detection and autonomous maintenance

Remote Monitor

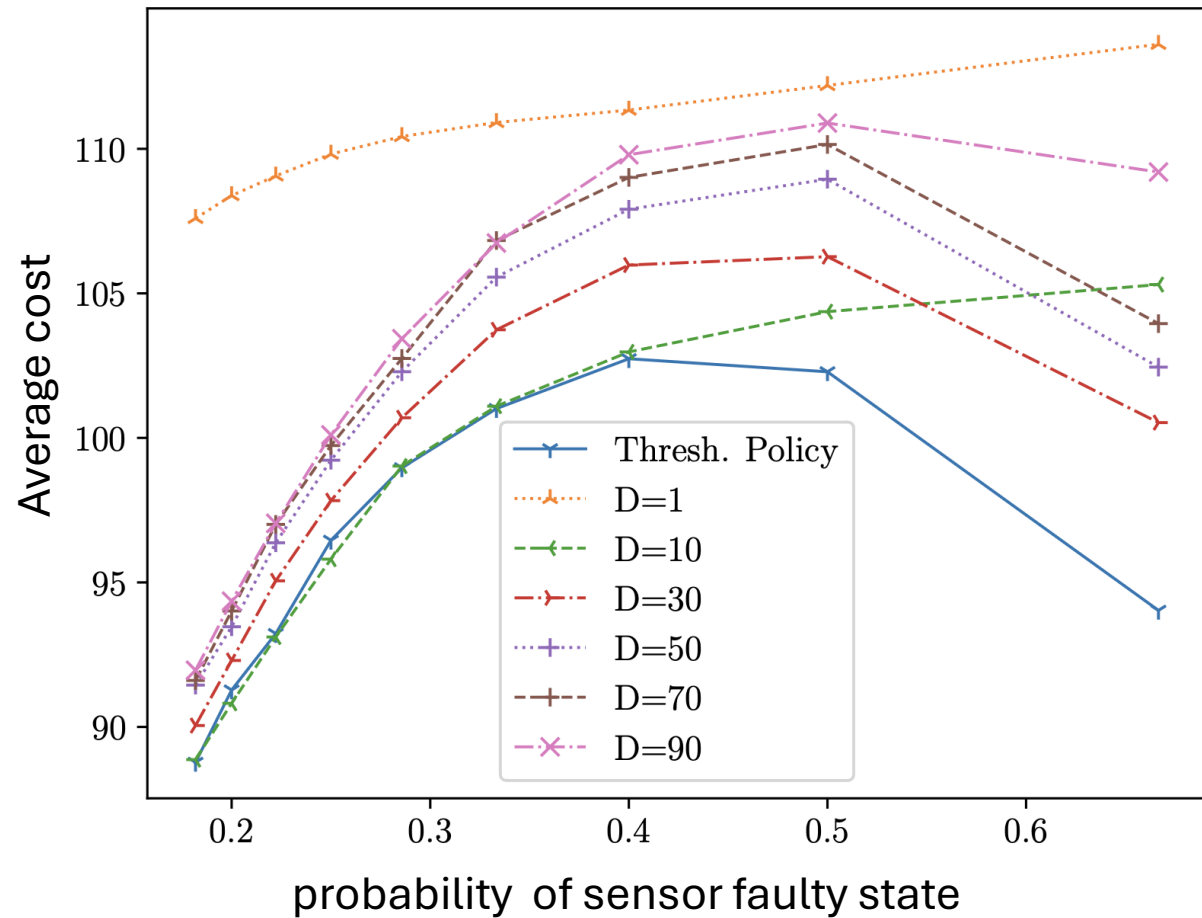


Sensor

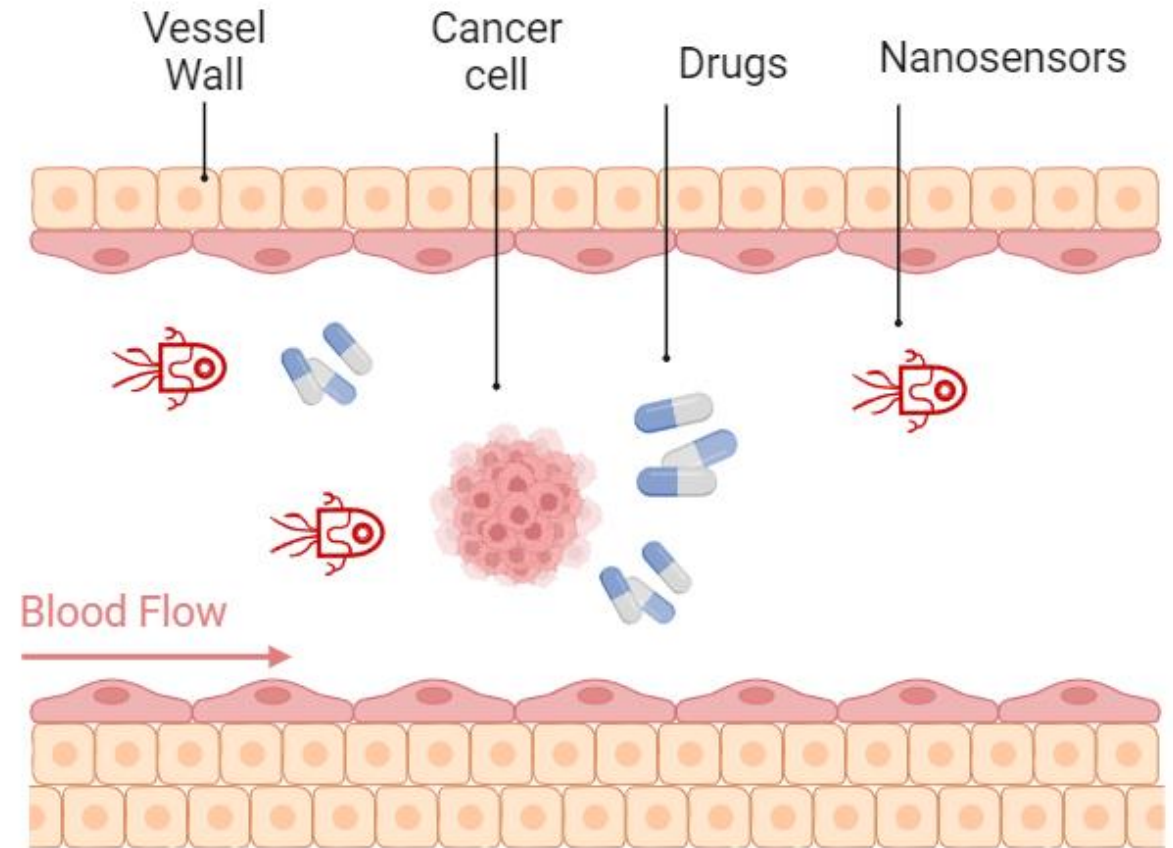
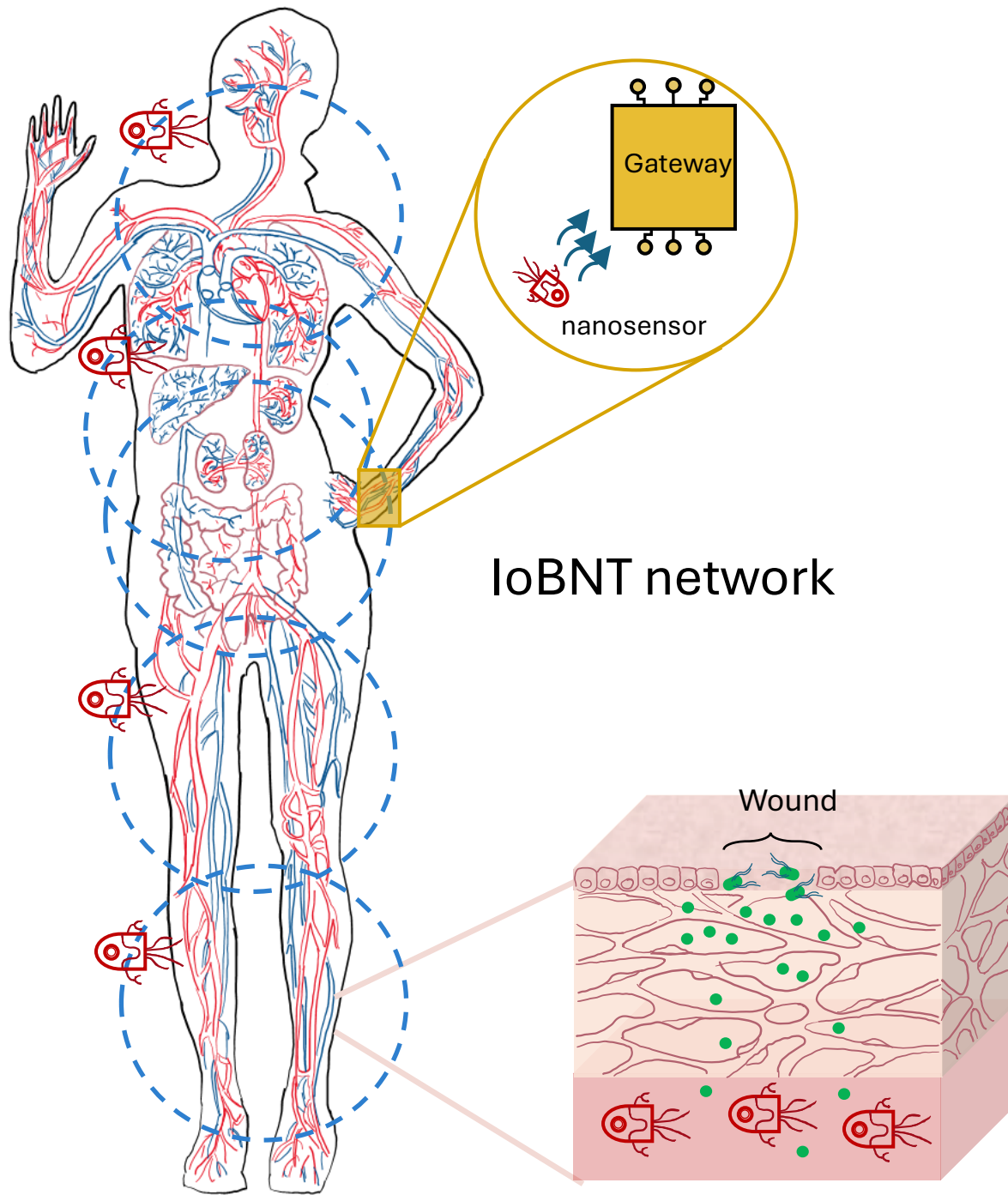


on/off  
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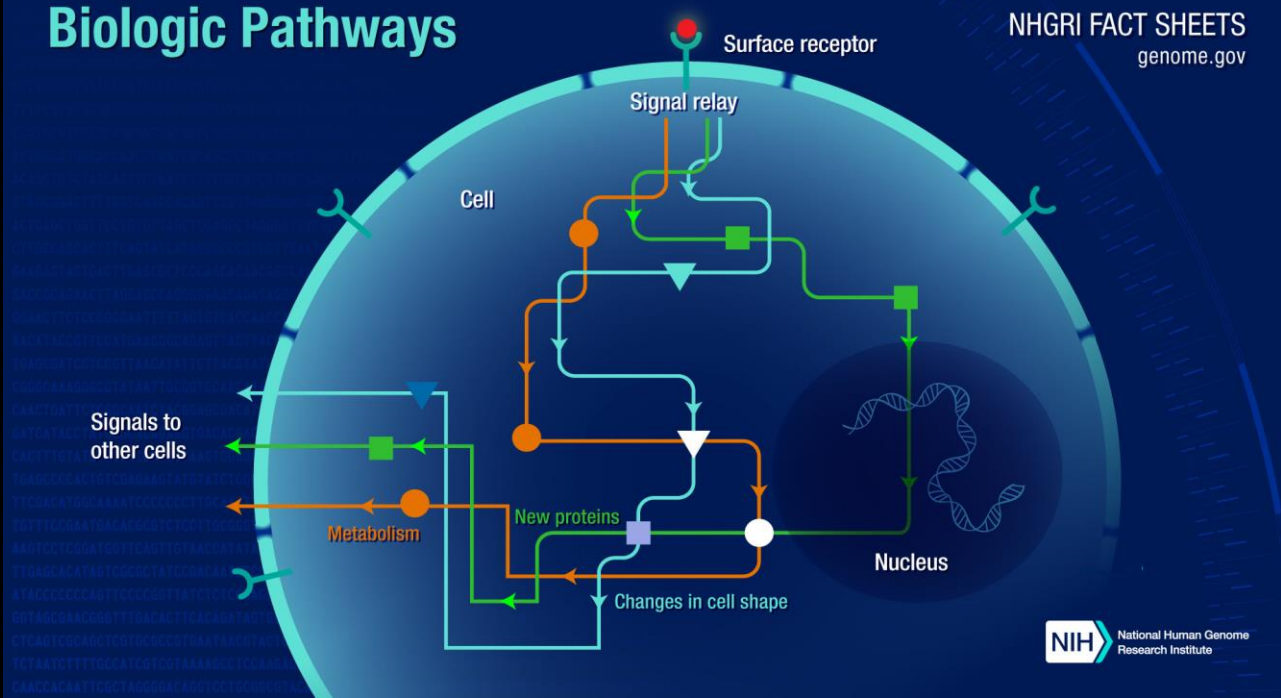
- Sensor State: **healthy** or **faulty**
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# Molecular Communications



[1] Jorge Torres Gómez, Joana Angjo and Falko Dressler, "Age of Information-based Performance of Ultrasonic Communication Channels for Nanosensor-to-Gateway Communication," IEEE Transactions on Molecular, Biological and Multi-Scale Communications, vol. 9 (2), pp. 112–123, June 2023.



Biochemical Pathways

[1] <https://www.genome.gov/about-genomics/fact-sheets/Biological-Pathways-Fact-Sheet>

[2][https://bionumbers.hms.harvard.edu/bionumber.aspx?id=104756&ver=1&trm=lif  
e+cycle+gene+regulation+homo+sapiens&org=](https://bionumbers.hms.harvard.edu/bionumber.aspx?id=104756&ver=1&trm=life+cycle+gene+regulation+homo+sapiens&org=)

[3][https://bionumbers.hms.harvard.edu/bionumber.aspx?id=106404&ver=2&trm=lif  
e+cycle+metabolism&org=](https://bionumbers.hms.harvard.edu/bionumber.aspx?id=106404&ver=2&trm=life+cycle+metabolism&org=)

[4] A. McMichael and P. Bowness, ‘HLA-B27: natural function and pathogenic role in spondyloarthritis’, Arthritis Res, vol. 4, no. Suppl 3, pp. S153–S158, 2002, doi: 10.1186/ar571.

Component	Lifecycle
Mitosis HeLa cells	1.10 hours [2]
Protein HLA-B27 [3]	4 hours [4]



# Human Microbiome

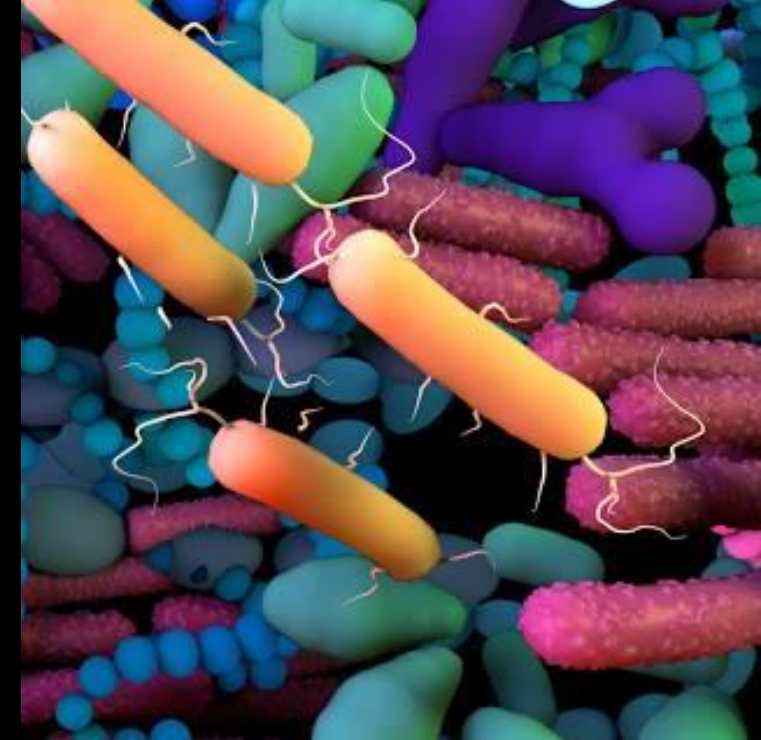
[1] <https://www.genome.gov/about-genomics/fact-sheets/Biological-Pathways-Fact-Sheet>

[2] <https://bionumbers.hms.harvard.edu/bionumber.aspx?id=104756&ver=1&trm=lifecycle+cycle+gene+regulation+homo+sapiens&org=>

[3] <https://bionumbers.hms.harvard.edu/bionumber.aspx?id=106404&ver=2&trm=lifecycle+cycle+metabolism&org=>

[4] A. McMichael and P. Bowness, 'HLA-B27: natural function and pathogenic role in spondyloarthritis', Arthritis Res, vol. 4, no. Suppl 3, pp. S153–S158, 2002, doi: 10.1186/ar571.

[5] I. F. Akyildiz, M. Ghovanloo, U. Guler, T. Ozkaya-Ahmadov, A. F. Sarioglu, and B. D. Unluturk, 'PANACEA: An Internet of Bio-NanoThings Application for Early Detection and Mitigation of Infectious Diseases', IEEE Access, pp. 1–1, 2020, doi: 10.1109/ACCESS.2020.3012139.



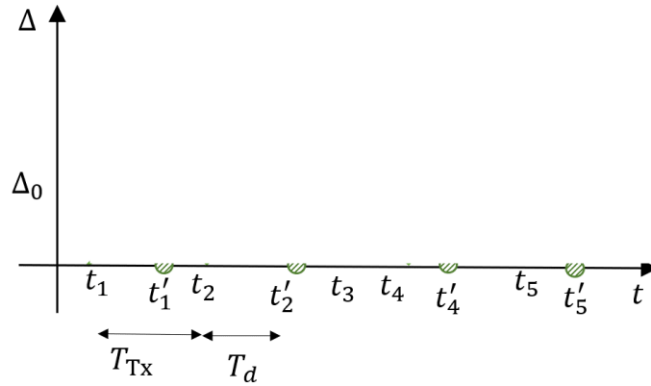
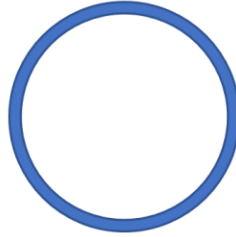
Component	Lifecycle
Mitosis HeLa cells	1.10 hours [2]
Protein HLA-B27 [3]	4 hours [4]
Bacteria P. Aeruginosa	1.5 – 2 hours [5]

# Molecular Communication Channels

Emitter



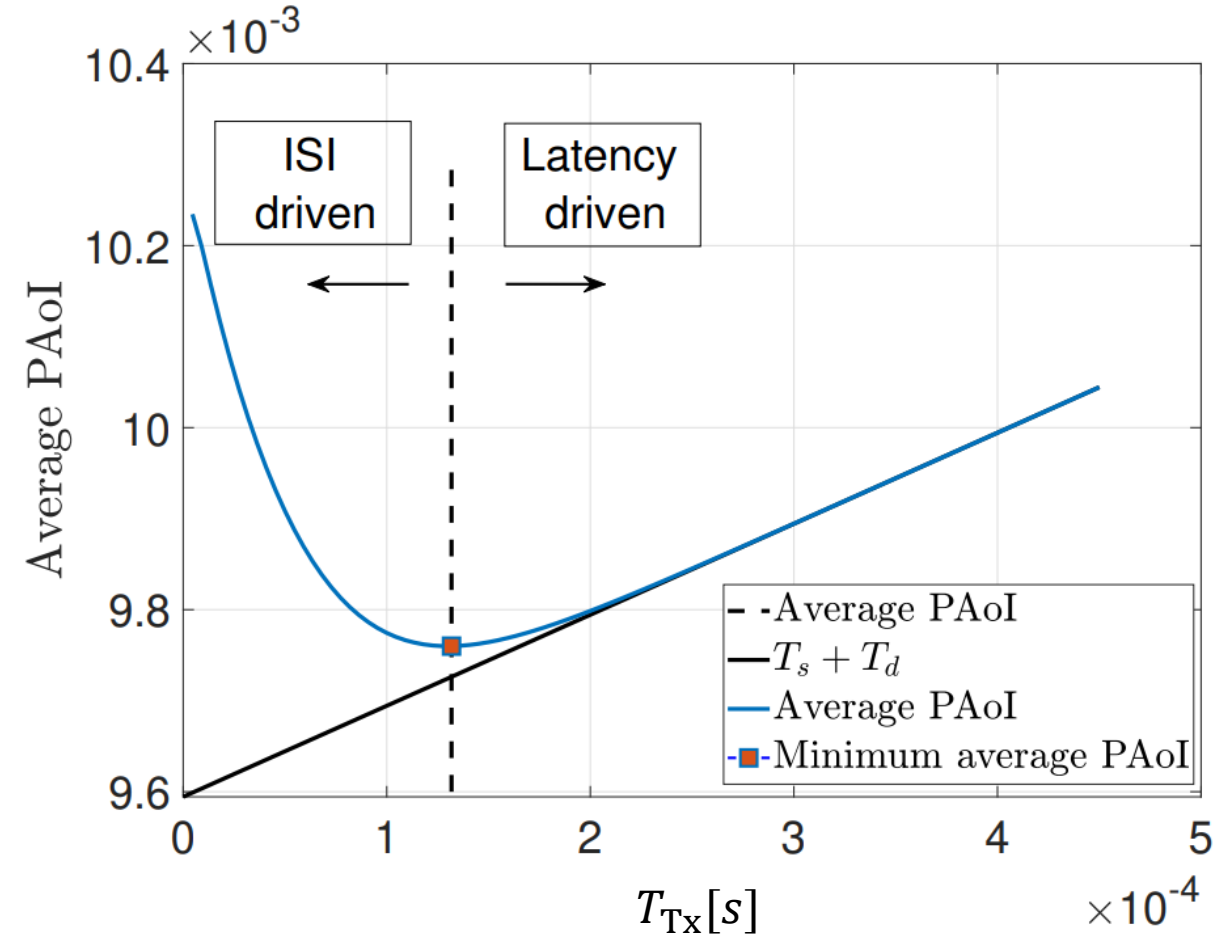
Receiver



Average PAoI

$$\Delta^{(p)} = \frac{1}{T} \sum_{i=1}^{N(t)} A_i = \mathbb{E}[T_{Tx}] + \mathbb{E}[T_d] \quad (1)$$

$$= T_{Tx} + \frac{1}{1 - p_e} \frac{d^2}{6D} \quad (2)$$





## Age of Information A New Concept, Metric, and Tool

Antzela Kosta, Nikolaos Pappas  
and Vangelis Angelakis

now  
the essence of knowledge



# A Perspective on Time Toward Wireless 6G

*This article provides a systematic treatment of various timing measures in wireless communication, setting the basis for design and optimization for the next-generation real-time systems.*

By PETAR POPOVSKI<sup>1</sup>, Fellow IEEE, FEDERICO CHIARIOTTI<sup>2</sup>, Member IEEE,  
KAIBIN HUANG<sup>3</sup>, Fellow IEEE, ANDERS E. KALØR<sup>4</sup>, Graduate Student Member IEEE,  
MARIOS KOUNTOURIS<sup>5</sup>, Senior Member IEEE, NIKOLAOS PAPPAS<sup>6</sup>, Senior Member IEEE,  
AND BEATRIZ SORET<sup>7</sup>, Member IEEE

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ComSoc  
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Digital Object Identifier 10.1109/OJCOMS.2024.3371871

## Toward Natively Intelligent Semantic Communications and Networking

STYLIANOS E. TREVLAKIS<sup>1</sup> (Member, IEEE), NIKOLAOS PAPPAS<sup>2</sup> (Senior Member, IEEE),  
AND ALEXANDROS-APOSTOLOS A. BOULOGEORGOS<sup>3</sup> (Senior Member, IEEE)

INTERNET OF THINGS AND SENSOR NETWORKS

# Semantics-Empowered Communication for Networked Intelligent Systems

Marios Kountouris and Nikolaos Pappas

IEEE Communications Magazine • June 2021

INTERNET OF THINGS AND SENSOR NETWORKS

# On the Role of Age of Information in the Internet of Things

Mohamed A. Abd-Elmagid, Nikolaos Pappas, and Harpreet S. Dhillon

IEEE Communications Magazine • December 2019

## Age of Information

Foundations and Applications

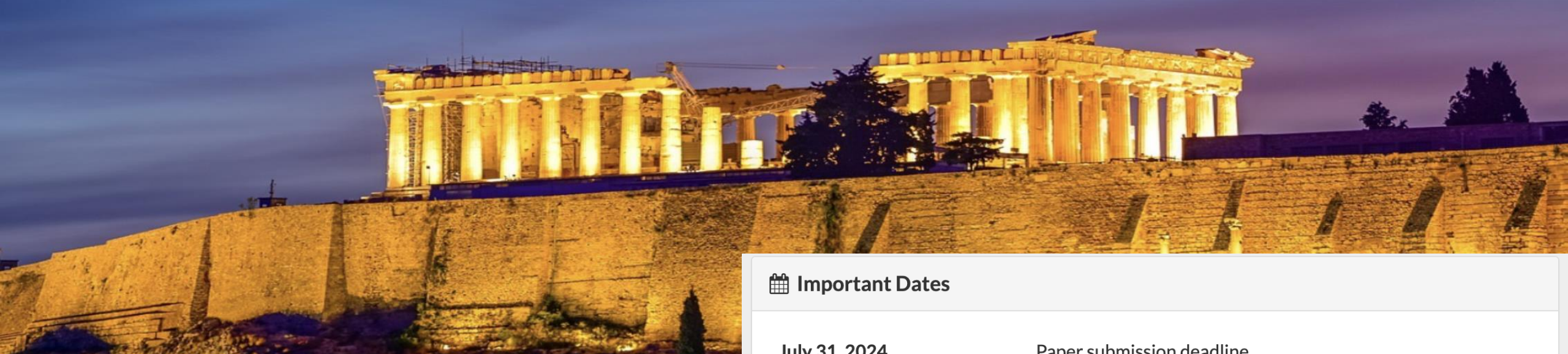
Edited by Nikolaos Pappas,  
Mohamed A. Abd-Elmagid, Bo Zhou,  
Walid Saad and Harpreet S. Dhillon



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# ACM MOBIHOC 2024<sup>27</sup>

OCT 14-17, 2024, Athens, Greece



## General Chairs

- [Nikolaos Pappas](#), Linköping University, Sweden
- [Yin Sun](#), Auburn University, Alabama, USA
- [Anthony Ephremides](#), University of Maryland, College Park, USA

### Important Dates

July 31, 2024	Paper submission deadline
August 20, 2024	Notification of acceptance
August 30, 2024	Camera-ready version
October 14, 2024	Workshop event

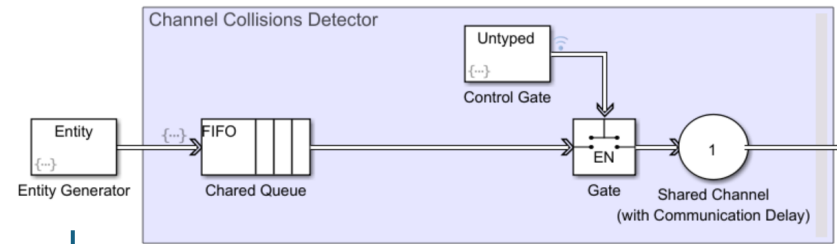
Part II  MATLAB®

# Implementing Aol-related metrics in wireless links

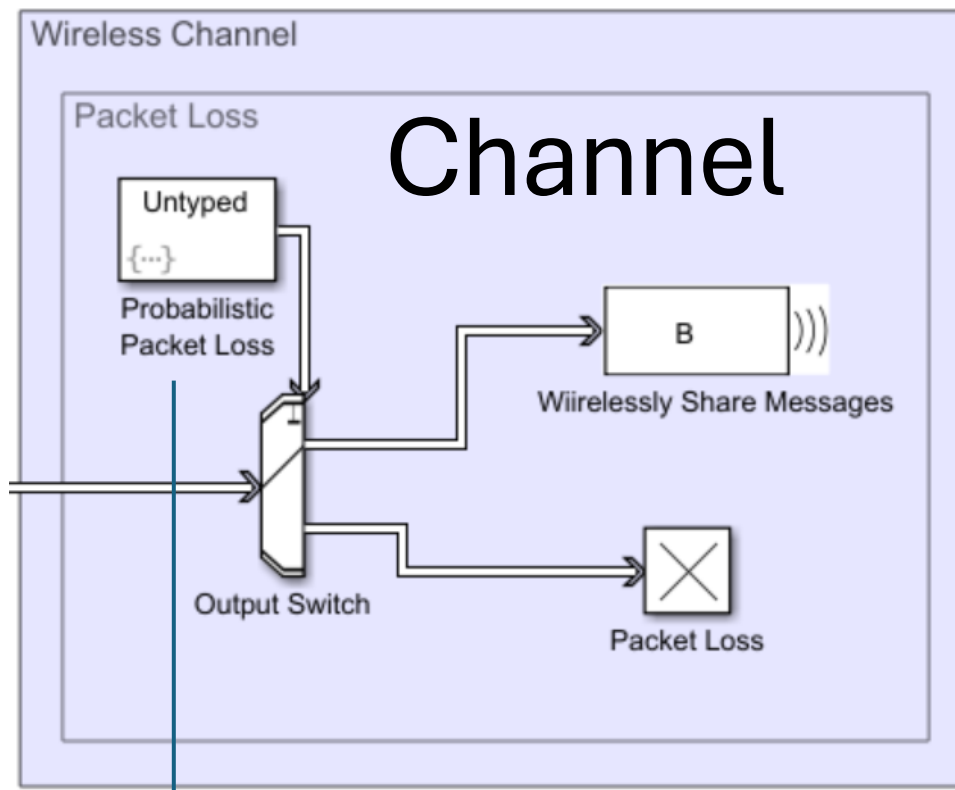
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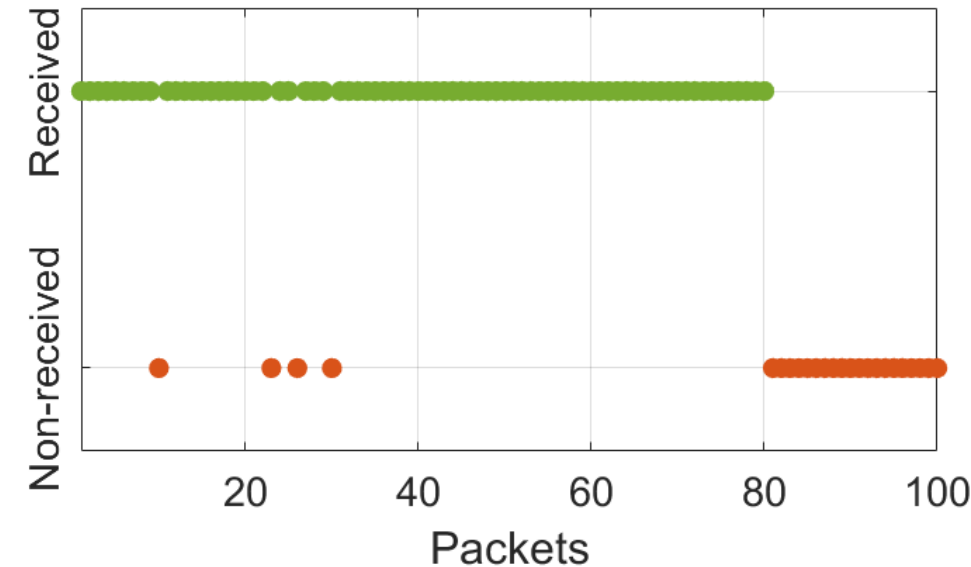
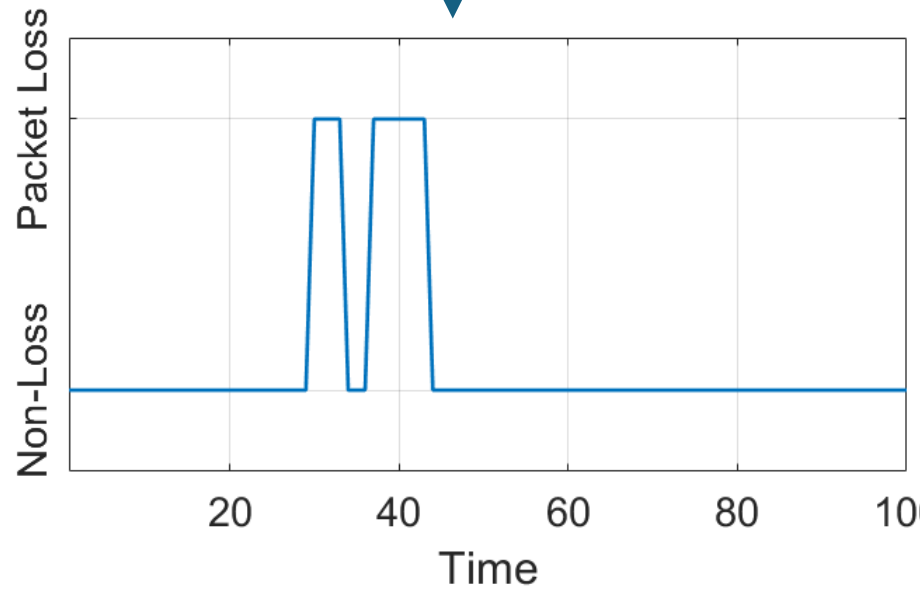
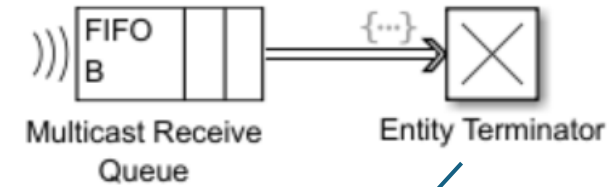
# Transmitter



Attribute	Value
Text	Aol Workshop
MessageID	{1,2,3,...,N}
Generation	{1,2,3,...,N}



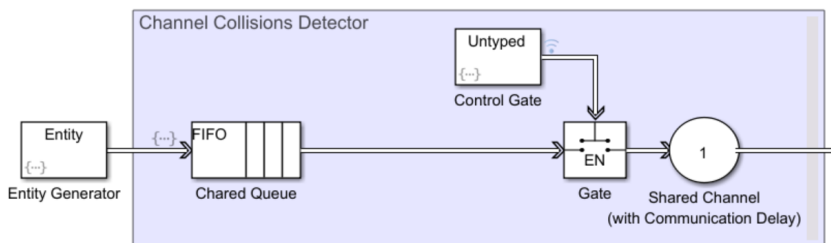
# Receiver



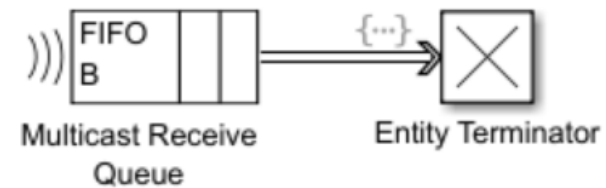
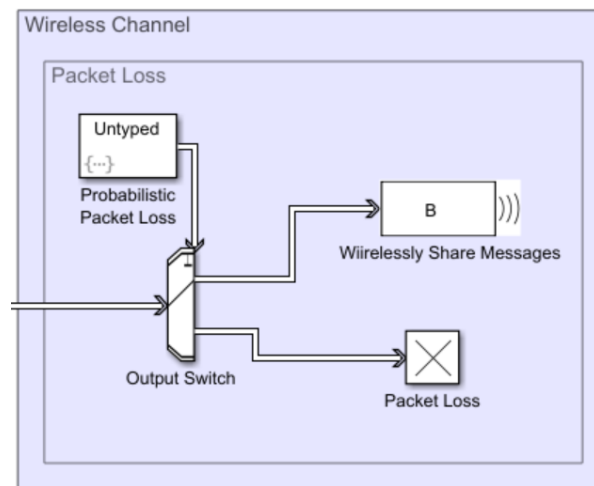




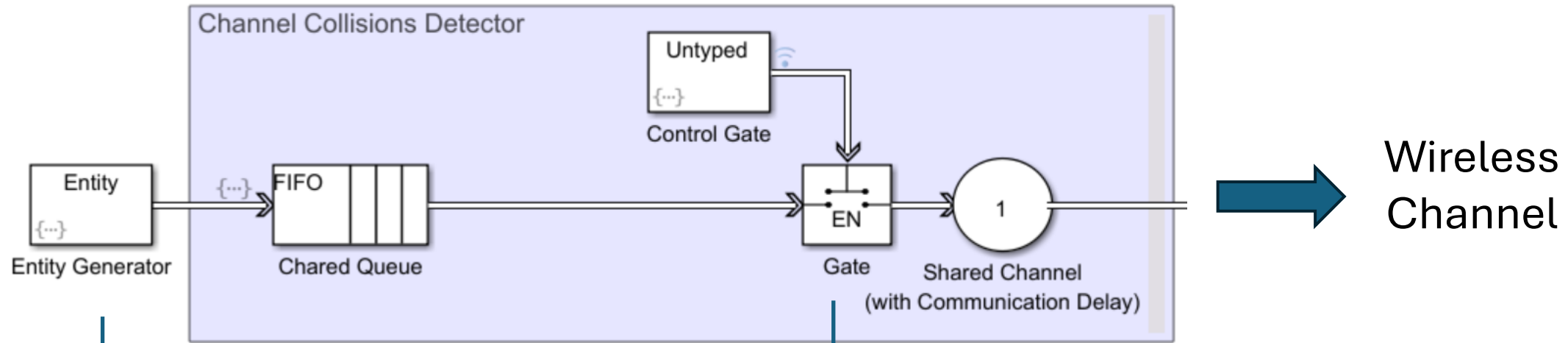
GitHub Repo



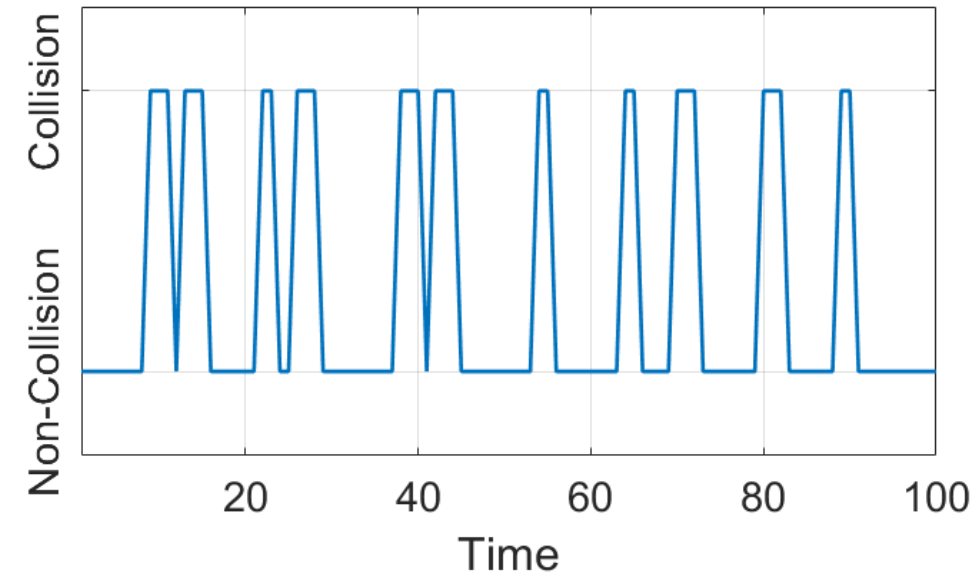
Matlab Access



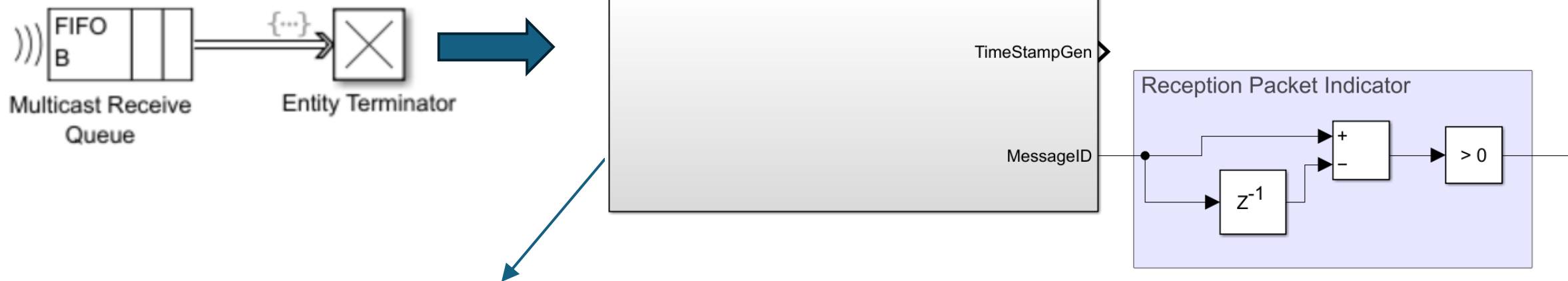
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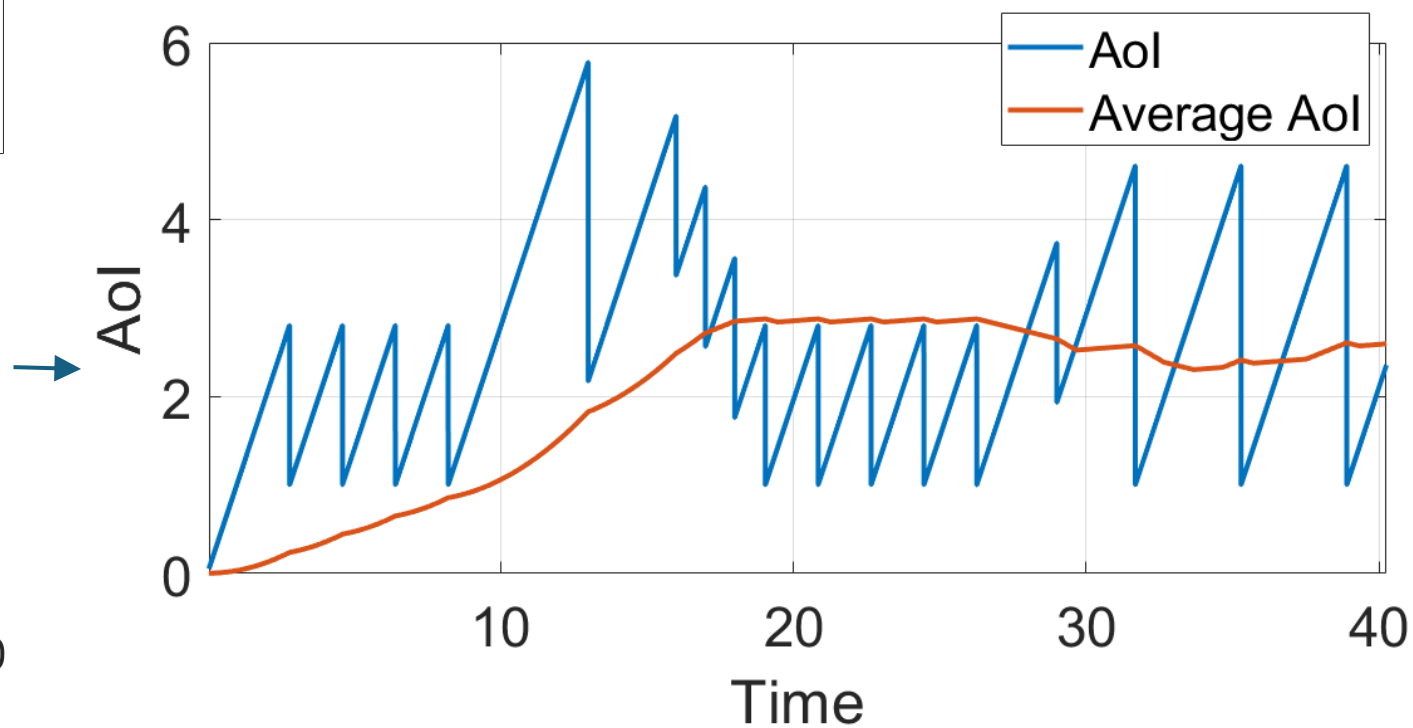
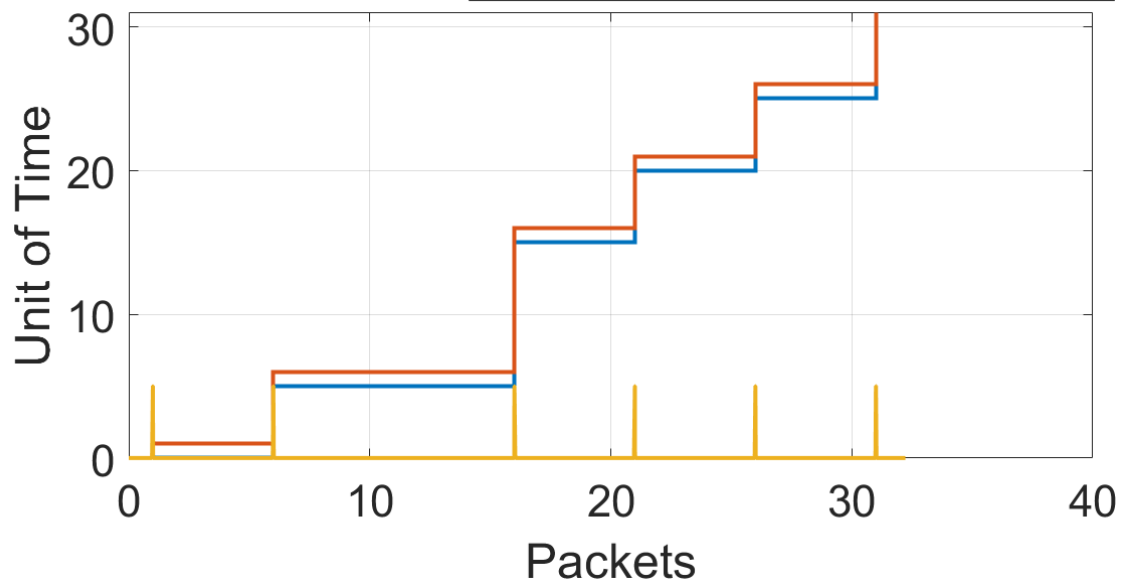
Attribute	Value
Text	Aol Workshop
MessageID	{1,2,3,....,total_packets}
TimeStampGenerati on	{1,2,3,....,total_packets}



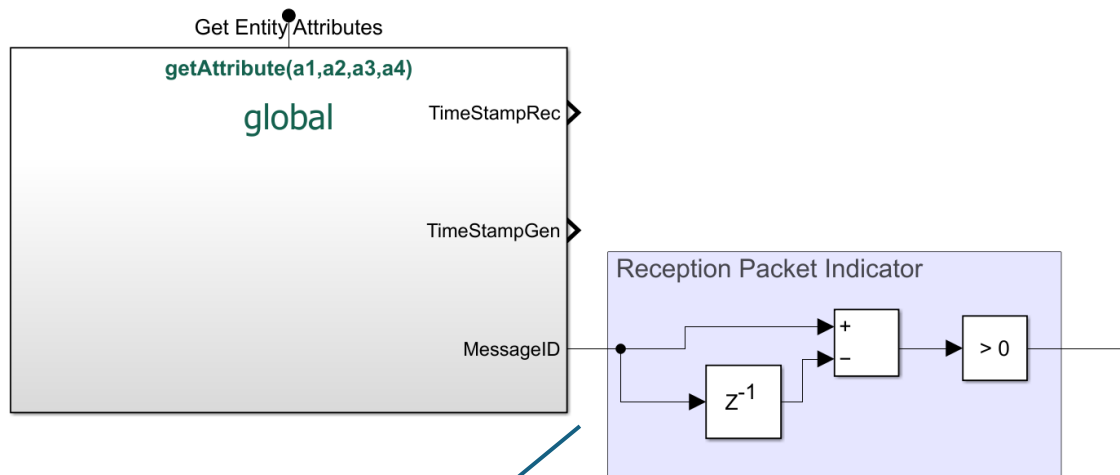
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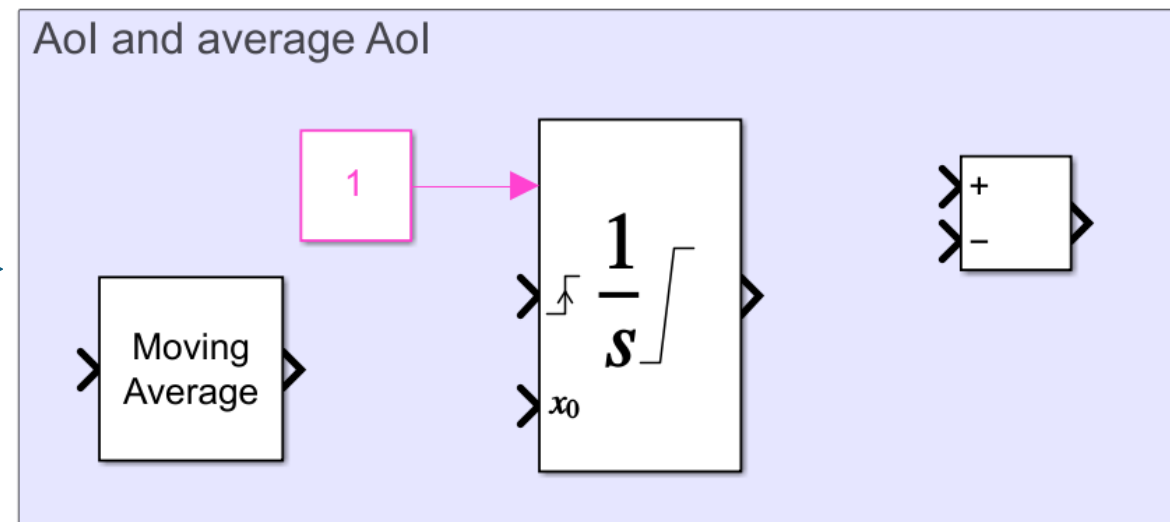
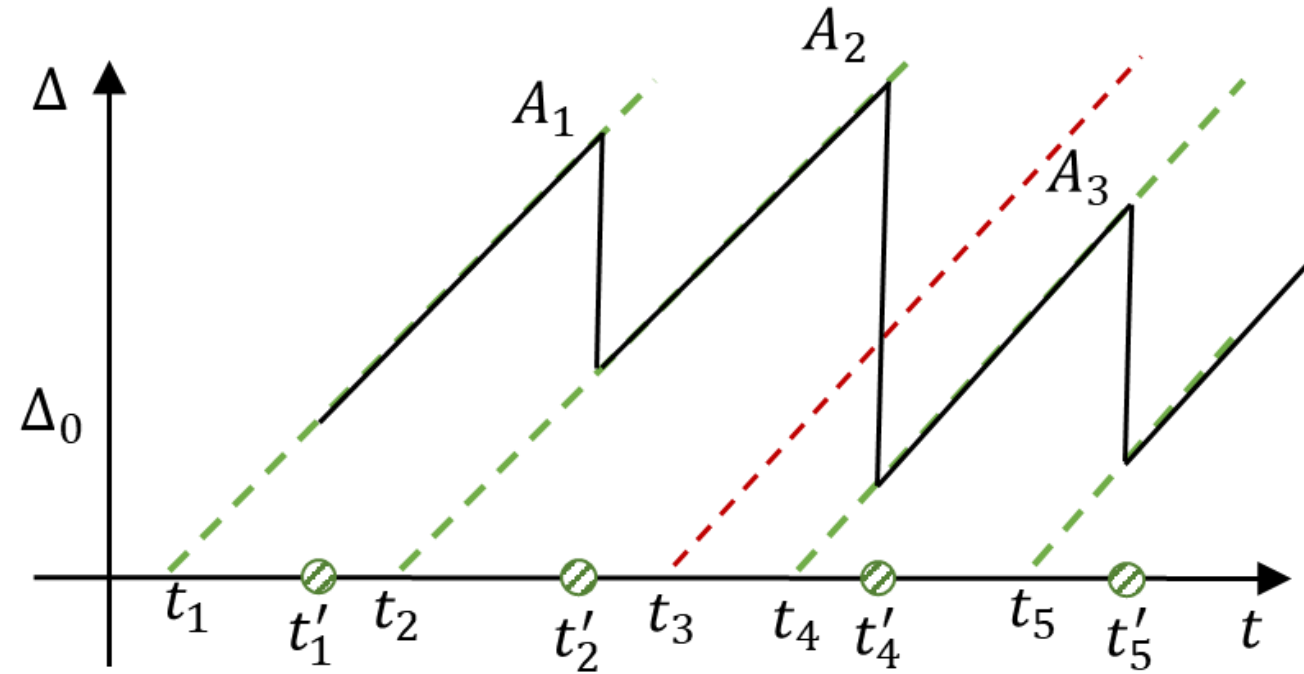
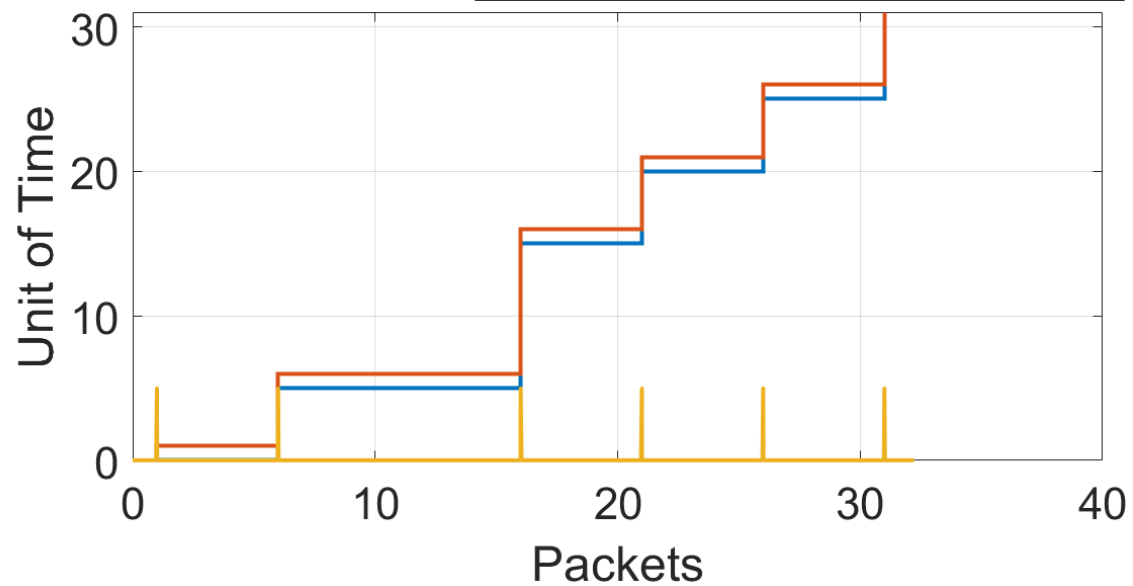
— Transmitted Packet Time Stamp  
 — Received Packet Time Stamp  
 — Reception Indicator



# Receiver

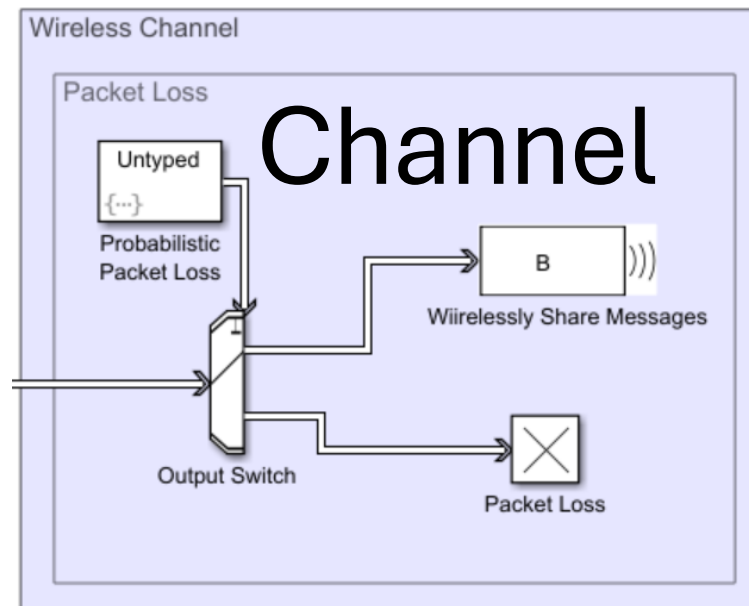
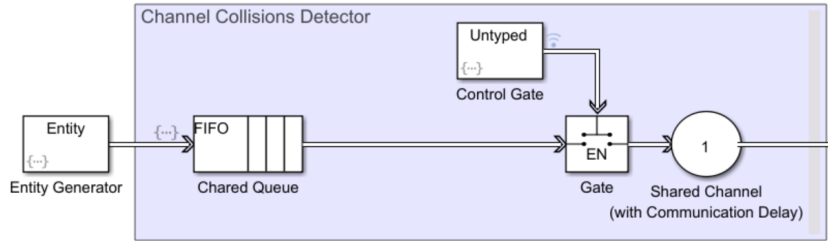


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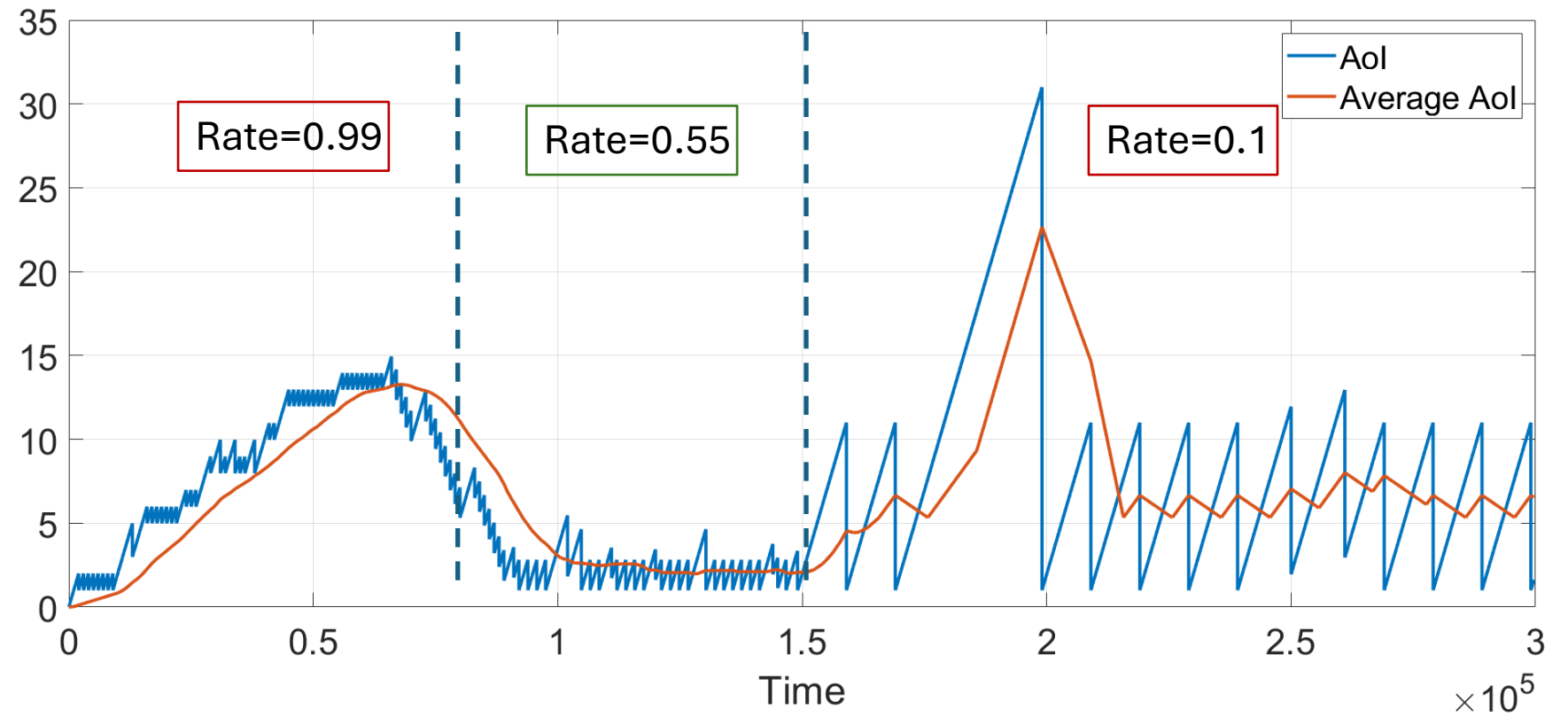
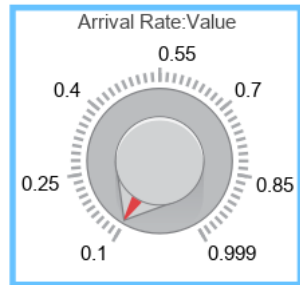
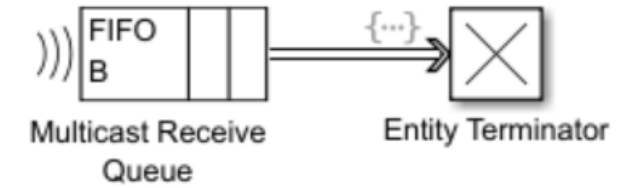




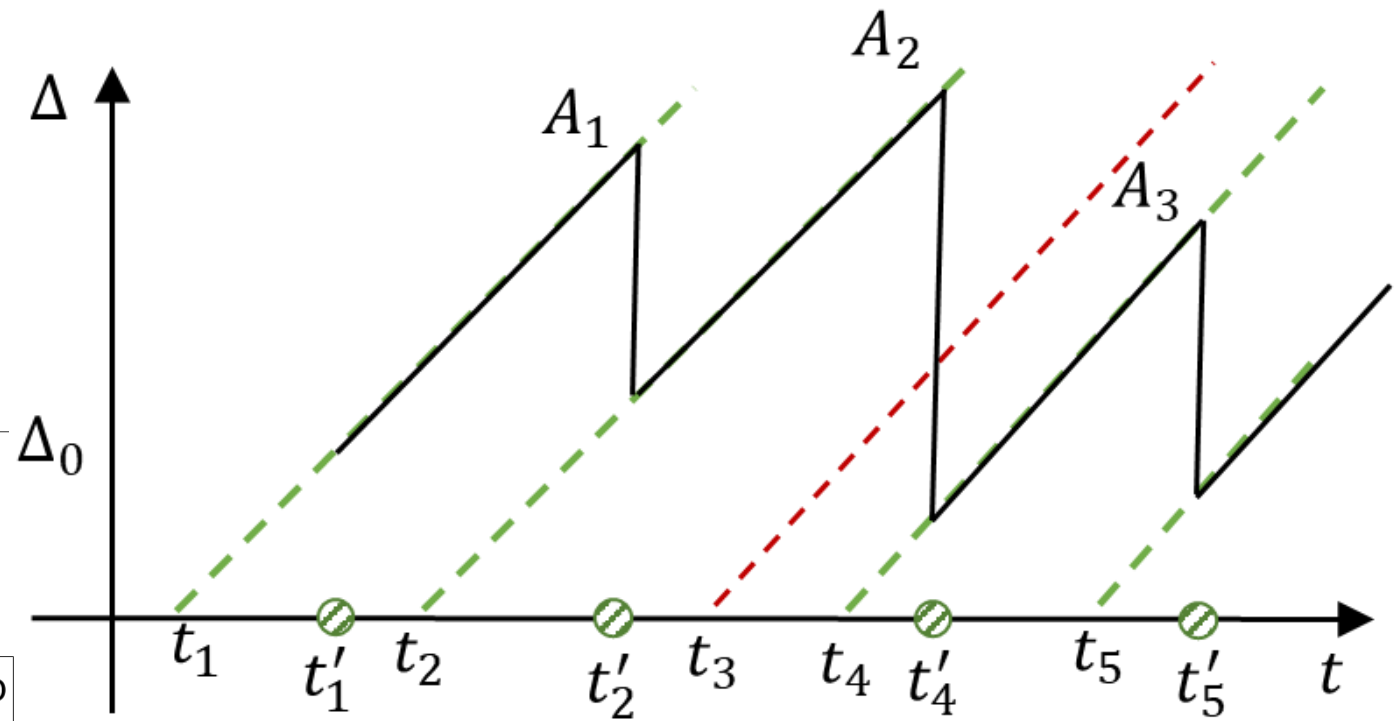
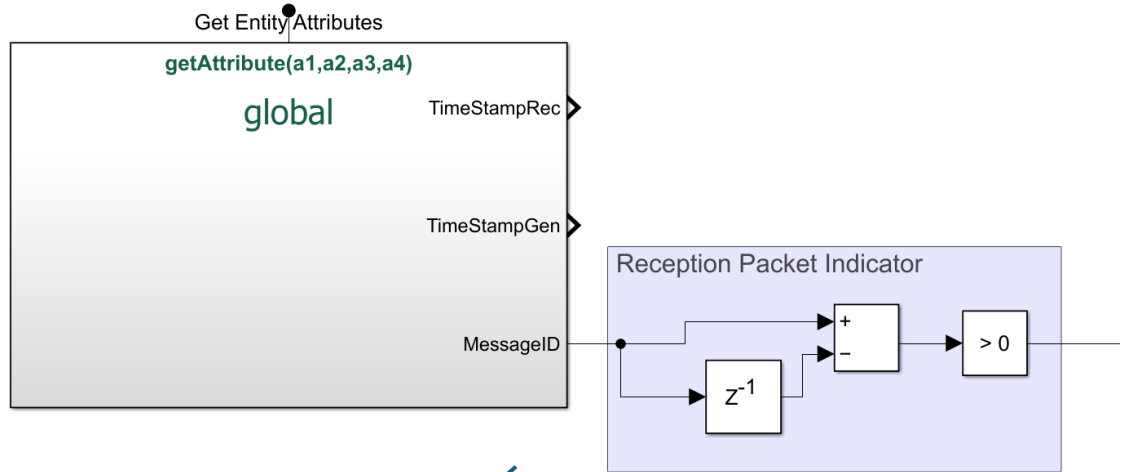
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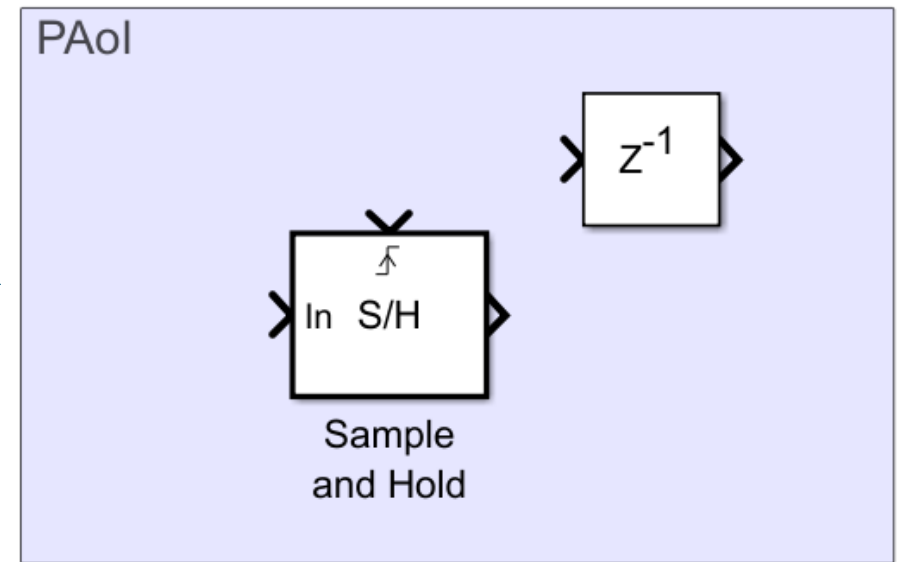
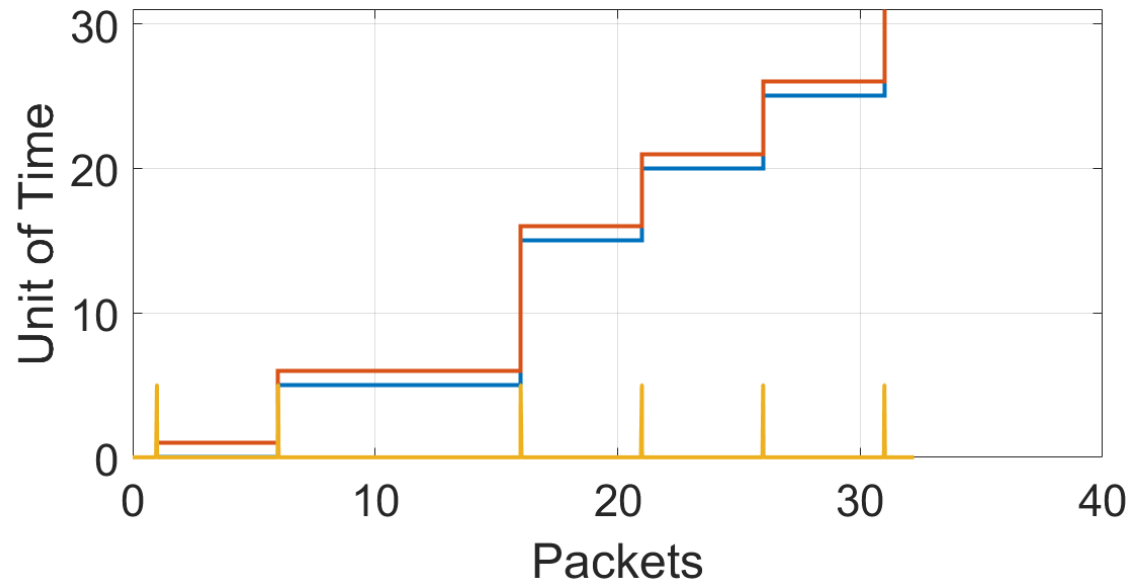
# Receiver



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 — Received Packet Time Stamp  
 — Reception Indicator



# Recommended readings

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# AGE OF INFORMATION (AOI) A TOOL FOR DESIGNING TIME-CRITICAL NETWORKS

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