

Information Freshness - Lecture 1: Introduction

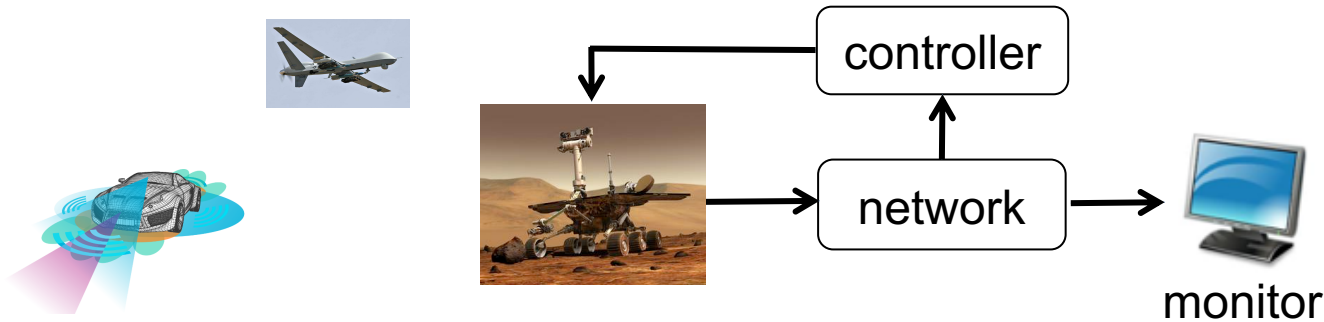
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Real-time Services Need Fresh Data

- **Real-time Monitoring and Control**



Sensor networks, Internet-of-Things, Cyber-Physical Systems, Robotics, Health, Security, etc.

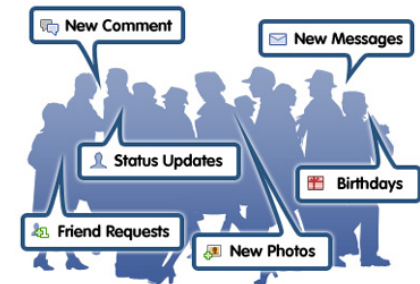
- **Real-time Data Analytics and Learning**



Crowdsourcing

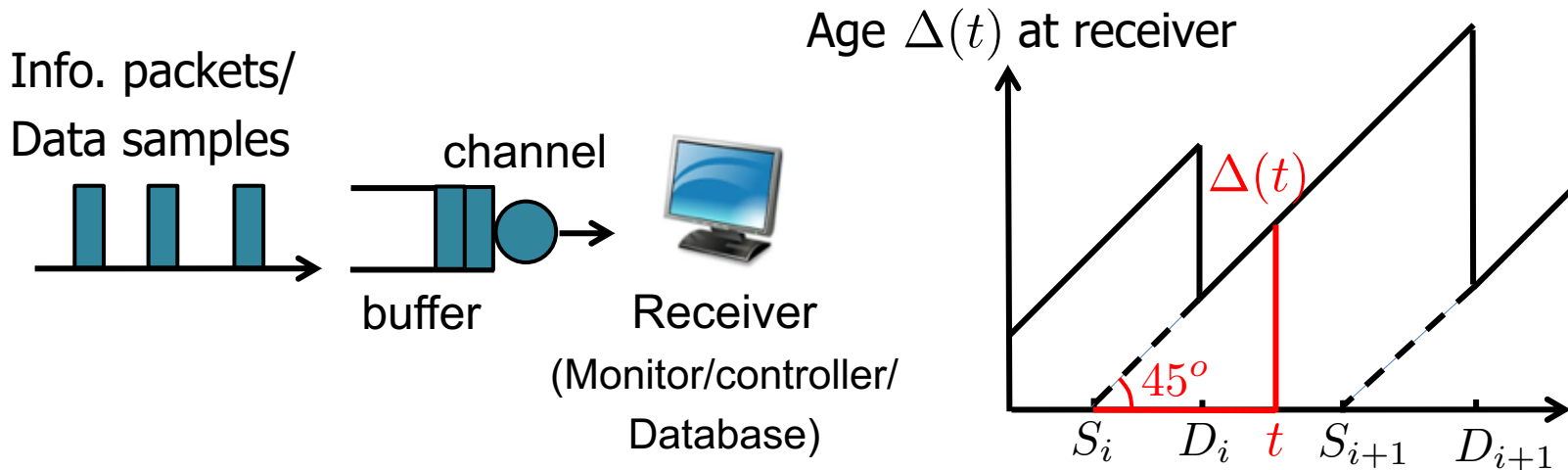


Online Learning
(ads bidding)



Social networks

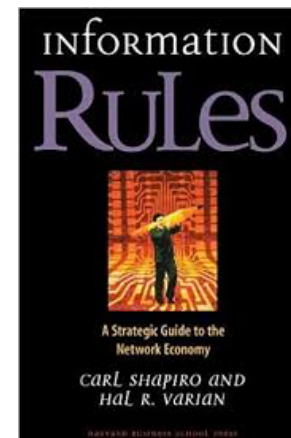
Information Freshness Metric: Age of Information



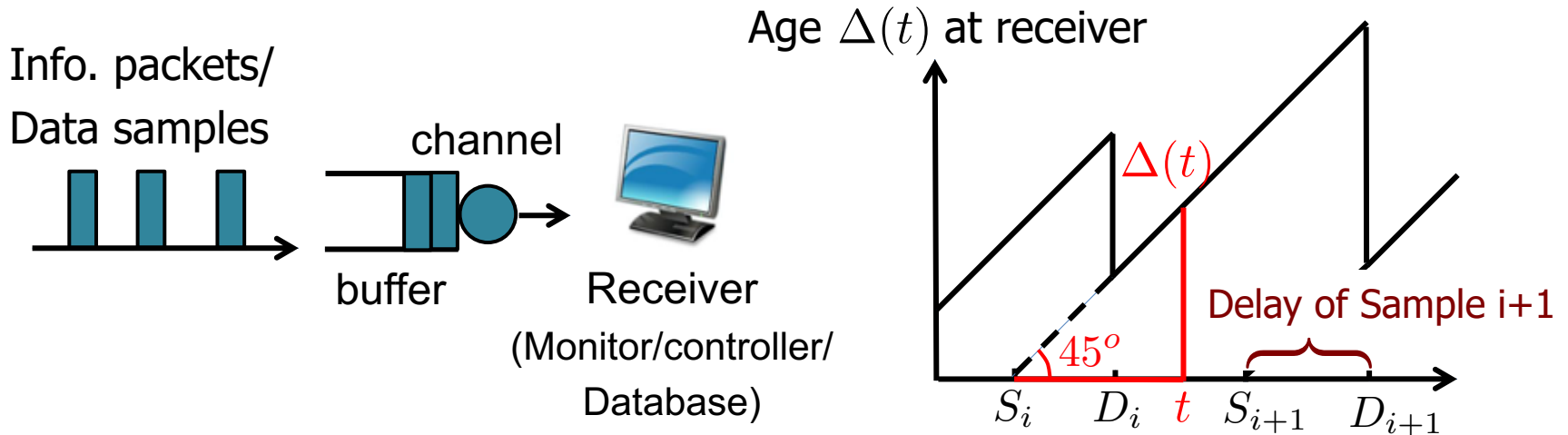
- In **real-time** applications, **fresh** data is more **important** than stale data
 - E.g., UAV/vehicle/robotic control, wildfire/tornado monitoring ...

- “Information is like an oyster: it usually has the greatest value when it is fresh.”

- Carl Shapiro, Hal R. Varian, *Information Rules: A Strategic Guide to the Network Economy*, 1999



Age of Information: Definition



Definition: At time t , the **Age of Information** $\Delta(t)$ is time difference between the current time t and the generation time of the **freshest** sample packets that have been **delivered** to the receiver by time t

- If sample i is generated at S_i and delivered at D_i

$$\Delta(t) = t - \max\{S_i : D_i \leq t\}$$

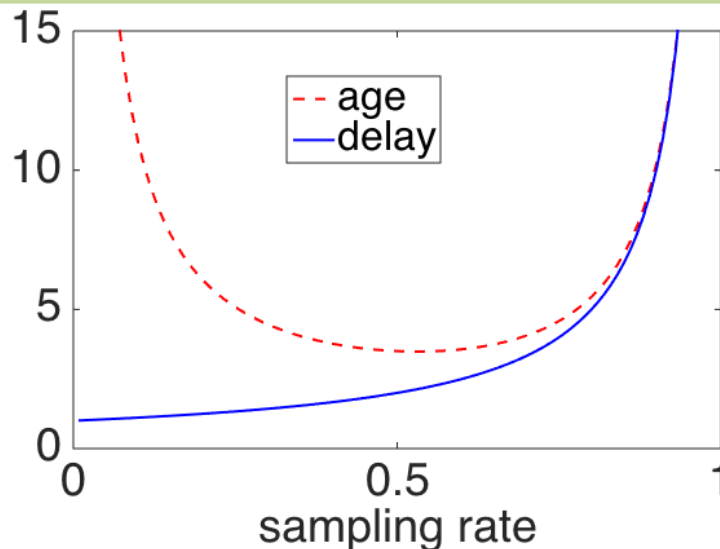
- AoI is a function of time; delay is a function of packet.
- AoI increases over time and drops when a fresher packet is delivered.

Difference between Age & Delay



In M/M/1 FIFO queues: [Kaul, Yates, Gruteser'12]

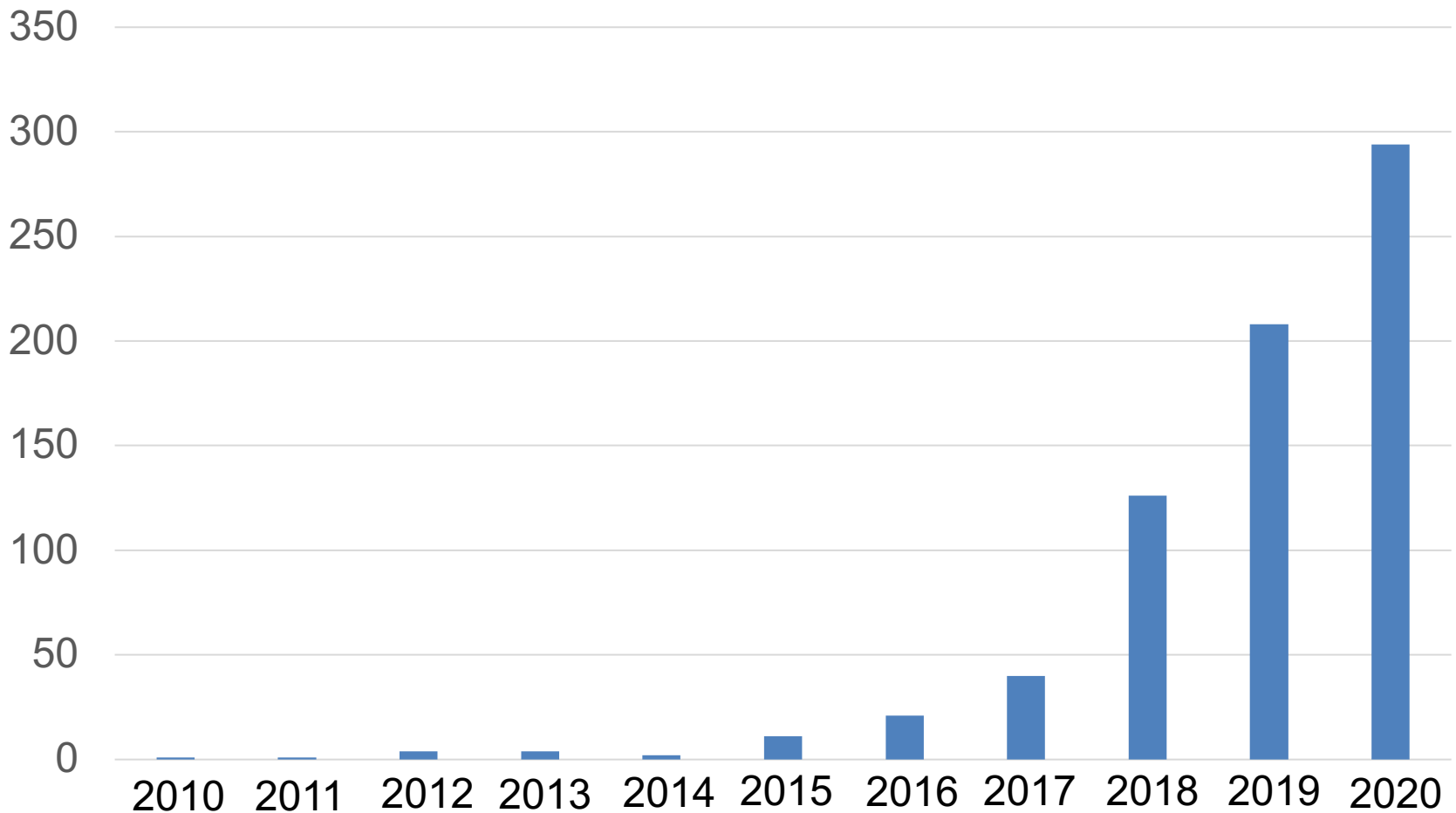
- Age first **decreases**, then **increases** with sampling rate
- Delay **increases** with sampling rate



A Brief History on Age of Information

- Defined in real-time databases [Song-Liu'90,...]
- Queueing analysis [Kaul-Gruteser-Rai-Kenney'11, Yates-Kaul'12, Kam-Kompella-Ephremides'13,14, ...]
- Scheduling and age minimization [Altman et al.'10(19), Yates'15, He-Yuan-Ephremides'16, Sun et al.'16, Bedewy-Sun-Shroff'16&17,...]
- Source coding [Zhong-Yates'16, Zhong-Yates-Soljanin'17,...]
- Channel coding [Najm-Yates-Soljanin'17, Yates-Najm-Soljanin-Zhong'17,...]
- Energy harvesting [Bacinoglu-Ceran-Uysal'15, Wu-Yang-Wu'17, Bacinoglu-Uysal'17, Arafa-Ulukus'17,...]
- Freshness of Channel State Information [Costa-Valentin-Ephremides'15, Farazi-Klein-Brown'17,...]
- Caching [Yates-Ciblat-Yener-Wigger'17, Kam et al.'17]
- Game theory [Nguyen et al. 17, Xiao-Sun'18]
- Age of information and Information Theory [Baknina-Ozel-Yang-Ulukus-Yener'18]
- Age of information and learning [Sert-Sonmez-Baghaee-Uysal-Biyikoglu'18, Ceran-Gunduz-Gyorgy'18]
- Age of information and Control [Zhang-Wang'18, Soleymani-Baras-Johansson'18,...]
- Human in the loop [Bastopcu-Ulukus'18, Bin-Liu'19]

Number of papers on AoI



Sources: Google Scholar

AoI paper list: auburn.edu/~yzs0078/AoI.html

Aol Paper List

The Ongoing History of the Age of Information:

This page contains a list of the papers about the Age of Information, organized in sections by subject. Last updated on September 14, 2020.

Yin Sun

For any queries and concerns, please contact [Md Kamran Chowdhury Shisher](#), [Tasmeen Zaman Ornee](#), and [Yin Sun](#).

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Age of Information Workshops:

1. [The 1st Age of Information Workshop](#) was held on April 16, 2018 in Honolulu, Hawaii, USA.
2. [The 2nd Age of Information Workshop](#) was held on April 29, 2019 in Paris, France. [Opening Talk](#)
3. [The 3rd Age of Information Workshop](#) was held on July 6, 2020 in Toronto, Canada.
4. [The 4th Age of Information Workshop](#) will be held in conjunction with *IEEE INFOCOM 2021*. The submission deadline is **January 7, 2021**.

Call for Papers:

1. [Call for Papers](#) for the Frontiers in Communications and Networks Special Issue on “Age of Information.” The submission deadline is **09 June 2021**.
2. [Call for Papers](#) for the Entropy Special Issue on “Age of Information: Concept, Metric and Tool for Network Control”. The submission deadline is **20 June 2021**.

Book and Overview on Age of Information:

1. [Age of Information: An Introduction and Survey](#)
Roy D. Yates, Yin Sun, D. Richard Brown III, Sanjit K. Kaul, Eytan Modiano, and Sennur Ulukus, 2020
2. [Age of Information: A New Concept, Metric, and Tool](#)
Antzela Kosta, Nikolaos Pappas, and Vangelis Angelakis, *Foundations and Trends in Networking*, 2017.

- <https://auburn.edu/~yzs0078/Aol.html>

Course Objectives

- Target on the foundations and state-of-the-art in the emerging area of “Age of Information”
 - Help students master theoretical concepts that are useful for not only Aol, but also other directions
- Explore the numerous applications of Aol
 - Estimation, Machine Learning, Autonomous Driving, Robotic Control, etc.
- Training on research
 - Improve students’ confidence to understand challenging papers, and work on cutting-edge research



Grading Policy

- No test or exam.
- Homework, reading, project, presentation.
 - Details TBD through the semester.
- Target on manageable load
 - Feedback is more than welcome!

References for the Course

- Roy D. Yates, Yin Sun, D. Richard Brown III, Sanjit K. Kaul, Eytan Modiano, and Sennur Ulukus, “Age of Information: An Introduction and Survey,” arXiv preprint arXiv: 2007.08564 (2020).
- Yin Sun, Igor Kadota, Rajat Talak, and Eytan Modiano, *Age of Information: A New Metric for Information Freshness*, Morgan & Claypool Publishers, 2019.
- Antzela Kosta, Nikolaos Pappas, and Vangelis Angelakis, *Age of Information: A New Concept, Metric, and Tool*, Foundations and Trends in Networking, 2017.
- R. Srikant and Lei Ying, *Communication Networks: An Optimization Control and Stochastic Networks Perspective*, Cambridge University Press, 2014
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Course Outline

1. Overview (1 lecture)
2. Graphical Decomposition Analysis and AoI in Elementary Queues (5)
3. Stochastic Hybrid Systems based AoI Analysis (3)
4. Non-linear AoI Metrics and Sample-path Scheduling Method (3)
5. AoI for Energy Harvesting Sources (3)
6. Real-time Sampling, Estimation, and Control Systems (4)
7. AoI based Scheduling in Wireless Networks (4)
8. Machine Learning for AoI Optimization (3)
9. Application Examples: AoI in Robots and Machine Learning (2)

Excused Absence

- See Syllabus