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

Jorge Torres Gómez, TU Berlin
Nikolaos Pappas, Linköping University
July, 2024

Telecommunication Networks Group

Outline

- **Part I: Fundamentals**
- Introduction
- Definition of Age of Information
- Age of Information Metrics
- Goal-oriented communications

- **Part II: Hands-on in Wireless Channels**
- AoI calculation
- Average AoI
- Average PAoI

Introduction

Case 1

Generation Time > Packet delay

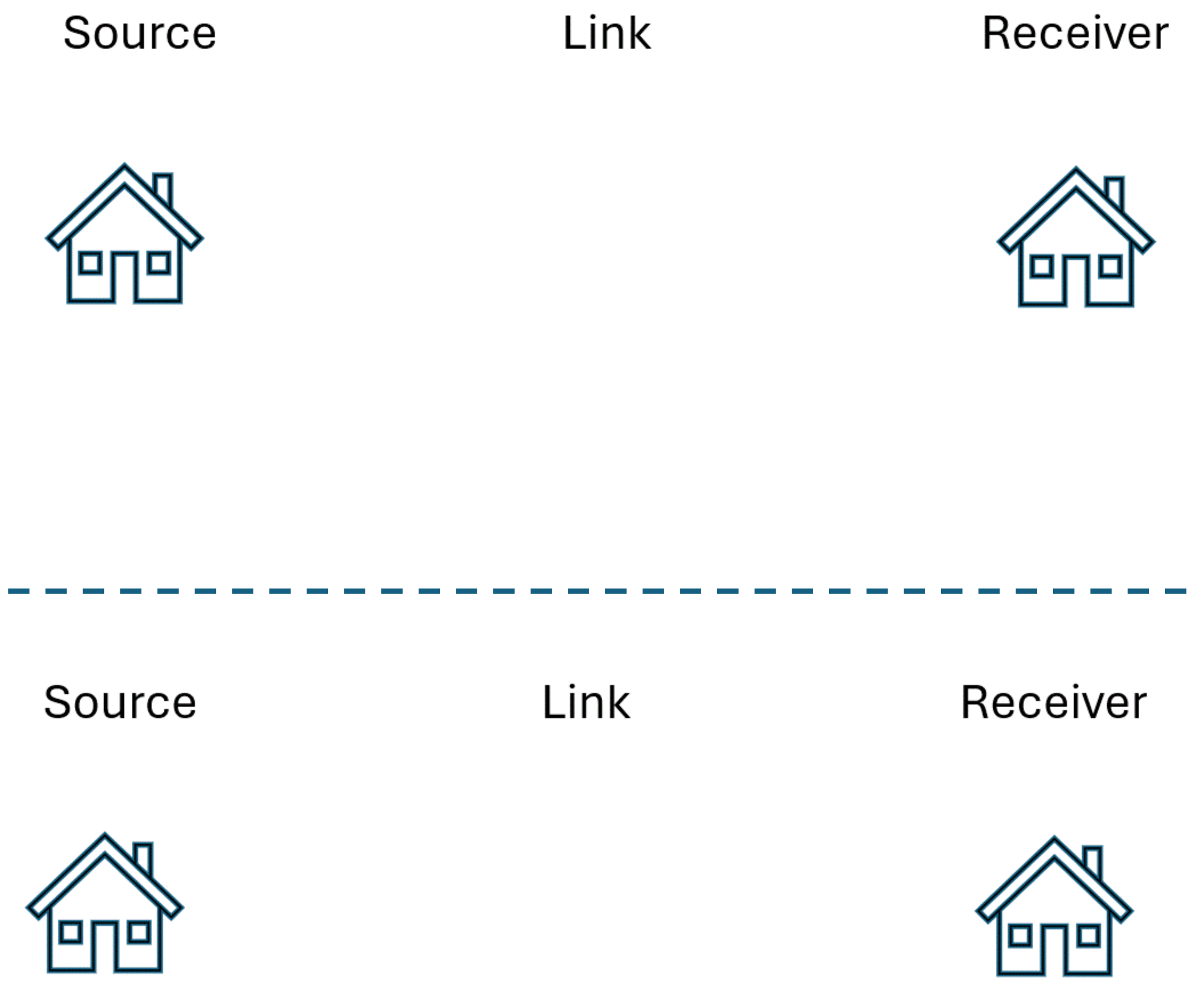
Case 2

Generation Time < Packet delay

Introduction

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

Information Freshness



Information Freshness

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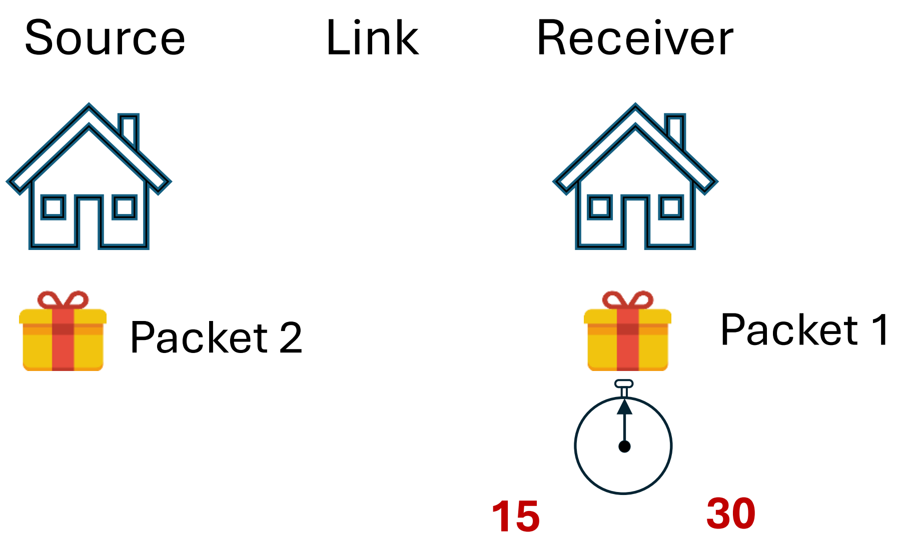
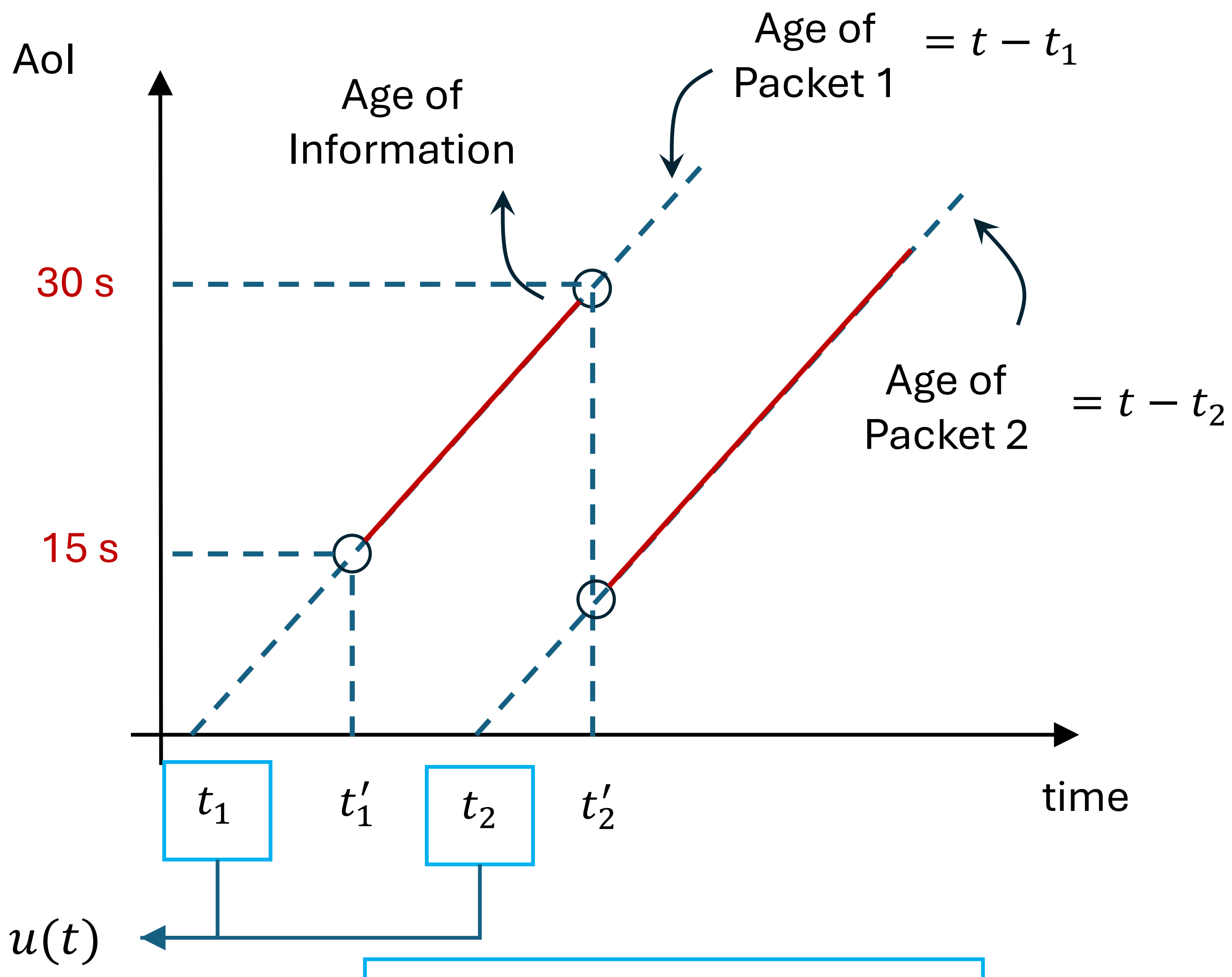
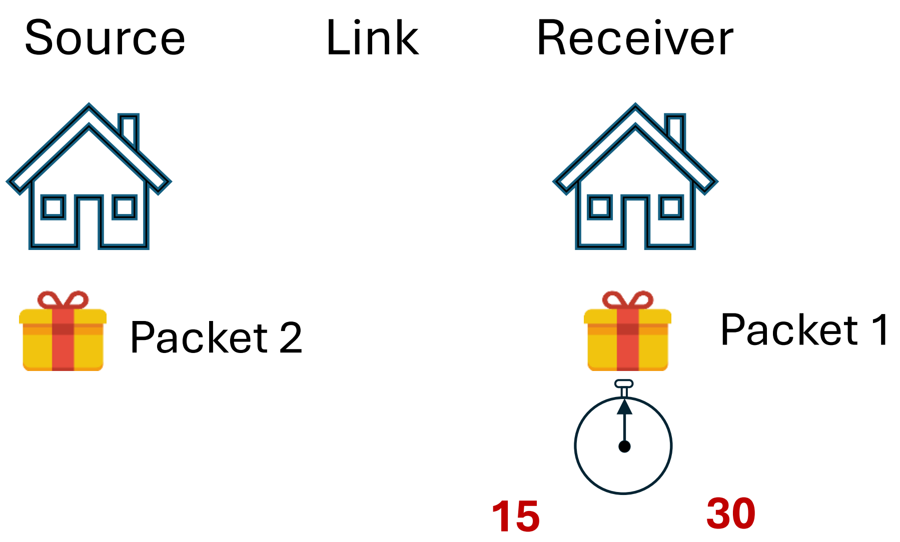




Definition

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

Information Freshness



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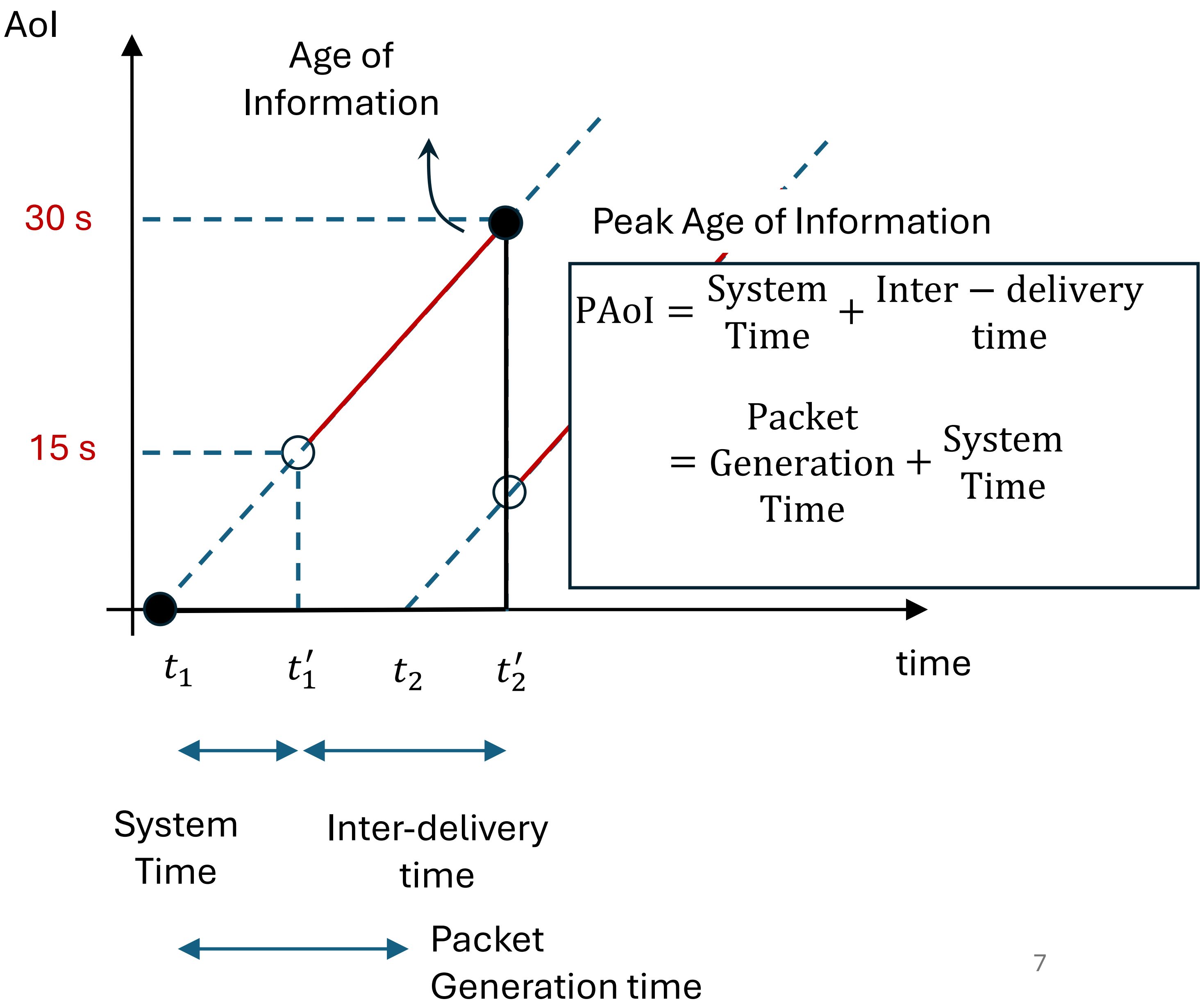
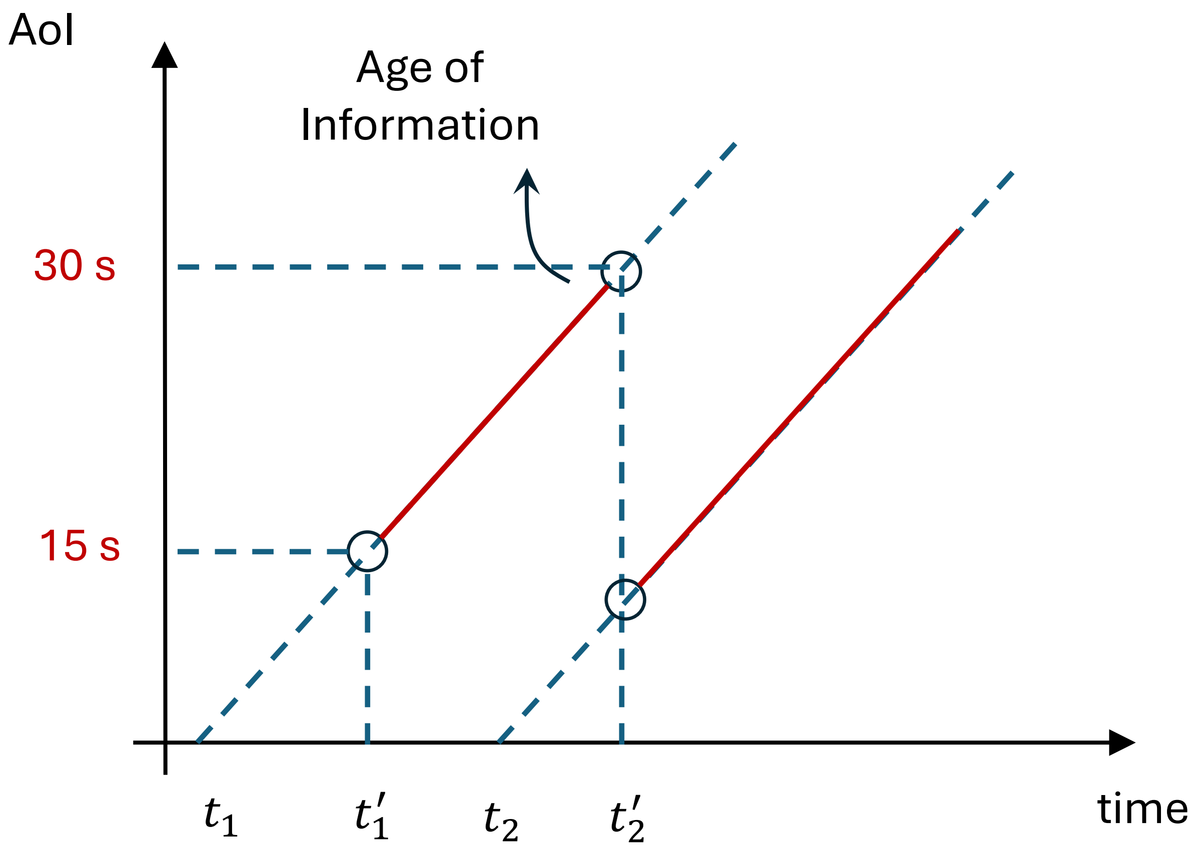


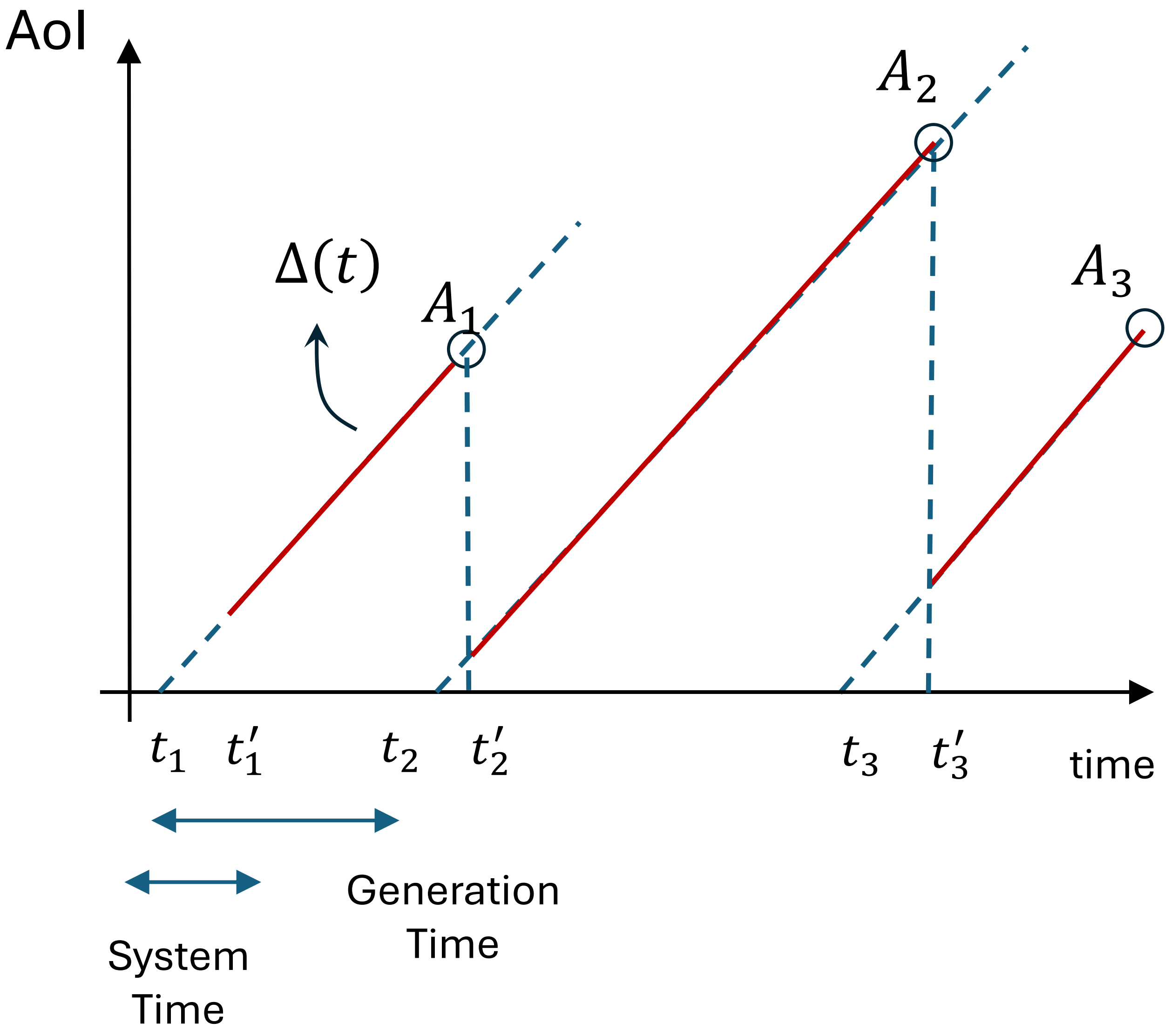
Information Freshness

Remarks

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



AoI metrics



Average AoI

$$\Delta = \lim_{T\to\infty} \int_0^T \Delta(t)\, dt \qquad (1)$$

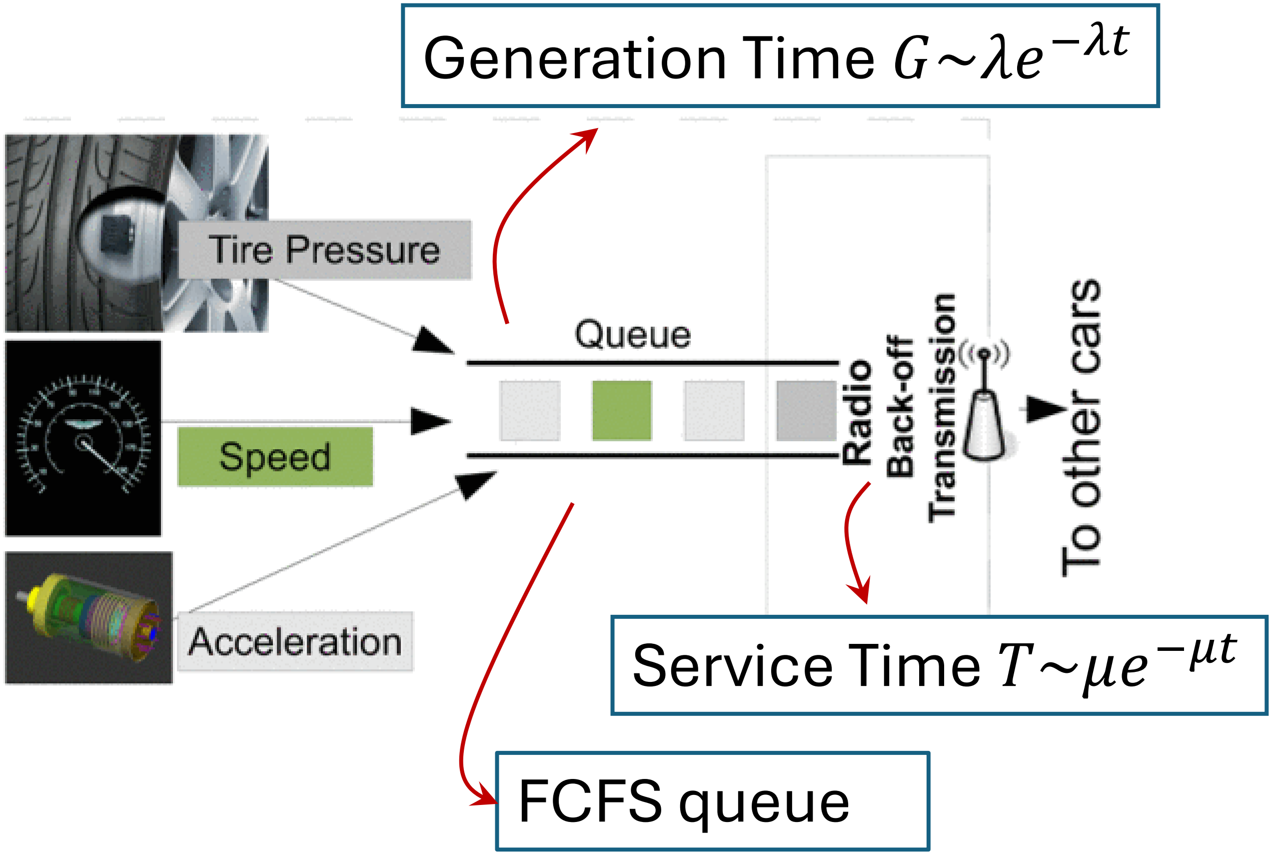
$$= \lambda\left(\mathrm{E}[GT] + \frac{\mathrm{E}[G^2]}{2}\right),\ \lambda = \lim_{T\to\infty} \frac{N(T)}{T}$$

Average PAoI

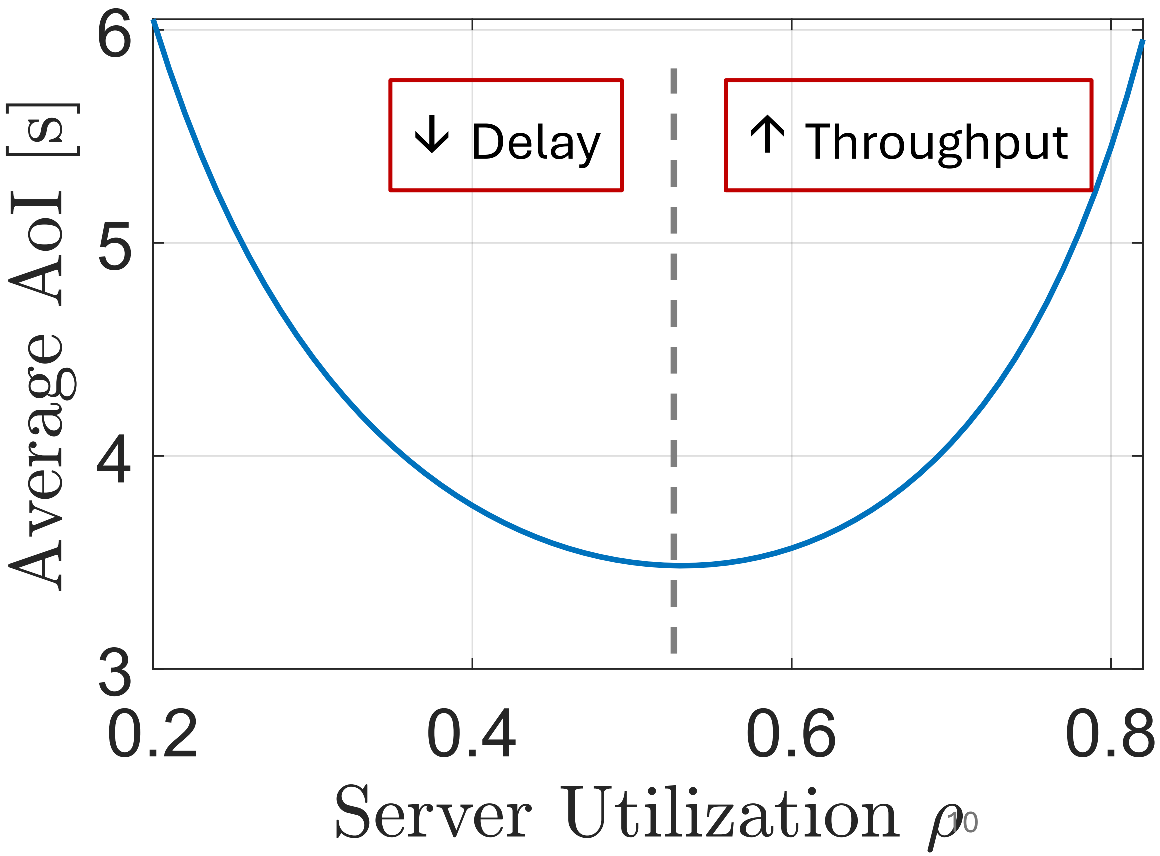
$$\Delta^{(p)} = \mathrm{E}[A_i] \qquad (2)$$

$$= \mathrm{E}[G] + \mathrm{E}[T]$$

Average AoI metric: FCFS queue

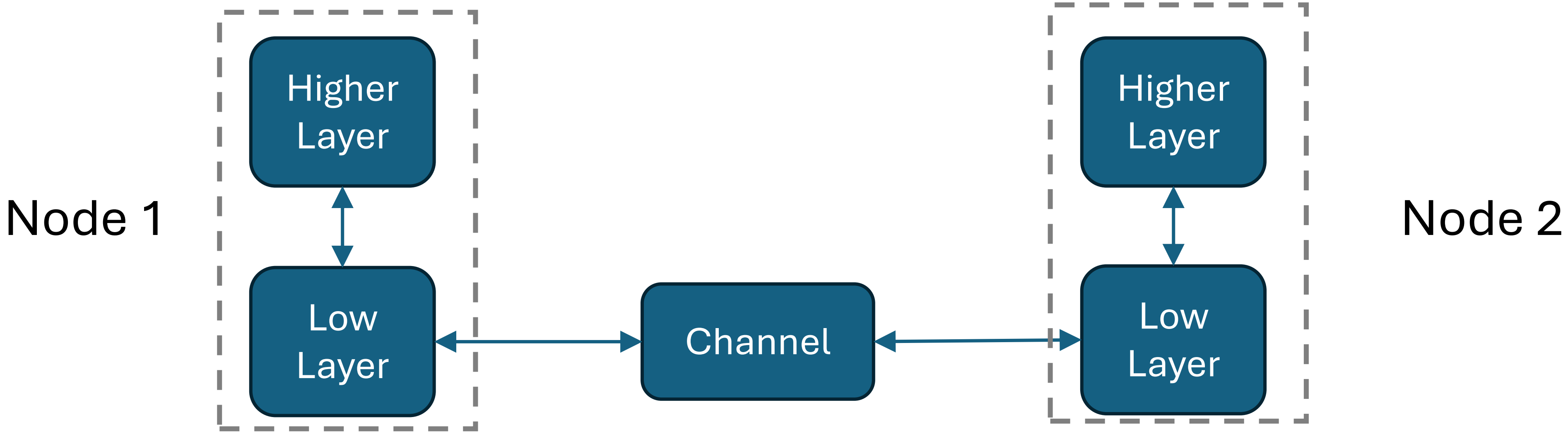


$$\Delta = \frac{1}{\mu}\left(1 + \frac{1}{\rho} + \frac{\rho^2}{1-\rho}\right) \quad , \rho = \frac{\lambda}{\mu} \qquad (1)$$



S. Kaul, R. Yates and M. Gruteser, "Real-time status: How often should one update?," 2012 Proceedings IEEE INFOCOM, Orlando, FL, USA, 2012, pp. 2731-2735.

Remarks on the AoI metrics



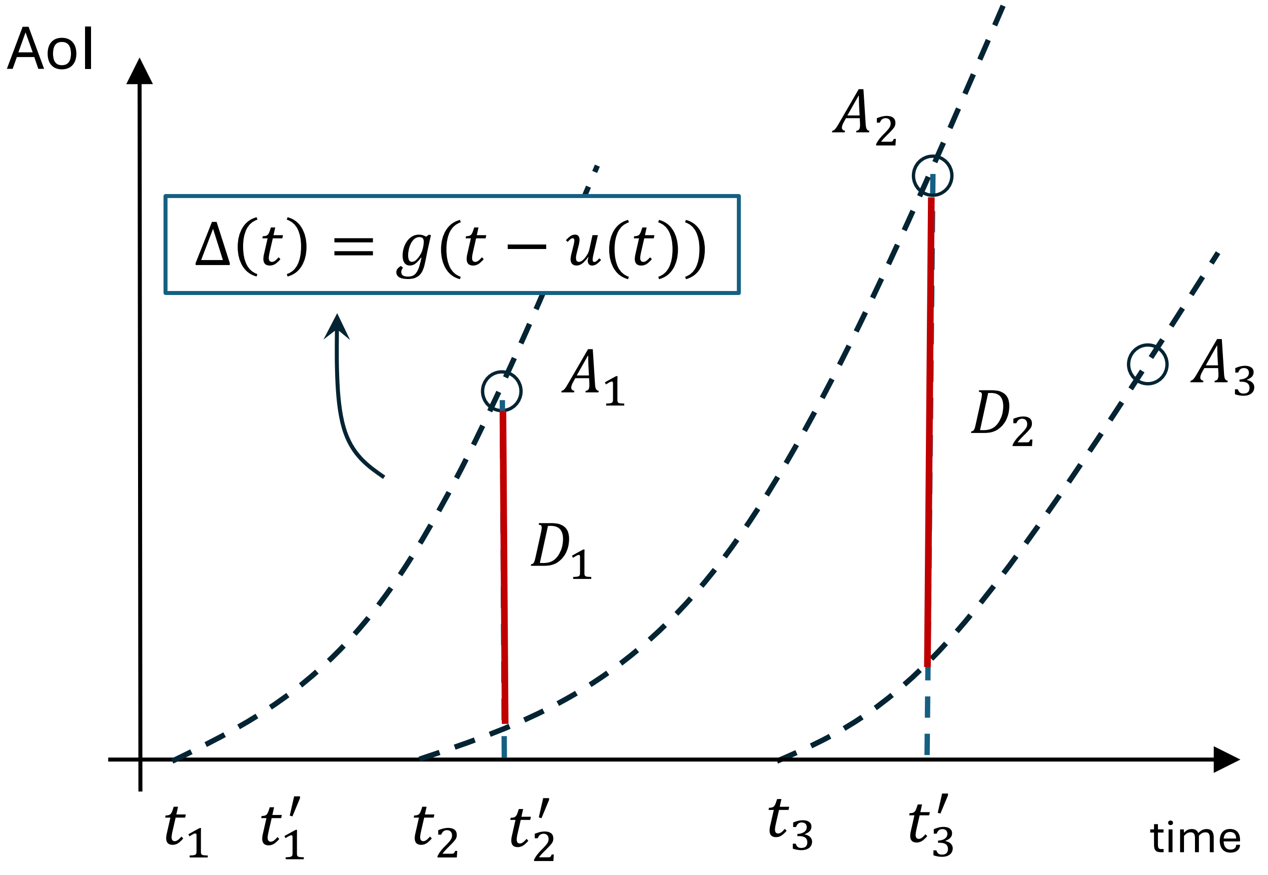
Statistical Framework

- 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 AoI-metrics



- Cost of Update Delay

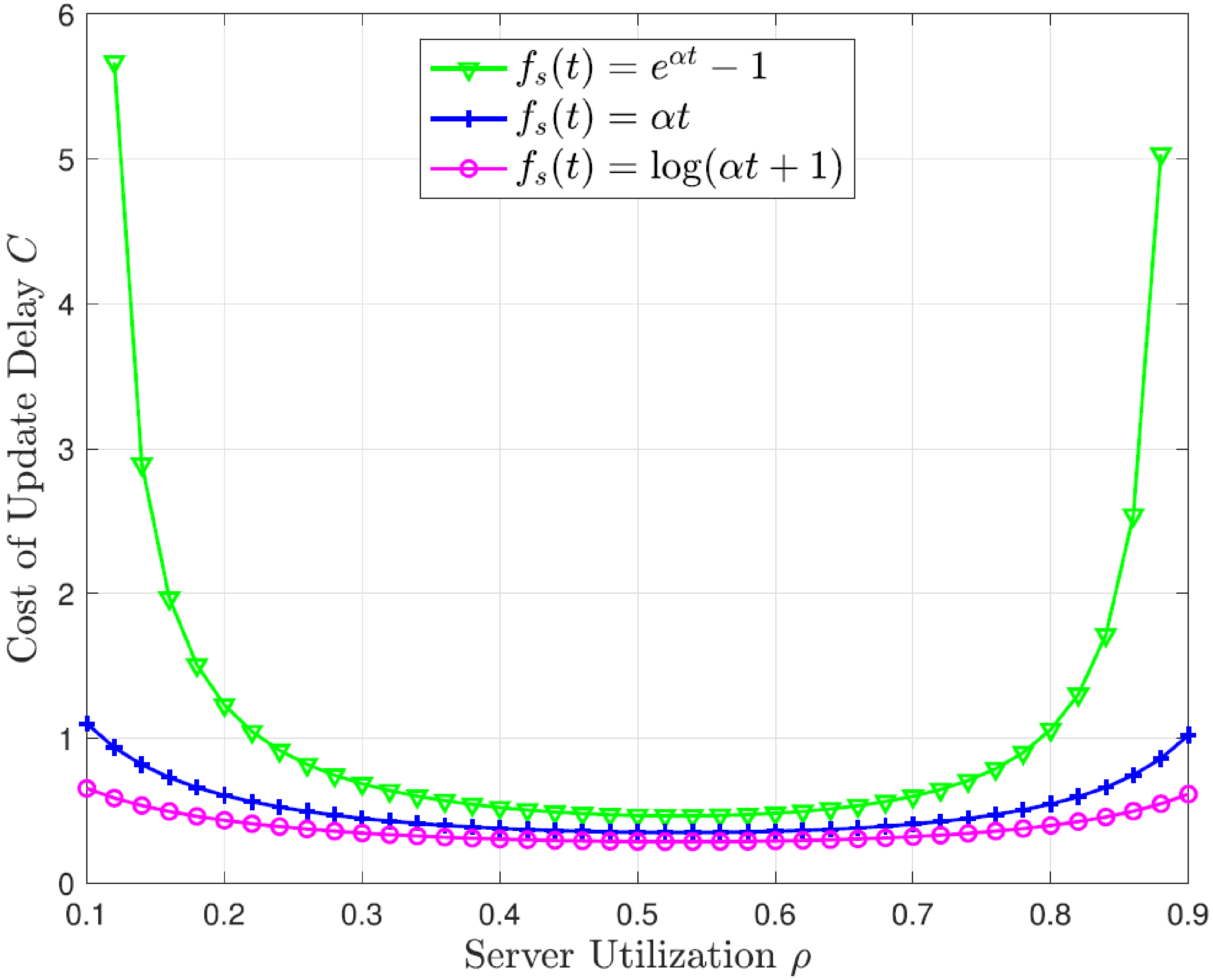
$$g(t) = \begin{cases} \alpha t \\ e^{\alpha t} - 1 \\ \log(\alpha t + 1) \end{cases}$$

- Value of Information Update

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

[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 AoI-metrics



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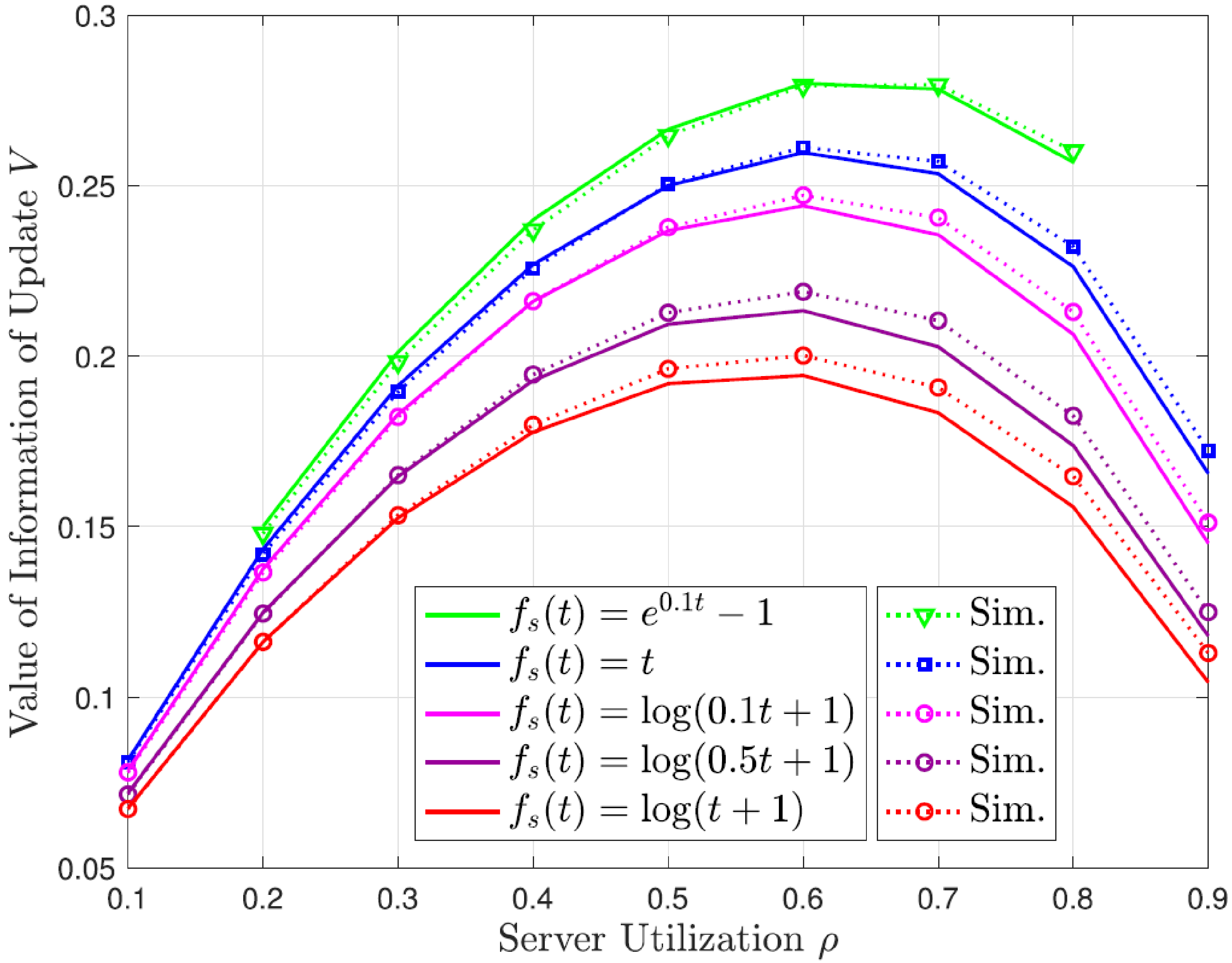

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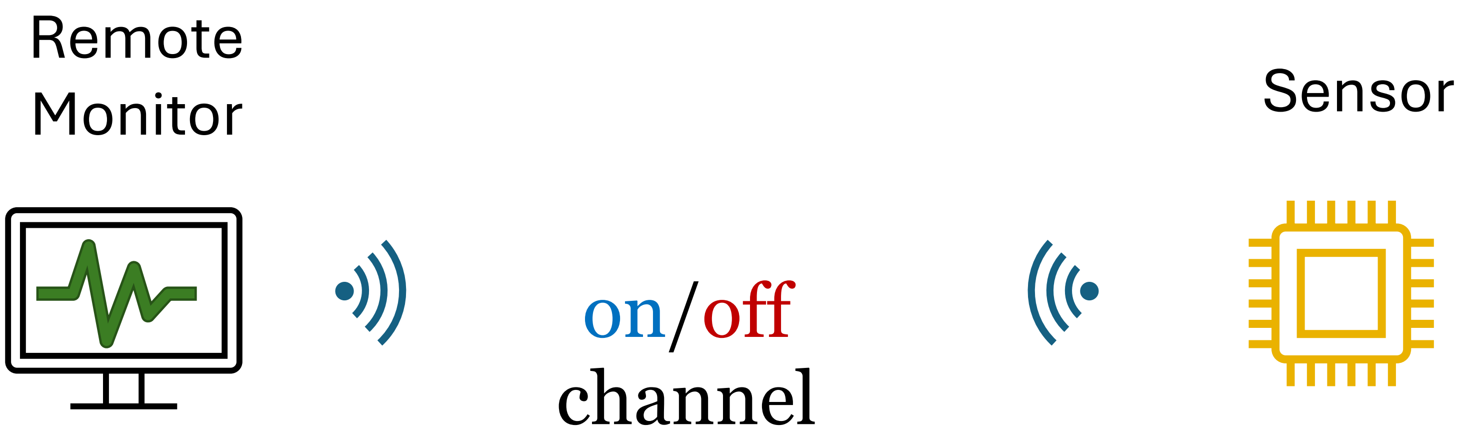
Goal Oriented Communications

- 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



- 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.

G. Stamatakis, N. Pappas, A. Fragkiadakis, N. Petroulakis, A. Traganitis, “Semantics-Aware Active Fault Detection in Status Updating Systems", IEEE Open Journal of Communications Society, vol. 5, Feb. 2024.

Fault Detection and autonomous maintenance

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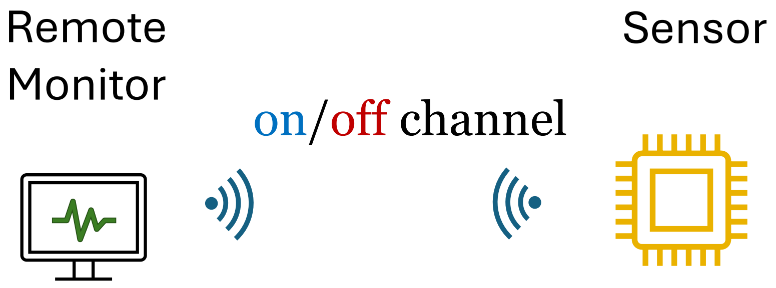

- Pull-based communication model

- Sensor State: healthy or faulty
- Slotted time

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.

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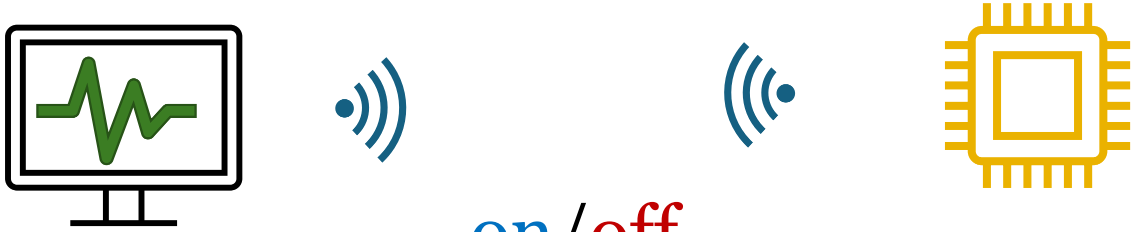
Fault Detection and autonomous maintenance

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

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

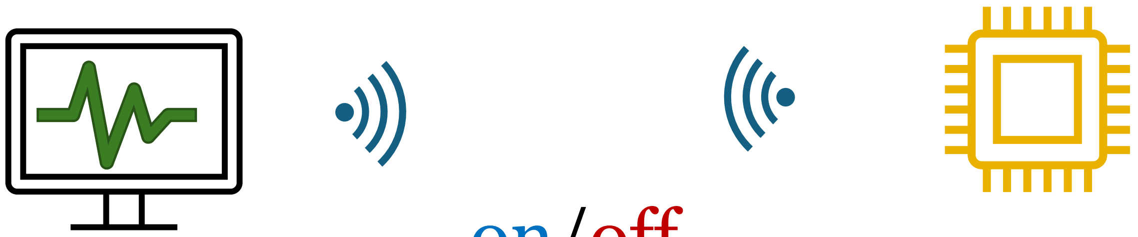
Transition cost

$$g = c + V$$

Fault Detection and autonomous maintenance

Remote Monitor

Sensor



on/off channel

- Sensor State: healthy or faulty
- Slotted time

Dynamic program

Probability of Observations

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

Transition cost

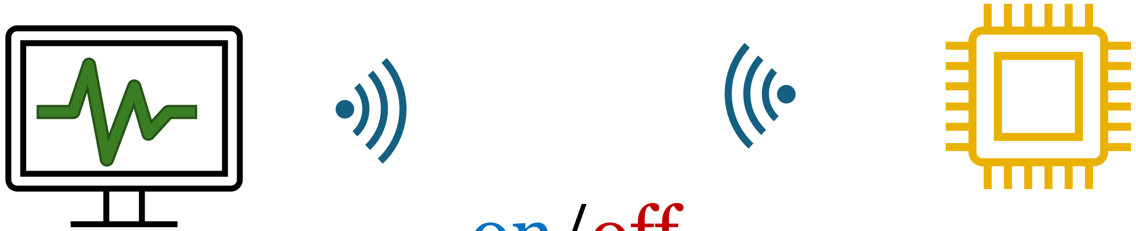
Observations

Actions

Fault Detection and autonomous maintenance

Remote Monitor

Sensor



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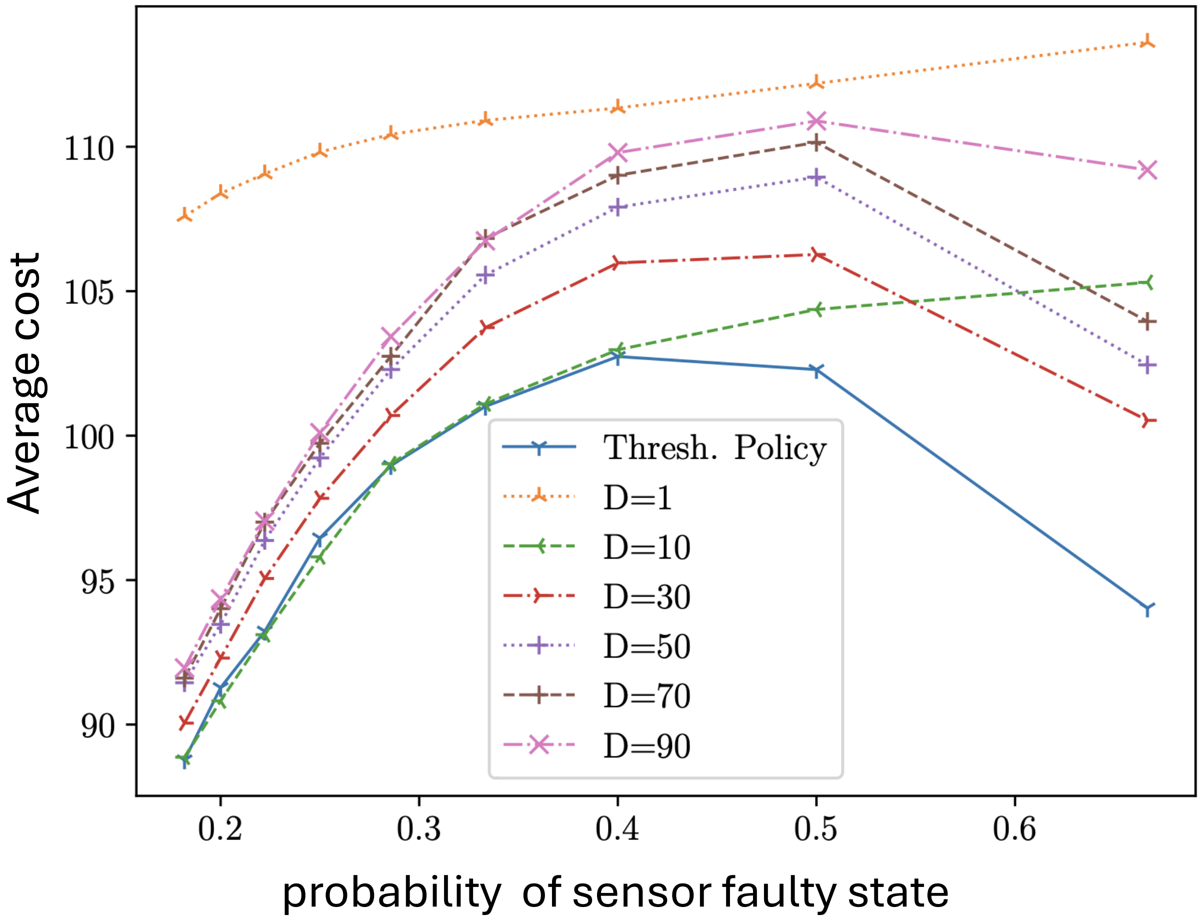
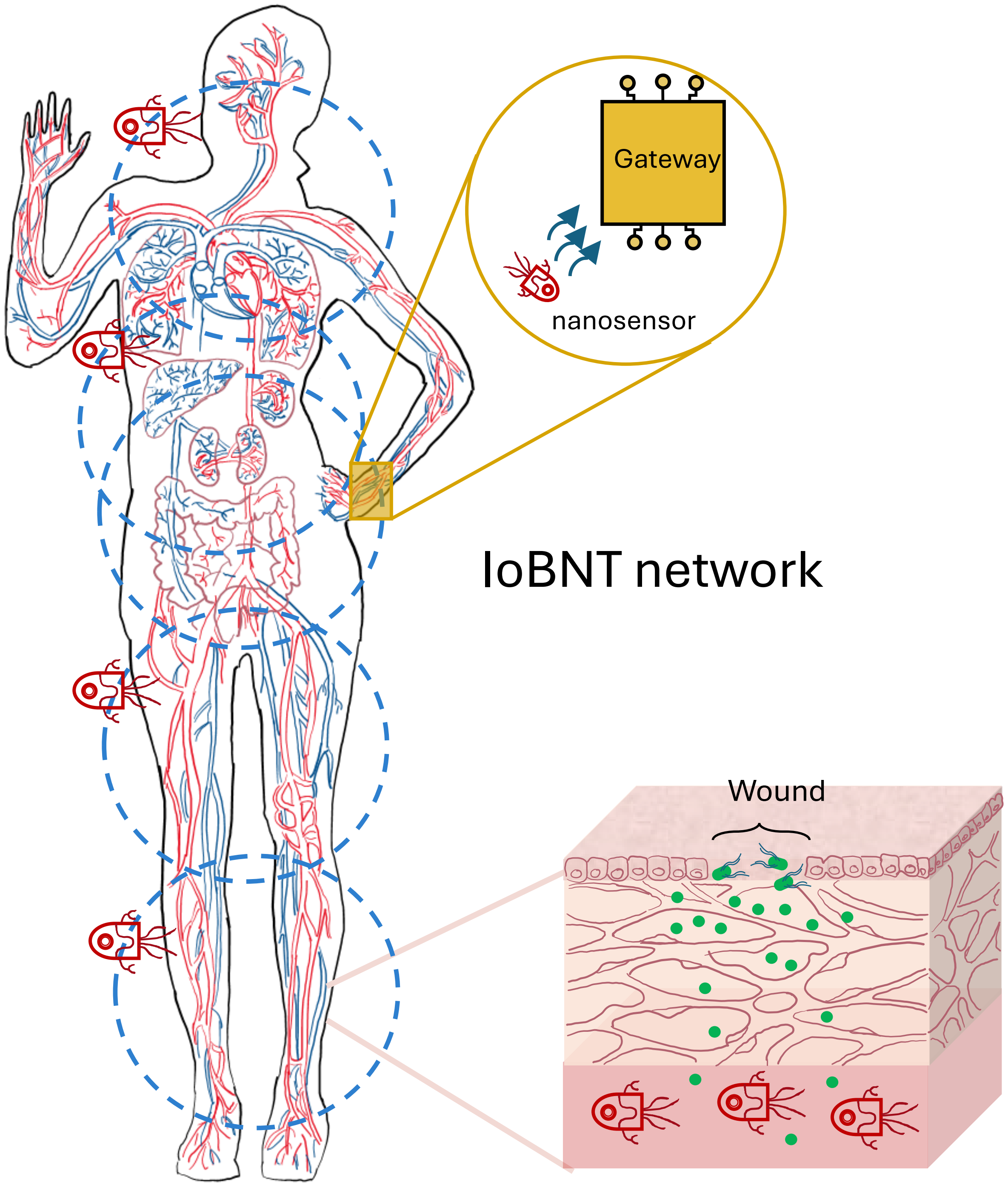
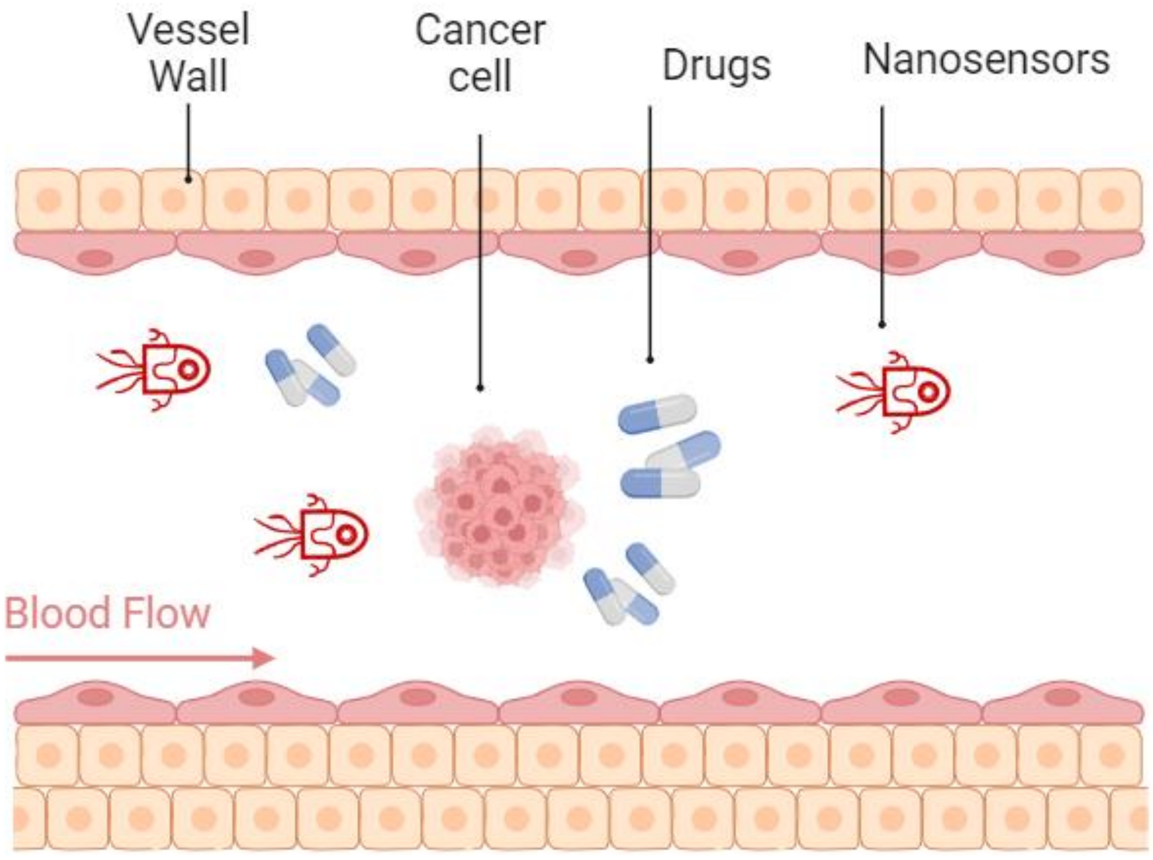


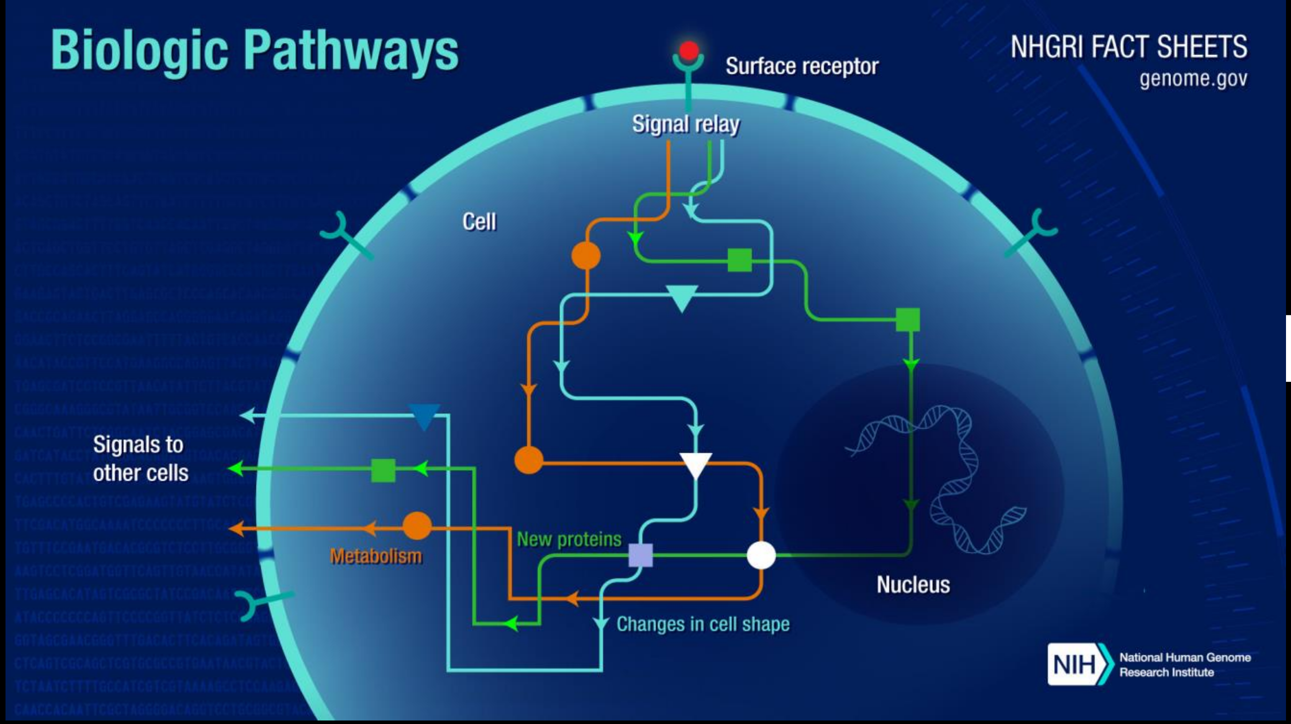
Molecular Communications



IoBNT network



[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=life+cycle+gene+regulation+homo+sapiens&org=

[3]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=life+cycle+gene+regulation+homo+sapiens&org=

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

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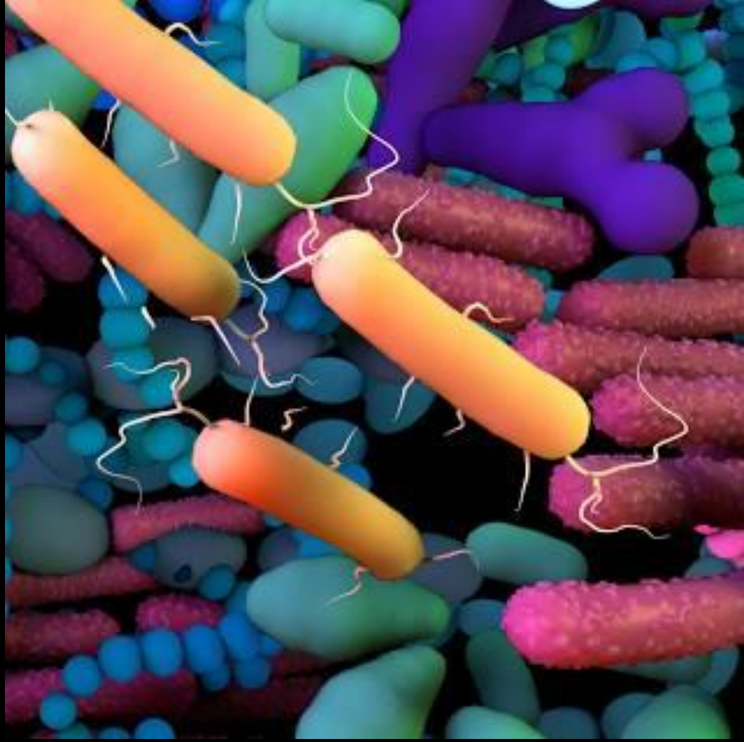
[5] I. F. Akyildiz, M. Ghovanloo, U. Guler, T. Ozkaya-Ahmadov, A. F. Sarioglu, and B. D. Unluturk, 'PANACEA: An Internet of Bio-NanoThings Application for Early Detection and Mitigation of Infectious Diseases', IEEE Access, pp. 1–1, 2020, doi: 10.1109/ACCESS.2020.3012139.



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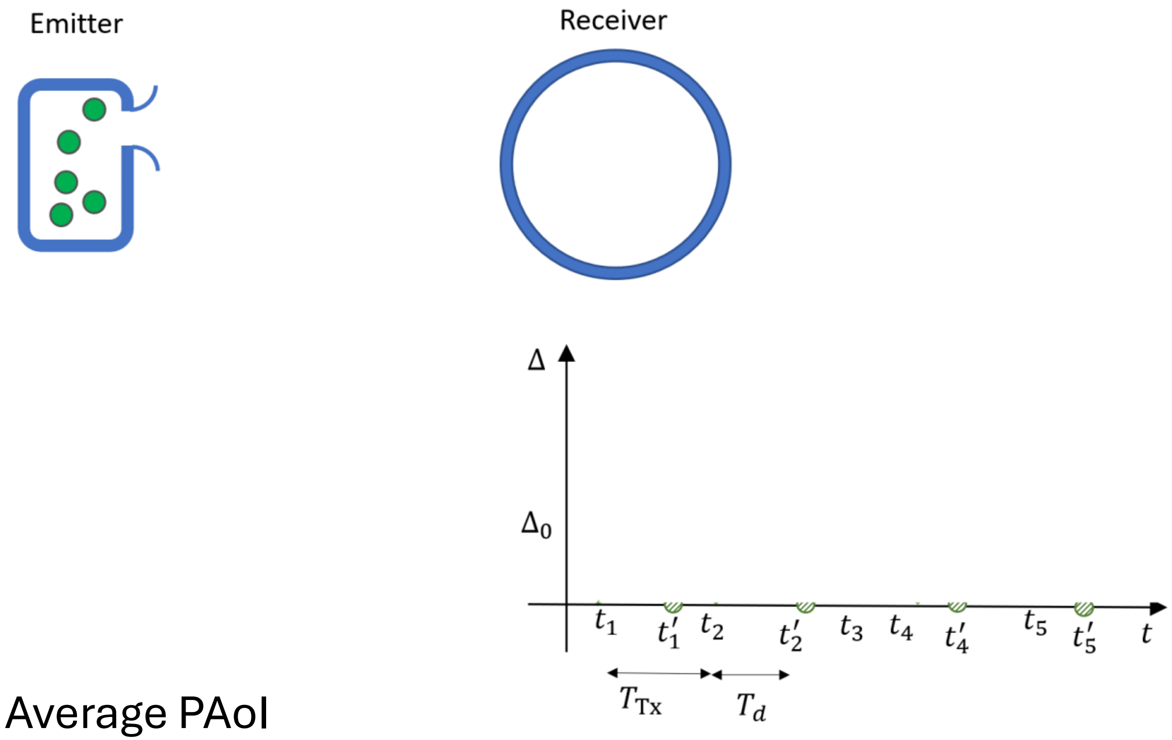
Protein HLA-B27 [3]	4 hours [4]
Bacteria P. Aeruginosa	1.5 – 2 hours [5]

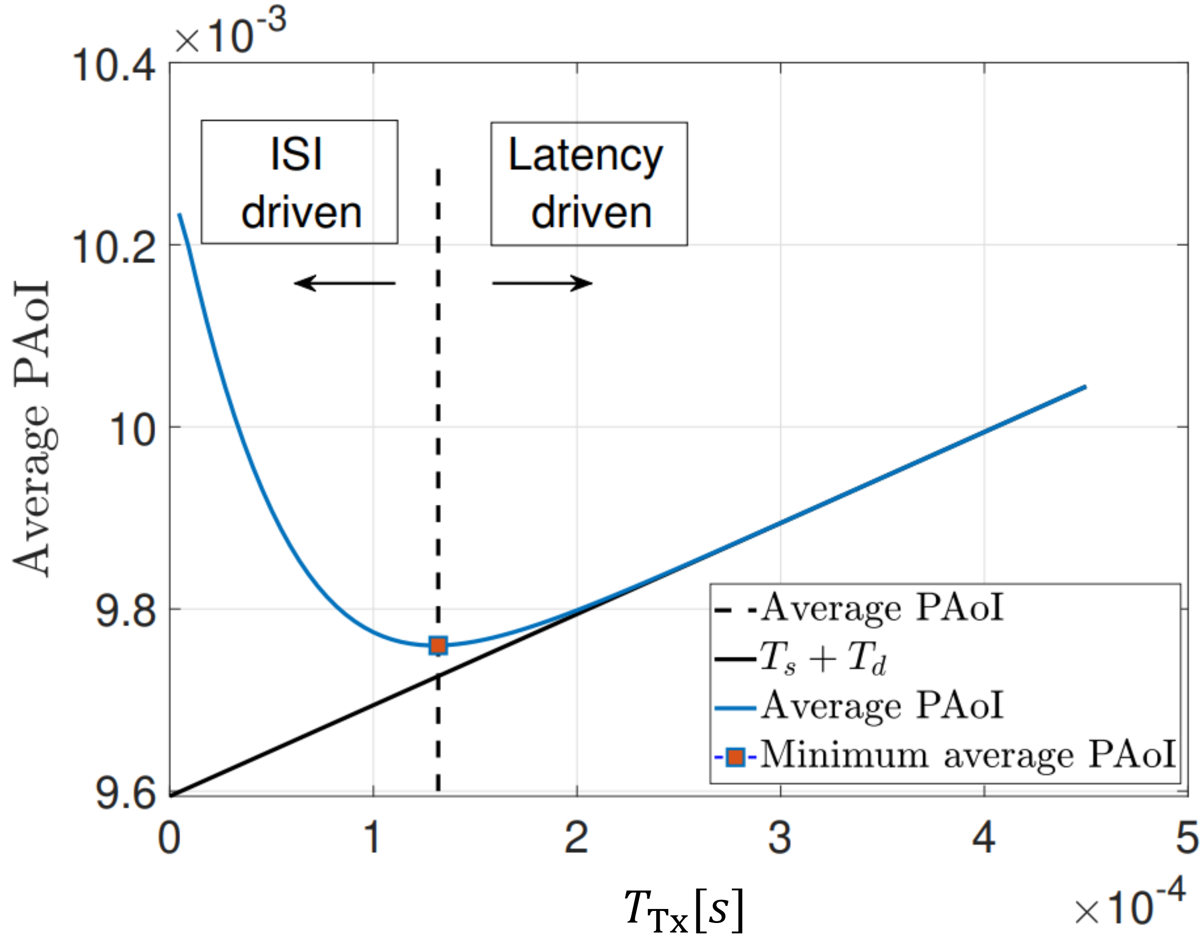
Molecular Communication Channels



Average PAoI

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

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



[1] Jorge Torres Gómez, Ketki Pitke, Lukas Stratmann and Falko Dressler, "Age of Information in Molecular Communication Channels," Elsevier Digital Signal Processing (DSP), Special Issue on Molecular Communication, vol. 124, pp. 103108, May 2022.

Foundations and Trends® in Networking
12:3

Age of Information
A New Concept, Metric, and Tool

Antzela Kosta, Nikolaos Pappas and Vangelis Angelakis

now
the essence of knowledge

CONTRIBUTED PAPER

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, *Fellow IEEE*, Federico Chiariotti, *Member IEEE*, Kaibin Huang, *Fellow IEEE*, Anders E. Kalør, *Graduate Student Member IEEE*, Marios Kountouris, *Senior Member IEEE*, Nikolaos Pappas, *Senior Member IEEE*, and Beatriz Soret, *Member IEEE*

IEEE ComSoc IEEE Open Journal of the Communications Society

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Digital Object Identifier 10.1109/OJCOMS.2024.3371871

Toward Natively Intelligent Semantic Communications and Networking

STYLIANOS E. TREVLAKIS[1] (Member, IEEE), NIKOLAOS PAPPAS[2] (Senior Member, IEEE), AND ALEXANDROS-APOSTOLOS A. BOULOGEORGOS[3] (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

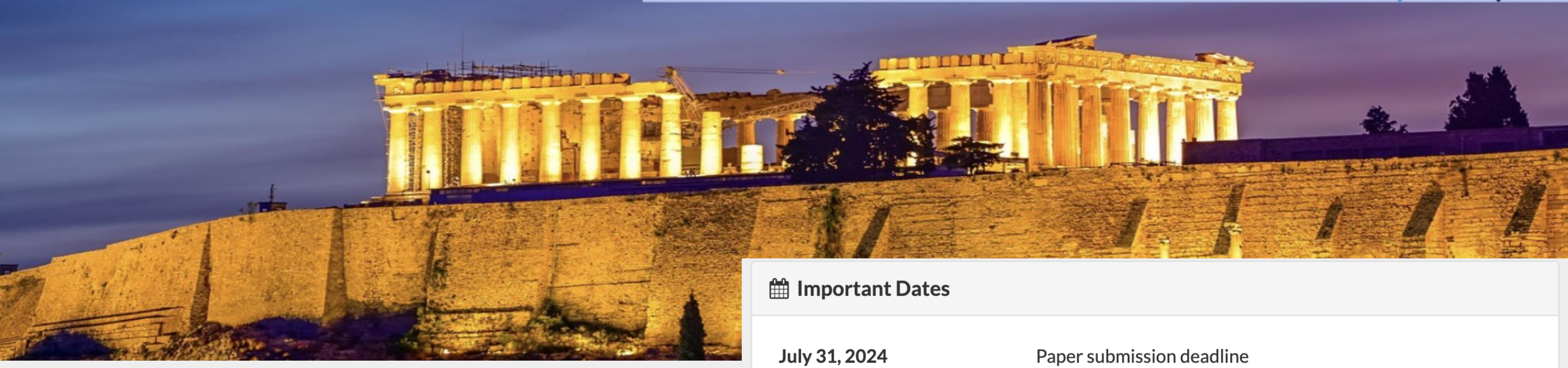
Age of Information
Foundations and Applications

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

Cambridge University Press

ACM MOBIHOC 2024

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

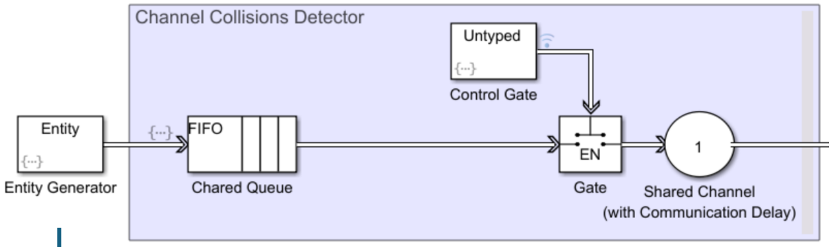
Part II

Implementing AoI-related metrics in wireless links

Jorge Torres Gómez
TU Berlin

Nikolaos Pappas
Linköping University

Transmitter



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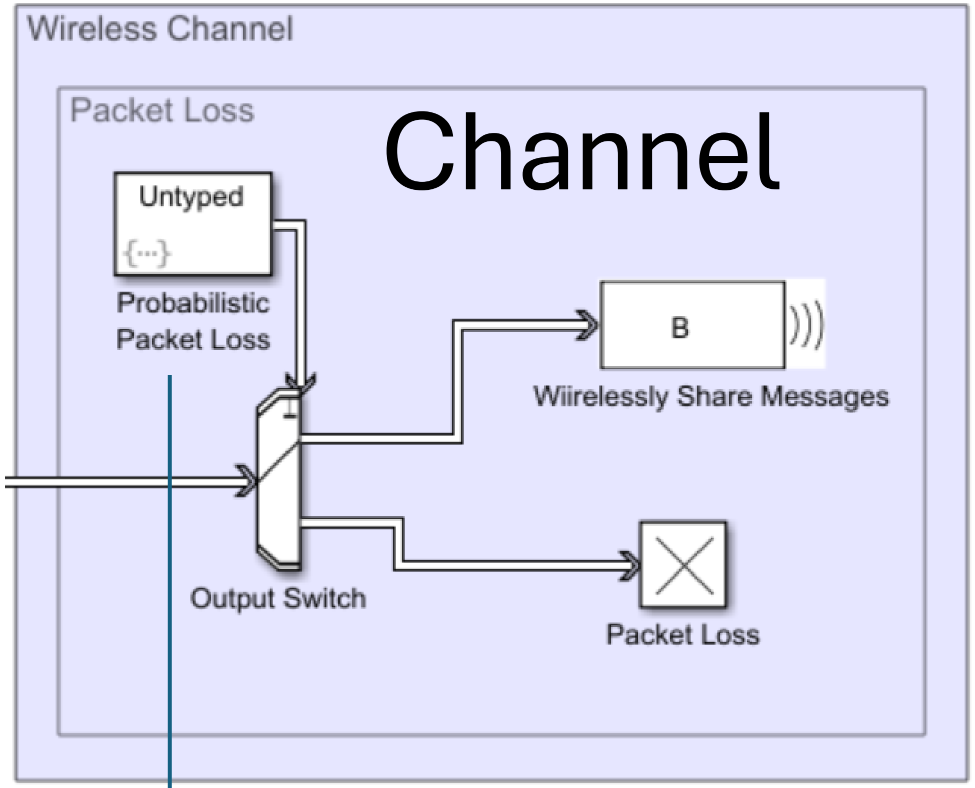
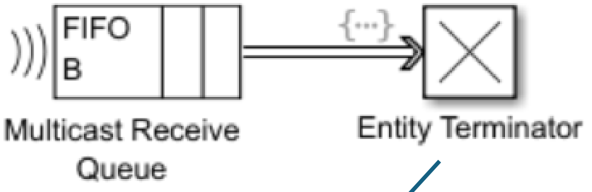
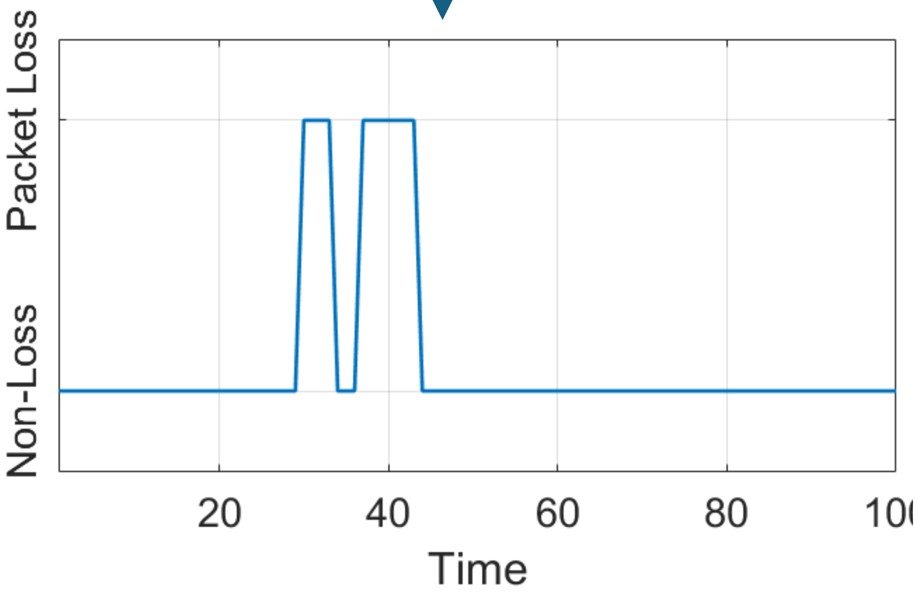
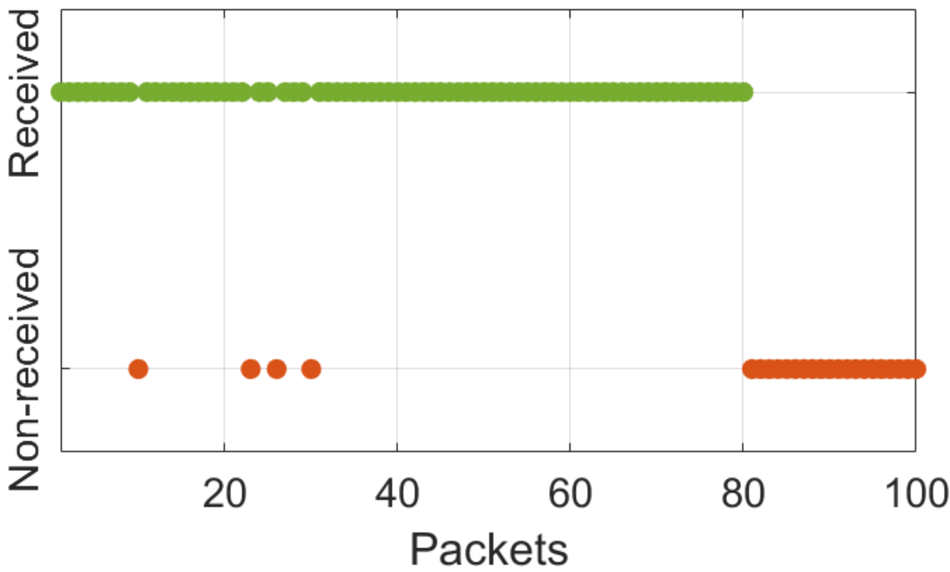
MessageID	{1,2,3,..,N}
Generation	{1,2,3,..,N}



Receiver



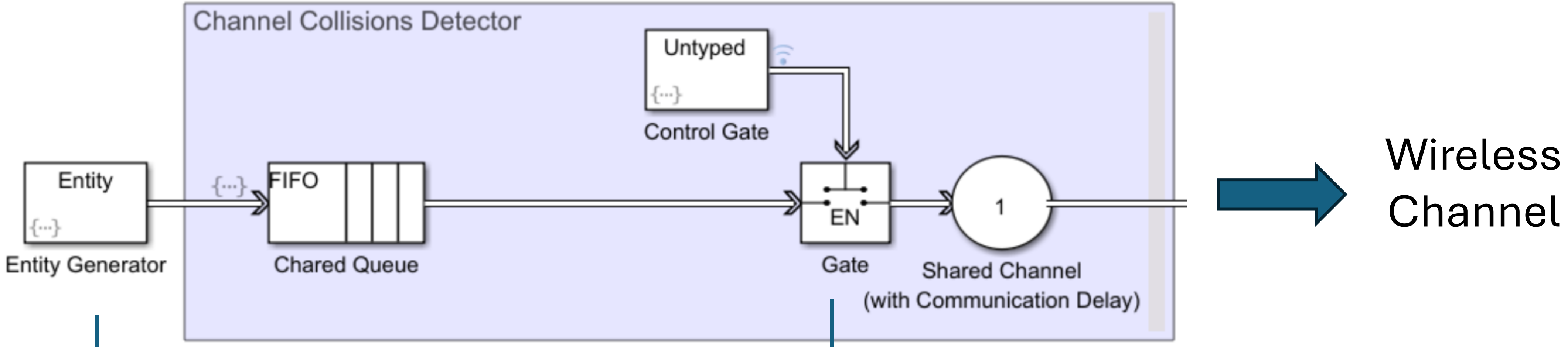




GitHub

MATLAB®

Transmitter



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Text	AoI Workshop
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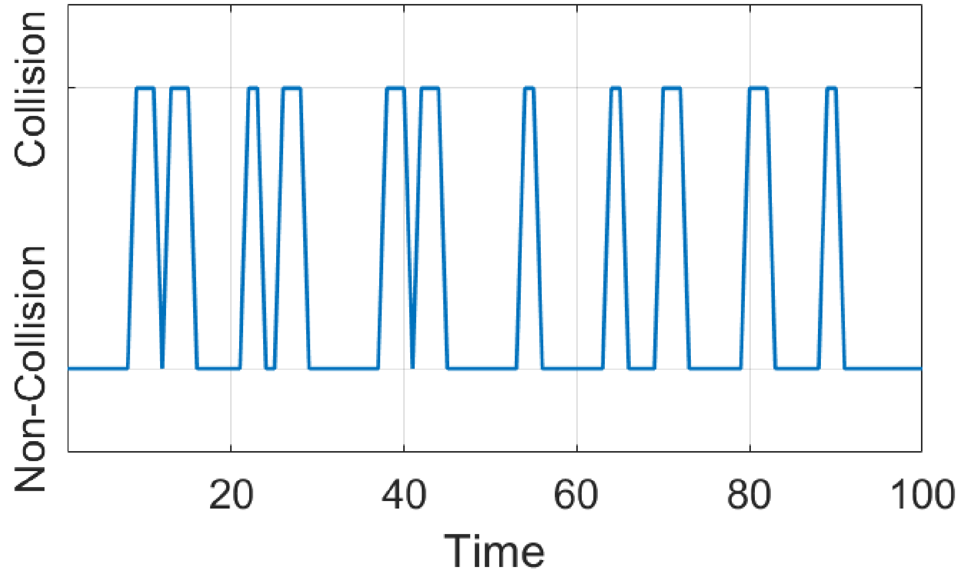
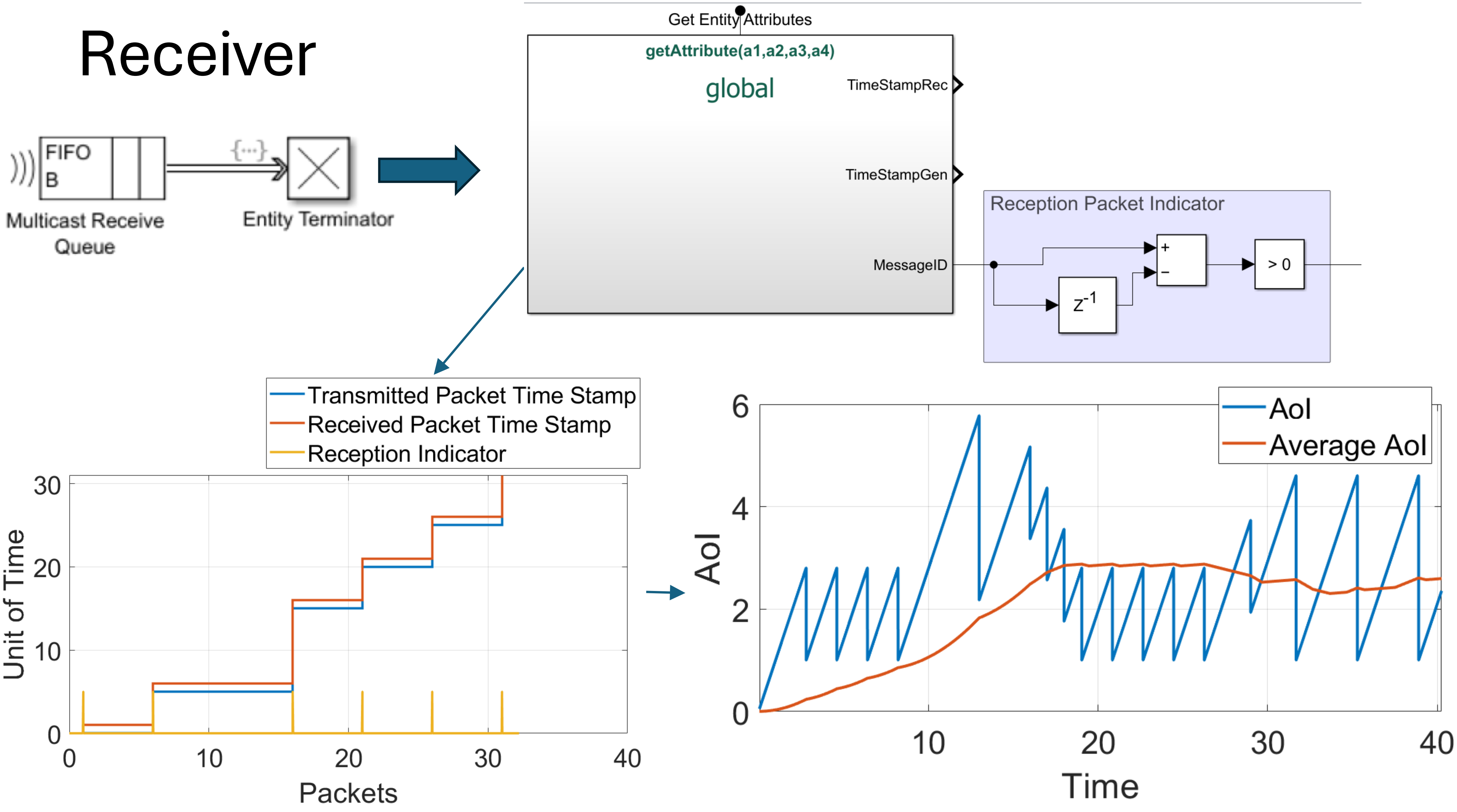
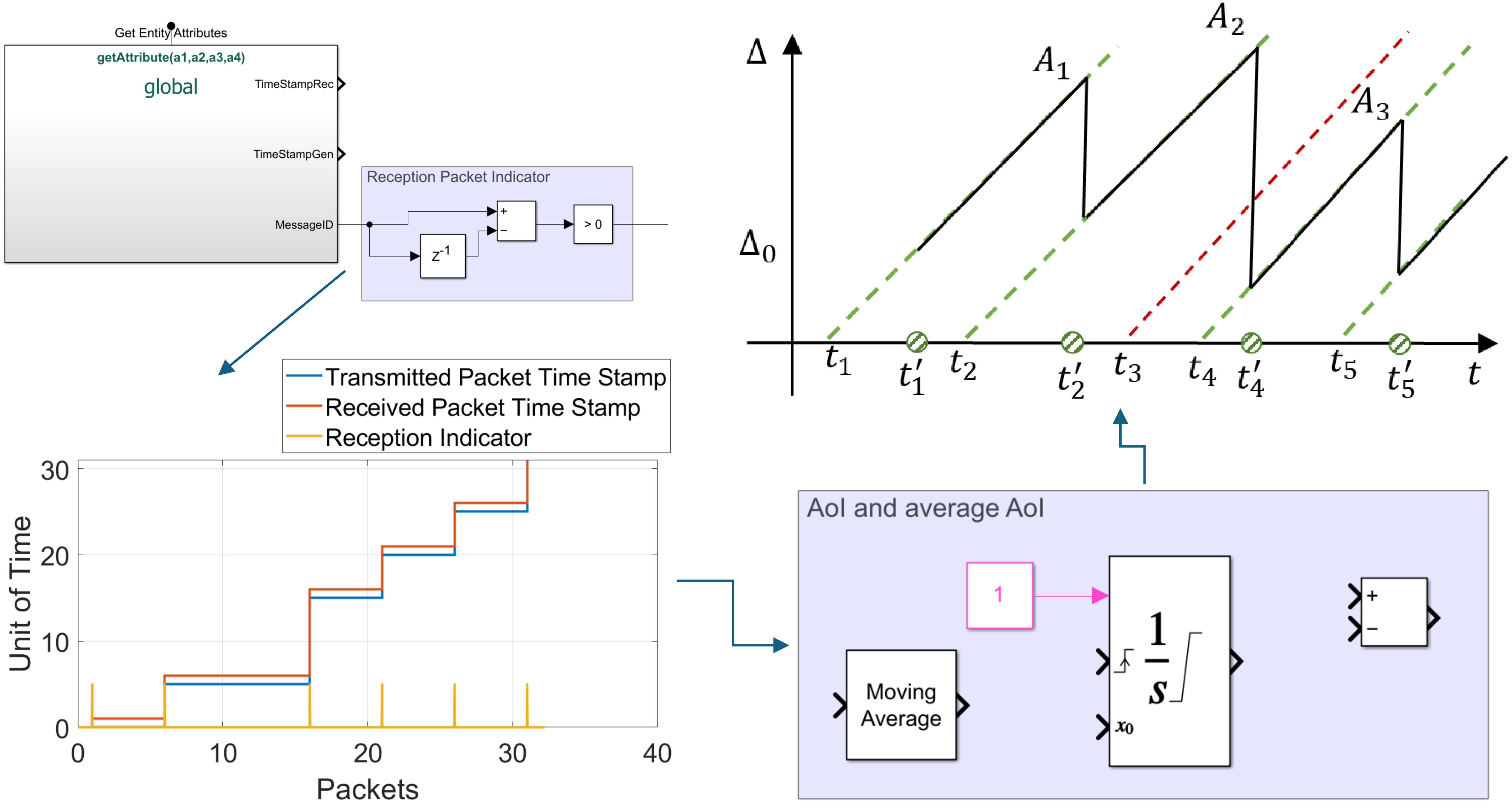
TimeStampGeneration	{1,2,3,....,total_packets}



Receiver


FIFO
B
Multicast Receive Queue
Entity Terminator
Get Entity Attributes
getAttribute(a1,a2,a3,a4)
global
TimeStampRec
TimeStampGen
MessageID
Reception Packet Indicator
+
−
z^{-1}
> 0
Transmitted Packet Time Stamp
Received Packet Time Stamp
Reception Indicator
Unit of Time
Packets
0
10
20
30
40
AoI
Average AoI
Time
2
4
6

Receiver



Get Entity Attributes
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TimeStampRec
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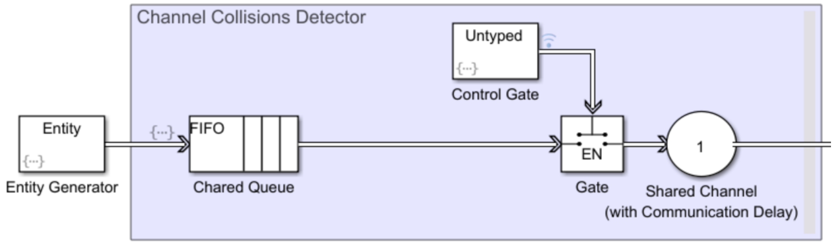
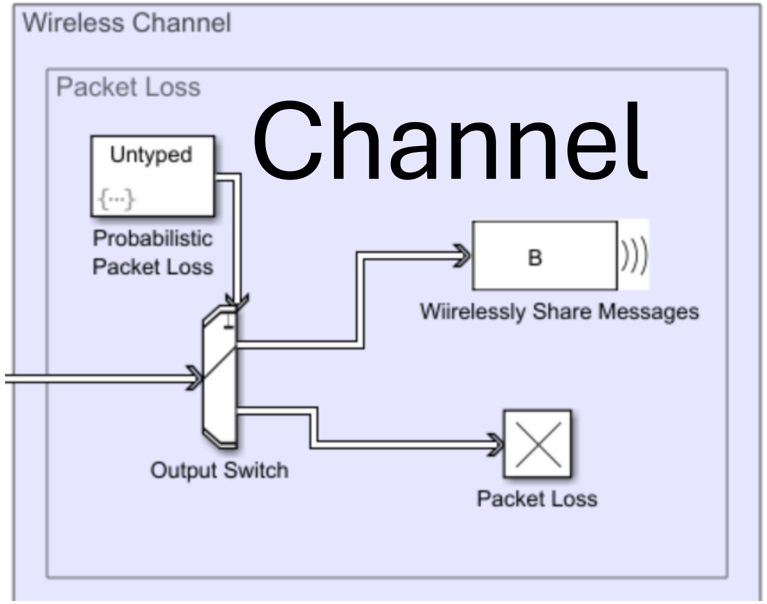
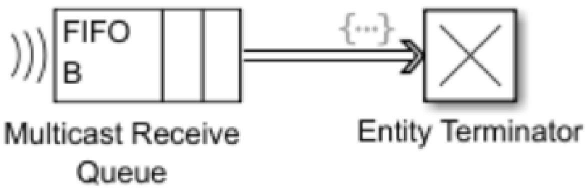
Reception Packet Indicator
+
−
z^{-1}
> 0
Transmitted Packet Time Stamp
Received Packet Time Stamp
Reception Indicator
Unit of Time
0
10
20
30
0
10
20
30
40
Packets
Δ
Δ_0
A_1
A_2
A_3
t_1
t_1'
t_2
t_2'
t_3
t_4
t_4'
t_5
t_5'
t
AoI and average AoI
1
Moving Average
$\frac{1}{s}$
x_0
+
−

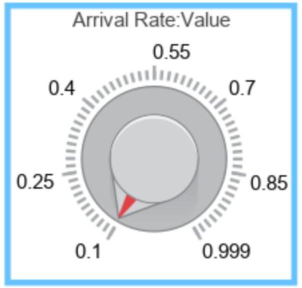
Transmitter

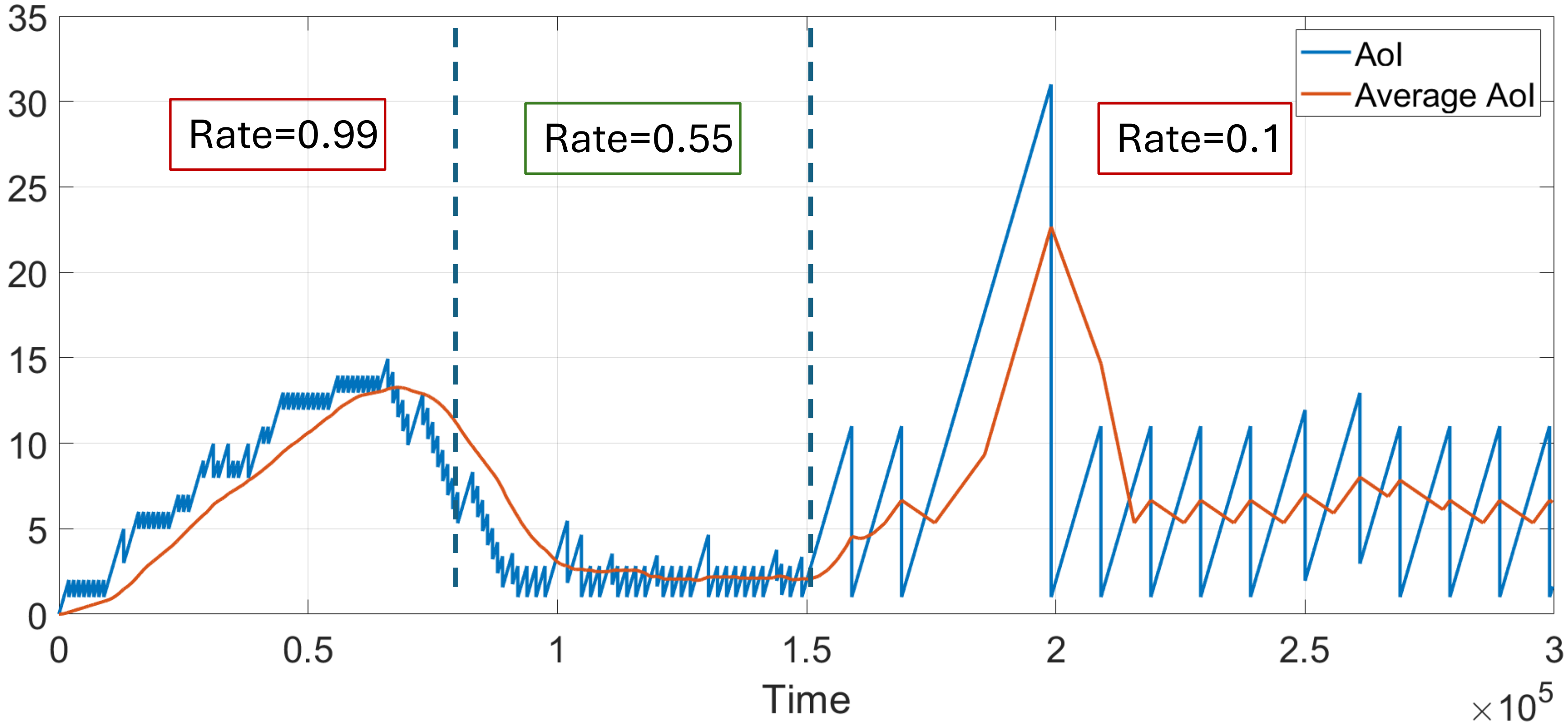




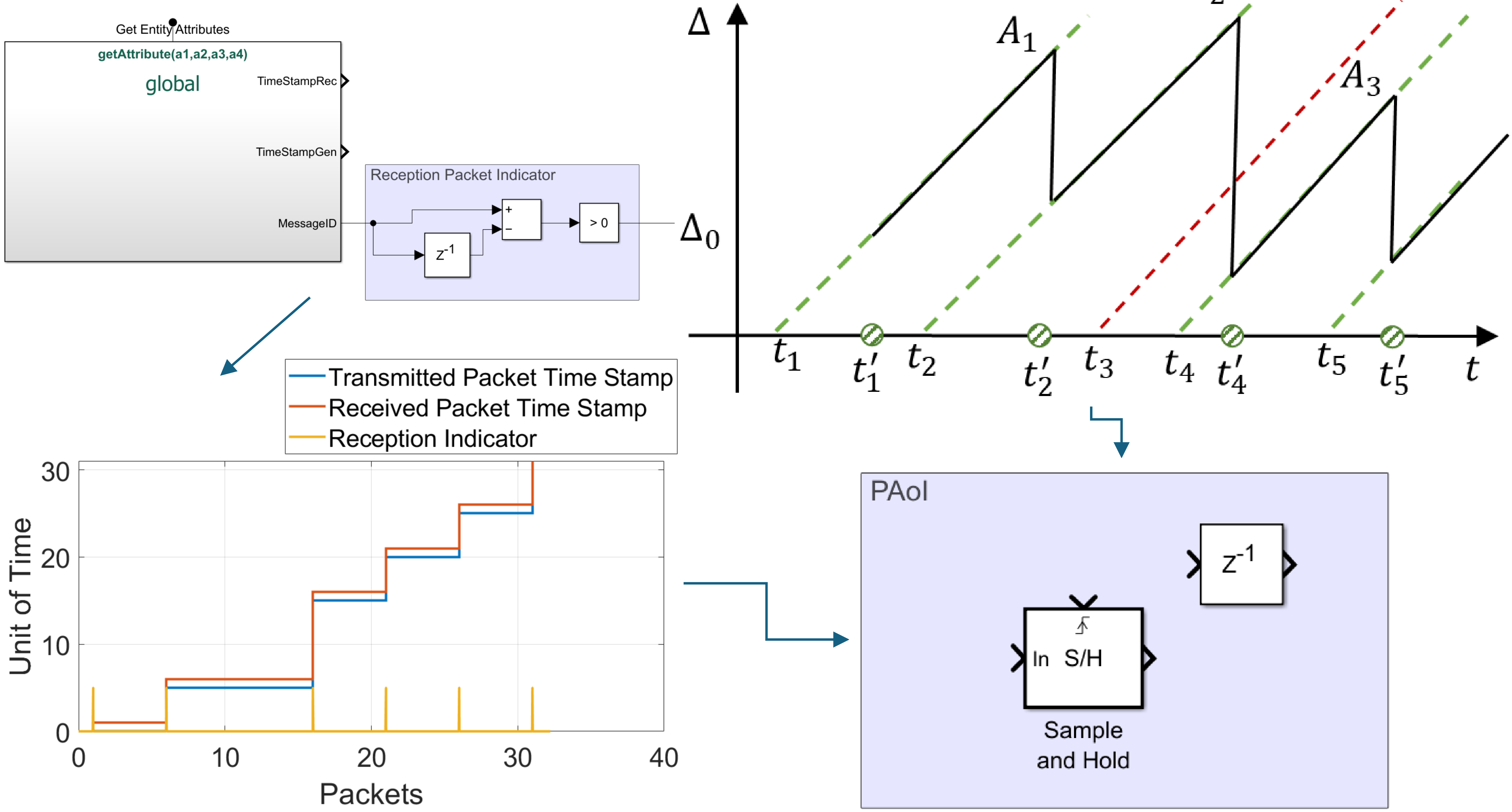
Receiver







Receiver



Get Entity Attributes
getAttribute(a1,a2,a3,a4)
global
TimeStampRec
TimeStampGen
MessageID
Reception Packet Indicator
+
−
z^{-1}
> 0
Transmitted Packet Time Stamp
Received Packet Time Stamp
Reception Indicator
Unit of Time
Packets
0
10
20
30
40
Δ
Δ_0
A_1
A_2
A_3
t_1
t_1'
t_2
t_2'
t_3
t_4
t_4'
t_5
t_5'
t
PAoI
z^{-1}
In S/H
Sample and Hold

Recommended readings

[1] R. D. Yates, Y. Sun, D. R. Brown III, S. K. Kaul, E. Modiano, and S. Ulukus, “Age of Information: An Introduction and Survey”, IEEE JSAC SI AoI, May 2021.

[2] A. Kosta, N. Pappas, V. Angelakis, “Age of Information: A New Concept, Metric, and Tool”, Foundations and Trends in Networking: Vol. 12, No. 3, 2017.

[3] S. Kaul, R. Yates and M. Gruteser, "Real-time status: How often should one update?," 2012 Proceedings IEEE INFOCOM, Orlando, FL, USA, 2012, pp. 2731-2735, doi: 10.1109/INFCOM.2012.6195689.

[4] S. Kaul, R. Yates, M. Gruteser, “Status updates through queues”, CISS 2012.

[5] 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.

[6] P. Popovski et al., "A Perspective on Time Toward Wireless 6G," in Proceedings of the IEEE, vol. 110, no. 8, pp. 1116-1146, Aug. 2022, doi: 10.1109/JPROC.2022.3190205.

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

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