NetSys 2023, International Conference on Networked Systems 2023
4-7 September 2023 – Potsdam, Germany

NetSys 2023 Tutorial on Age of Information

Age of information: A new performance metric for measuring freshness of information
Part I

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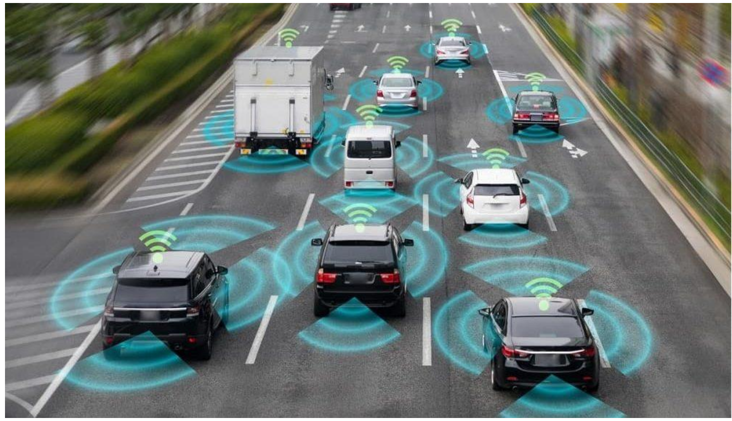
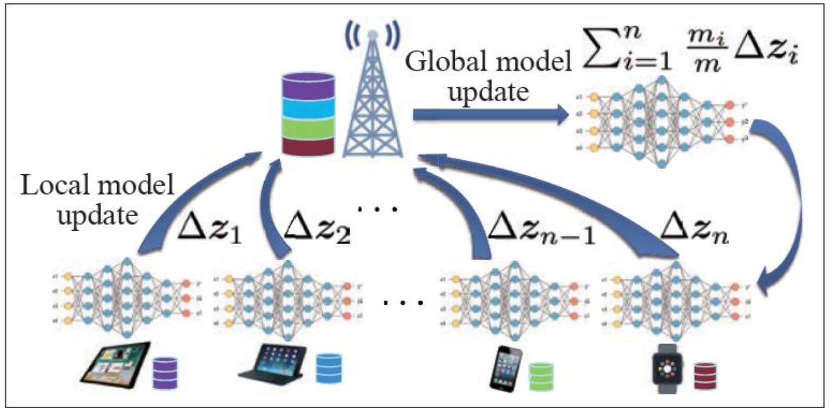
Outline - Part I

- Introduction
- Measuring freshness
  - Age of Information (AoI)
  - Value of Information and Cost of Update Delay
  - Interplay of AoI with other metrics
  - Beyond AoI
- Goal-oriented and semantics-aware communications
- Concluding remarks

How to quantify freshness of information



- **Real-time / time sensitive systems**: *Information usually is more useful when it is fresh! (e.g., autonomous driving: info about location/speed/sensors)*
- *Age of Information (AoI):*
  - *AoI and its variants: simple, quantitative proxy metrics of information semantics*
  - ***Instrumental in establishing suboptimality of separate handling of sampling and communication***
- Other cases such as
  - Quality of Information (QoI)
  - Value of Information (VoI)



- Performance metrics used in the literature to characterize time sensitive information:
  - **Packet delay** tracks the time that elapsed from the generation of the packet until its delivery,
  - **inter-delivery time** is the time between two successive deliveries.
- These metrics are not sufficient to maintain fresh information at the destination.
- Even in the simplest queueing systems, *timely updating* is not the same as maximizing the utilization of the system that delivers these updates, nor the same as ensuring that updates are received with minimum delay.

Definition and Modeling of AoI

Definition of Age of Information (AoI)

- AoI is an end-to-end metric that can characterize latency in status updating systems and applications and captures the timeliness of the information.
- An update packet with timestamp u has age $t-u$ at a time t.
- An update is fresh if its age is zero.
- When the monitor's freshest received update at time t has timestamp $u(t)$, the age is the random process $\Delta(t) = t - u(t)$.

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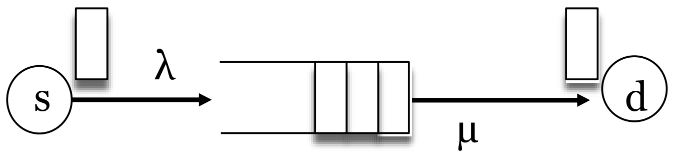
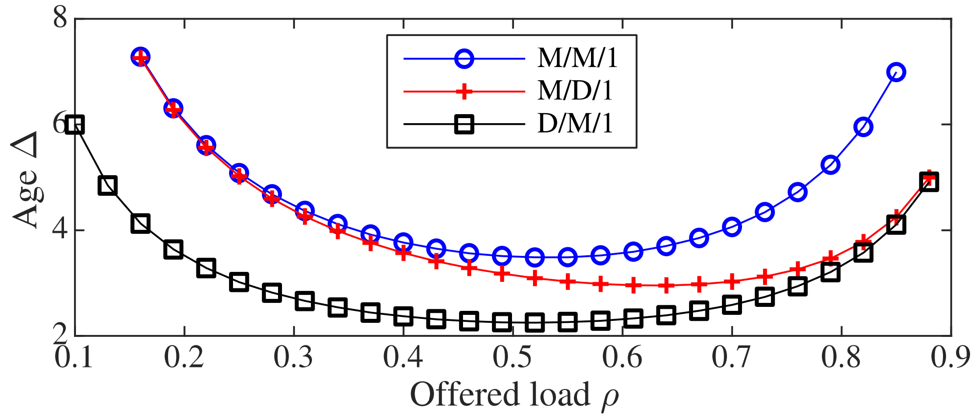
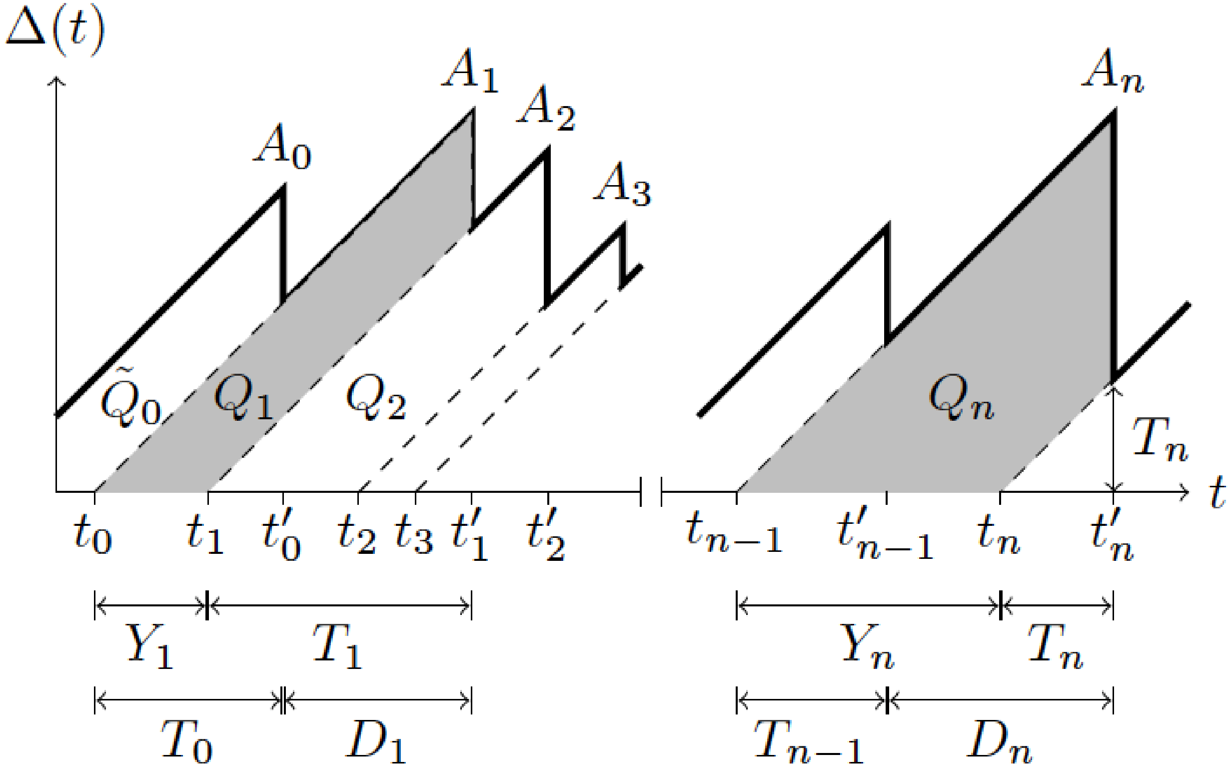




Time Average AoI – Sawtooth Sample path

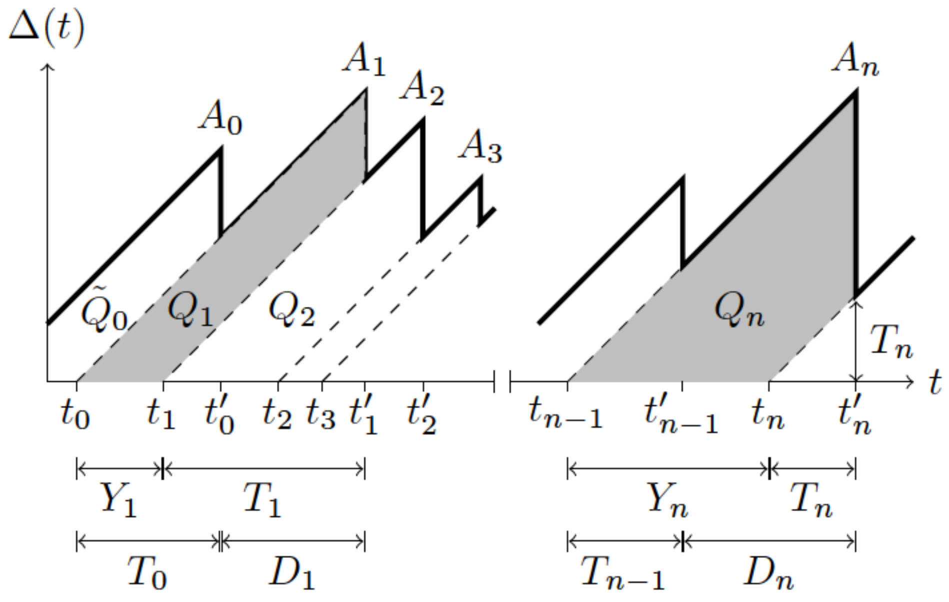


- $t_o, t_1, t_2, \ldots$ times that are updates are generated
- $t_o', t_1', t_2', \ldots$ times that updates are received at the monitor

- For the n-th received update
  - $Y_n = t_n - t_{n-1}$ interarrival time
  - T_n system time
  - $D_n = t_n' - t_{n-1}'$ interdeparture time
  - A_n corresponding peak age

- 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.
- 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.

Time Average AoI $\frac{1}{\mathcal{T}}\int_0^{\mathcal{T}} \Delta(t)dt \quad \mathcal{T} = t'_n$



$$Q_n = \frac{1}{2}(T_n + Y_n)^2 - \frac{1}{2}T_n^2 = Y_n T_n + Y_n^2/2$$

$$N(\mathcal{T})/\mathcal{T} \to 1/\mathrm{E}[Y]$$

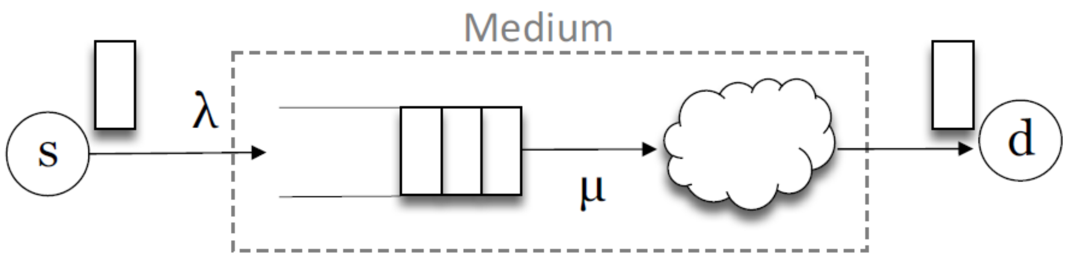
$$\frac{1}{N(\mathcal{T})}\sum_{j=1}^{N(\mathcal{T})} Q_j \to \mathrm{E}[Q] \quad \mathcal{T} \to \infty$$

$$\Delta = \frac{\mathrm{E}[Q_n]}{\mathrm{E}[Y_n]} = \frac{\mathrm{E}[Y_n T_n] + \mathrm{E}\left[Y_n^2\right]/2}{\mathrm{E}[Y_n]}$$

- Large interarrival time allows queue to be empty, thus, the waiting time can be small, causing small system time T_n.
- Y_n and T_n are negatively correlated which complicates the calculation of $E[Y_n T_n]$

Single-source and single-server systems

i.i.d interarrival times with expected value E[Y]
λ=1/ E[Y] : arrival rate
E[S] : expected service time
μ=1/ E[S] : service rate
ρ = λ/ μ : offered load



For FCFS M/M/1 queue the average is $\Delta_{\mathrm{M/M/1}} = \frac{1}{\mu}\left(1 + \frac{1}{\rho} + \frac{\rho^2}{1-\rho}\right)$
The optimal age is achieved for $\rho^* \approx 0.53$

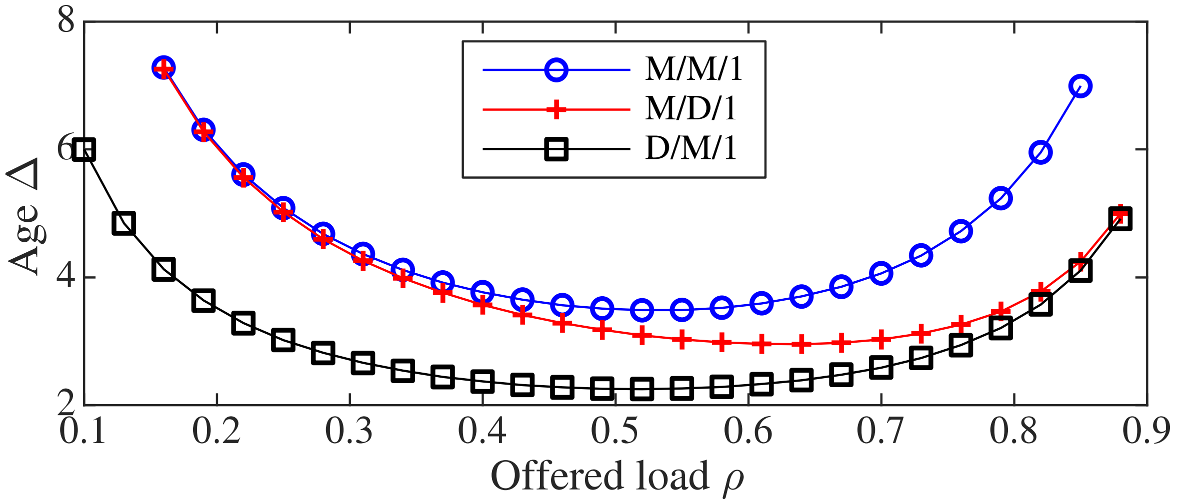
- Optimal age is achieved by choosing a λ which makes the server being slightly busy than being idle.
- If ρ is close to 1 we maximize the throughput.
- If ρ is close to 0, we minimize the delay.

- S. Kaul, R. Yates, and M. Gruteser, "Real-time status: How often should one update?" IEEE INFOCOM 2012.
- Y. Inoue, H. Masuyama, T. Takine, and T. Tanaka, "A general formula for the stationary distribution of the age of information and its application to single-server queues," IEEE Trans. Info. Theory 2019.

Single-source and single-server systems

For M/D/1 and D/M/1 queues the average AoI are given by

$$\Delta_{\mathrm{M/D/1}} = \frac{1}{\mu}\left(\frac{1}{2(1-\rho)} + \frac{1}{2} + \frac{(1-\rho)\exp(\rho)}{\rho}\right) \qquad \Delta_{\mathrm{D/M/1}} = \frac{1}{\mu}\left(\frac{1}{2\rho} + \frac{1}{1-\gamma(\rho)}\right) \qquad \gamma(\rho) = -\rho\mathcal{W}\left(-\rho^{-1}e^{(-1/\rho)}\right)$$



- At low load, randomness in the interarrivals dominates the average age.
- At high load, M/D/1 and D/M/1 outperform M/M/1 because the determinism in either arrivals or service helps to reduce the average queue length.
- Unique value of ρ that minimizes the average age.

Single-source and single-server systems – Packet management

- The arrival rate can be optimized to balance frequency of updates against congestion.
    - Departure from the external arrivals assumption.
- Study of lossy queues that may discard an arriving update while the server was busy or replace an older waiting update with a fresher arrival.
- ***Packet management inherently prioritizes some packets over others which is indication of different value of the packets thus the prioritization!***

- S. Kaul, R. Yates, M. Gruteser, "Status updates through queues", CISS 2012.
- N. Pappas, J. Gunnarsson, L. Kratz, M. Kountouris, V. Angelakis, "Age of Information of Multiple Sources with Queue Management", IEEE ICC 2015.
- M. Costa, M. Codreanu, A. Ephremides, "On the age of information in status update systems with packet management", IEEE Trans. Info. Theory 2016.
- A. Kosta, N. Pappas, A. Ephremides, V. Angelakis, "Age of Information Performance of Multiaccess Strategies with Packet Management", IEEE/KICS JCN, June 2019.

Non-linear Ageing

- AoI grows over time linearly
  - The performance degradation caused by information aging may not be a linear function of time.
- Capture the nonlinear behaviour of information aging
  - *Define freshness and staleness as nonlinear functions of AoI.*
- A penalty function of the AoI is non-decreasing.
  - *Outdated data is usually less desirable than fresh data.*
- *Cost of Update Delay (CoUD)*

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

Cost of Update Delay (CoUD)

- CoUD metric associates the cost of staleness with the statistics of the source
- $C(t) = f_s(t\text{-}u(t))$
  - $f_s(t)$ is a monotonically increasing function
  - $u(t)$ timestamp of the most recently received update
- Different cost functions can represent different utilities

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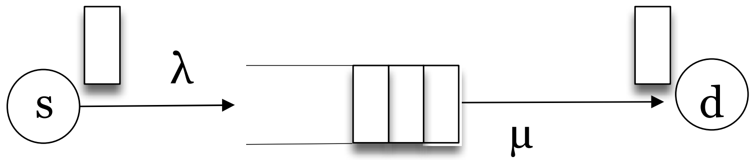
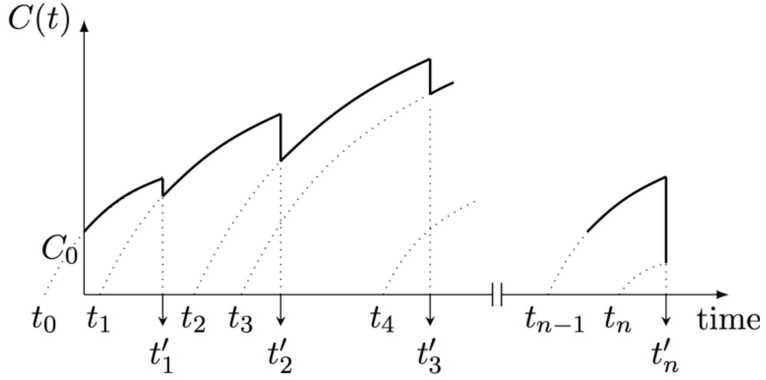


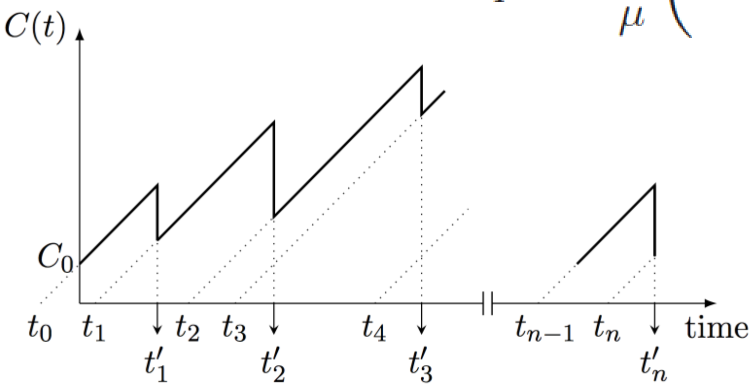
$f_s(t) = \log(\alpha t + 1) \; \rightarrow$ high autocorrelation



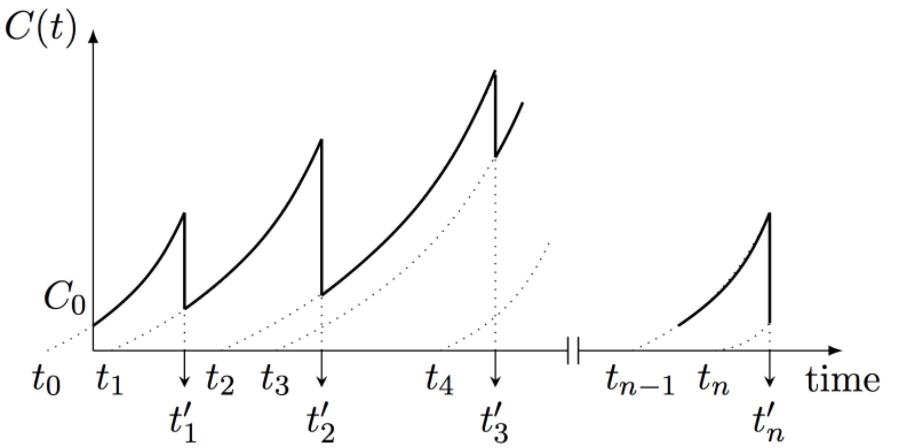
$$C_L = \frac{1}{\alpha(\lambda-\mu)^2}\left(e^{-\frac{\mu\rho}{\alpha}}\left(\mu(1-\rho)Ei\left[-\frac{\mu}{a}\right](\alpha\mu+\lambda^2-\lambda\mu)\,e^{\frac{\mu(\rho+1)}{\alpha}} - \alpha\mu^2(1-\rho)Ei\left[-\frac{\lambda}{\alpha}\right]e^{\frac{\lambda+\mu\rho}{\alpha}} - \alpha e^{\mu/\alpha}(\lambda-\mu)^2 Ei\left[-\frac{\mu(1-\rho)}{\alpha}\right]\right) - \alpha\lambda(1-\rho)(\mu-\lambda)\right)$$

$f_s(t) = \alpha t$

$$C_P = \alpha\frac{1}{\mu}\left(1+\frac{1}{\rho}+\frac{\rho^2}{1-\rho}\right)$$



$f_s(t) = e^{\alpha t} - 1 \; \rightarrow$ low autocorrelation

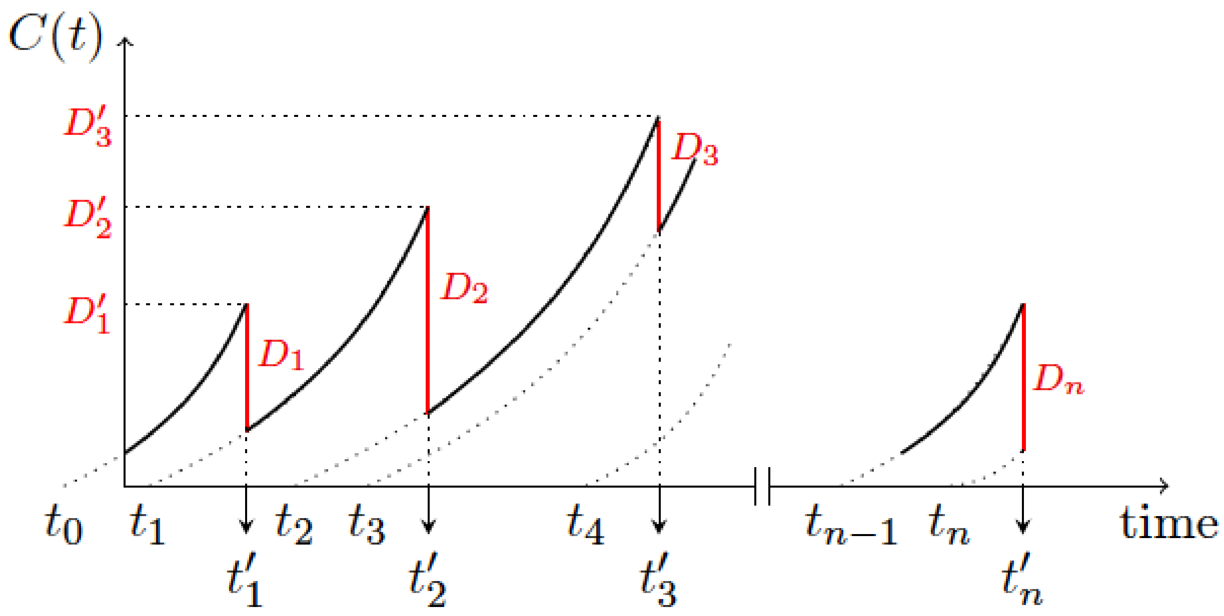


$$C_E = \mu(\rho-1)\left(\frac{\alpha(\alpha-(\lambda+\mu))}{(\lambda-\alpha)(\alpha-\mu)^2}+\frac{1}{\alpha-\mu(1-\rho)}+\frac{1}{\mu(1-\rho)}\right)$$

Value of Information of Update (VoIU)

- It captures *the degree of importance of an update*

$$V_i = \frac{f_s(t_i'-t_{i-1})-f_s(t_i'-t_i)}{f_s(t_i'-t_{i-1})} = \frac{D_i}{D_i'}.$$



- In the linear CoUD case, VoIU is independent of the cost assigned per time unit →the Value is independent of the slope.

$$V_i = \lim_{t_i' \to t_i} \frac{f_s(t_i'-t_{i-1})-f_s(t_i'-t_i)}{f_s(t_i'-t_{i-1})} = 1$$

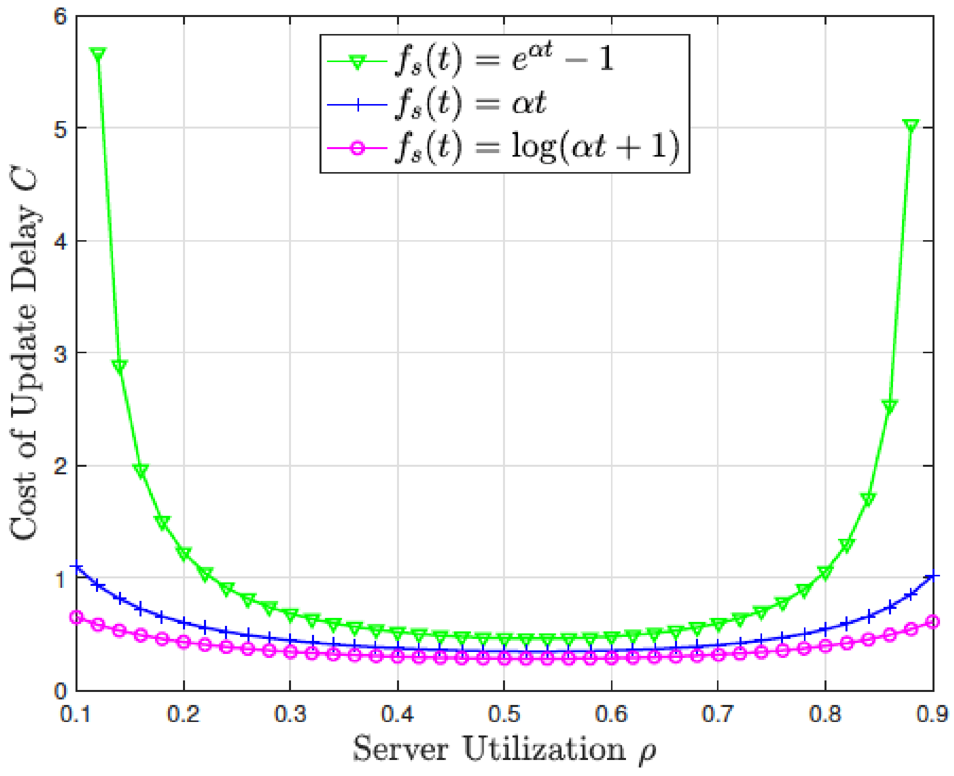
- Linear case, the average VoIU for the M/M/1 system with an FCFS queue discipline.

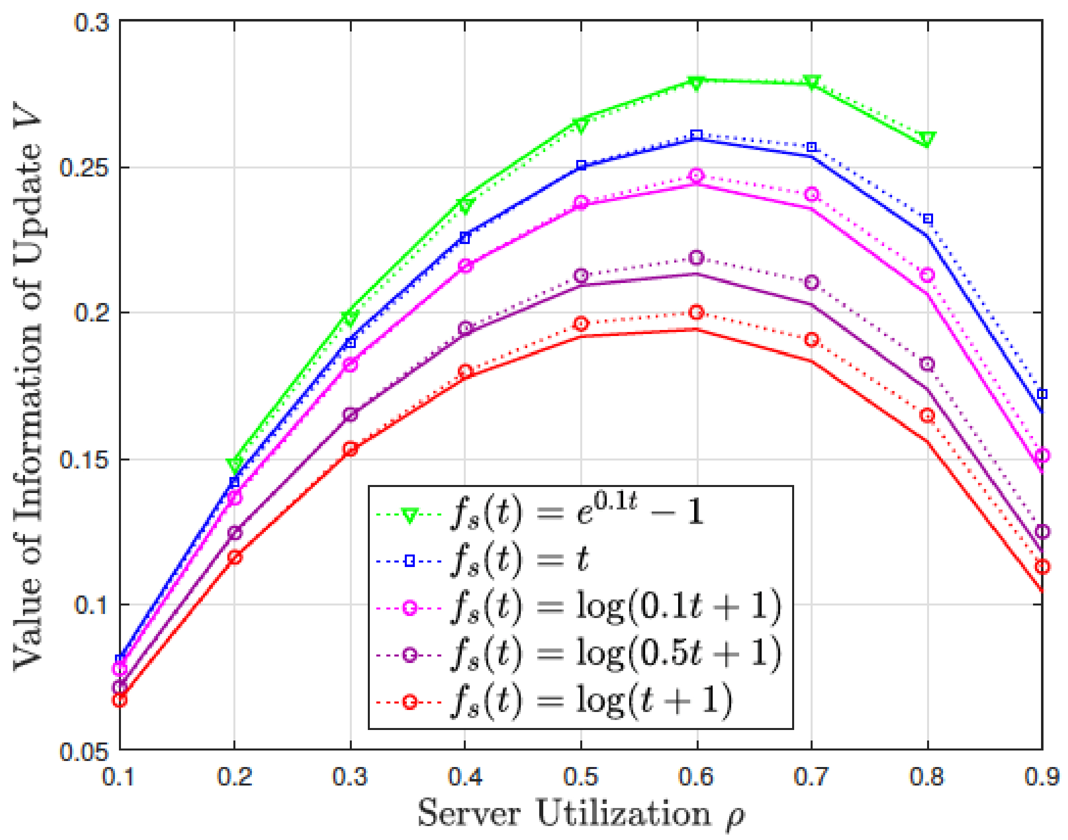
$$V_P = \lambda \frac{(1-\rho)}{2\rho} {}_2F_1\left(1, 2;3;2-\frac{1}{\rho}\right)$$

$${}_2F_1(a, b;c;z) = \sum_{n=0}^{\infty} \frac{(a)_n (b)_n}{(c)_n} \frac{z^n}{n!}$$

Pochhammer symbol

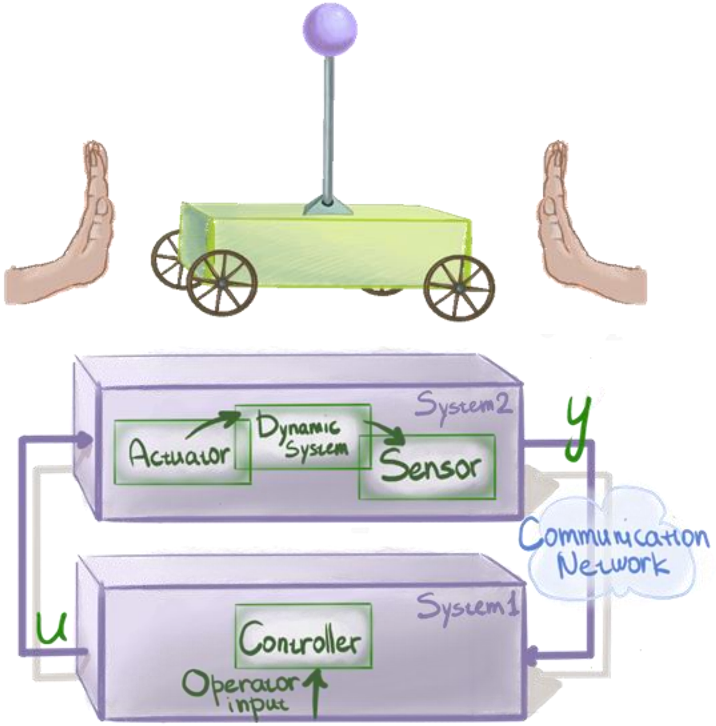
Numerical evaluation





Communication for Networked Control Systems

- Machine-to-Machine: Sensing & Actuation
- Control over communication networks
  - quality of control degrades due to adverse effects of the network
- **Metrics beyond linear AoI** can be used at MAC and transport layer to **prioritize most relevant information** and minimize control (LQG) cost



Credits to Polina Kutsevol

O. Ayan, et al. "Age-of-Information vs. Value-of-Information Scheduling for Cellular Networked Control Systems", 10th ACM/IEEE ICCPS 2019.
Ayan O. et al. "Task-oriented scheduling for networked control systems: An age of information-aware implementation on software-defined radios", arXiv:2202.09189.
Kutsevol P., Ayan O., Kellerer W., "Towards Semantic-Aware Transport Layer Protocols: A Control Performance Perspective", arXiv:2301.13653.

Towards a complete characterization of the AoI distribution

- Stochastic hybrid systems are utilized to analyze AoI moments and the moment generating function of AoI in networks
  - R. D. Yates, "The Age of Information in Networks: Moments, Distributions, and Sampling," IEEE Trans. Info. Theory 2020.

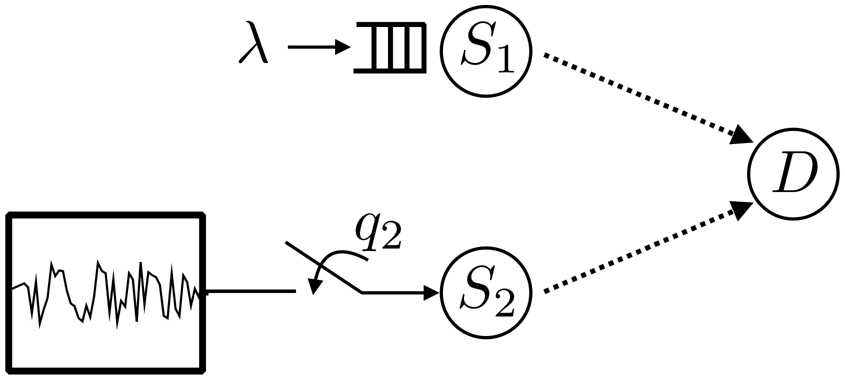
- A general formula of the stationary distribution of AoI is obtained and applied to a wide class of continuous-time single server queues with different disciplines
  - Y. Inoue, H. Masuyama, T. Takine, and T. Tanaka, "A general formula for the stationary distribution of the age of information and its application to single-server queues," IEEE Trans. Info. Theory 2019.

- Complete characterization of the AoI stationary distribution in a discrete time queueing system for: FCFS, preemptive LCFS, a bufferless system with packet dropping.
  - ***A methodology for analyzing general non-linear age functions, using representations of functions as power series.***
  - A. Kosta, N. Pappas, A. Ephremides, V. Angelakis, "The Age of Information in a Discrete Time Queue: Stationary Distribution and Non-linear Age Mean Analysis", IEEE JSAC SI on AoI, 2021. (shorter version in IEEE ICC 2020).

Interplay between AoI and other metrics

AoI and Delay Violation Probability Interplay in the Two-user MAC

- Two sources sending packets to a common destination.
- Source S_1 has external traffic with stringent delay requirements.
- Source S_2 monitors a sensor and samples a status update on each slot w.p. q_2.
  - Then, transmits the update to the destination through a channel with success probability p_2.
  - **If the transmission of a status update fails, then it is dropped.**
  - *Departure from the classical model of external updates that was common in the early studies of AoI.*

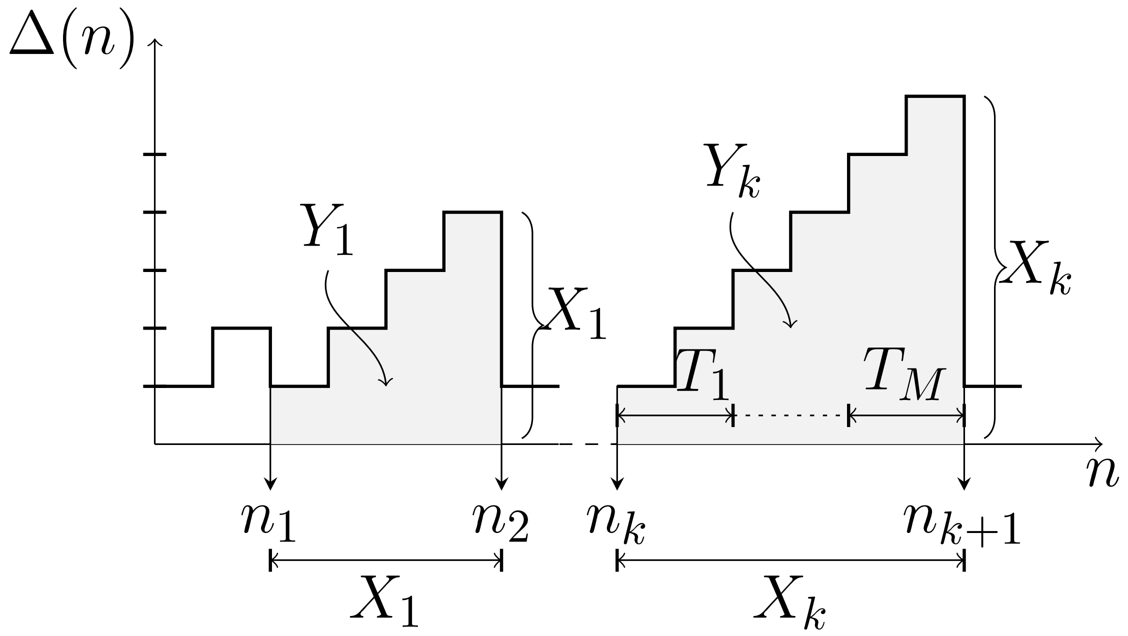


- Time is slotted.
- Instantaneous and error-free ACK/NACK.

N. Pappas, M. Kountouris, "Delay Violation Probability and Age-of-information Interplay in the Two-user Multiple Access Channel", *IEEE SPAWC* 2019.

Average AoI

T_i: time between two consecutive attempted transmissions
X_k: elapsed time at the destination between successful reception of k-th and the $(k+1)$-th status updates
M: number of attempted transmissions between two successfully received status updates at D



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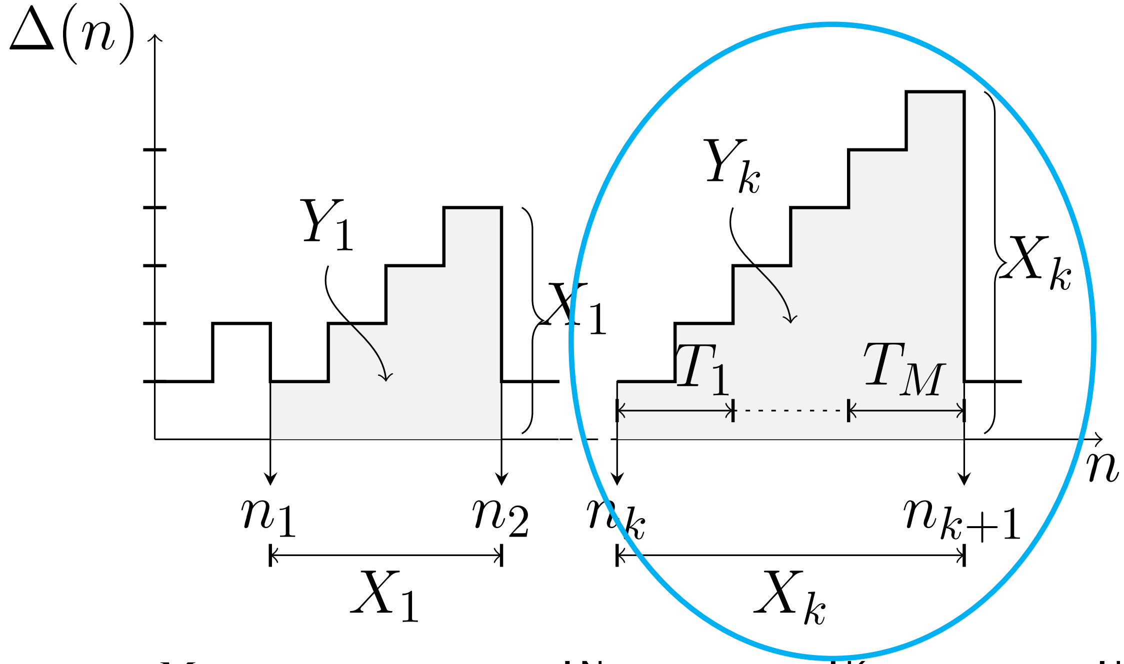

$$X_k = \sum_{i=1}^{M} T_i \qquad \Delta_N = \frac{1}{N}\sum_{n=1}^{N}\Delta(n) = \frac{1}{N}\sum_{k=1}^{K} Y_k = \frac{K}{N}\frac{1}{K}\sum_{k=1}^{K} Y_k$$

$$\Delta = \lim_{N \to \infty} \Delta_N = \frac{E[Y]}{E[X]} \qquad Y_k = \sum_{m=1}^{X_k} m = \frac{X_k(X_k+1)}{2}$$

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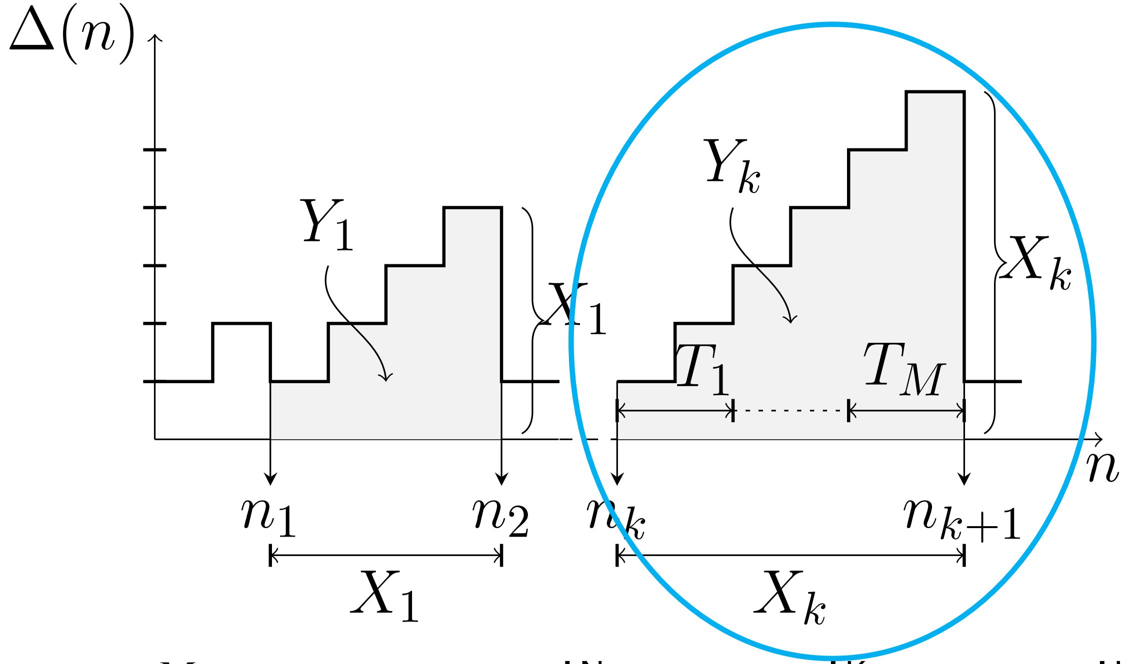

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$$\Delta_N = \frac{K}{N}\frac{1}{K}\sum_{k=1}^{K} Y_k = \frac{E\left[\frac{X_k^2}{2} + \frac{X_k}{2}\right]}{E[X]} = \frac{E[X^2]}{2E[X]} + \frac{1}{2}$$

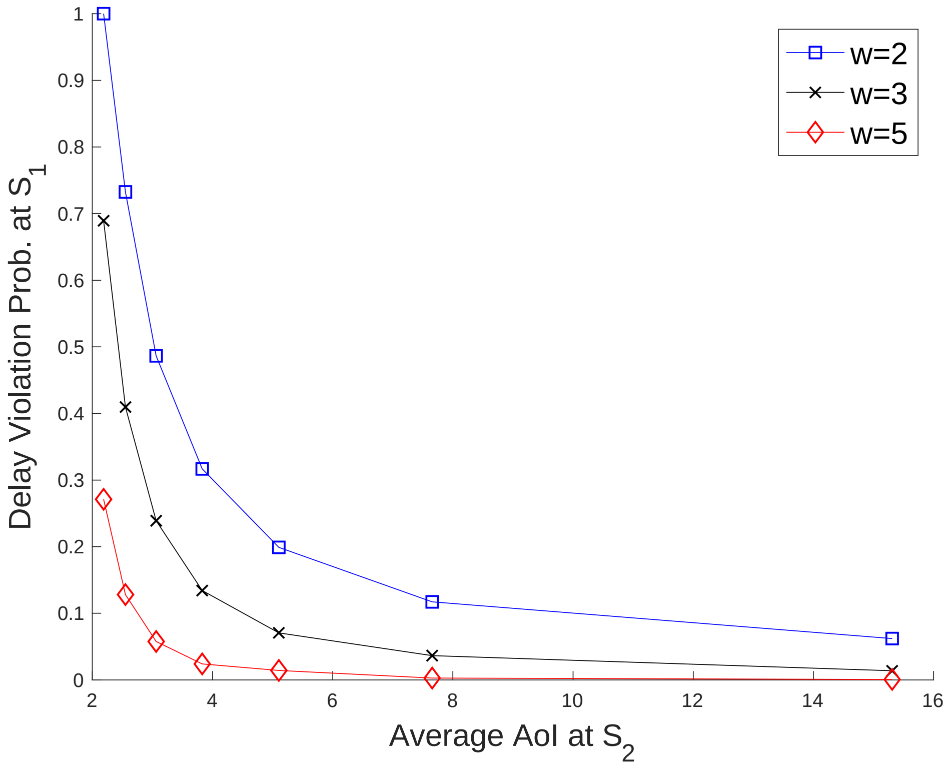
$$E[X] = \sum_{M=1}^{\infty} M E[T](1-p_2)^{M-1} p_2 = \frac{E[T]}{p_2}$$

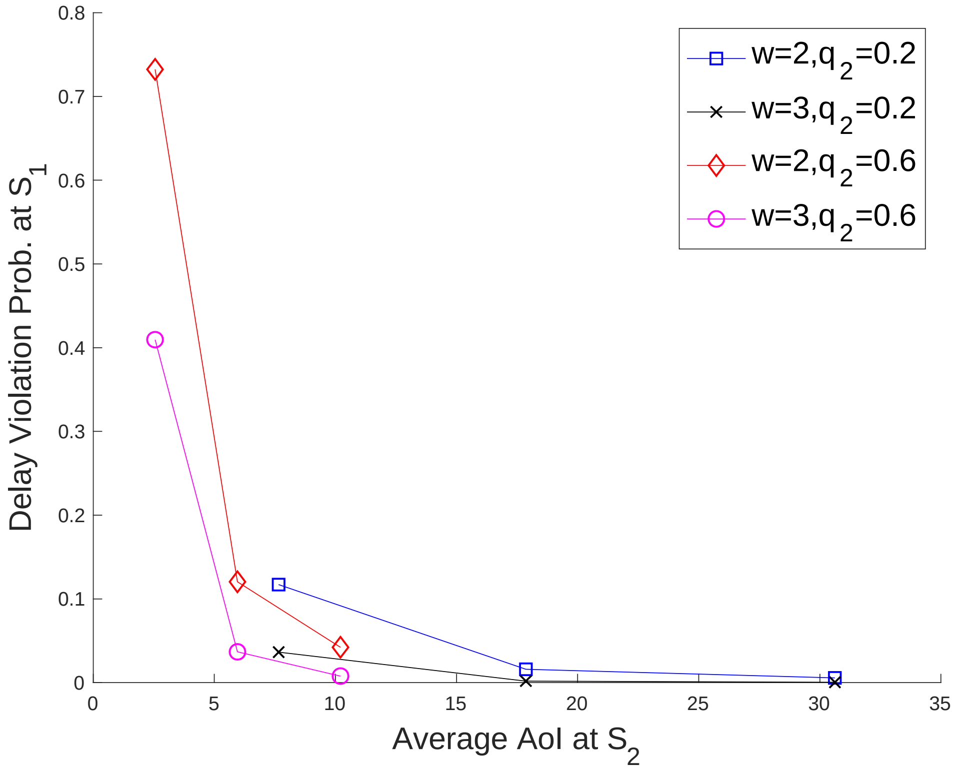
$$E[X^2] = \sum_{M=1}^{\infty} E[X^2|M](1-p_2)^{M-1} p_2$$

$$\overset{p_2 \ge 0}{=} \frac{E[T^2]}{p_2} + \frac{2(1-p_2)E[T]^2}{p_2^2}$$

$$\Delta = \frac{E[T^2]}{2E[T]} + \frac{E[T](1-p_2)}{p_2} + \frac{1}{2}$$

$$= \frac{1}{q_2 p_2}$$



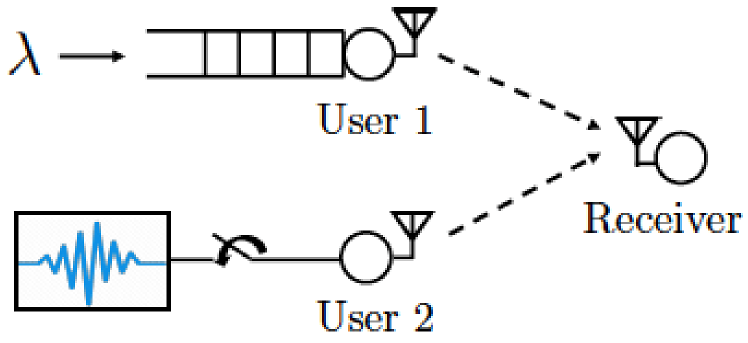


- As w increases, the delay violation probability decreases since S_1 becomes more delay tolerant.
- Increasing the transmit power of S_1 results in significant decrease of the delay violation probability and an increase of AoI due to larger interference.

Both delay violation probability and AoI can be kept low *even for stringent delay constraints* ***if the sampling rate is properly adapted***.

AoI and Packet Drop Rate Interplay

- The first user has deadline-constrained traffic and access the channel with probability q_1 when there is a packet in its queue
- User 2 (AoI-oriented) accesses the channel only if samples an update with a probability q_2
- If the transmission of a status update by user 2 fails, then is dropped (avoid transmitting outdated information)
- *For the AoI-oriented user, we provide the distribution of the AoI, the average AoI, and the probability the AoI to be larger than a value for each time slot.*



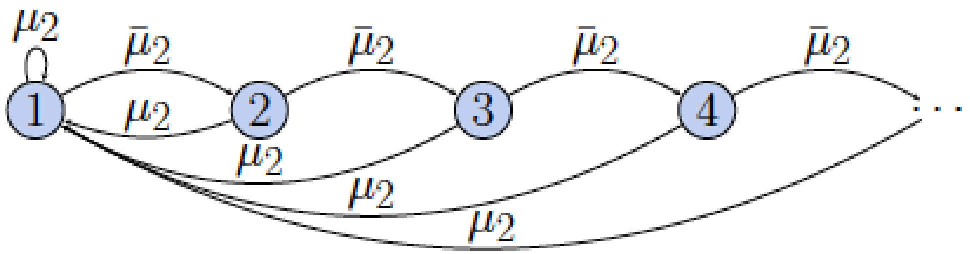
E. Fountoulakis, T. Charalambous, N. Nomikos, A. Ephremides, N. Pappas, "Information Freshness and Packet Drop Rate Interplay in a Two-User Multi-Access Channel", IEEE ITW, Apr. 2021.

AoI and Packet Drop Rate Interplay

- ***We model the evolution of AoI as a Discrete Time Markov Chain***
- The probability that AoI has value *i* is given by

$$\pi_i^A = (1-\mu_2)^{(i-1)}\mu_2, \forall i$$

$$\mu_2 = q_2(1 - q_1 P\{Q>0\})P_{2/2} + q_2 q_1(\Pr\{Q>0\}P_{2/2,1})$$



- The average AoI is $\bar{A} = \dfrac{1}{\mu_2}$,
- We can also obtain the *AoI violation probability* as

$$P\{A>x\} = (1-\mu_2)^x,$$

E. Fountoulakis, T. Charalambous, N. Nomikos, A. Ephremides, N. Pappas, "Information Freshness and Packet Drop Rate Interplay in a Two-User Multi-Access Channel", IEEE ITW, Apr. 2021.

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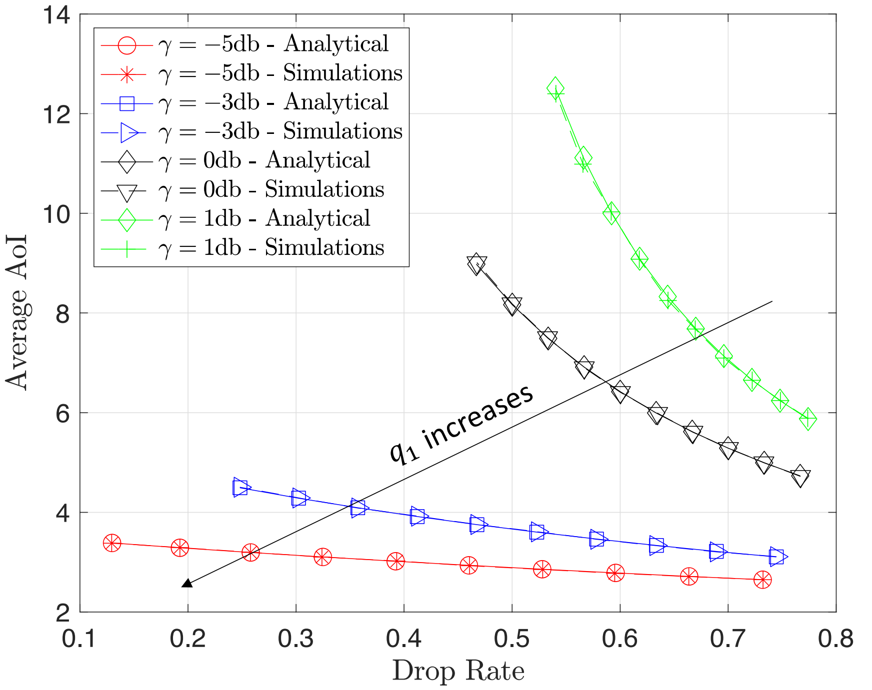

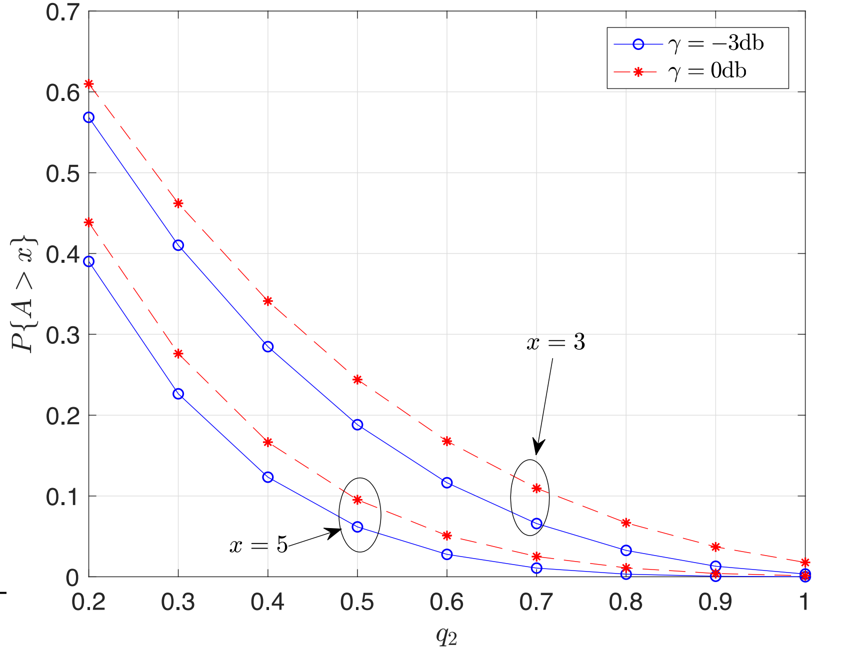

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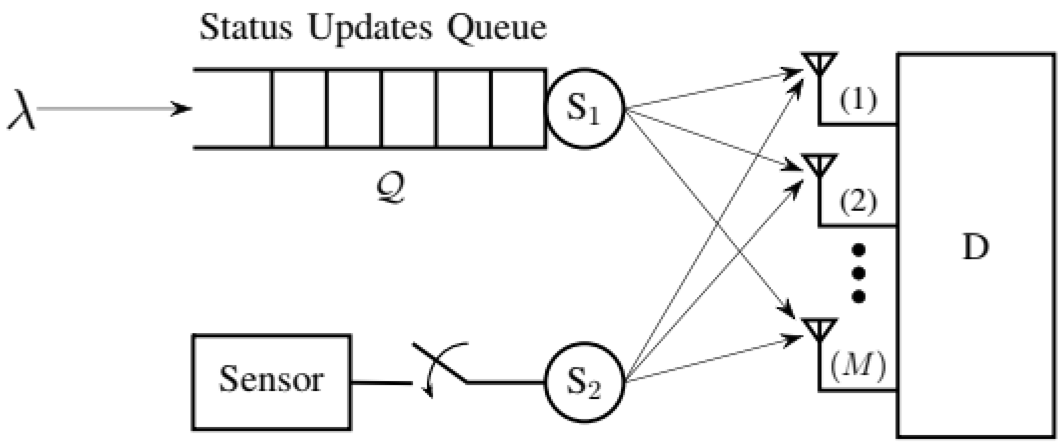
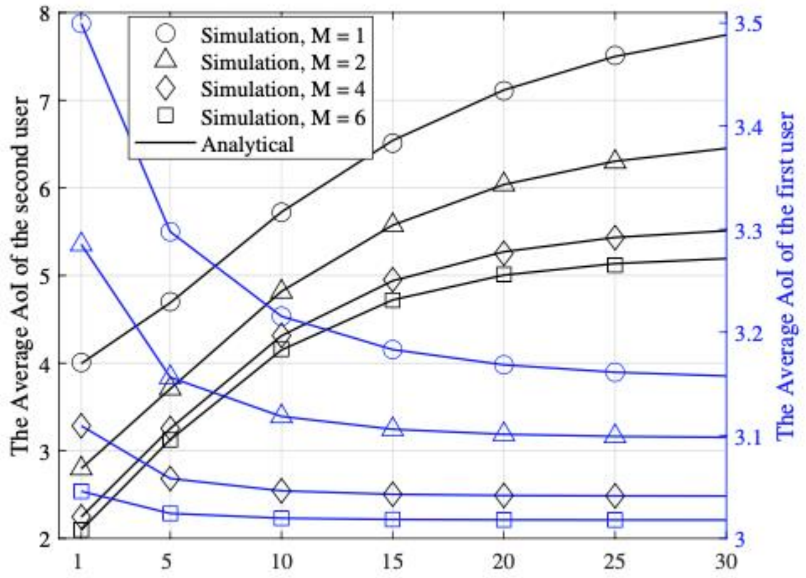
Two-user multiple access with multiple antennas

- Both users have AoI-oriented traffic with different characteristics
- User 1 has externally generated traffic without control
- User 2 controls the generation of status updates and deploys an AoI threshold-based sampling policy

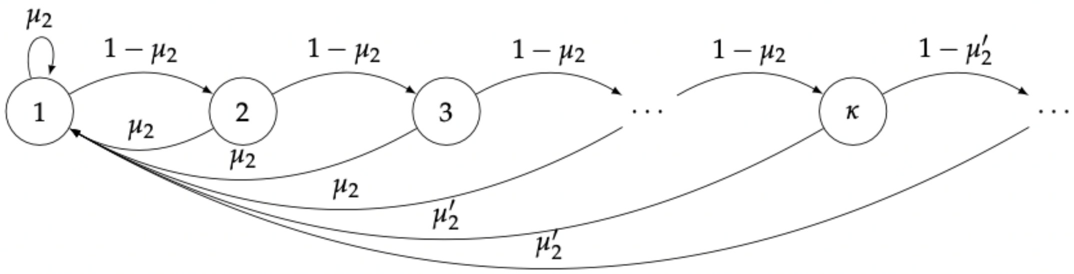




The average AoI of S_1 and S_2 for γ=3dB, λ=0.5, q_1=1, q_2=0.2, q_2' =0.5, κ = 1,5,10,...,30, and various values of M.

AoI distribution of the second user

$$\pi_i = \begin{cases} (1-\mu_2)^{i-1}\pi_1 & ,i<\kappa \\ \left(\frac{1-\mu_2}{1-\mu_2'}\right)^{\kappa-1}(1-\mu_2')^{i-1}\pi_1 & ,i\geqslant\kappa \end{cases} \qquad \pi_1 = \begin{cases} \mu_2' & ,\kappa=1 \\ \frac{\mu_2\mu_2'}{\mu_2'+(\mu_2-\mu_2')(1-\mu_2)^{\kappa-1}} & ,\kappa\geqslant 2. \end{cases}$$



M. Salimnejad, N. Pappas, "On the Age of Information in a Two-User Multiple Access Setup", Entropy Special Issue "Age of Information: Concept, Metric and Tool for Network Control", Apr. 2022.

Beyond AoI

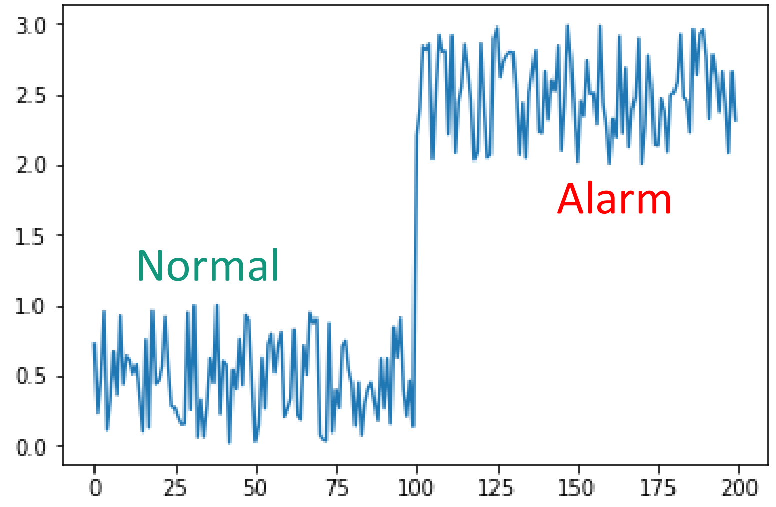
Extending AoI

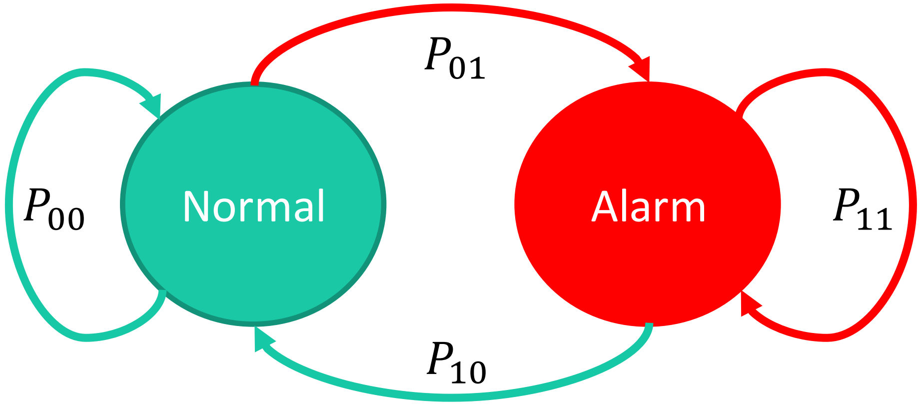
- The classical AoI does not capture properties of the source
  - Except timeliness itself which is a semantic property
- With non-linear AoI and the VoI, we go a step further
- Here we will discuss another extension of AoI

G. Stamatakis, **N. Pappas**, A. Traganitis, "Control of Status Updates for Energy Harvesting Devices that Monitor Processes with Alarms", IEEE GLOBECOM Workshops, Dec. 2019.

Stochastic process with alarms (or a two-state)

- Short timescale: Stochastic process Z_k evolves over discrete time k.
- Long timescale: A two state Markov Process
  - States: Normal, Alarm,
  - Geometrically distributed sojourn times in each state.
- The alarm state indicates the need for more frequent updates
  - Closely follow/track the evolution of Z_k to make informed decisions.
- Examples of Z_k
  - the network load under normal operation and under a DoS attack.
  - Physical phenomena such as temperature, water levels, and air pollution.
  - *Tracking of a process in general*.
- Objective: Optimize the freshness of status updates at the destination while considering the energy resources currently available as well as future demands for energy (especially during alarm periods).



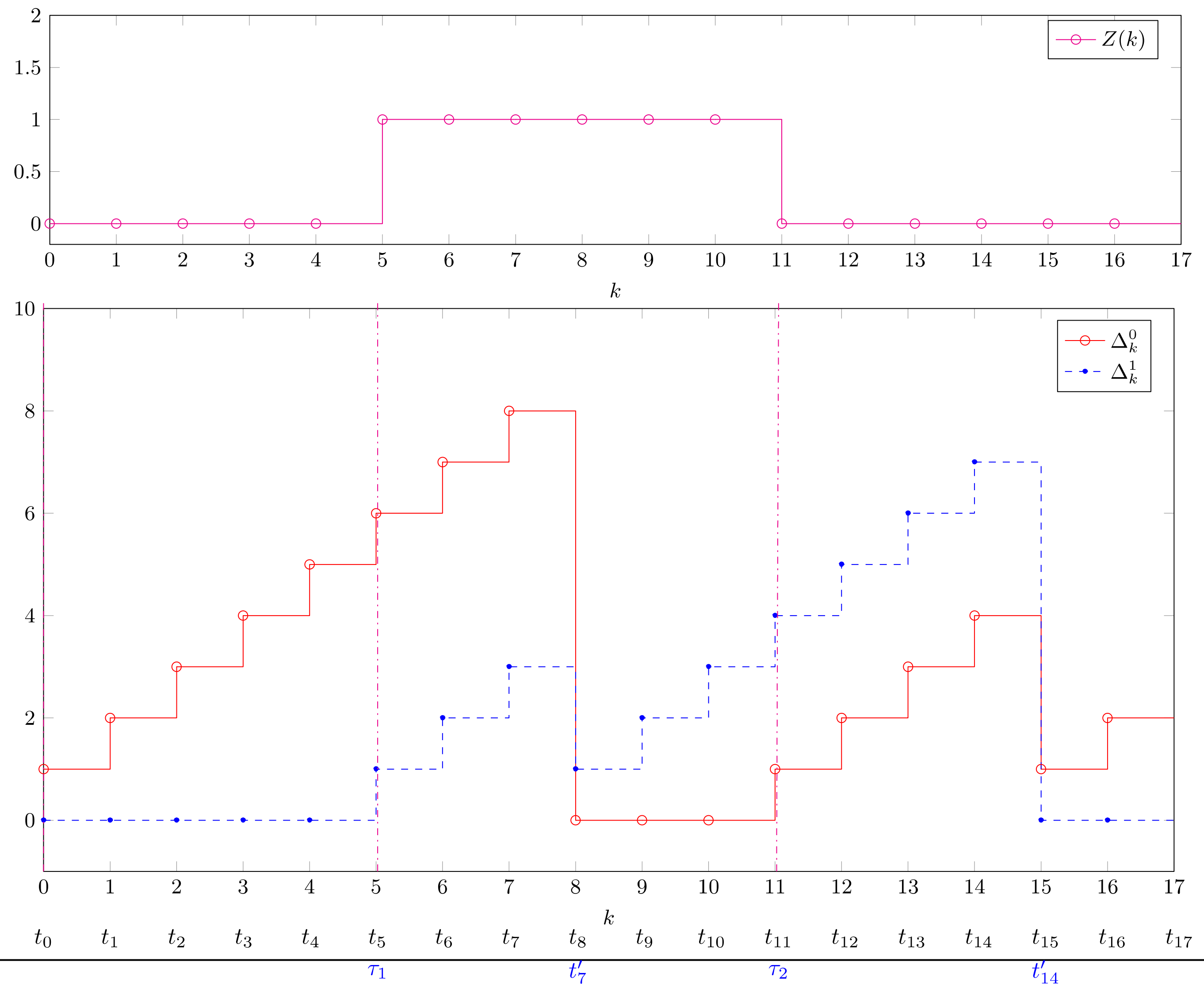


G. Stamatakis, N. Pappas, A. Traganitis, "Control of Status Updates for Energy Harvesting Devices that Monitor Processes with Alarms", IEEE GLOBECOM Workshops, Dec. 2019.

AoI for stochastic processes with alarms

- Extend the definition of AoI
  - the amount of time that has elapsed since the generation the last status update that has been successfully received by the monitor (typical)
  - the amount of time that has elapsed since the last state change of the stochastic process for which the destination in uninformed (new)
- Use two AoI variables, one for each state of the process $\Delta_{\mathrm{k}}^{z}, z \in \{0,1\}$.
- The destination knows the stochastic process to be in state Z_k^d.
  - Not necessarily the actual state of the stochastic process indicated with Z_k.
- Sequence of time indices where a state change has occurred
  - $\{\tau_n : Z_{\tau_n} \neq Z_{\tau_{n-1}}, n = 1,2, \dots\}$

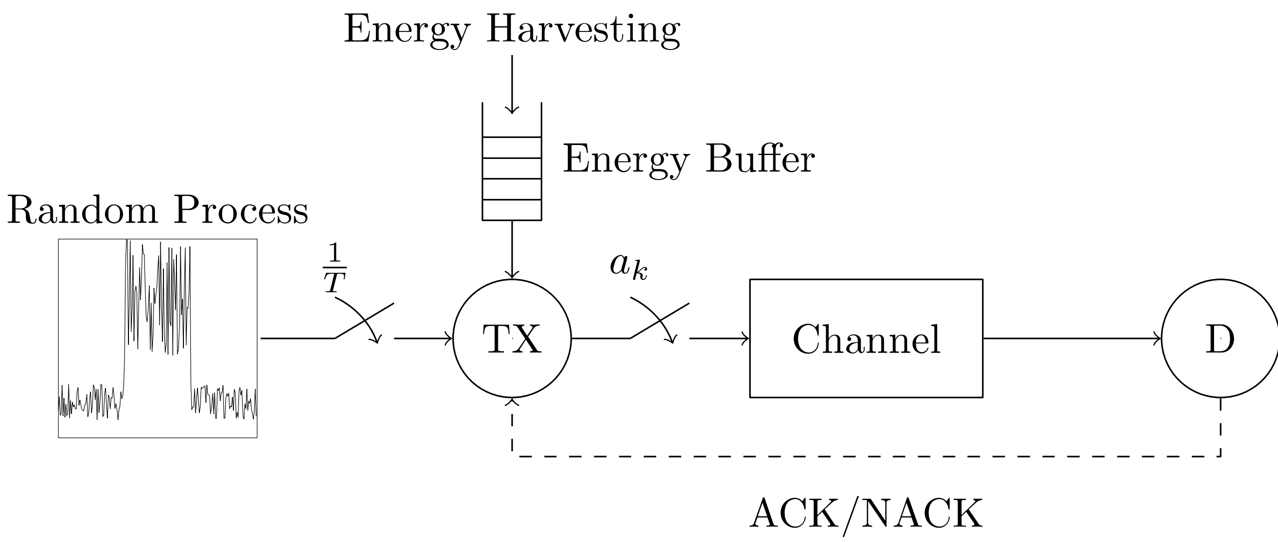
Extended AoI - illustration for the two-state process



$$\Delta_k^z = \begin{cases} k - U_k, & \text{if } z = Z_k^d \\ k - \tau_n, & \text{if } z \neq Z_k^d \text{ and } z = Z_k \\ 0, & \text{if } z \neq Z_k^d \text{ and } z \neq Z_k \end{cases}$$

System model (State & Action spaces)

- At the beginning of the k-th timeslot the sensor samples/senses the stochastic process in order to assess Z_k.
- The sensor also considers
  - The state of the process known at the destination Z_k^d.
  - The energy stored at the energy buffer E_k
  - The values of both AoI variables $\Delta_\mathrm{k}^0, \Delta_\mathrm{k}^1$
- These features constitute the **state** of the system
  - $s_k = [Z_k, Z_k^d, E_k, \Delta_\mathrm{k}^0, \Delta_\mathrm{k}^1]$
- Given s_k the sensor must choose whether to transmit a fresh status update or not, $a_k \in \{0,1\}$.



System model (Stochastics & Dynamics)

- By the end of the k-th timeslot
  - An energy unit may have been harvested as indicated by random variable $W_k^e \in \{0,1\}$ with P_e
  - The state of the stochastic process will change randomly $W_k^z \in \{0,1\}$
    - $P_z = \begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}$
  - If a transmission is attempted, it will succeed with probability
    - $P_s = P\{W_k^s = 1\}, W_k^s \in \{0,1\}$

- Determine the state of the system at the beginning of the $(k+1)$-th time-slot
  - $Z_{k+1} = W_k^z$
  - $Z_{k+1}^d = \begin{cases} Z_k^d, \text{ if } W_k^s = 0 \\ Z_{k,} \text{ if } W_k^s = 1 \end{cases}$
  - $E_{k+1} = \begin{cases} E_k + W_k^e - 1, \text{if } a_k = 1 \\ E_k + W_k^e, \text{ if } a_k = 0 \end{cases}$
  - $\Delta_{\mathrm{k+1}}^0, \Delta_{\mathrm{k+1}}^1$ are given by a recursive expression equivalent to the definition presented.

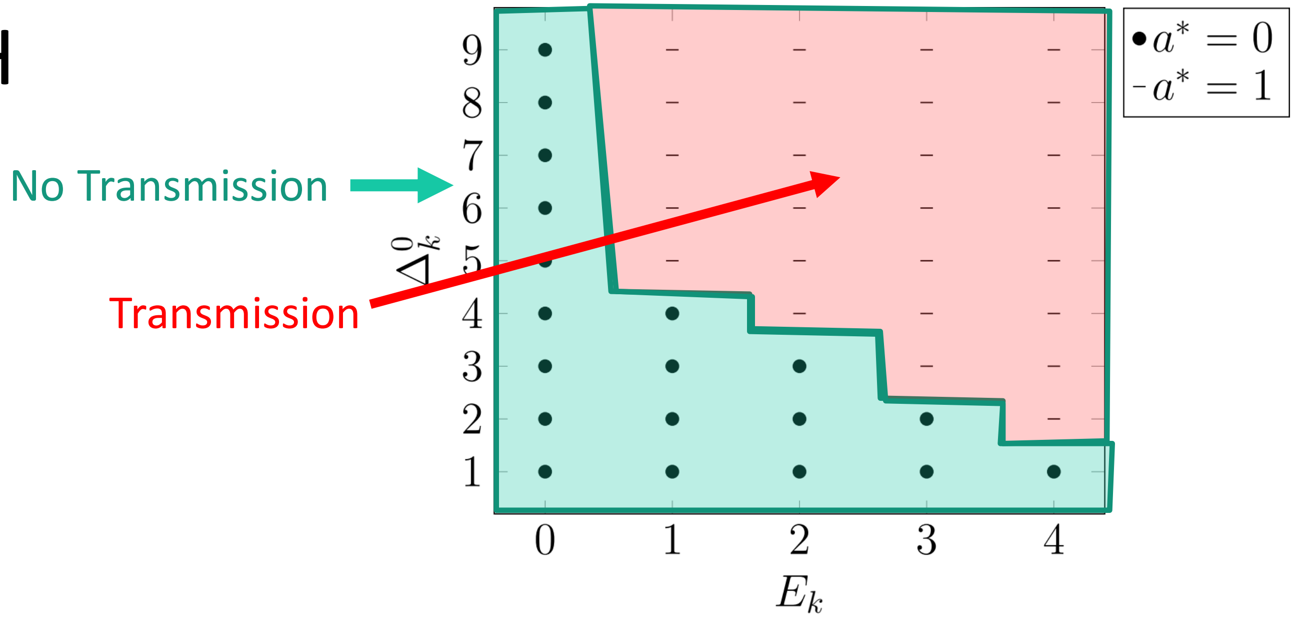
System model (Transition & Total Cost, Optimal policy)

- At the end of each time-slot a cost is paid by the sensor.
- The transition cost is an increasing function of Δ_{k}^{0} and Δ_{k}^{1}.
- $g(\Delta_{\mathrm{k}}^{0}, \Delta_{\mathrm{k}}^{1}) = g_0(\Delta_{\mathrm{k}}^{0}) + g_1(\Delta_{\mathrm{k}}^{1})$
  - **$g_1(\cdot)$ increases faster than $g_0(\cdot)$.**
  - ***This expresses the need for frequent status updates when in alarm state →The value of information in that case is higher!***
- Examples:
  - $g(\Delta_{\mathrm{k}}^{0}, \Delta_{\mathrm{k}}^{1}) = (1 - \mathrm{Z}_{\mathrm{k}})\Delta_{\mathrm{k}}^{0} + Z_k\left(\Delta_{\mathrm{k}}^{1}\right)^2$
  - i.e., cost is a function of the true state of the stochastic process and not the one perceived by the destination.
  - $g(\Delta_{\mathrm{k}}^{0}, \Delta_{\mathrm{k}}^{1}) = \Delta_{\mathrm{k}}^{0} + \left(\Delta_{\mathrm{k}}^{1}\right)^2$
  - cost considers both AoI variables simultaneously (Upcoming work)

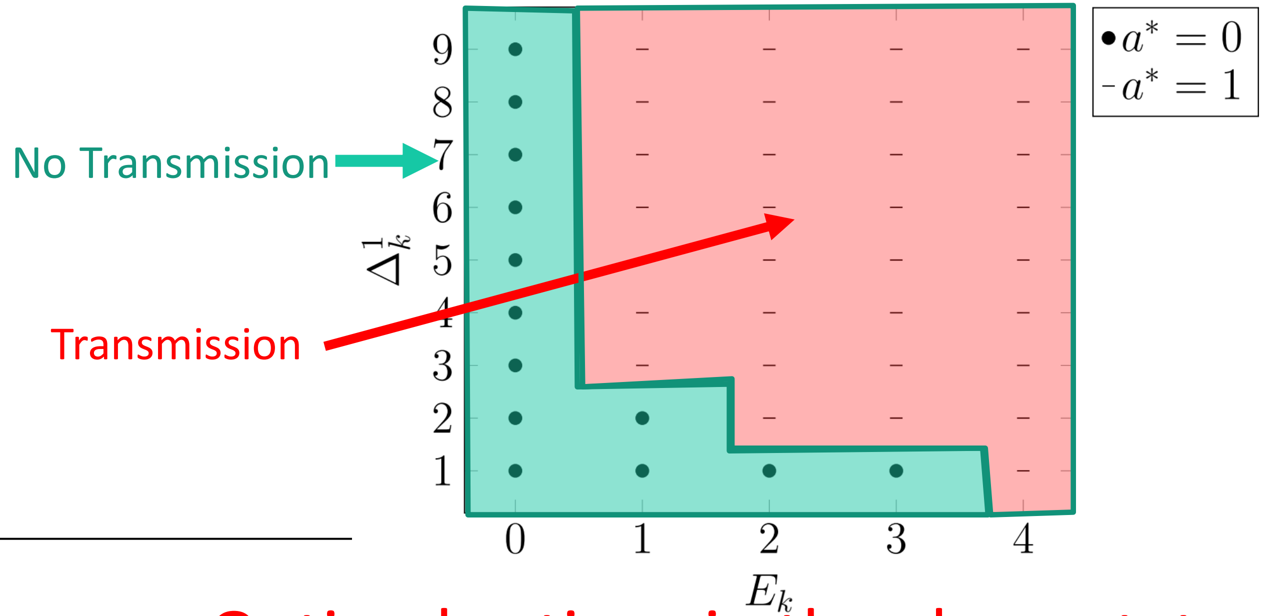
- Objective: Find an optimal policy that, given s_k, decides whether to transmit a status update to minimize the discounted transition costs accumulated over an infinite horizon.
- The problem is a Markov Decision Process, and the optimal policy can be found via the Value Iteration algorithm.
- *The curse of dimensionality can be circumvented by utilizing structural results for the optimal policy.*

Optimal Policy - Low Probability EH ($P_e = 0.4$) - $P_s = 0.8$

- Scenario
  - the process spends most of its time in normal mode with relative short periods of alarm states.
    - State transition matrix $P_z = \begin{bmatrix} 0.9 & 0.1 \\ 0.2 & 0.8 \end{bmatrix}$
- *The optimal policy will save energy in the normal state in order to be able to transmit in the alarm state*
  - Threshold structure: Transmissions occur when Δ_k^0 and Δ_k^1 is larger than a threshold value given E_k.



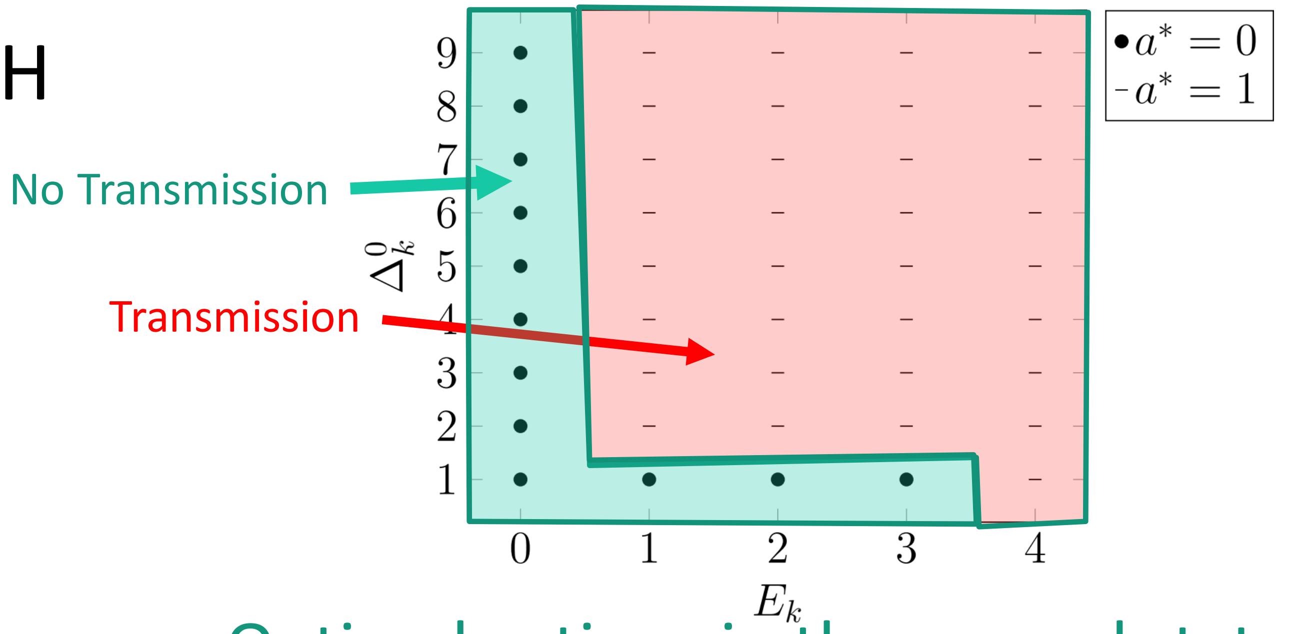
Optimal actions in the normal state



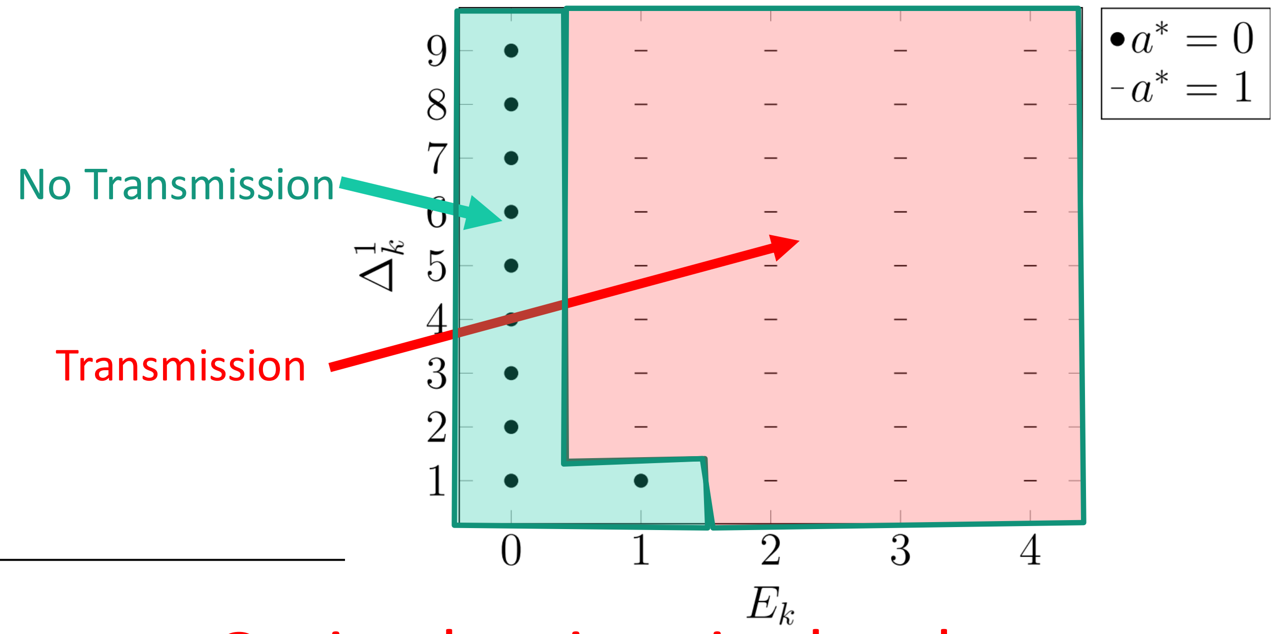
Optimal actions in the alarm state

Optimal Policy - High Probability EH ($P_e = 0.8$) - $P_s = 0.8$

- Scenario
  - the process spends most of its time in normal mode with relative short periods of alarm states.
    - State transition matrix $P_z = \begin{bmatrix} 0.9 & 0.1 \\ 0.2 & 0.8 \end{bmatrix}$
- *Energy saving is less important when EH occurs with high probability*
  - Threshold structure: Transmissions occur when Δ_k^0 and Δ_k^1 is larger than a threshold value given E_k.



Optimal actions in the normal state



Optimal actions in the alarm state

Cost-to-go for different state transition probabilities, $P_e = 0.8, P_s = 0.8$

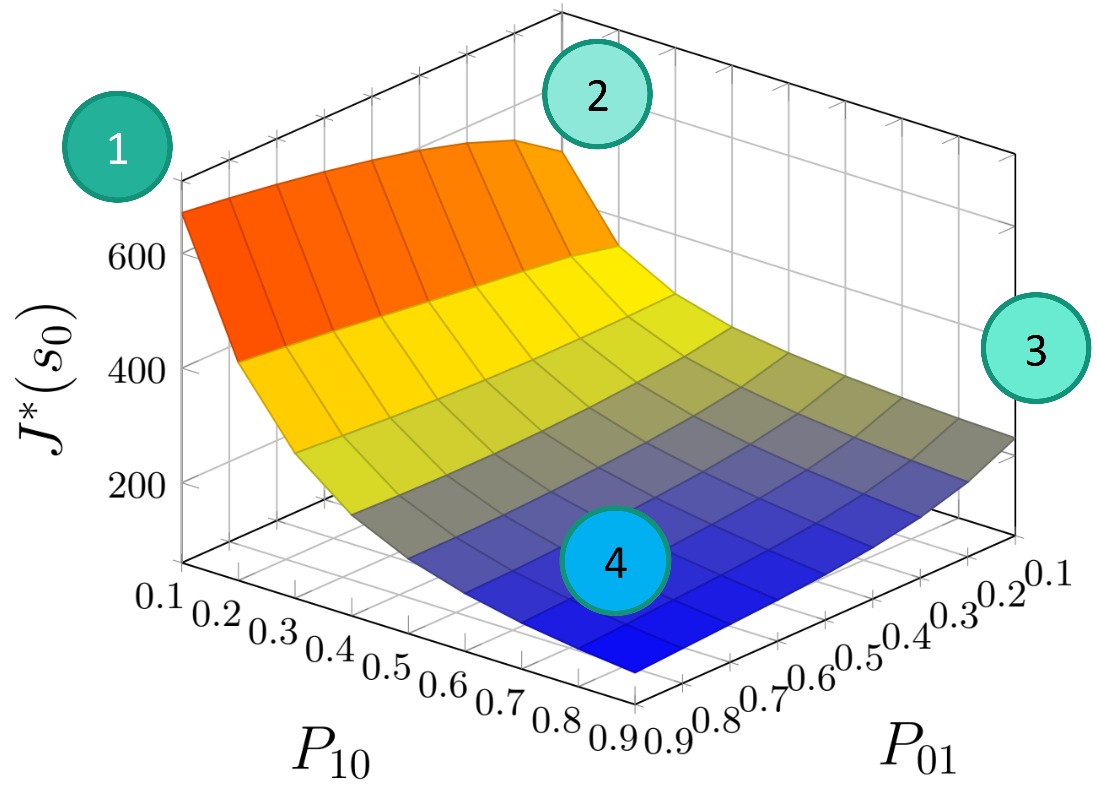
- Cost-to-go starting from a state s_0 where the stochastic process is in normal mode, the destination is aware of it, the energy buffer is empty and $\Delta_k^0 = 1, \Delta_k^1 = 0$.
- Various combinations of P_{10}, P_{01}
  - $P_z = \begin{bmatrix} 1 - P_{01} & P_{01} \\ P_{10} & 1 - P_{10} \end{bmatrix}$

1 Large sojourn time in the alarm state.
  - Large probability to enter the alarm state and small probability to leave out of it.

2 Large sojourn times in both states
  - Small probability to leave a state once in it.

3 Large sojourn time in the normal state.
  - AoI may increase up to large values.

4 The stochastic process oscillates between normal and alarm state with small sojourn times in each state.
  - AoI and costs remain small due to the short sojourn times.



Discussion

- *Some other metrics appeared after that work*
  - Age of Incorrect Information
  - Pull based AoI

- A. Maatouk, S. Kriouile, M. Assaad and A. Ephremides, "The Age of Incorrect Information: A New Performance Metric for Status Updates", IEEE/ACM Trans. on Networking 2020.
- J. Holm, A. E. Kalør, F. Chiariotti, B. Soret, S. Jensen, T. Pedersen, and P. Popovski, "Freshness on demand: Optimizing Age of Information for the query process", IEEE ICC 2021.
- F. Li, Y. Sang, Z. Liu, B. Li, H. Wu, and B. Ji, "Waiting but not aging: Optimizing information freshness under the pull model", IEEE/ACM Trans. on Networking 2021.
- X. Zheng, S. Zhou, and Z. Niu, "Urgency of Information for context aware timely status updates in remote control systems", IEEE Trans. on Wir. Comm. 2020.

- *Another relevant metric is the Version AoI*

- R. D. Yates, "The Age of Gossip in Networks," IEEE International Symposium on Information Theory (ISIT), 2021.
- B. Buyukates, M. Bastopcu and S. Ulukus, "Version Age of Information in Clustered Gossip Networks," IEEE Journal on Selected Areas in Information Theory 2022.
- E. Delfani and N. Pappas, "Version Age-Optimal Cached Status Updates in a Gossiping Network with Energy Harvesting Sensor". WiOpt, Aug. 2023.

Goal-oriented and semantics-aware communications

Towards Goal-oriented Semantic Communication

- Communication is about achieving specific goals.
- *Semantics: the semantic value of information is its usefulness in attaining a certain goal (pragmatics).*
- *Influence the relevance and effectiveness of the information we generate and communicate, depending on the objectives of the applications.*
- Utilize ***innate*** and ***contextual*** attributes of information.
- *A holistic redesign of the entire process of information generation, processing, transmission, and reconstruction.*

- [Chapter 7] 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.
- P. Popovski, O. Simeone, F. Boccardi, D. Gunduz, and O. Sahin, "Semantic-effectiveness filtering and control for post-5G wireless connectivity," *Journal of the Indian Institute of Science, 2020.*
- M. Kountouris, N. Pappas, "Semantics-Empowered Communication for Networked Intelligent Systems", *IEEE Communications Magazine, June 2021.*
- N. Pappas, M. Kountouris, "Goal-Oriented Communication for Real-Time Tracking in Autonomous Systems", *IEEE International Conference on Autonomous Systems (ICAS), Aug. 2021.*
- P. Popovski, F. Chiariotti, K. Huang, A. Kalor, M. Kountouris, N. Pappas, B. Soret, *"A Perspective on Time toward Wireless 6G", Proceedings of the IEEE, Aug. 2022.*

General description of **Semantics of Information (SoI)** metric

- A comprehensive system metric, *Semantics of Information (SoI)*, which captures the significance and usefulness of information w.r.t the goal of data exchange and the application requirements.
- Information attributes, which can be decomposed into *innate* (objective) and *contextual* (subjective).
- **Innate** are the attributes inherent to information regardless of its use, such as AoI, precision, correctness.
- **Contextual** are attributes that depend on the particular context or application for which information is being used.
  - For example, timeliness – as a function of AoI, accuracy (distortion), perception via divergence or distance function.

- N. Pappas, M. Kountouris, "Goal-Oriented Communication for Real-Time Tracking in Autonomous Systems", *IEEE International Conference on Autonomous Systems (ICAS), Aug. 2021.*
- M. Kountouris, N. Pappas, "Semantics-Empowered Communication for Networked Intelligent Systems", *IEEE Communications Magazine, June 2021.*

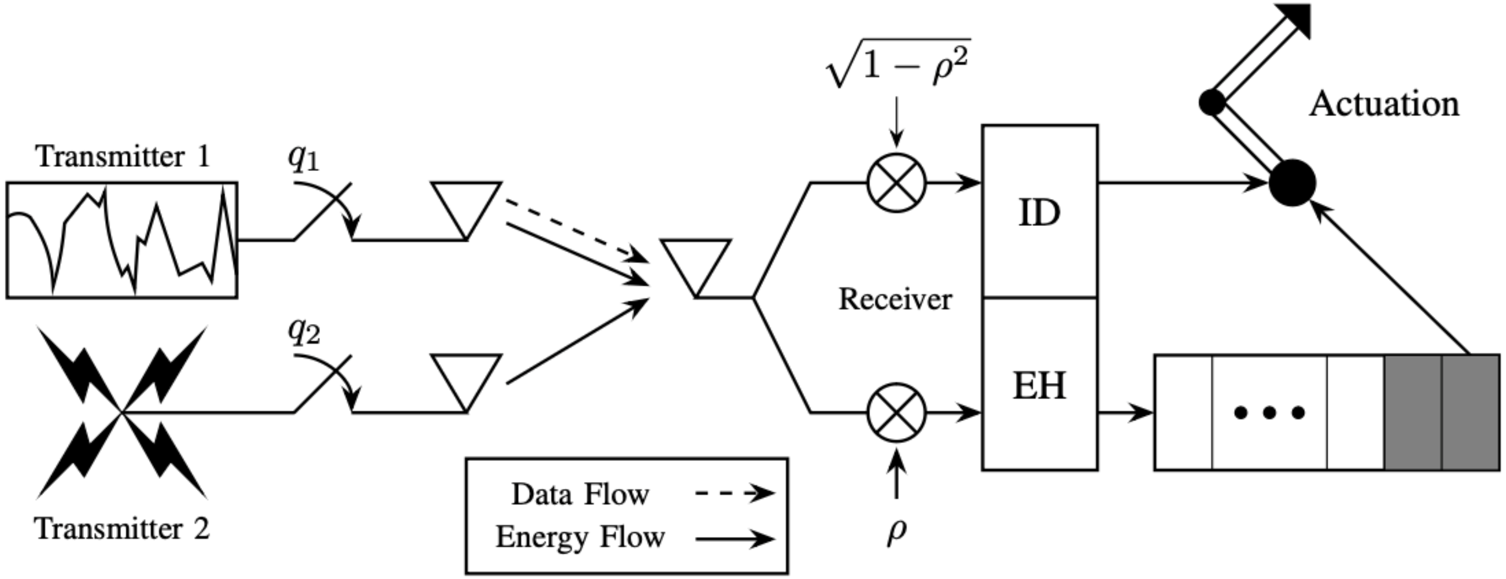
Age of Actuation in a Wireless Power Transfer System

A. Nikkhah, A. Ephremides, N. Pappas, “Age of Actuation in a Wireless Power Transfer System", IEEE INFOCOM - 6th Age of Information Workshop, May 2023.

LINKÖPING UNIVERSITY

System Model

- Observations from an external process are transmitted through status updates to a battery-powered receiver.
- The receiver is informed about the status of the process and if there is sufficient energy, uses them to perform an actuation to achieve a goal.
- We consider a wireless power transfer model.
- We propose a new metric, the *Age of Actuation (AoA)* which is relevant when the receiver utilizes the status updates to perform actions in a timely manner.



Age of Actuation (AoA)

- In order to perform an action, we need to receive a status update and a non-empty battery at the receiver.

$$A(t) \; = \; t - a(t)$$

time of the last performed actuation

$$\bar{A} = \begin{cases} \bar{A}_1 = \frac{1}{P_{\mathcal{D}}} & \frac{P_{\bar{\mathcal{D}},\mathcal{E}}}{P_{\mathcal{D},\bar{\mathcal{E}}}} \geq 1 \\ \bar{A}_2 = \frac{1}{P_{\mathcal{D}} \frac{P_{\bar{\mathcal{D}},\mathcal{E}}}{P_{\mathcal{D},\bar{\mathcal{E}}}} + P_{\mathcal{D},\mathcal{E}} \left(1 - \frac{P_{\bar{\mathcal{D}},\mathcal{E}}}{P_{\mathcal{D},\bar{\mathcal{E}}}}\right)} & \frac{P_{\bar{\mathcal{D}},\mathcal{E}}}{P_{\mathcal{D},\bar{\mathcal{E}}}} < 1 \end{cases}$$

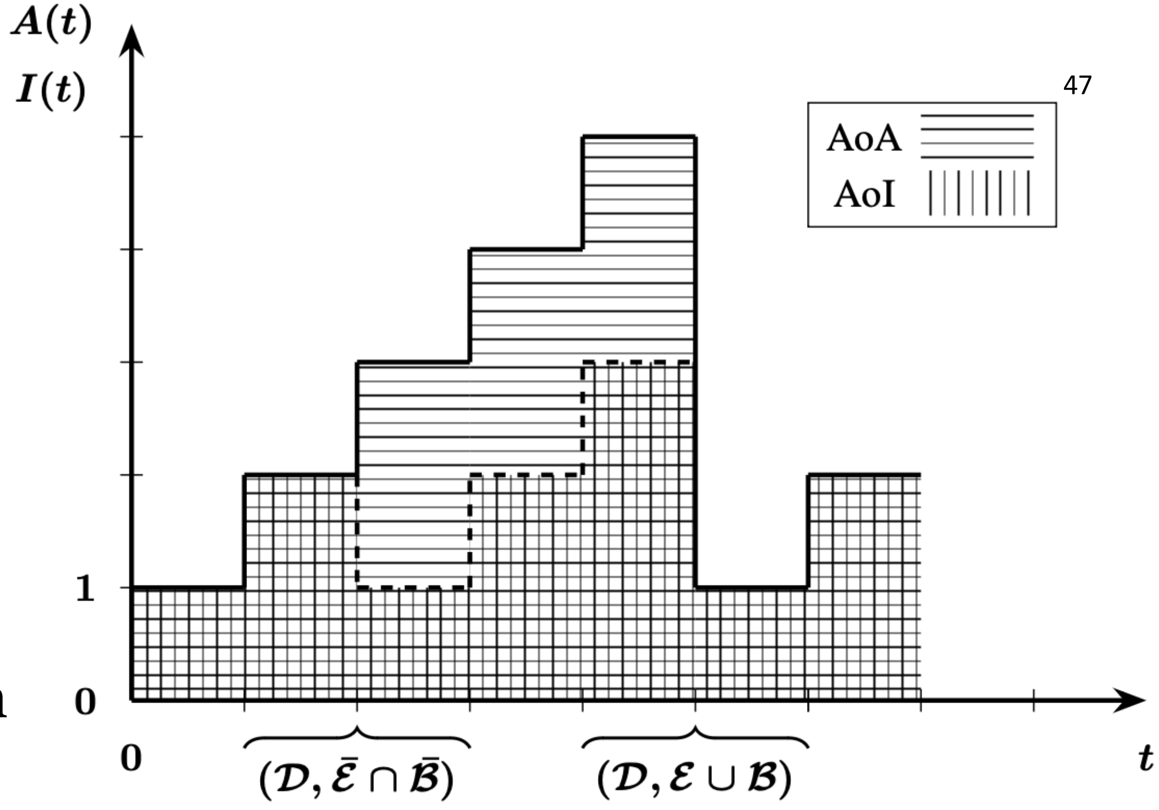


Fig. 2. The evolution of AoA and AoI metrics.

Numerical results

SUCCESS PROBABILITIES OF DATA AND ENERGY TRANSMISSION.

	P_{d1}	P_{d12}	P_{e2}	P_{e12}
Setup 1	1	0.62	0.20	0.23
Setup 2	1	0.34	0.60	0.63

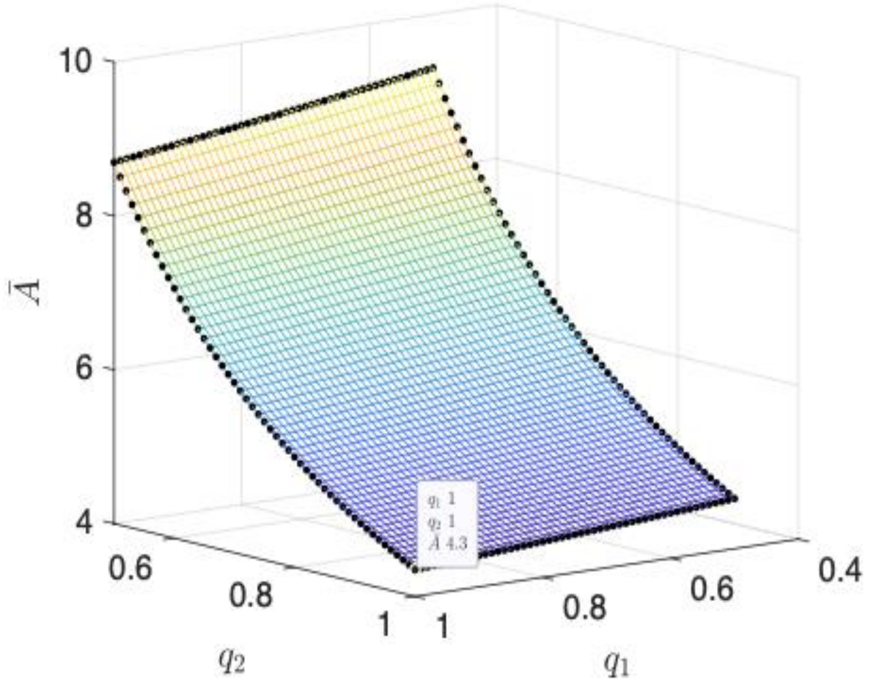


Fig. 3. Average AoA for the infinite-sized battery for the first setup. The minimum $\bar{A}^* = 4.3$ is achieved by $q_1^* = 1$ and $q_2^* = 1$.

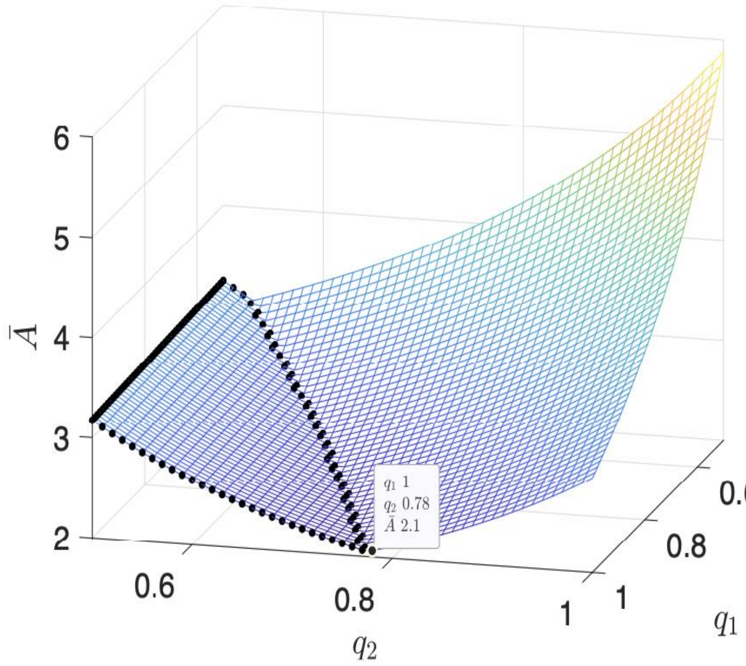
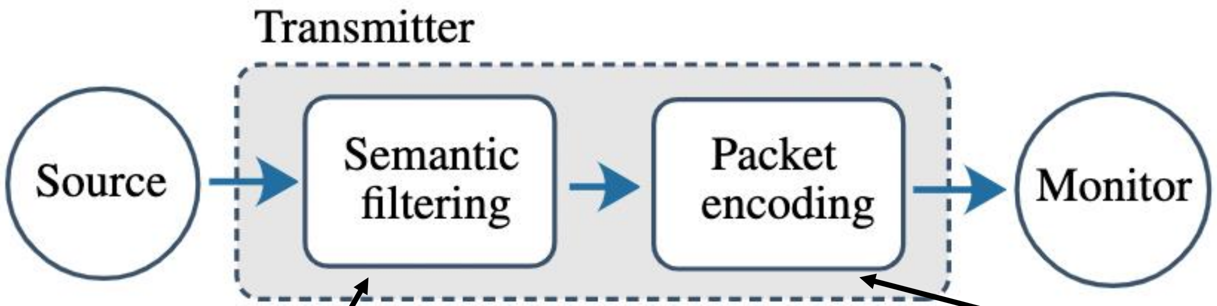


Fig. 4. Average AoA for the infinite-sized battery for the second setup. The minimum $\bar{A}^* = 2.1$ is achieved by $q_1^* = 1$ and $q_2^* = 0.78$.

Semantics-aware Source Coding

P. Agheli, N. Pappas and M. Kountouris, “Semantics-Aware Source Coding in Status Update Systems”, IEEE ICC Workshop on Semantic Communications, May 2022

Semantics-aware source coding



$\mathcal{X} = \{x_1, x_2, \cdots, x_n\}$
Discrete symbols

Probability of realization
$\tilde{p}_i = P_X(x_i)$ – known PMF
wlog $\tilde{p}_i \geq \tilde{p}_j, \forall\, i \leq j$

Importance-based Selective Encoding

Importance/semantic value
only k *most/least* probable realizations selected
packets from remaining $n{-}k$ realizations discarded

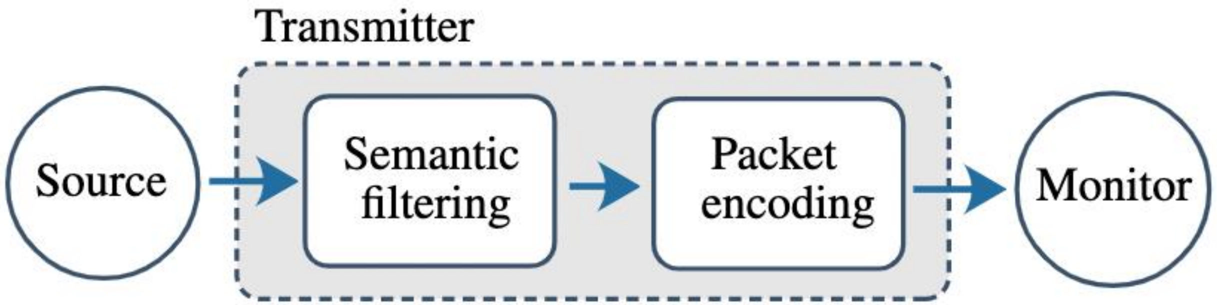
- TX encodes an admitted packet from the i-th realization using a prefix-free code based on the truncated distribution with conditional probabilities

$$p_i = \frac{\tilde{p}_i}{q_k}, \forall\, i \in \mathcal{I}_k \subset \mathcal{I}, \text{ where } q_k = \sum_{i \in \mathcal{I}_k} \tilde{p}_i$$

- Information source generates status updates (packets) and forwards them to a TX
- i.i.d. sequence of observations
- Packets generated according to Poisson(λ)
- TX encodes the packets and sends them to a remote monitor (RX)
- TX is bufferless (a newly-admitted packet is blocked when the channel is busy)
- Error-free channel

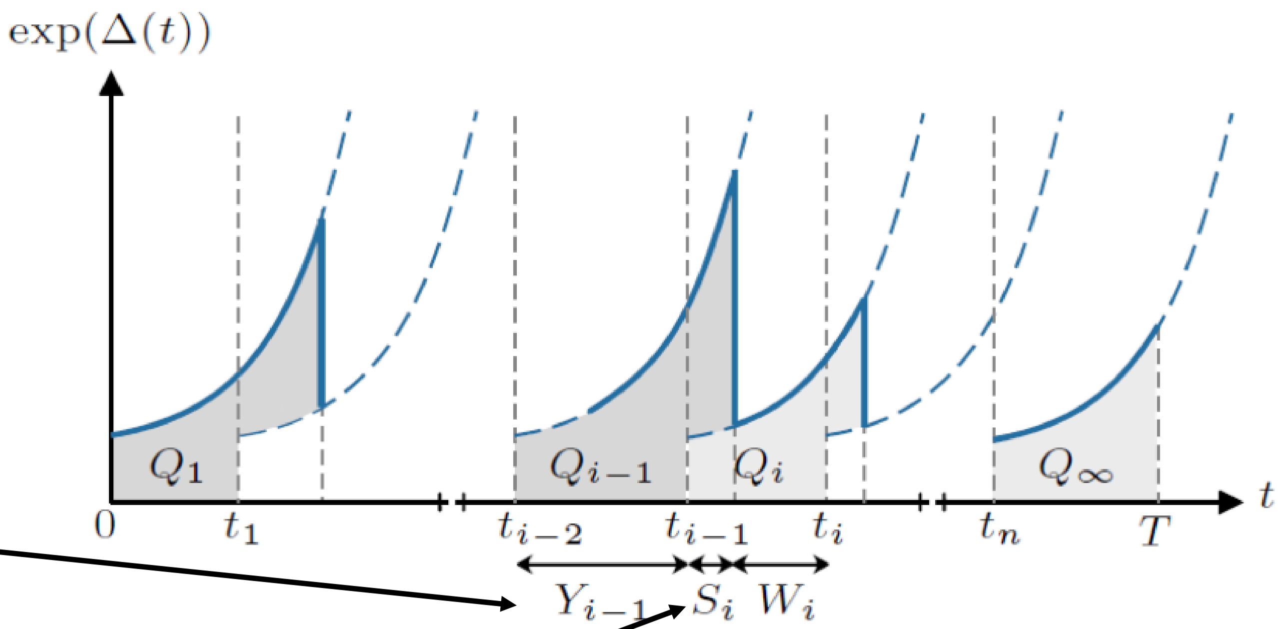
M.Bastopcu, B.Buyukates, S.Ulukus,"Optimal selective encoding for timely updates," CISS 2020.

Average SoI



- Timeliness (SoI): $\mathcal{S}(t) = g\big(\Delta(t)\big)$
  - $g: \mathbb{R}_0^+ \to \mathbb{R}$ a utility function of information freshness
  - AoI: $\Delta(t) = t - u(t)$

$$L(\Delta) = \lim_{T\to\infty} \frac{1}{T}\int_0^T g(\Delta(t))\mathrm{d}t = \lim_{T\to\infty}\frac{1}{T}\left\{\sum_{i=1}^{\mathcal{N}(T)} Q_i + Q_\infty\right\} = \eta\mathbb{E}[Q].$$



$Y_i = t_i - t_{i-1}$
update interval between the i-th successive arrival and its next one

service time
$S_i = \ell_i$ time units
ℓ_i: length of the codeword assigned to x_i

waiting time $W_i = \sum_{k=1}^{N} Z_k$
N: # admitted arrivals generated before finding the channel idle
Z_k: time between two admitted arrivals, $\sim \exp(\gamma)\,, \gamma = 1/(\lambda q_k)$

- **Aim**: Find the codeword lengths ℓ_i that optimize a weighted sum of the average SoI and the average length for a cost function $\varphi(\ell_i)$, i.e., $\sum_i p_i \varphi(\ell_i)$.

$$\min_{\{\ell_i\}} \quad L(\Delta) + w \sum_{i \in \mathcal{I}_k} p_i \phi(\ell_i)$$
$$\text{s.t.} \quad \sum_{i \in \mathcal{I}_k} 2^{-\ell_i} \leq 1$$
$$\ell_i \in \mathbb{Z}^+$$

Relaxation

$$\min_{\{\ell_i\}} \quad \underbrace{\mathbb{E}[Q] + w \sum_{i \in \mathcal{I}_k} p_i(\alpha \ell_i + \beta \ell_i^2)}_{\mathcal{J}_{\mathrm{SoI}}}$$
$$\text{s.t.} \quad \sum_{i \in \mathcal{I}_k} 2^{-\ell_i} \leq 1,$$
$$\ell_i \in \mathbb{R}^+.$$

$$L(\Delta) = \lim_{T \to \infty} \frac{1}{T} \int_0^T f(\Delta(t)) \mathrm{d}t$$ $f: \mathbb{R}_0^+ \to \mathbb{R}$ a non-decreasing function

$$\phi(x) = \alpha x + \beta x^2,\ \alpha, \beta \geq 0$$

- Quadratic cost function for the codeword length under binary alphabetic
- φ convex: longer (shorter) codewords are penalized more (less) than the linear case (e.g., Huffman coding)

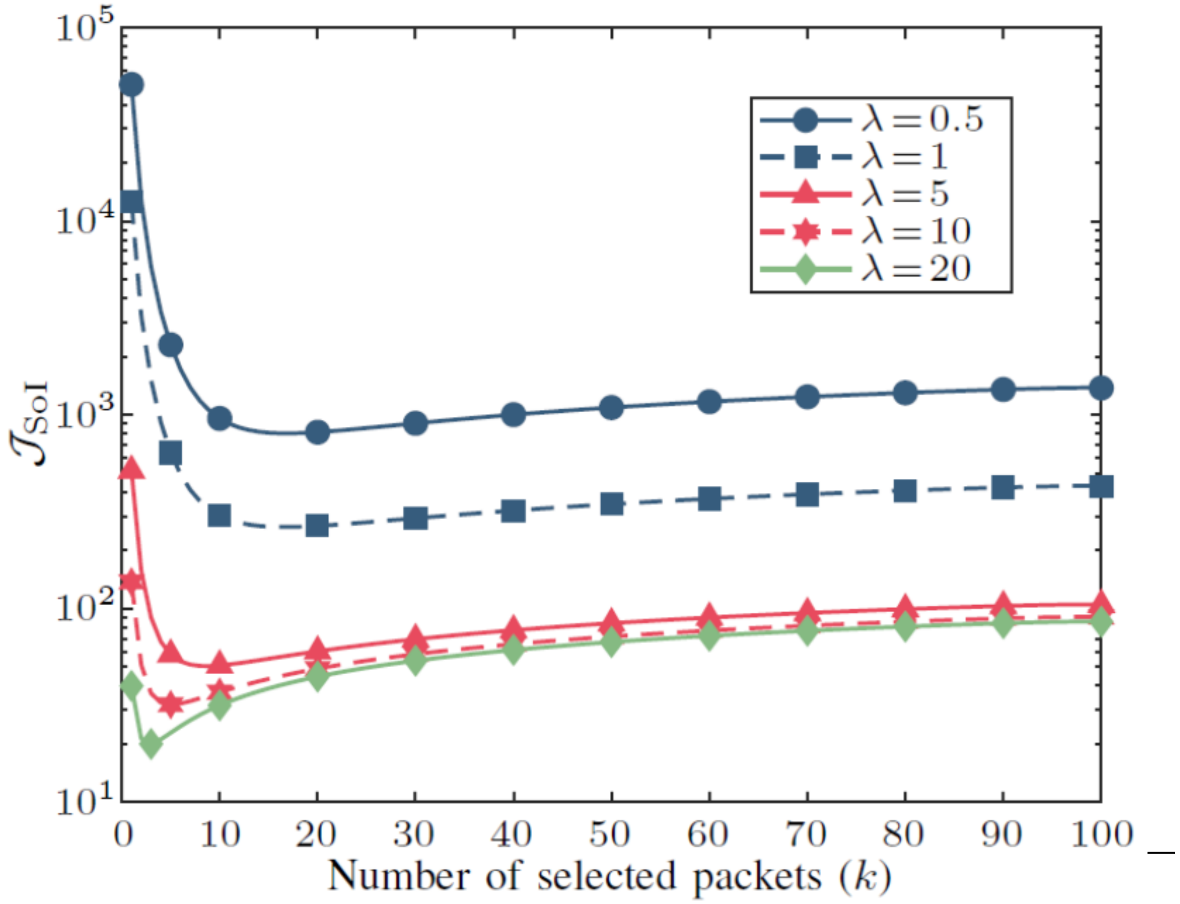
Kraft-McMillan inequality: existence of a uniquely decodable code for a given set of codeword lengths

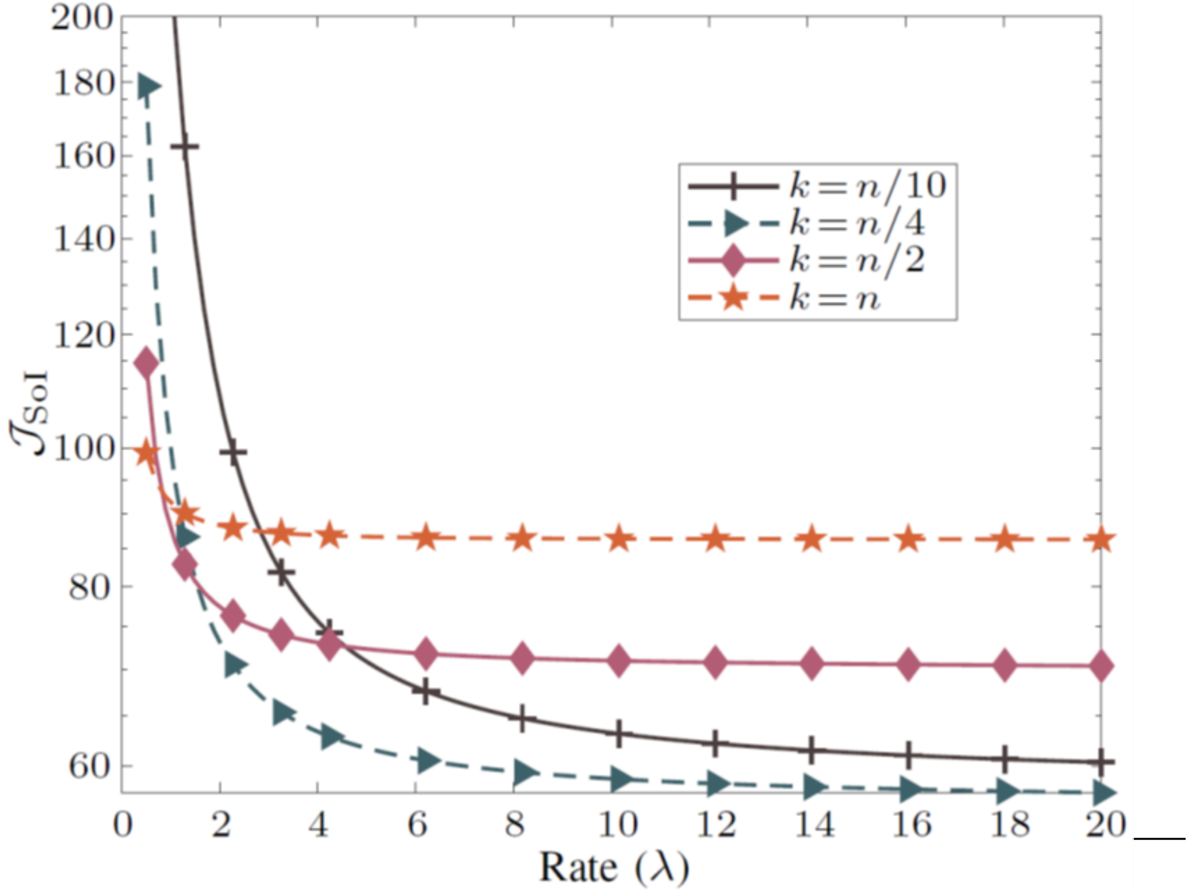
Numerical evaluation

Zipf(n, s) distribution with pmf $P_X(x) = \frac{1/x^s}{\sum_{j=1}^{n} 1/j^s}$

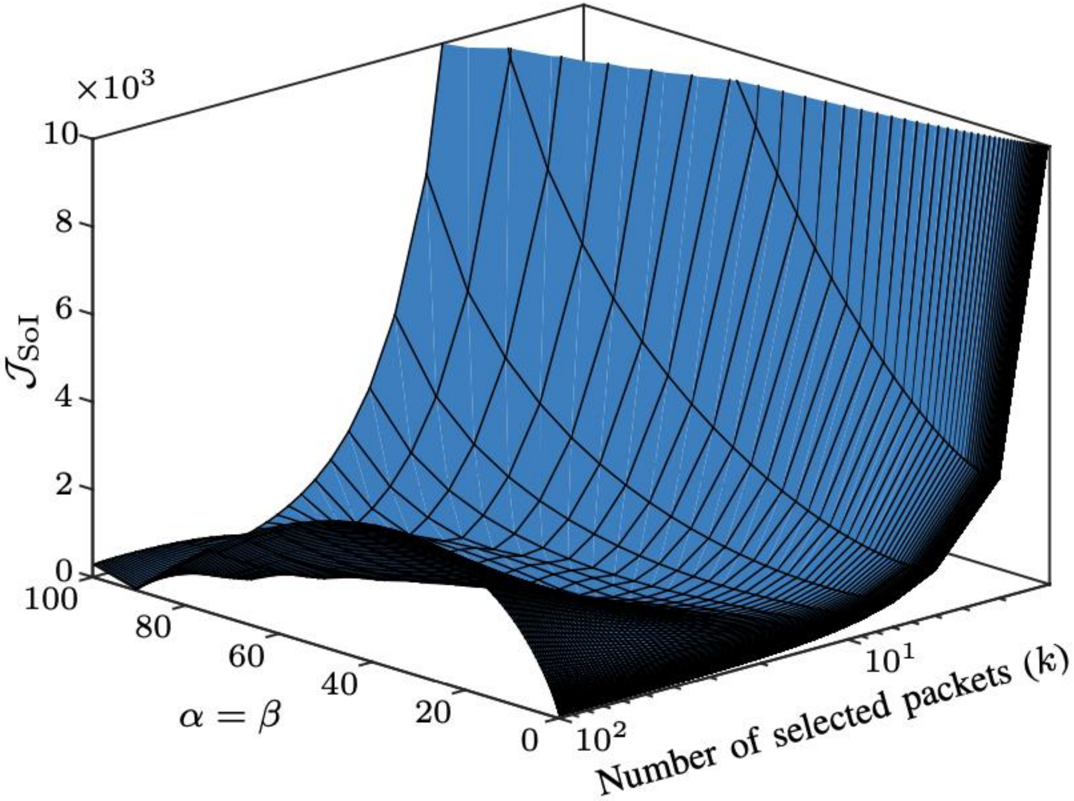
$n = |\mathcal{X}| = 100$ and exponent $s = 0.4$

$s = 0$ uniform, $\nearrow s$ “peaky distribution”





Interplay among SoI, semantic filtering (k), and codeword length



OPTIMAL PARAMETERS UNDER THE EDT SCENARIO.

λ	k	$\alpha = \beta$	λ	k	$\alpha = \beta$
0.5	20	1.26	10	5	2.5
1	18	1.58	20	2	12.59
5	10	1.99			

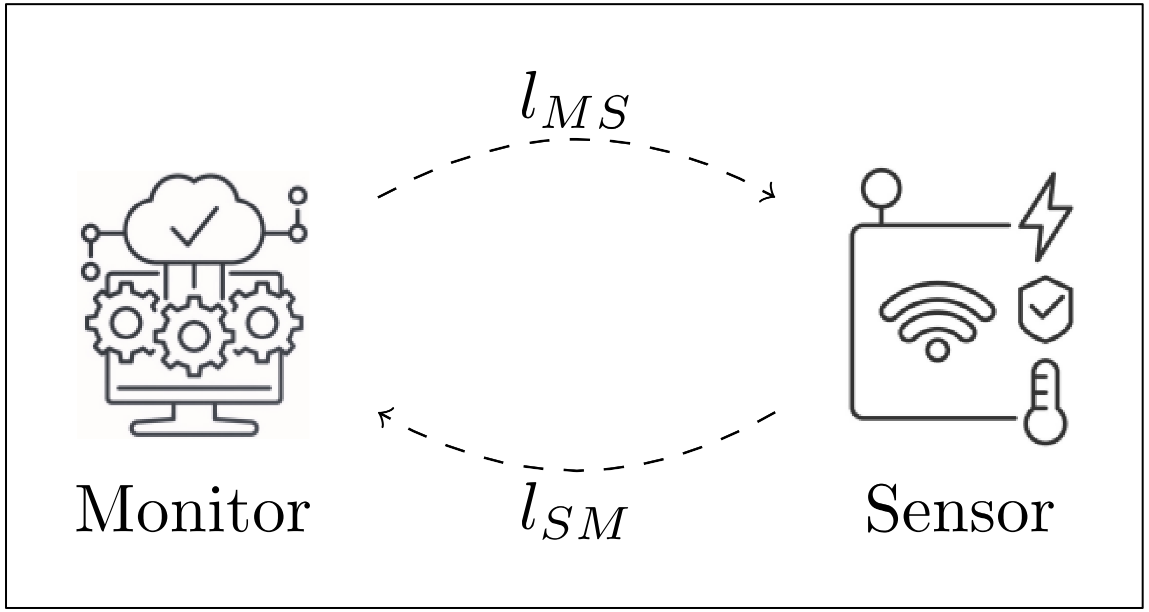
- Objective function continuously increases as cost parameters increase for small k
- *For large* k: increasing cost parameters causes the objective function to increase then decrease
- *Increasing the input rate* (hence, decreasing k^*), optimal cost parameters increase
- *When input rate is high*: larger penalties for the codeword length must be assigned to ensure transmitting the most important data.

Fault Detection and autonomous maintenance

- **G. Stamatakis, N. Pappas, A. Fragkiadakis, A. Traganitis, "Semantics-Aware Active Fault Detection in IoT", 20th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), Sep. 2022.**
- G. Stamatakis, N. Pappas, A. Fragkiadakis, A. Traganitis, "Autonomous Maintenance in IoT Networks via AoI-driven Deep Reinforcement Learning", IEEE INFOCOM - 4th Age of Information Workshop, May 2021.

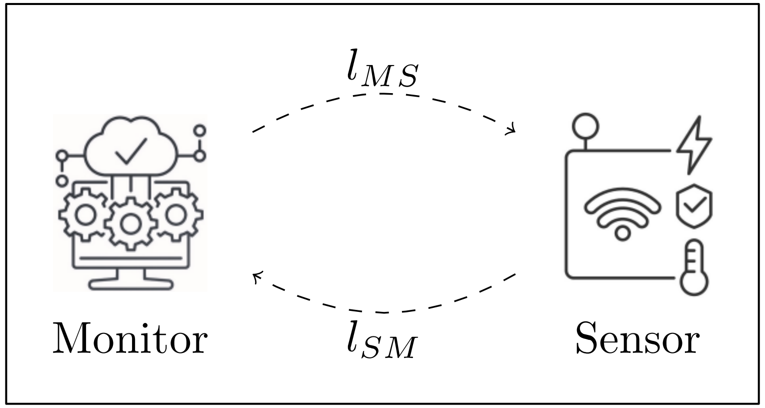
System Model

- A sensor transmits status updates to monitor.
- Wireless links between monitor/device and device/monitor subject to failure, on/off channels according to a Markov Chain.
- If a link is in on/off state, the transmission is successful/failed.
- Slotted time
- The sensor can be in healthy/faulty state according to a Markov Chain.
  - If the sensor is in a healthy state can generate an update with probability P_g and transmits it over the link l_{SM}.



➢ *After a successful reception of a probe* through l_{MS}, the sensor will generate a fresh status update at the next time slot with probability 1/0, if it is in a healthy/faulty state.

System Model



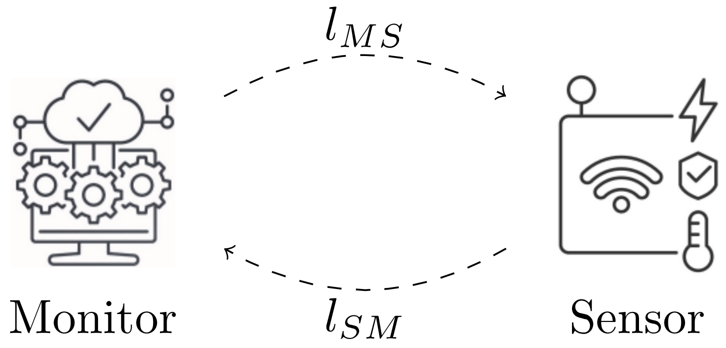
- We consider the problem of a monitoring agent that must *optimally decide*, at the beginning of a time slot, *to probe or not the sensor*.
- A transition cost is induced on the agent by the end of each time slot due to its decision and the dynamics of the system.
- ***Minimize the total accumulated cost over a finite time horizon***.
- The transition cost is a function of
  - the agent's confidence in its belief about the joint health status of the sensor and links,
  - the *staleness of the status updates* it has received up to that time slot,
  - and a *cost value c* associated with the *probing action*.

Problem formulation

V_t quantifies the importance of receiving a fresh status update at the monitor at time t.

Value of Information

$$V_t = \lambda_1 H_t + \lambda_2 \bar{\Delta}_t$$



The agent's confidence in the health status belief vector is expressed by its entropy.

Normalized AoI over the horizon

$$\Delta_t = \begin{cases} 1, & \text{if } z_t = 1 \\ \min\{N, \Delta_t + 1\}, & \text{if } z_t = 0 \end{cases}$$

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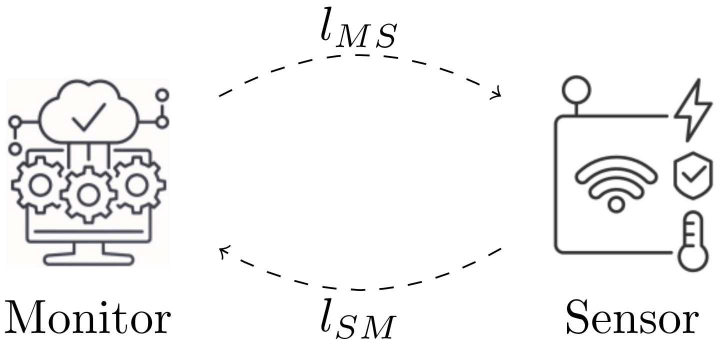

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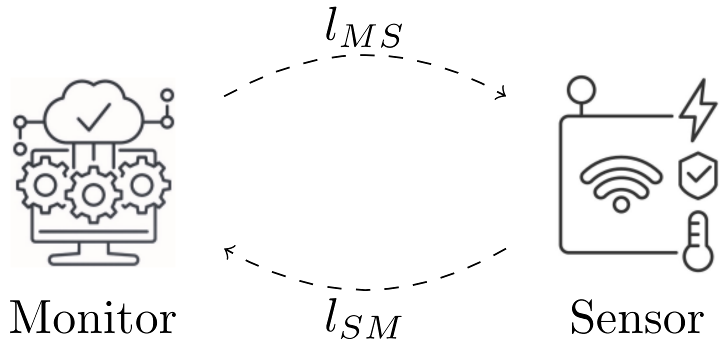

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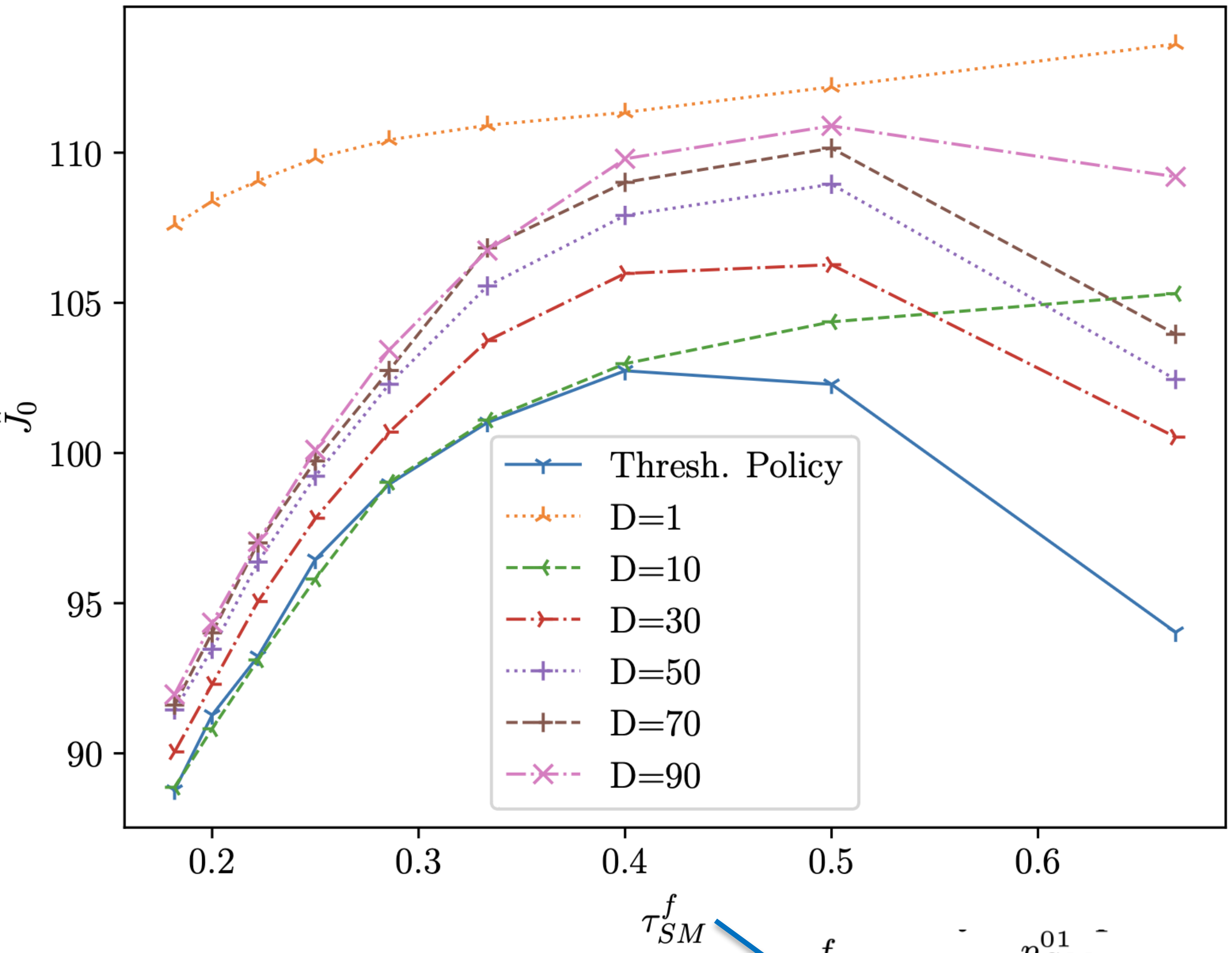
Remark: Probing will lead to the reduction of both AoI and entropy? **No, not always!**
Probing makes the generation of a status update mandatory; however, probing introduces a new type of uncertainty due to the transmission failures.

Numerical results

c = 1, λ_1 = 1, λ_2 = 1, P_g = 0.1, N=100

$$P^{MS} = \begin{bmatrix} 0.9 & 0.1 \\ 0.9 & 0.1 \end{bmatrix} \quad P^{S} = \begin{bmatrix} 0.9 & 0.1 \\ 0.9 & 0.1 \end{bmatrix}$$

$$P^{SM} = \begin{bmatrix} 0.9 & 0.1 \\ 1 - p_{SM}^{11} & p_{SM}^{11} \end{bmatrix}$$



$$\tau_{SM}^{f} = \frac{p_{SM}^{01}}{1 - p_{SM}^{11} + p_{SM}^{01}}$$

- Comparative results with a delay based probing policy.
- For large values of τ_{SM}^{f} , the monitor was confident that l_{SM} was in a faulty state, and this resulted in a reduced cost due to health status entropy.
- Despite the reduction of J_o for all policies **the effect of persistent probing is still evident** and especially for the delay policies with D = 1 and 10.

Concluding remarks

Remarks and future directions

- AoI has emerged as an end-to-end performance metric for systems that employ status updates.

- Introduction of **information freshness** requirements ***will create systems that work smarter than harder***, so they will be **more *effective***.
  - The updating process should not underload nor overload the system.
  - The system should process new updates rather than old.
  - The system should avoid processing updates without sufficient novelty.

Remarks and future directions

- There are still many interesting research directions
  - Definition of effective age (term coined by Prof. Ephremides in ITA 2015)
  - Sampling and remote reconstruction
  - Deploying of AoI in machine learning
  - Security
- It provides stronger connections with areas such as Signal Processing
- Metrics that can capture the requirements of Wireless Networked Control Systems
- AoI is one of the dimensions of *semantics-empowered communications*!
  - AoI is an ***innate*** attribute of information
  - Non-linear AoI can be a ***contextual*** attribute

- M. Kountouris, N. Pappas, "Semantics-Empowered Communication for Networked Intelligent Systems", *IEEE Communications Magazine, June 2021.*
- P. Popovski, F. Chiariotti, K. Huang, A. Kalor, M. Kountouris, N. Pappas, B. Soret, *"A Perspective on Time toward Wireless 6G", Proceedings of the IEEE, Aug. 2022.*
- *N. Pappas, M. A. Abd-Elmagid, B. Zhou, W. Saad, H. S. Dhillon, "Age of Information: Foundations and Applications", Cambridge University Press, Feb. 2023.*

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Age of Information
A New Concept, Metric, and Tool

Antzela Kosta, Nikolaos Pappas and Vangelis Angelakis

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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*

ABSTRACT | With the advent of 5G technology, the notion of *latency* got a prominent role in wireless connectivity, serving as a proxy term for addressing the requirements for real-time communication. As wireless systems evolve toward 6G, the ambition to immerse the digital into physical reality will increase. Besides making the real-time requirements more stringent, this immersion will bring the notions of time, simultaneity, presence, and causality to a new level of complexity. A growing body of research points out that latency is insufficient to parameterize all real-time requirements. Notably, one such requirement that received significant attention is information freshness, defined through the Age of Information (AoI) and its derivatives. In general, the metrics derived from a conventional black-box approach to communication network design are not representative of new distributed paradigms, such as sensing, learning, or distributed consensus. The objective of this article is to investigate the general notion of timing in wireless communication systems and networks, and its relation to effective information generation, processing, transmission, and reconstruction at the senders and receivers. We establish a general statistical framework of *timing* requirements in wireless communication systems, which subsumes both latency and AoI. The framework is made by associating a timing component with the two basic statistical operations: decision and estimation. We first use the framework to present a representative sample of the existing works that deal with timing in wireless communication. Next, it is shown how the framework can be used with different communication models of increasing complexity, starting from the basic Shannon one-way communication model and arriving at communication models for consensus, distributed learning, and inference. Overall, this article fills an important gap in the literature by providing a systematic treatment of various timing measures in wireless communication and sets the basis for design and optimization for the next-generation real-time systems.

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

Projects funding this research

- "Semantics-Empowered Communication for Networked Intelligent Systems", Swedish Research Council
- "Information Handling in Industrial IoT", ELLIIT
- "Low Latency Communications for Wireless Networks: Exploiting Traffic Characteristics", CENIIT
- *"Self-evolving terrestrial/non-terrestrial hybrid networks", HORIZON-JU-SNS-2022-STREAM-B-01-03 — Communication Infrastructure Technologies and Devices.*
- *Four more Horizon Europe projects will start by the end of 2023.*
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