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Communications for Human and Machine Intelligence

TUT-02: Age of Information: Theory, Applications, and Testbed Implementation

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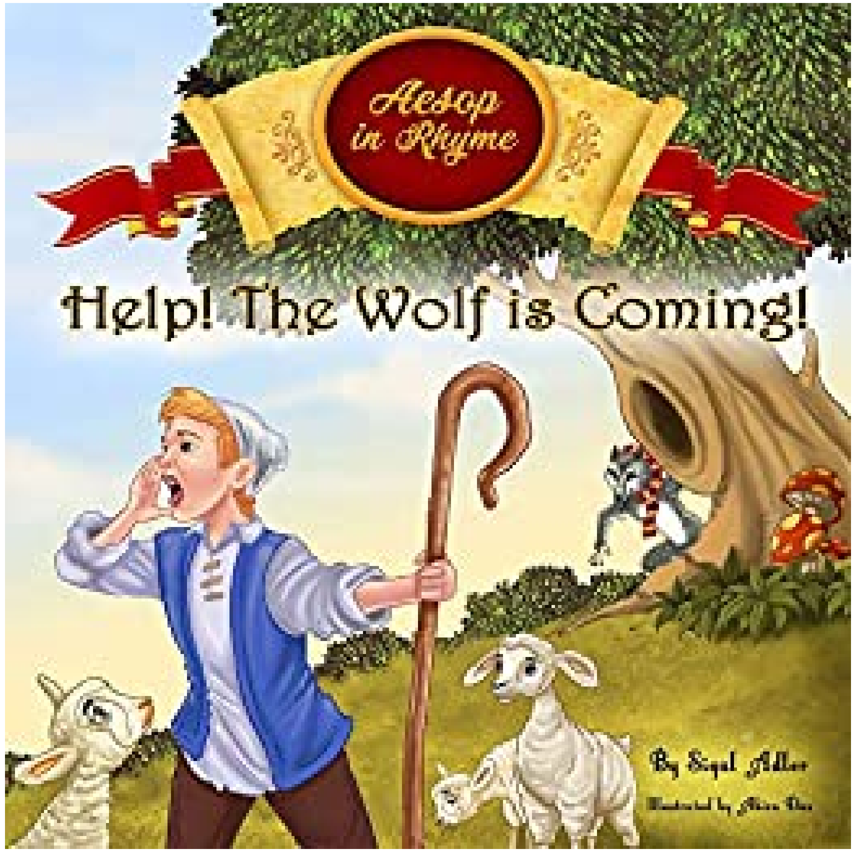
Outline of the Tutorial

- Overview
- Definition and Modeling of AoI
- Interplay between AoI and other metrics
- AoI-oriented Multiuser Scheduling
- AoI-oriented Random Access
- Prototyping Testbed for Validation and Evaluation of AoI-oriented Designs
- Concluding remarks

Internet of Things (IoT)

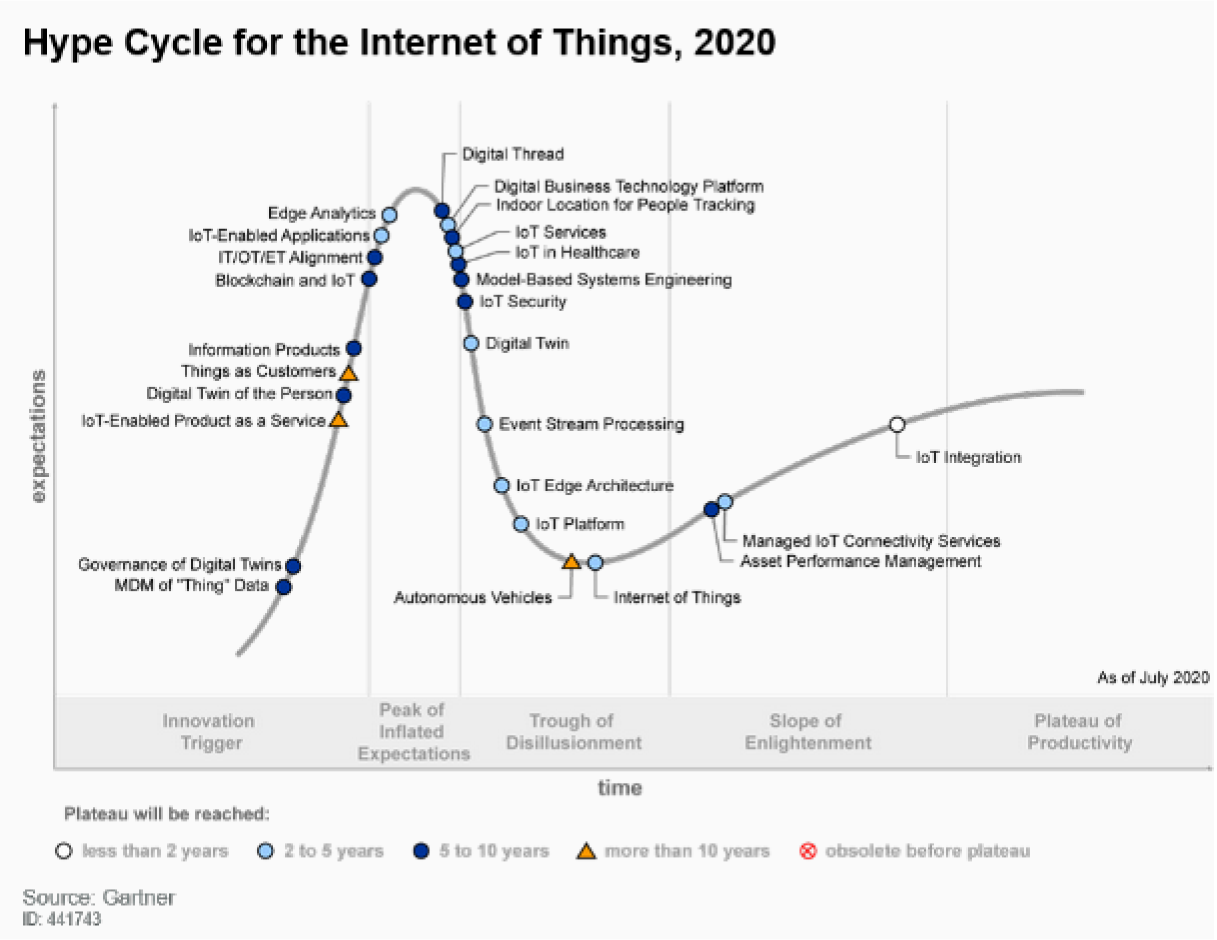


"Wolf is coming"

for too many times

M. A. Abd-Elmagid, N. Pappas, H. S. Dhillon, "On the Role of Age of Information in the Internet of Things", IEEE Communications Magazine, Dec. 2019

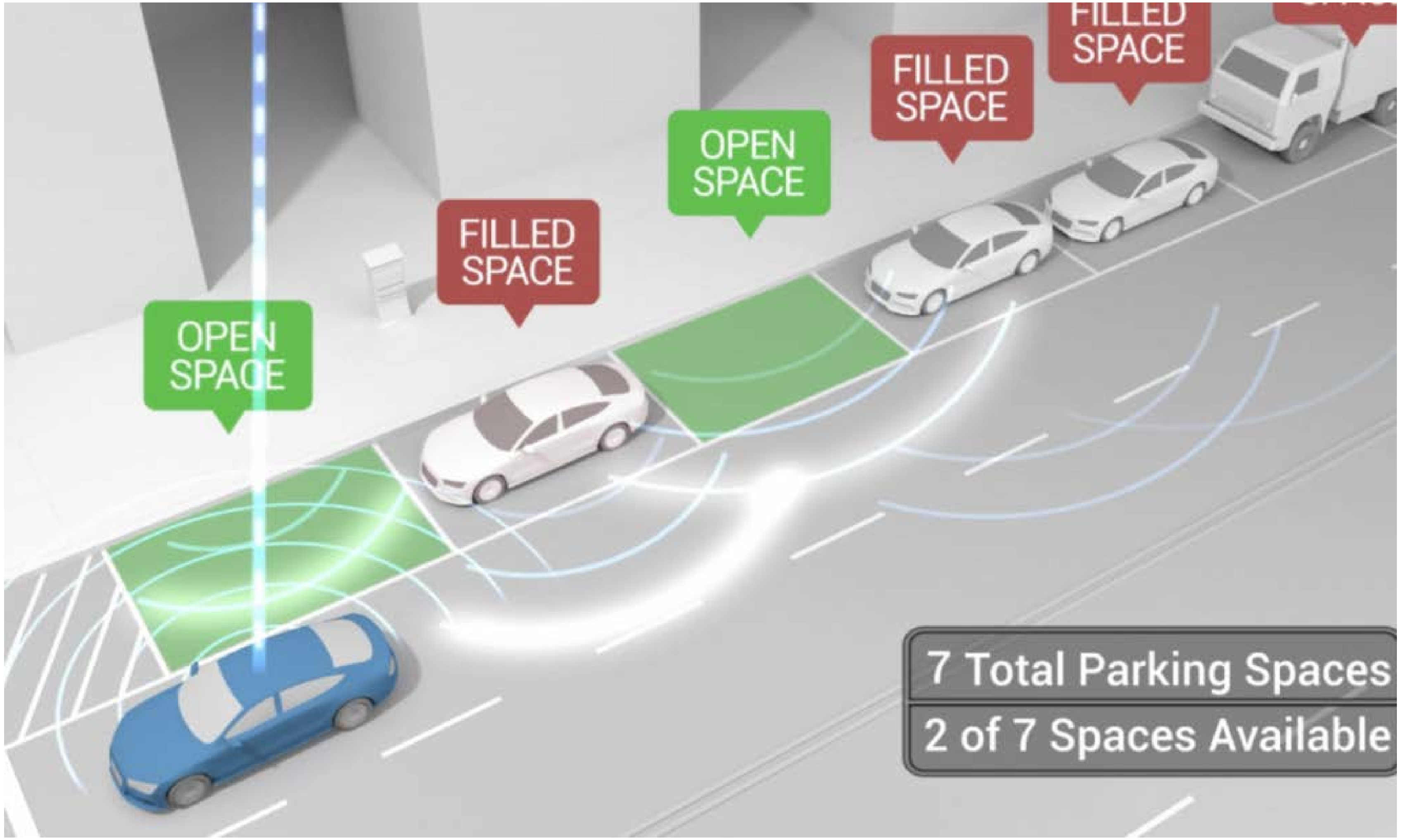
IoT is really coming



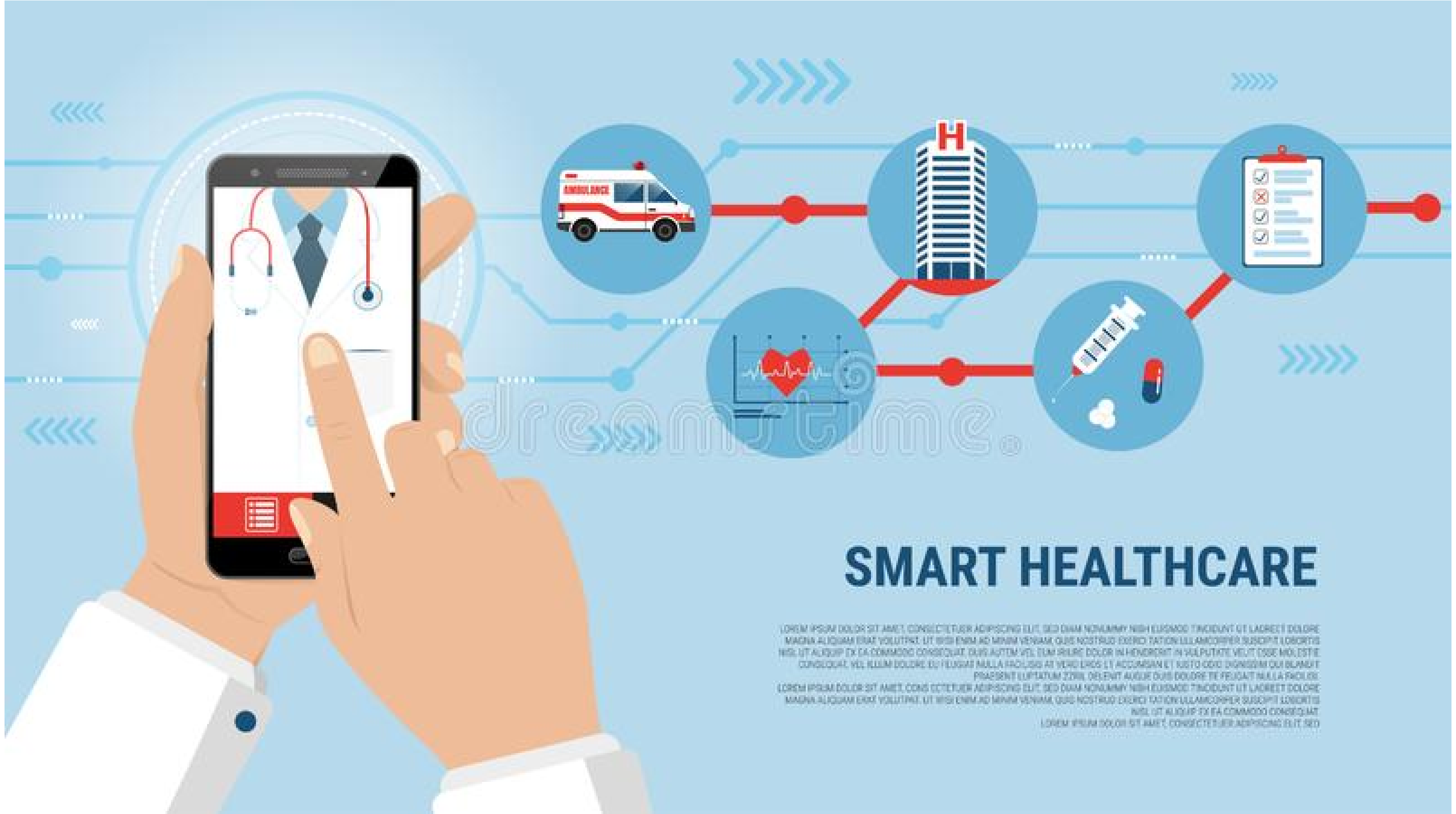
Source: https://www.primekey.com/gartner-report-hype-cycle-for-the-internet-of-things/

Smart Transportation

Smart Parking (Part of Smart City)



Smart Healthcare



Smart Factory

Remote Monitoring

- All aforementioned IoT applications involve remote monitoring
- Various sensors monitor a certain process and send its sampled statuses of the monitored process to a remote monitor --- status update system
- Information usually has the highest value when it is fresh.
- How to quantify information freshness?

Pass to Dr. Nikolaos PAPPAS

IEEE GLOBECOM 2020 Tutorial

Age of Information: Theory, Applications, and Testbed Implementation

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Why we need fresh data

- 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.

Why we need fresh data

- Timeliness of information has emerged as a new field of network research.
- 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.
  - While utilization is maximized by sending updates as fast as possible, this strategy will lead to a monitor receiving delayed updates that were backlogged in the communication system.
  - In this case, the timeliness of status updates at the receiver can be improved by reducing the update rate.
  - Reducing the update rate will cause outdated status information at the receiver due to the lack of updates.

S. Kaul, R. Yates, and M. Gruteser, "Real-time status: How often should one update?" IEEE INFOCOM 2012

Definition and Modeling of AoI

Nikolaos Pappas

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 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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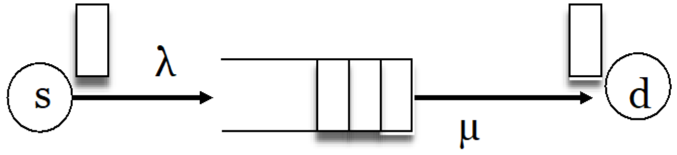
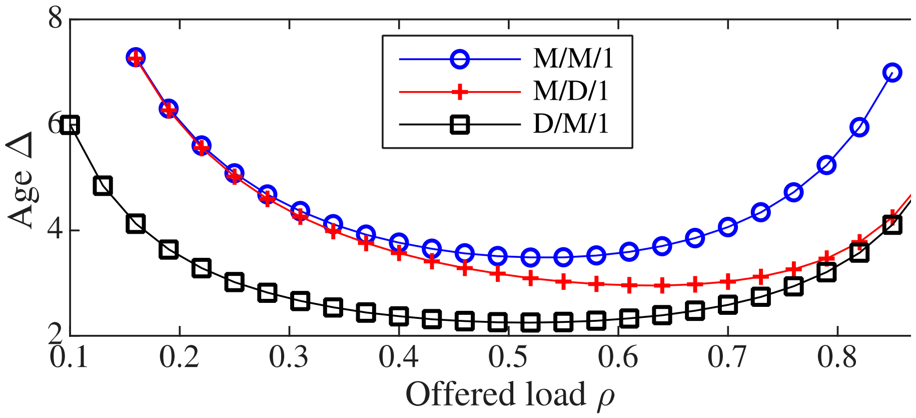
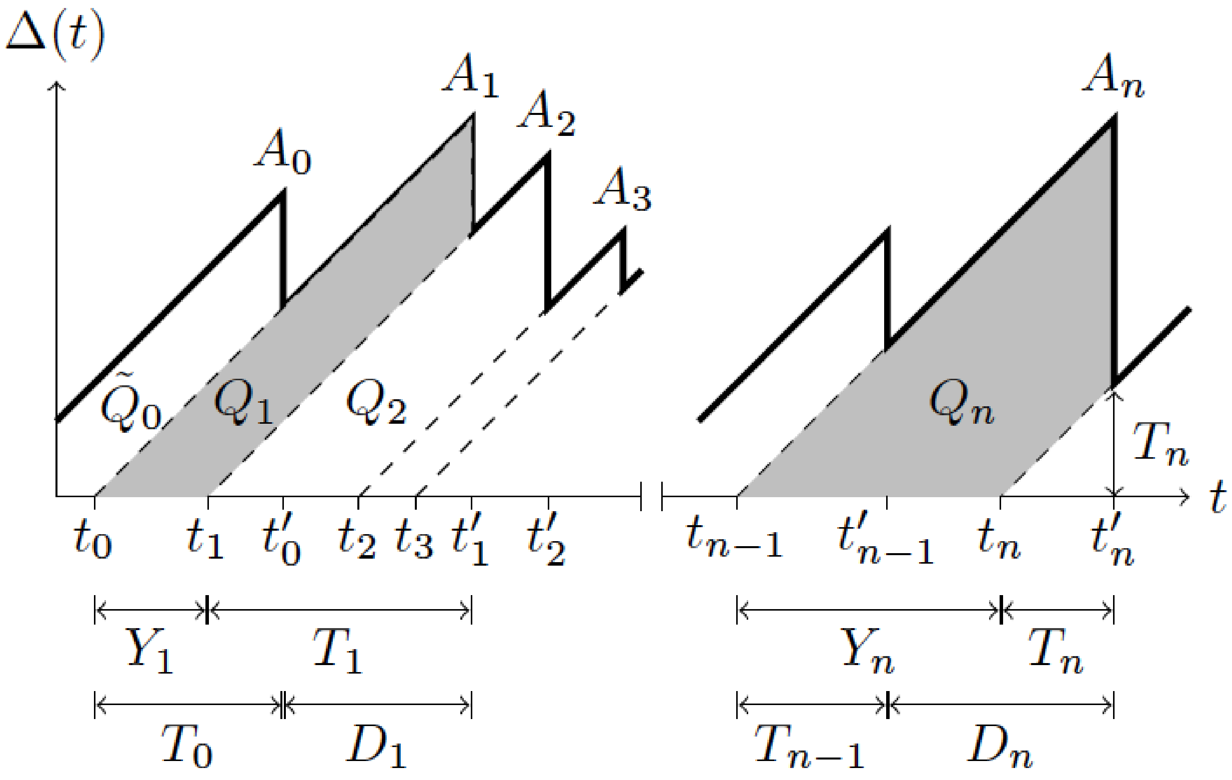




Time Average AoI – Sawtooth Sample path



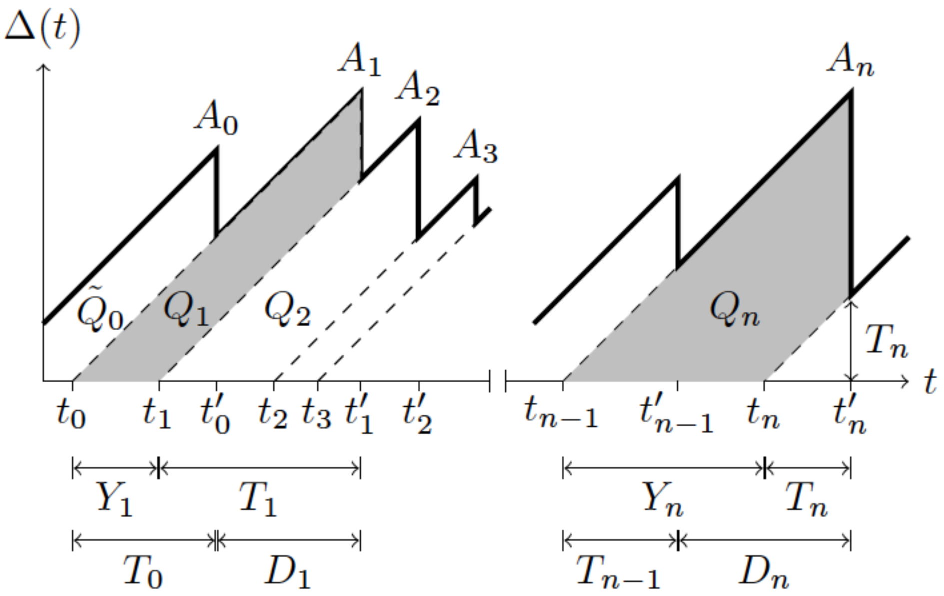
- $t_0, t_1, t_2, \ldots$ times that are updates are generated
- $t_o', t_1', t_2', \ldots$ times that updates are received at the monitor

- 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", arXiv:2007.08564, Jul. 2020

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



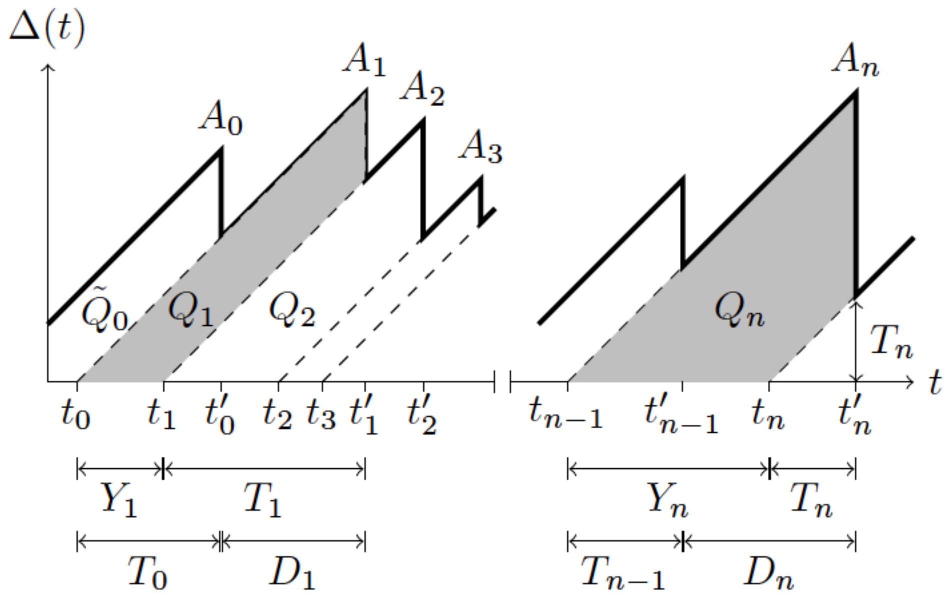
$$Q_n = \frac{1}{2}(T_n + Y_n)^2 - \frac{1}{2}T_n^2 = Y_n T_n + Y_n^2/2$$

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

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

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

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



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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 $E[Y_n T_n]$

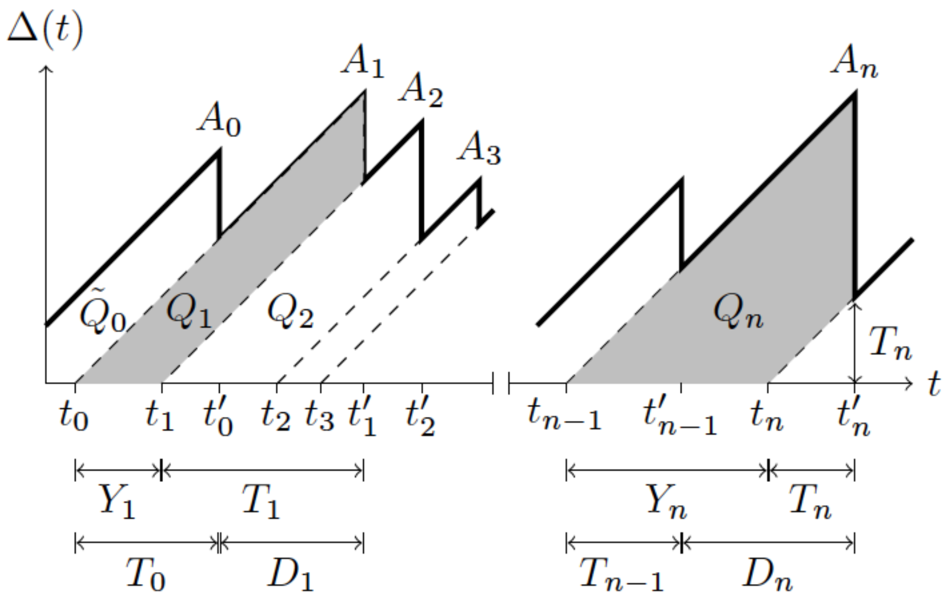
Peak AoI

- Alternative and more tractable metric than AoI

$$\Delta^{(p)} = \lim_{\mathcal{T}\to\infty} \frac{1}{N(\mathcal{T})} \sum_{n=1}^{N(\mathcal{T})} A_n$$

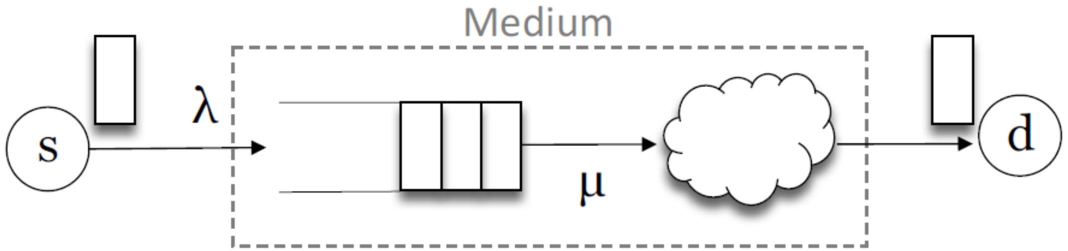
$$\Delta^{(p)} = \mathrm{E}[A] = \mathrm{E}[T_{n-1}] + \mathrm{E}[D_n]$$

$$\Delta^{(p)} = \mathrm{E}[Y] + \mathrm{E}[T]$$



M. Costa, M. Codreanu, and A. Ephremides, "Age of information with packet management", IEEE ISIT 2014.

Single-source and single-server systems



i.i.d interarrival times with expected value $E[Y]$

$\lambda = 1/E[Y]$: *arrival rate*

$E[S]$: expected service time

$\mu = 1/E[S]$: *service rate*

$\rho = \lambda/\mu$: *offered load*

For FCFS M/M/1 queue the average is $\Delta_{\text{M/M/1}} = \frac{1}{\mu}\left(1 + \frac{1}{\rho} + \frac{\rho^2}{1-\rho}\right)$

The optimal age is achieved for $\rho^* \approx 0.53$

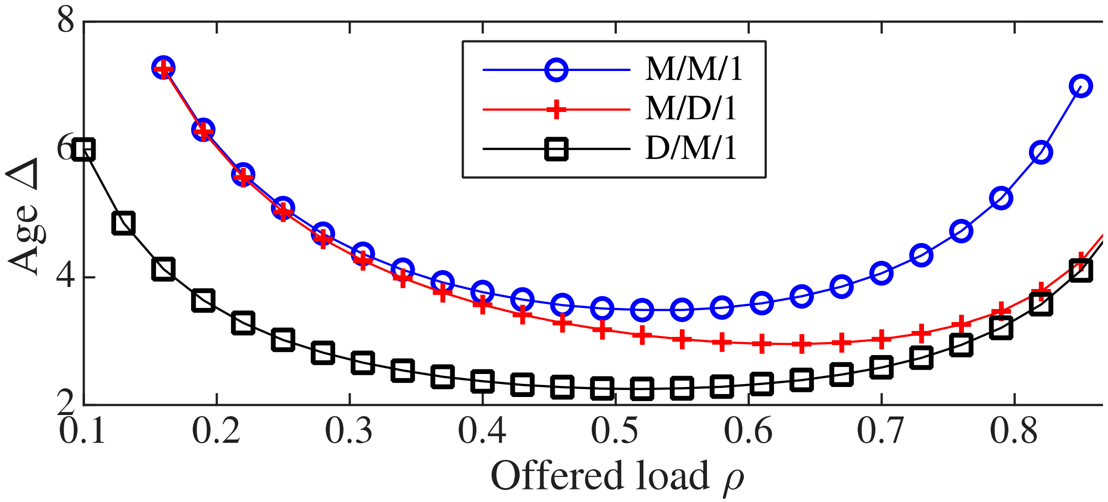
- Optimal age is achieved by choosing a λ which makes the server being slightly busy than being idle.
- If ρ is close to 1 we maximize the throughput.
- If ρ is close to 0, we minimize the delay.

S. Kaul, R. Yates, and M. Gruteser, "Real-time status: How often should one update?" IEEE INFOCOM 2012.
M. Costa, M. Codreanu, and A. Ephremides, "On the age of information in status update systems with packet management," IEEE Trans. Info. Theory 2016.
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.
- 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.

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.

Multiple sources at a single server source

- L. Huang and E. Modiano, "Optimizing age-of-information in a multiclass queueing system", IEEE ISIT 2015.
- E. Najm and E. Telatar, "Status updates in a multi-stream M/G/1/1 preemptive queue", IEEE INFOCOM Workshops 2018.
- R. D. Yates and S. K. Kaul, "The age of information: Real-time status updating by multiple sources", IEEE Trans. Info. Theory, 2019.
- G. Stamatakis, N. Pappas, A. Traganitis, "Optimal Policies for Status Update Generation in an IoT Device with Heterogeneous Traffic", IEEE IoT Journal, June 2020.
- M. Moltafet, M. Leinonen, and M. Codreanu, "On the age of information in multi-source queueing models", IEEE TCOM 2020.

Zero-wait

- Y. Sun, E. Uysal-Biyikoglu, R. Yates, C. E. Koksal, and N. B. Shroff, "Update or wait: How to keep your data fresh", *IEEE INFOCOM 2016* and *IEEE Trans. Inf. Theory, 2017.*

Queueing Networks

- C. Kam, S. Kompella, and A. Ephremides, "Age of information under random updates", IEEE ISIT 2013.
- C. Kam, S. Kompella, G. D. Nguyen, and A. Ephremides, "Effect of message transmission path diversity on status age", IEEE Trans. Info. Theory, 2016.
- R. D. Yates, "Status updates through networks of parallel servers", IEEE ISIT 2018.

Non-linear Ageing

- AoI grows over time linearly, the performance degradation caused by information aging may not be a linear function of time.
- One way to capture the nonlinear behavior of information aging is to 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.

Y. Sun, E. Uysal-Biyikoglu, R. Yates, C. E. Koksal, and N. B. Shroff, "Update or wait: How to keep your data fresh", IEEE Trans. Inf. Theory, 2017.
A. Kosta, N. Pappas, A. Ephremides, and V. Angelakis, "Age and value of information: Non-linear age case", IEEE ISIT 2017.
Y. Sun and B. Cyr, "Sampling for data freshness optimization: Nonlinear age functions", IEEE/KICS JCN 2019.
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)

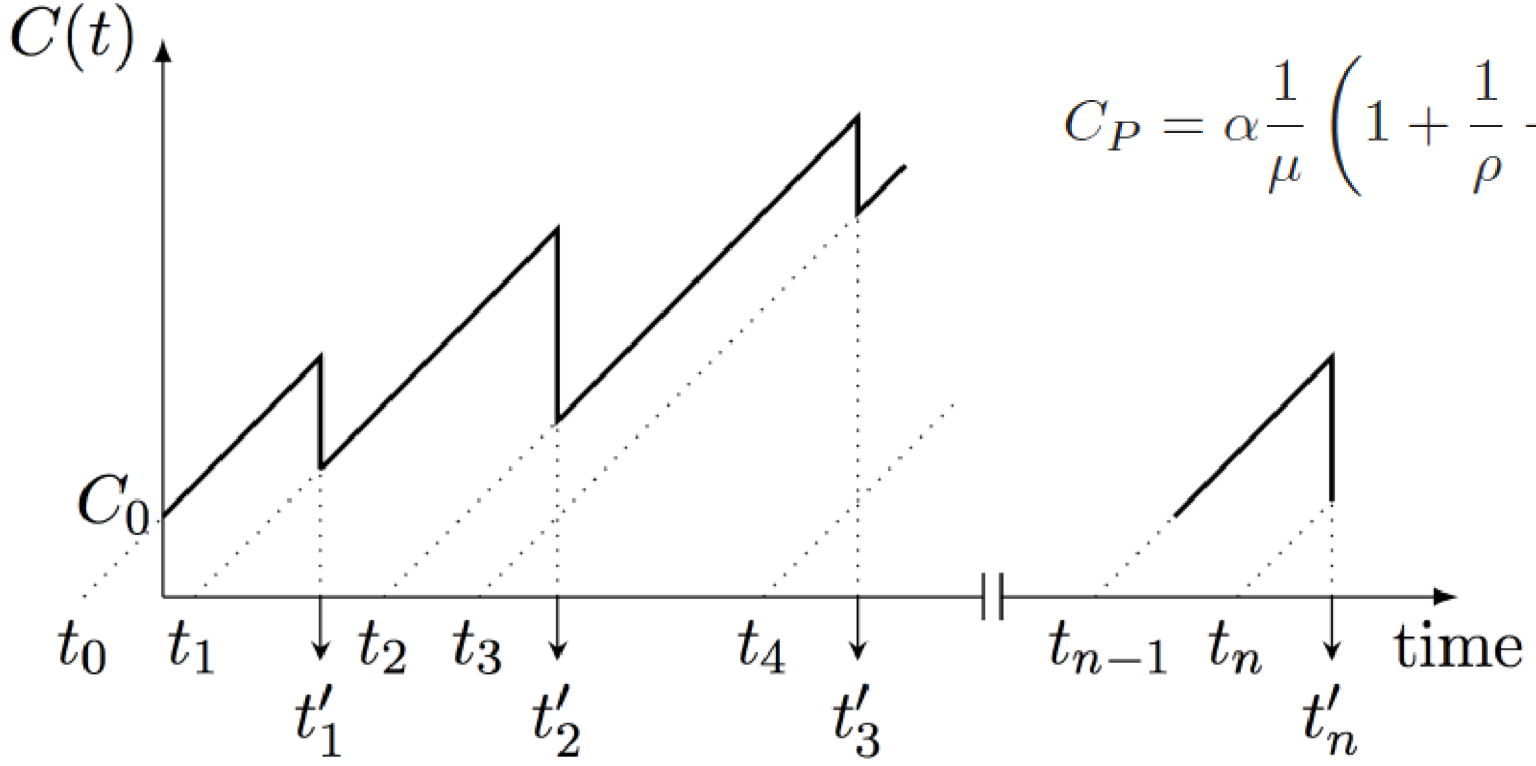
- CoUD metric associates the cost of staleness with the statistics of the source
- $C(t) = f_s(t-u(t))$
  - $f_s(t)$ is a monotonically increasing function
  - $u(t)$ timestamp of the most recently received update
- Different cost functions can represent different utilities

A. Kosta, N. Pappas, A. Ephremides, V. Angelakis, "Age and Value of Information: Non-linear Age Case", *IEEE ISIT* 2017.

A. Kosta, N. Pappas, A. Ephremides, V. Angelakis, "The Cost of Delay in Status Updates and their Value: Non-linear Ageing", IEEE Trans. Comm., 2020.

Cost of Update Delay (CoUD): The linear case

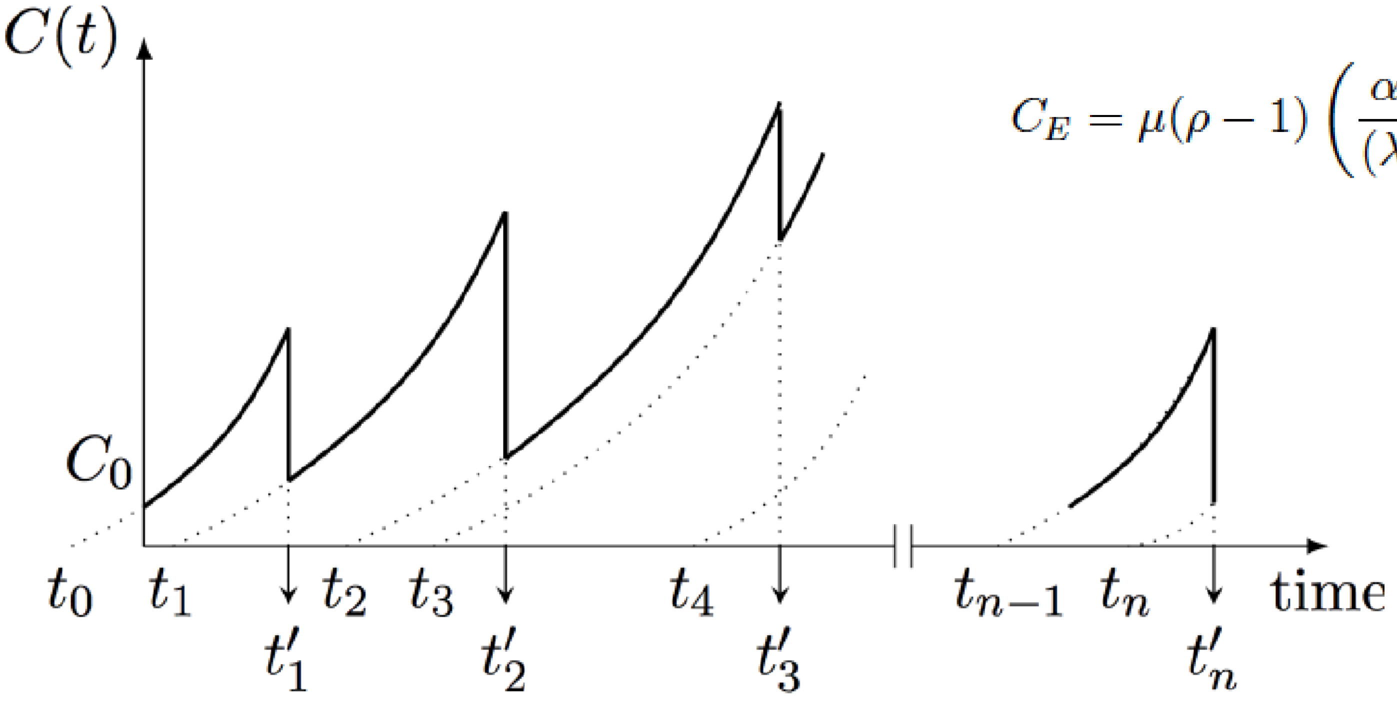
$$f_S(t) = ↵\, t$$



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

Cost of Update Delay (CoUD): The exponential case

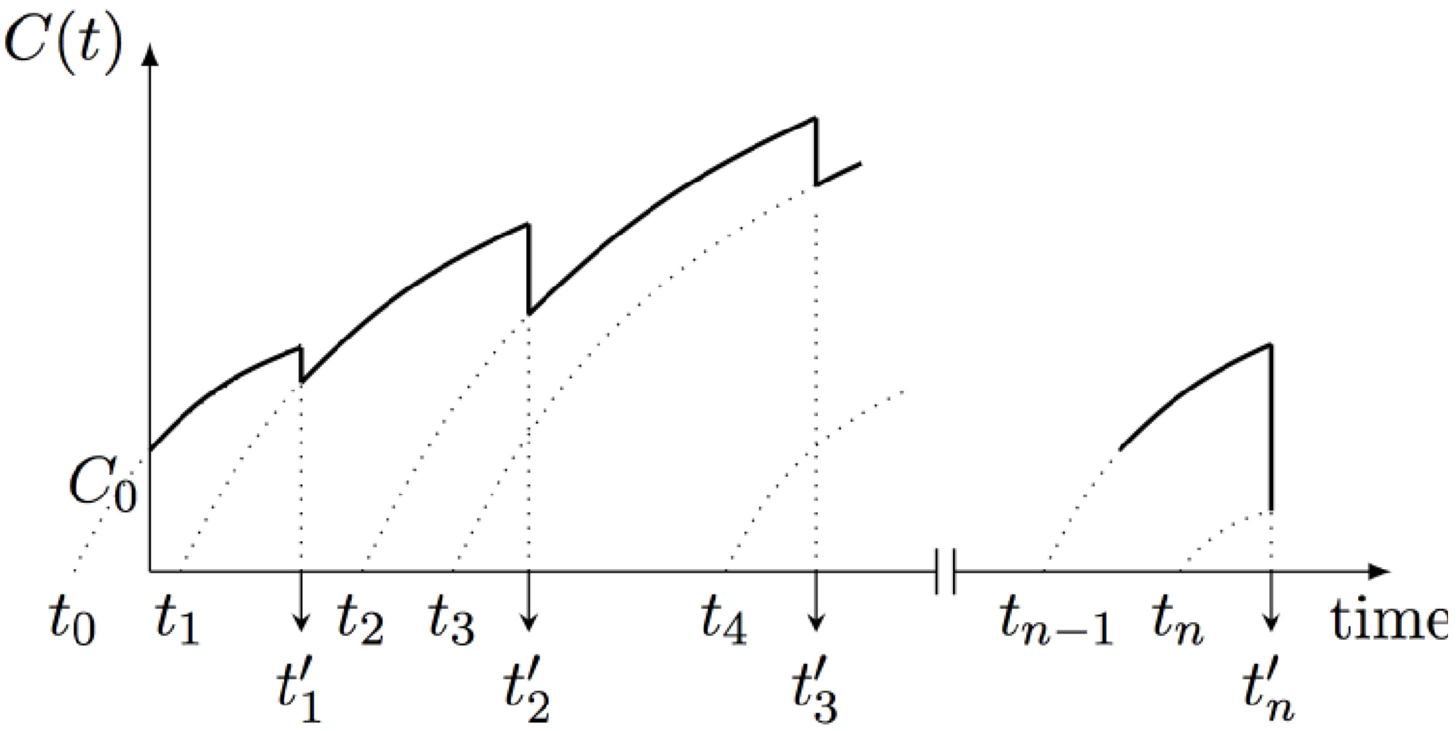
$f_S(t) = e^{\alpha t} - 1 \rightarrow$ low autocorrelation



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

Cost of Update Delay (CoUD): The logarithmic case

$f_s(t) = \log(\lambda t + 1)$! high autocorrelation



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

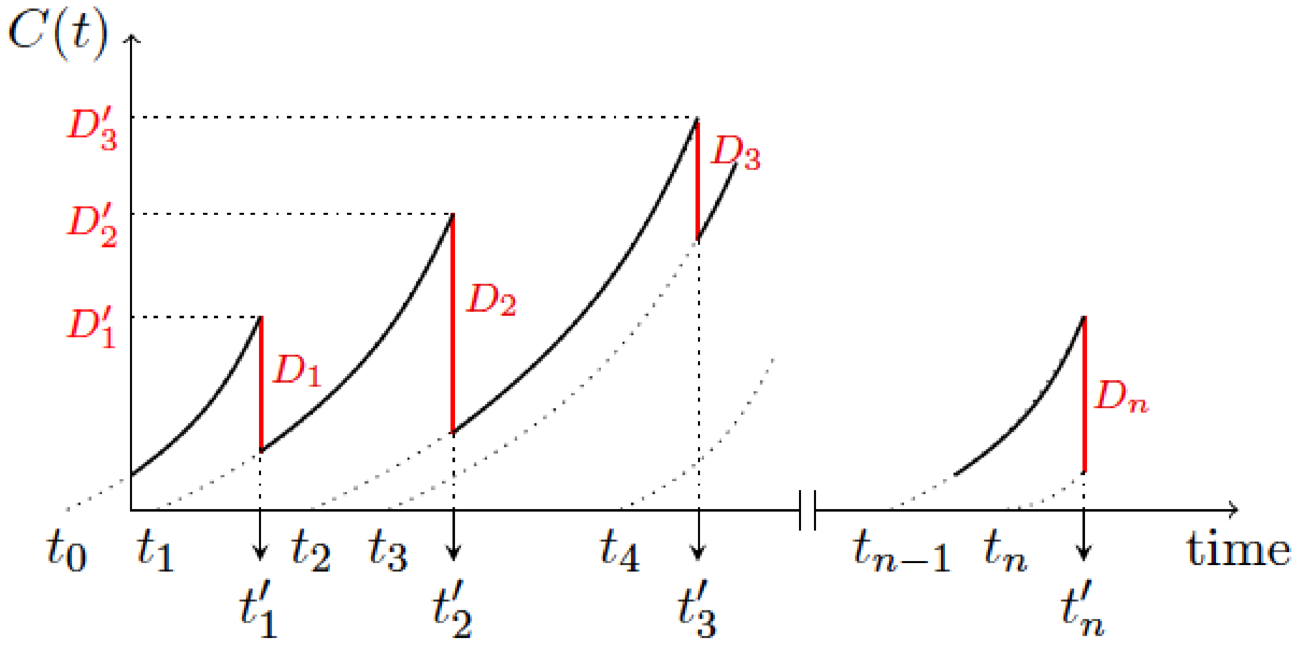
Value of Information of Update (VoIU)

- It captures the degree of importance of an update

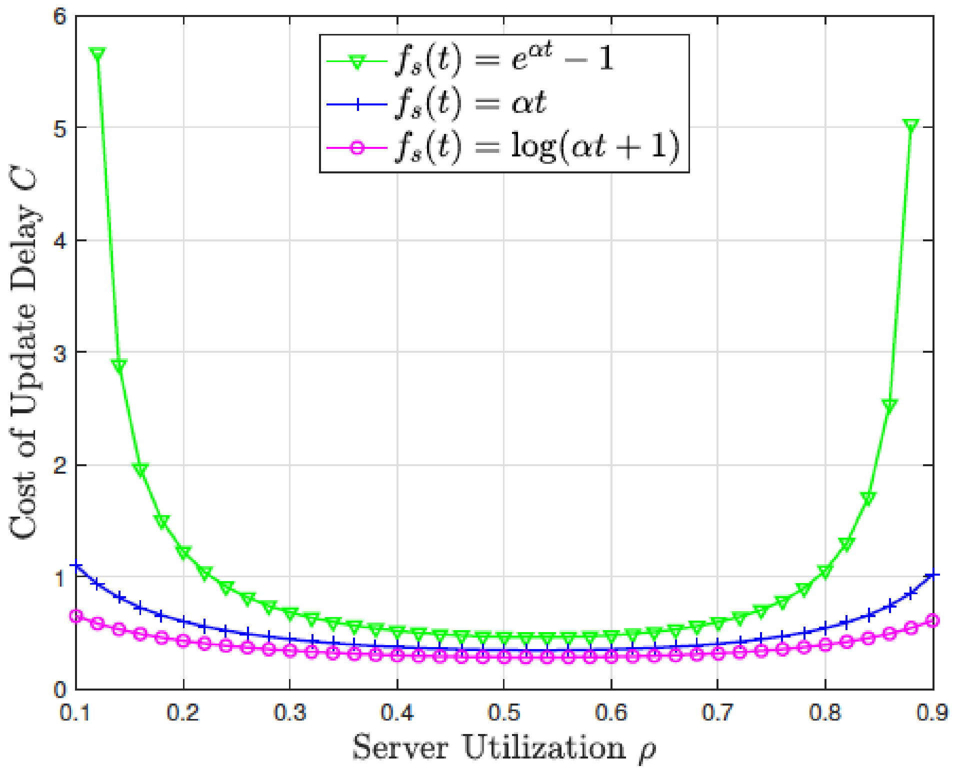
$$V_i = \frac{f_s(t_i'-t_{i-1})-f_s(t_i'-t_i)}{f_s(t_i'-t_{i-1})} = \frac{D_i}{D_i'}.$$

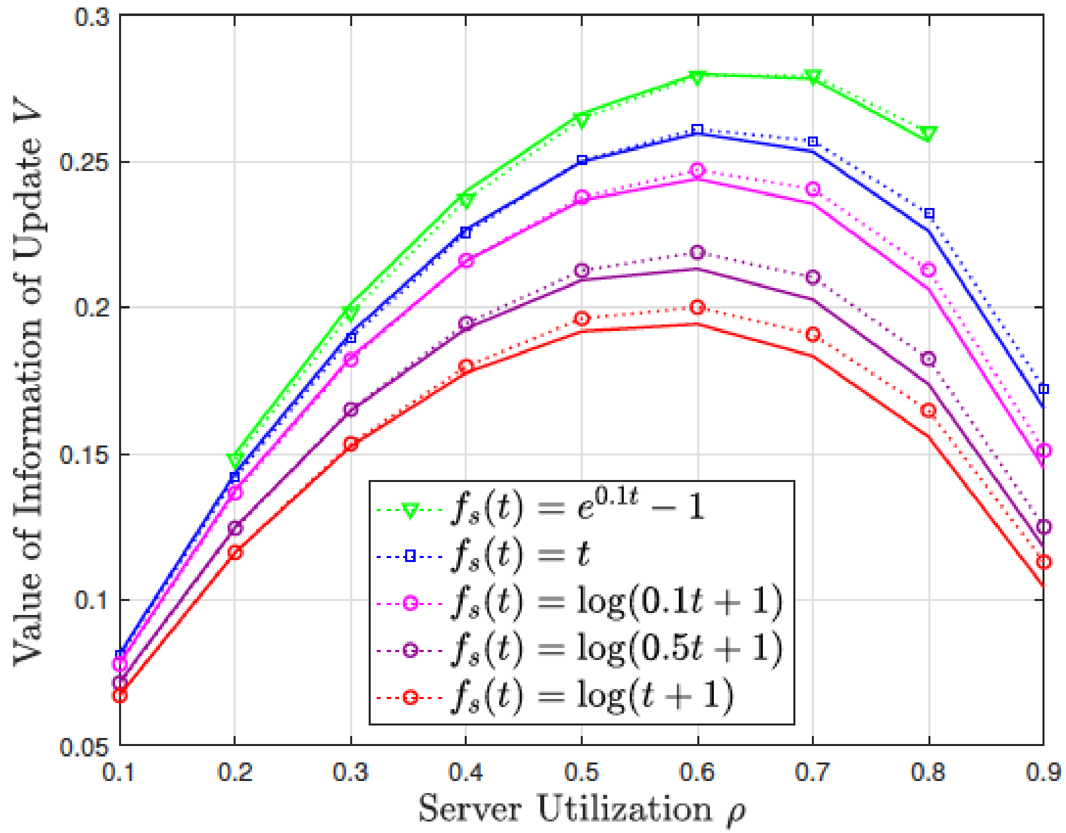
- In the linear CoUD case, VoIU is independent of the cost assigned per time unit →the Value is independent of the slope.

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



Numerical evaluation





AoI and VoI in Control

- AoI considers only the timeliness
- It has been shown that AoI alone does not capture the requirements of networked control loops
- Introduction of non-linear AoI facilitated the adoption in networked-control systems (NCS)
- VoI can reduce the estimation error in an NCS setup
- Very active research area that started recently

Onur Ayan, Mikhail Vilgelm, Markus Klügel, Sandra Hirche, and Wolfgang Kellerer, "Age-of-Information vs. Value-of-Information Scheduling for Cellular Networked Control Systems", 10th ACM/IEEE ICCPS 2019.

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.

- The distribution of AoI for the GI/GI/1/1 and GI/GI/1/2* systems, under non-preemptive scheduling
  - J. P. Champati, H. Al-Zubaidy, and J. Gross, "On the distribution of aoi for the GI/GI/1/1 and GI/GI/1/2* systems: Exact expressions and bounds," IEEE INFOCOM 2019.

Towards a complete characterization of the AoI distribution

- The AoI distribution in bufferless systems
    - G. Kesidis, T. Konstantopoulos, M.A. Zazanis, "The distribution of age-of-information performance measures for message processing systems", Queueing Systems 2020.

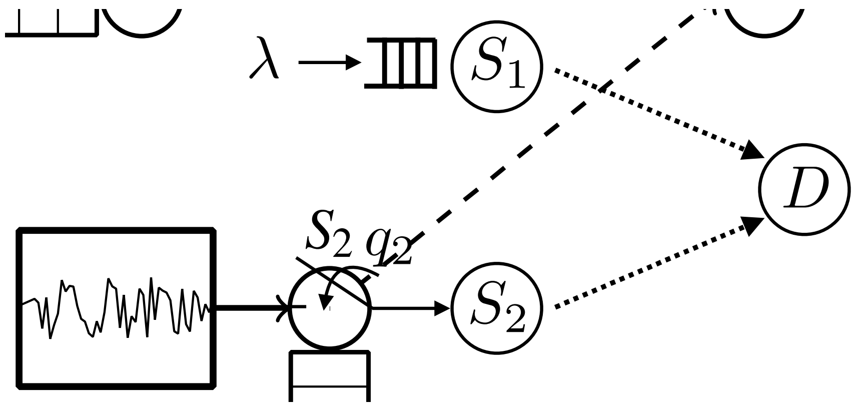
- Complete characterization of the AoI stationary distribution in a discrete time queueing system for: FCFS, preemptive LCFS, a bufferless system with packet dropping.
- *A methodology for analyzing general non-linear age functions, using representations of functions as power series.*
    - A. Kosta,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

Interplay between AoI and other metrics

Nikolaos Pappas

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

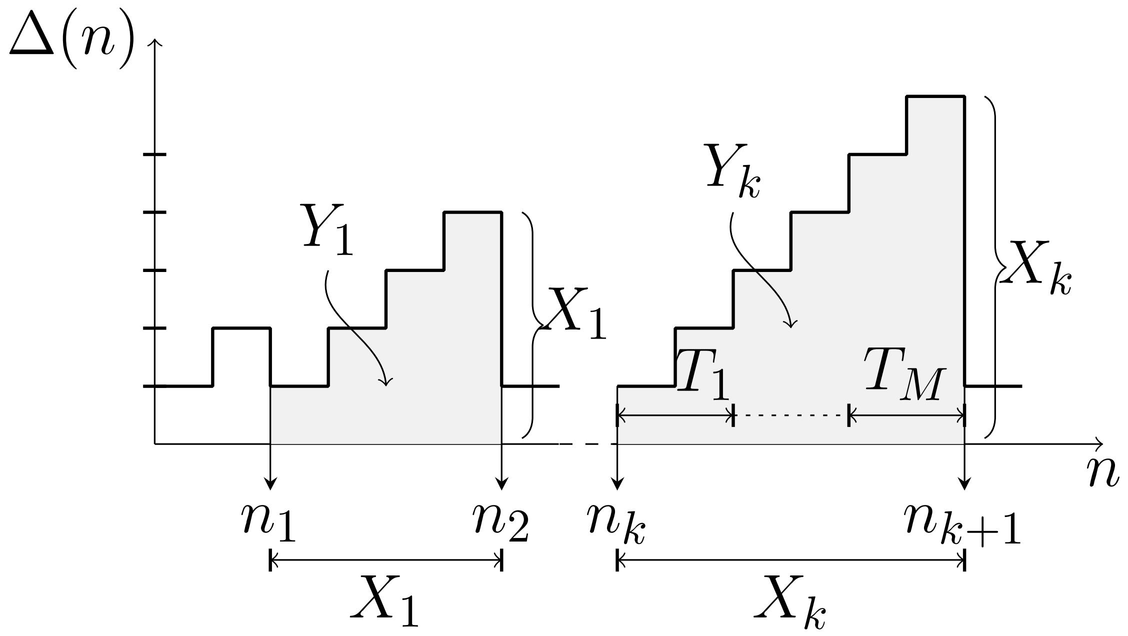
- Two sources sending packets to a common destination.
- Source S_1 has external traffic with stringent delay requirements.
- Source S_2 monitors a sensor and samples a status update on each slot w.p. q_2.
  - Then, transmits the update to the destination through a channel with success probability p_2.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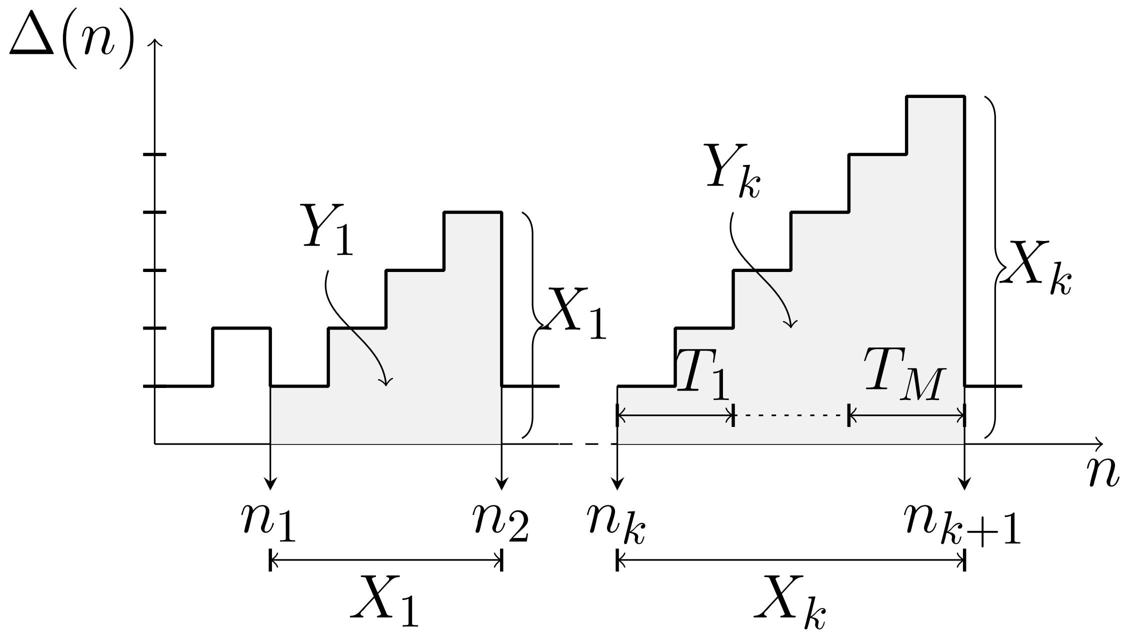

$$X_k = \sum_{i=1}^{M} T_i \qquad \Delta_N = \frac{1}{N}\sum_{n=1}^{N}\Delta(n) = \frac{1}{N}\sum_{k=1}^{K} Y_k = \frac{K}{N}\frac{1}{K}\sum_{k=1}^{K} Y_k$$

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

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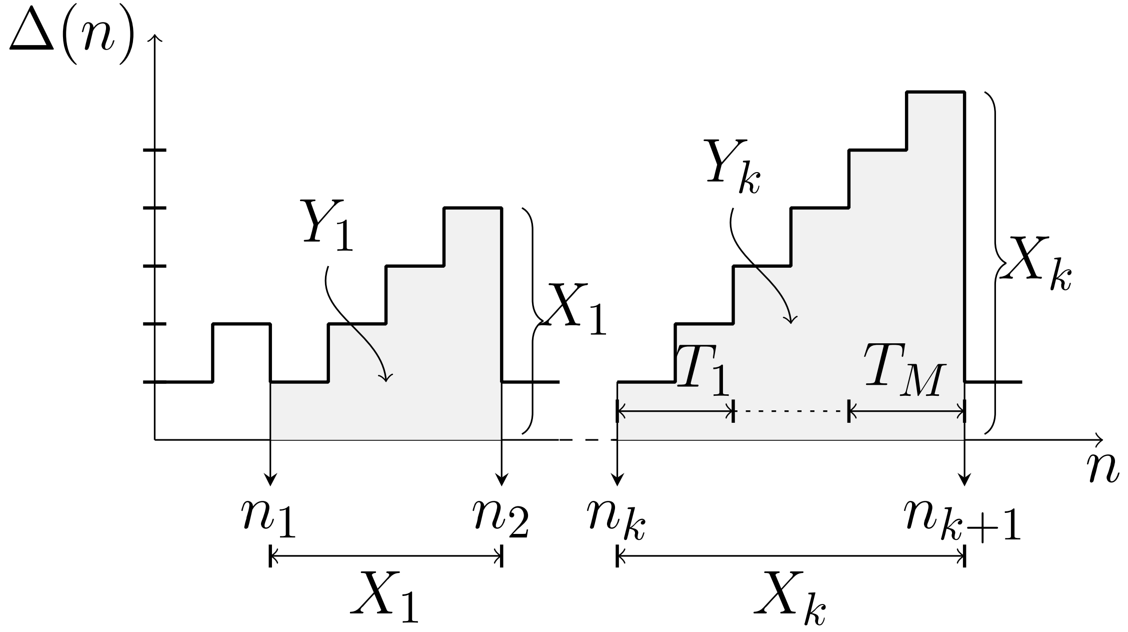

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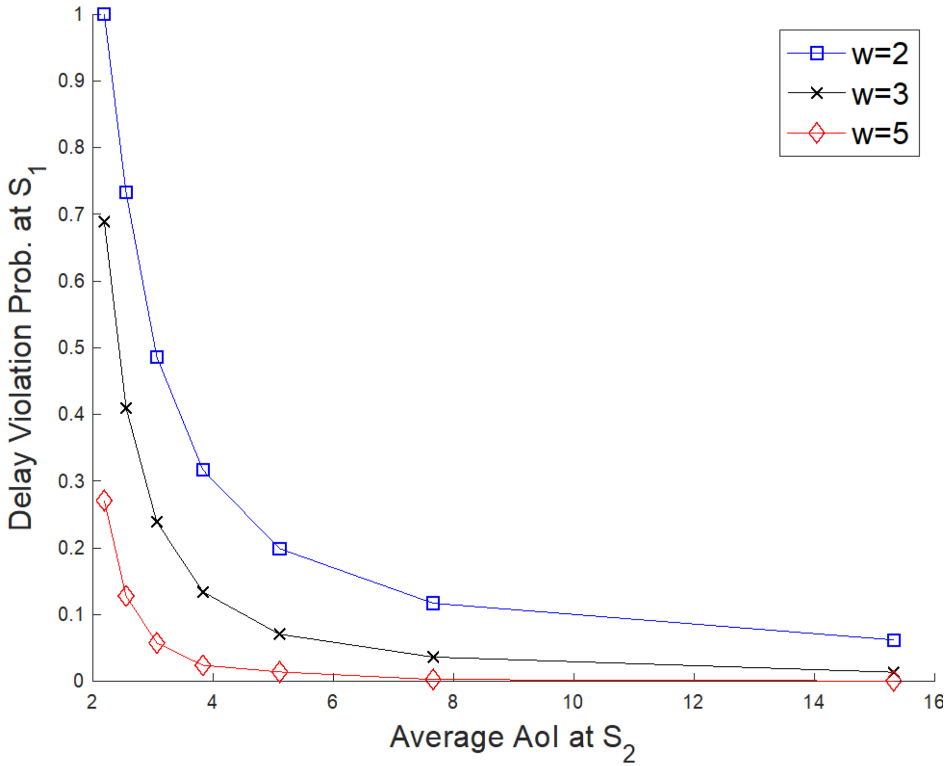
$$\Delta = \lim_{N \to \infty} \Delta_N = \frac{\mathrm{E}[Y]}{\mathrm{E}[X]} \qquad Y_k = \sum_{m=1}^{X_k} m = \frac{X_k (X_k + 1)}{2}$$

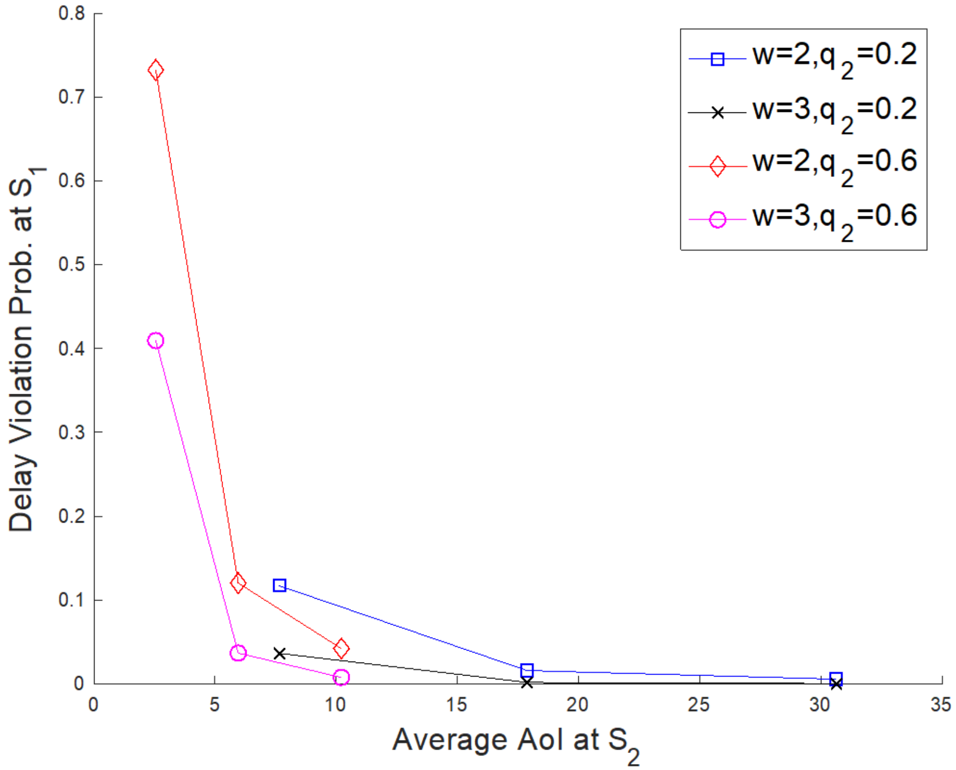
$$\Delta_N = \frac{K}{N}\frac{1}{K}\sum_{k=1}^{K} Y_k = \frac{\mathrm{E}\left[\frac{X_k^2}{2} + \frac{X_k}{2}\right]}{\mathrm{E}[X]} = \frac{\mathrm{E}[X^2]}{2\mathrm{E}[X]} + \frac{1}{2}$$

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

$$\mathrm{E}[X^2] = \sum_{M=1}^{\infty} \mathrm{E}[X^2 | M](1-p_2)^{M-1} p_2 \overset{p_2 > 0}{=} \frac{\mathrm{E}[T^2]}{p_2} + \frac{2(1-p_2)\mathrm{E}[T]^2}{p_2^2}$$

$$\Delta = \frac{\mathrm{E}[T^2]}{2\mathrm{E}[T]} + \frac{\mathrm{E}[T](1-p_2)}{p_2} + \frac{1}{2} = \frac{1}{q_2 p_2}$$



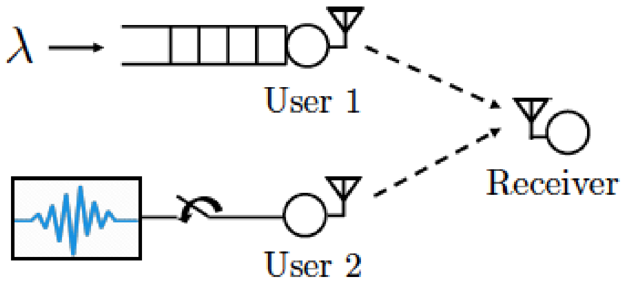


- As w increases, the delay violation probability decreases since S_1 becomes more delay tolerant.
- Increasing the transmit prob. results in significant decrease of the delay violation probability and an increase of AoI due to larger interference.

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 q1 when there is a packet in its queue
- User 2 (Age-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)



E. Fountoulakis, T. Charalambous, N. Nomikos, A. Ephremides, N. Pappas, "Information Freshness and Packet Drop Rate Interplay in a Two-User Multi-Access Channel", arXiv:2006.01515, 2020.

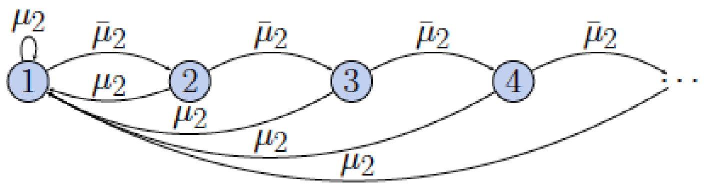
AoI and Packet Drop Rate Interplay

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

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

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

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



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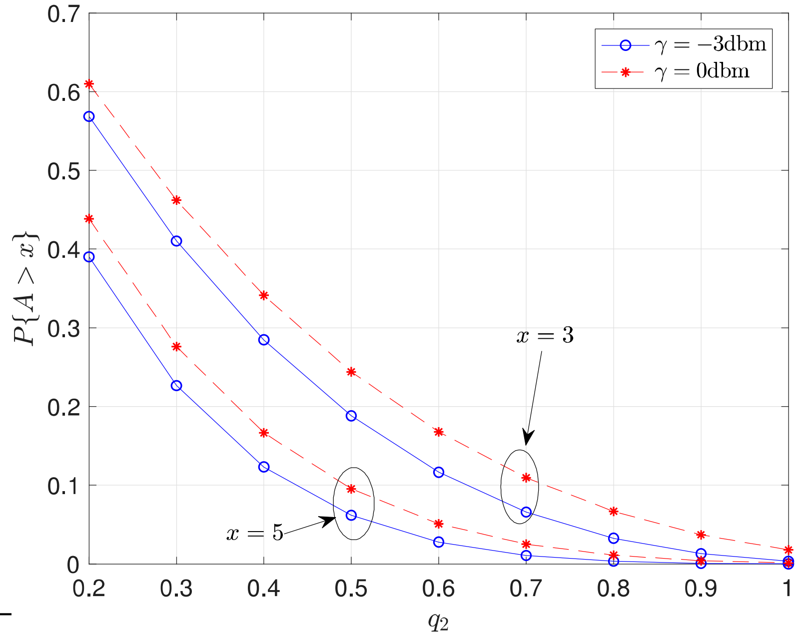
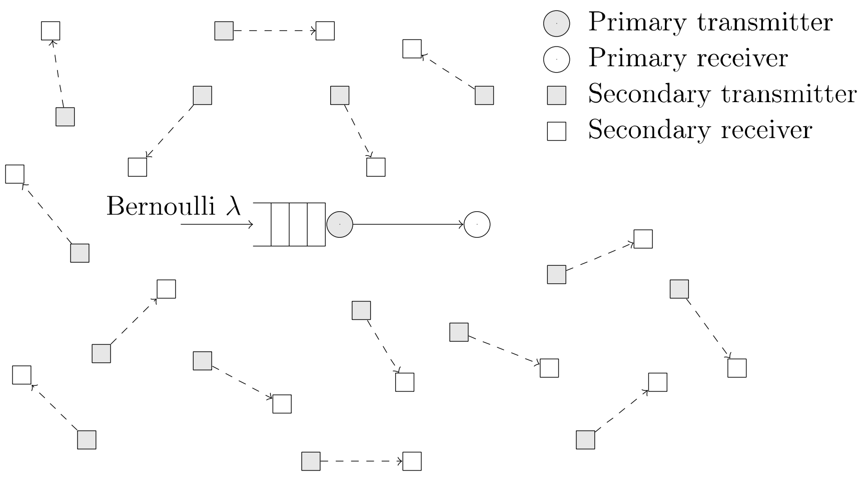
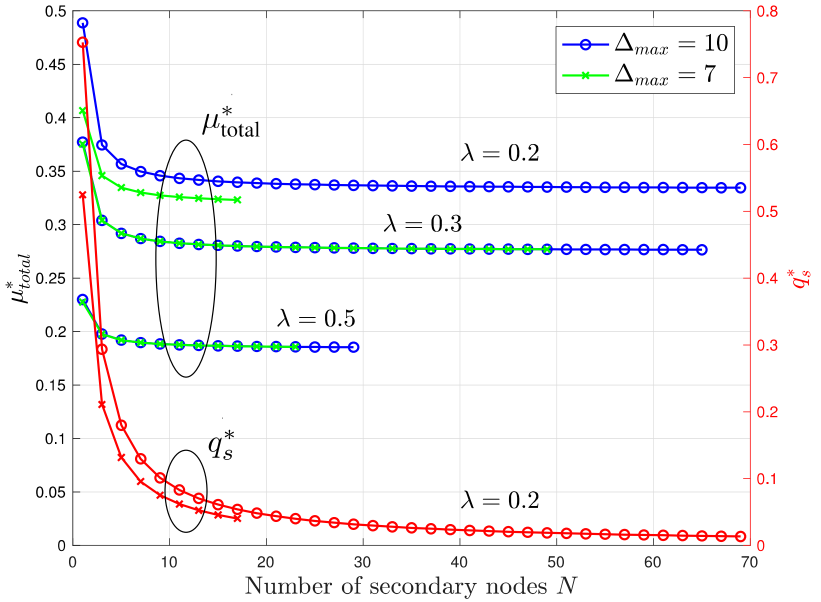
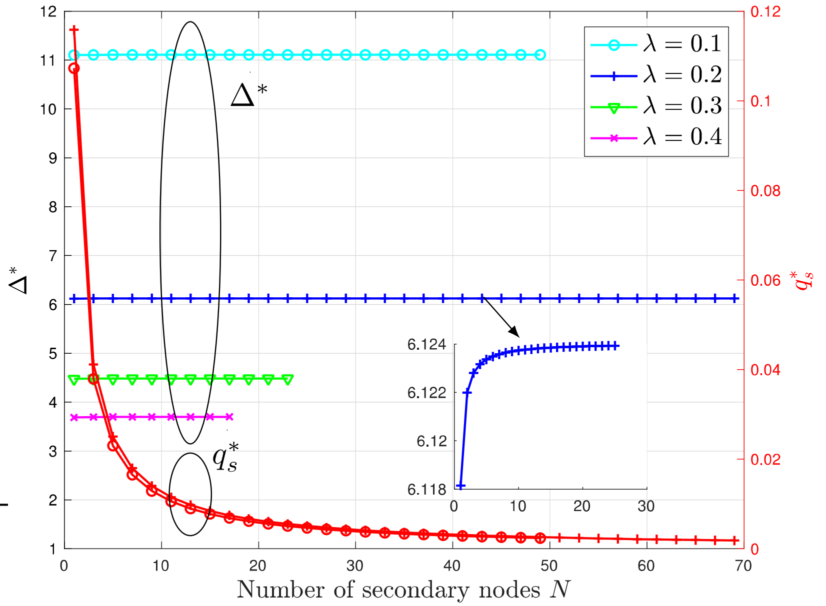


E. Fountoulakis, T. Charalambous, N. Nomikos, A. Ephremides, N. Pappas, "Information Freshness and Packet Drop Rate Interplay in a Two-User Multi-Access Channel", arXiv:2006.01515, 2020.

Age-throughput tradeoff in Cognitive Shared Access Network







- Age-oriented primary node, with external bursty traffic
- Throughput-oriented secondary nodes
- Random access, Raleigh fading, MPR
- Characterization of average AoI and the throughput,
- Two constrained optimization problems

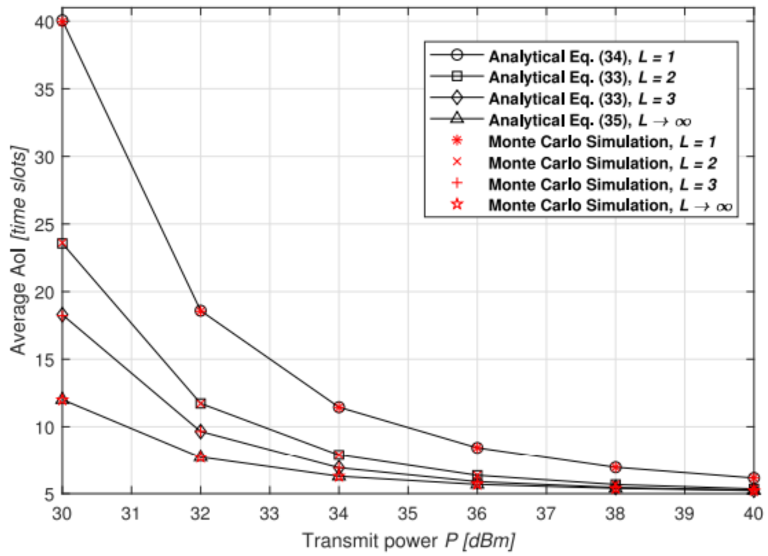
A. Kosta, N. Pappas, A. Ephremides, V. Angelakis, "Age of Information and Throughput in a Shared Access Network with Heterogeneous Traffic", IEEE GLOBECOM 2018.

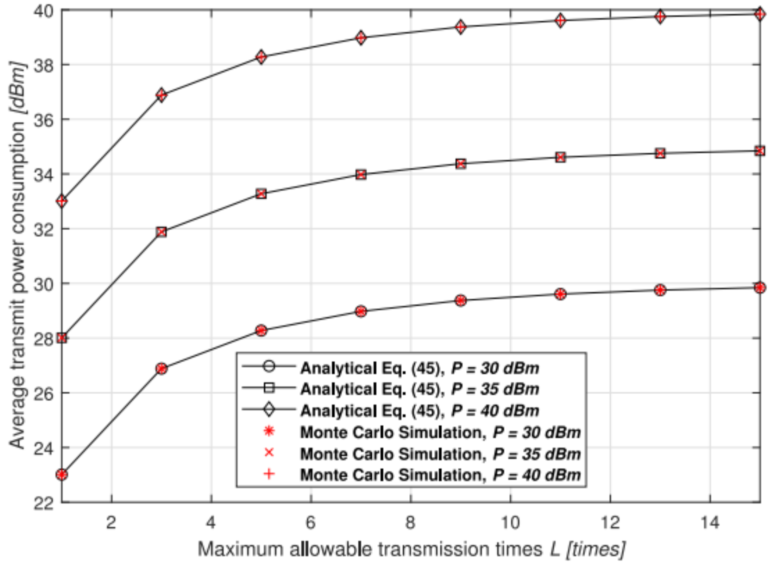
Age-tradeoff in Cognitive radio networks

- Inherent tradeoff between the age of primary user and that of the secondary user
  - Y. Gu, H. Chen, C. Zhai, Y. Li, and B. Vucetic, "Minimizing age of information in cognitive radio-based IoT systems: Underlay or overlay?" IEEE Internet of Things Journal, 2019.
  - Q. Wang, H. Chen, Y. Gu, Y. Li, and B. Vucetic, "Minimizing the age of information of cognitive radio-based IoT systems under a collision constraint," IEEE Transactions on Wireless Communications, accepted in Aug. 2020.

Age-energy tradeoff

- Point-to-point setup (sensor → AP)
- Stochastic arrival of status updates
- Truncated automatic repeat request (TARQ)
- Maximum allowable transmission (MAT) times
- Age-energy tradeoff: a larger value of the MAT times reduces the average AoI, at the cost of incurring higher average energy consumption at the IoT device.
- Closed-form analysis of average AoI and average energy consumption





Y. Gu, H. Chen, Y. Zhou, Y. Li, and B. Vucetic, "Timely Status Update in Internet of Things Monitoring Systems: An Age-Energy Tradeoff", IEEE Internet of Things Journal, 2019.

AoI-oriented Multiuser Scheduling

AoI-oriented Random Access

Prototyping Testbed for Validation and Evaluation of AoI-oriented Designs

AoI-Oriented Multiuser Scheduling

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2020.12.07 @ IEEE GLOBECOM 2020 Tutorial

香港中文大學

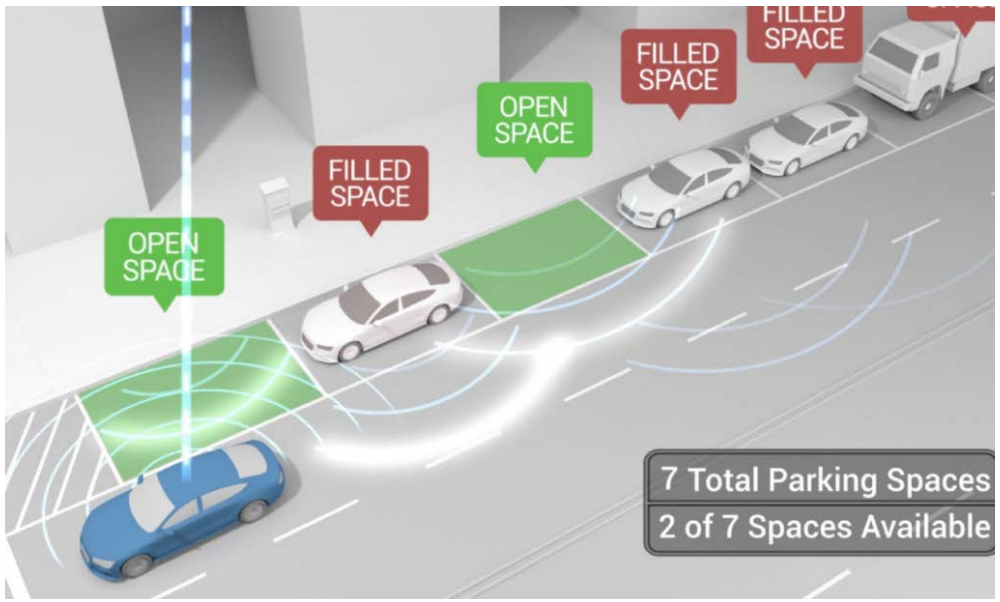
Multiuser Scheduling

- One of the most fundamental problems in wireless networks due to the shared medium
- Many work on designing and analyzing throughput- or delay-oriented multiuser scheduling schemes
- May no longer optimal when the AoI is concerned

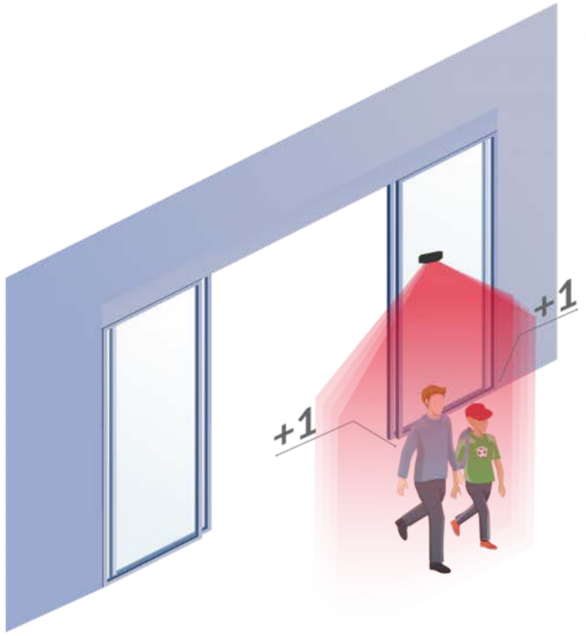
How to schedule the status updates of multiple users to minimize the network-wide AoI of the whole system?

Status update arrival model

- Generate-at-will

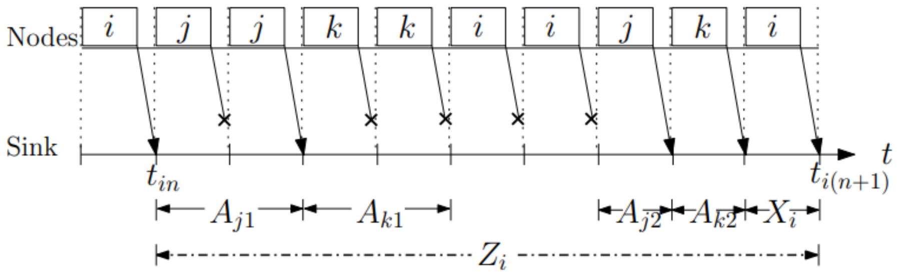


- Random (stochastic) Arrival



Homogenous Networks [Yates-Kaul’17]

- Generate-at-will model
- The channel error probability (when no collision) of all links are identical
- Once scheduled, the node can transmit the its status update for S times



Lemma 2. *For a homogeneous network of M nodes that take turns to transmit their state to a sink and get feedback on whether an update of state occurred, the network's AoI is minimized by allowing a node to keep transmitting packets during its scheduled turn until an update by the node occurs. Specifically, it is minimized in the limit as $S \to \infty$.*

- Always schedule the node with maximum instantaneous age

→ Maximum-age-first (MAF) policy

- MAF is age-optimal in homogenous networks

[Yates-Kaul’17] R. D. Yates and S. K. Kaul, "Status updates over unreliable multiaccess channels," 2017 IEEE International Symposium on Information Theory (ISIT), Aachen, 2017, pp. 331-335.

Heterogeneous Networks [Kadota'18] (1)

- A base station (BS) sending time-sensitive information to M clients (downlink)
- Time is slotted, with T consecutive slots forming a frame, indexed by k. Let n ∈ {1, ⋯ , T } be the index of the slot within a frame
- At the beginning of every frame, the BS generates one packet per client i
- In each frame, T out of M clients are scheduled to transmit
- The packet is successfully delivered to client i with probability $p_i \in (0, 1]$

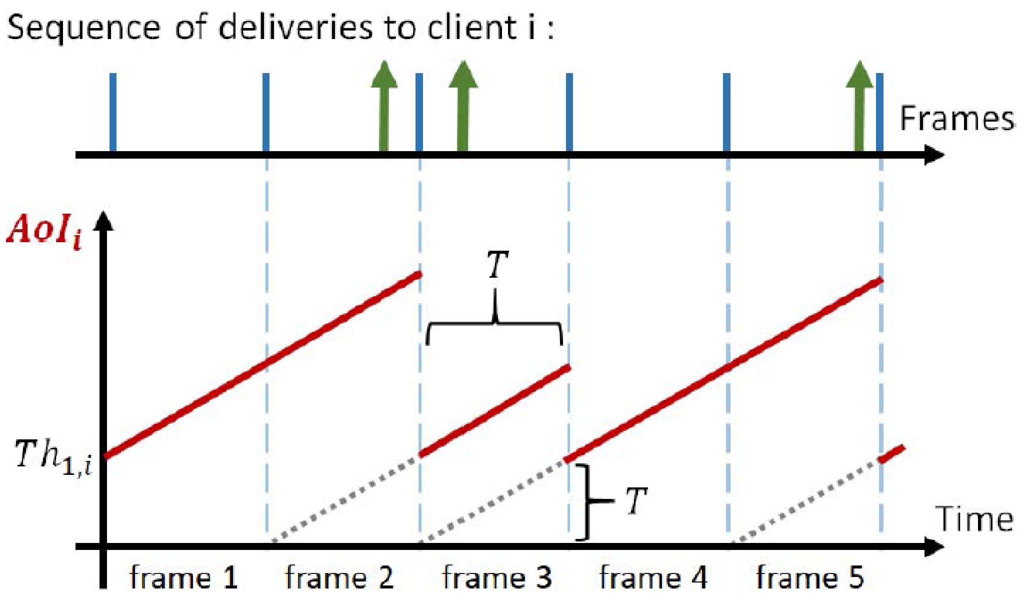
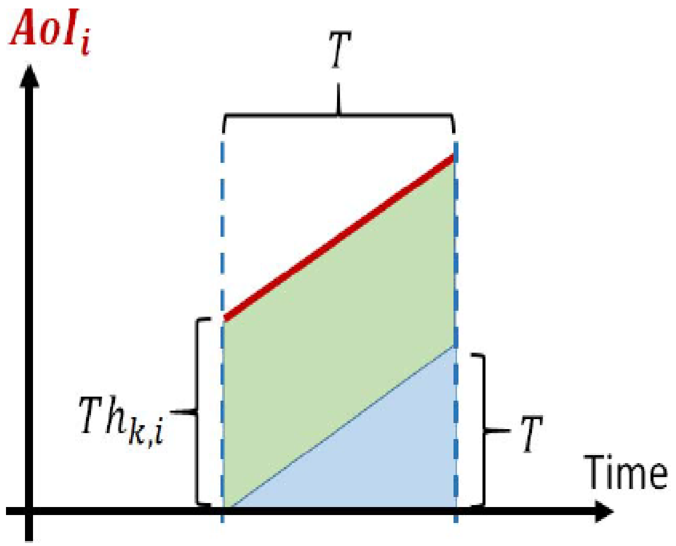


Fig. 2. On the top, a sample sequence of deliveries to client i during five frames. The upward arrows represent the times of packet deliveries. On the bottom, the associated evolution of the AoI_i.

[Kadota'18] I. Kadota, A. Sinha, E. Uysal-Biyikoglu, R. Singh and E. Modiano, "Scheduling Policies for Minimizing Age of Information in Broadcast Wireless Networks," in IEEE/ACM Transactions on Networking, vol. 26, no. 6, pp. 2637-2650, Dec. 2018.

Heterogeneous Networks [Kadota’18] (2)

- Non-anticipative scheduling policy: policies that do not use future knowledge in selecting clients, denoted by Π
- π ∈ Π be an arbitrary admissible policy
- In a slot (k, n), policy π can either idle or select a client with an undelivered packet.
- Performance measure---Expected Weighted Sum AoI



Area under AoI_i during any frame k in terms of $h_{k,i}$ and T.

$$\text{EWSAoI} = \frac{1}{KTM}\mathbb{E}\left[\sum_{k=1}^{K}\sum_{i=1}^{M}\alpha_i\left(\frac{T^2}{2}+T^2 h_{k,i}\right)\Bigg|\,\vec{h}_1\right]$$
$$= \frac{T}{2M}\sum_{i=1}^{M}\alpha_i + \frac{T}{KM}\mathbb{E}\left[\sum_{k=1}^{K}\sum_{i=1}^{M}\alpha_i h_{k,i}\,\Bigg|\,\vec{h}_1\right], \quad (2)$$

$h_{k,i}$: the number of frames since the last delivery to client i

α_i: the positive real value that denotes the client’s weight

[Kadota’18] I. Kadota, A. Sinha, E. Uysal-Biyikoglu, R. Singh and E. Modiano, "Scheduling Policies for Minimizing Age of Information in Broadcast Wireless Networks," in IEEE/ACM Transactions on Networking, vol. 26, no. 6, pp. 2637-2650, Dec. 2018.

Heterogeneous Networks [Kadota'18] (3)

$$\begin{aligned}\text{EWSAoI} &= \frac{1}{KTM}\mathbb{E}\left[\sum_{k=1}^{K}\sum_{i=1}^{M}\alpha_i\left(\frac{T^2}{2}+T^2h_{k,i}\right)\middle|\,\vec{h}_1\right]\\ &= \frac{T}{2M}\sum_{i=1}^{M}\alpha_i + \frac{T}{KM}\mathbb{E}\left[\sum_{k=1}^{K}\sum_{i=1}^{M}\alpha_i h_{k,i}\middle|\vec{h}_1\right], \quad (2)\end{aligned}$$

- Performance formulation (EWSAoI minimization)

$$\min_{\pi\in\Pi}\mathbb{E}\left[J_K^\pi\right], \text{ where } J_K^\pi = \frac{1}{KM}\sum_{k=1}^{K}\sum_{i=1}^{M}\alpha_i\, h_{k,i}^\pi,$$

- One possible approach is to use Dynamic Programming
- Computationally demanding, especially for networks with a large number of clients → low-complexity policy

[Kadota'18] I. Kadota, A. Sinha, E. Uysal-Biyikoglu, R. Singh and E. Modiano, "Scheduling Policies for Minimizing Age of Information in Broadcast Wireless Networks," in IEEE/ACM Transactions on Networking, vol. 26, no. 6, pp. 2637-2650, Dec. 2018.

Heterogeneous Networks [Kadota’18] (4)

- **Greedy policy**: in each slot (k, n), schedules a transmission to the client with highest value of $h_{k,i}$ that has an undelivered packet
- Greedy follows a Round Robin-like pattern
- Consider a **symmetric** network with channel reliabilities $p_i = p \in (0, 1]$ and weights $\alpha_i = \alpha > 0$, $\forall i$.
  - Among the class of admissible policies Π, the Greedy policy attains the minimum expected sum AoI

[Kadota’18] I. Kadota, A. Sinha, E. Uysal-Biyikoglu, R. Singh and E. Modiano, "Scheduling Policies for Minimizing Age of Information in Broadcast Wireless Networks," in IEEE/ACM Transactions on Networking, vol. 26, no. 6, pp. 2637-2650, Dec. 2018.

Heterogeneous Networks [Kadota’18] (5)

- Stationary Randomized Policy

Randomized policy selects in each slot (k, n) *client* i *with probability* $\beta_i / \sum_{j=1}^{M} \beta_j$, *for every client* i *and for positive fixed values of* $\{\beta_i\}_{i=1}^{M}$. *The BS transmits the packet if the selected client has an undelivered packet and idles otherwise.*

- this policy uses no information from current or past states of the network.

[Kadota’18] I. Kadota, A. Sinha, E. Uysal-Biyikoglu, R. Singh and E. Modiano, "Scheduling Policies for Minimizing Age of Information in Broadcast Wireless Networks," in IEEE/ACM Transactions on Networking, vol. 26, no. 6, pp. 2637-2650, Dec. 2018.

Heterogeneous Networks [Kadota'18] (6)

- Max-Weight Policy
  - Derived based on Lyapunov Optimization

    Max-Weight policy schedules in each slot (k, n) a transmission to the client with highest value of $p_i \alpha_i h_{k,i}(h_{k,i} + 2)$ that has an undelivered packet, with ties being broken arbitrarily.

  - Observe that when $\alpha_i = \alpha$ and $p_i = p$, prioritizing according to $p_i \alpha_i h_{k,i}(h_{k,i}+2)$, i.e. Max-Weight is identical to Greedy.
  - Max-Weight is AoI-optimal for symmetric networks.

[Kadota'18] I. Kadota, A. Sinha, E. Uysal-Biyikoglu, R. Singh and E. Modiano, "Scheduling Policies for Minimizing Age of Information in Broadcast Wireless Networks," in IEEE/ACM Transactions on Networking, vol. 26, no. 6, pp. 2637-2650, Dec. 2018.

Heterogeneous Networks [Kadota'18] (7)

- Whittle's Index policy
  - Reformulated as Restless Multi-Armed Bandit (RMAB) problem
  - the optimal solution to a relaxation of the RMAB problem

Whittle's Index policy schedules in each slot (k, n) a transmission to the client with highest value of

$$C_i(h_{k,i}) = p_i \alpha_i h_i \left[h_i + \frac{1 + (1 - p_i)^T}{1 - (1 - p_i)^T} \right],$$

that has an undelivered packet,

  - Look similar to the Max-Weight policy
  - Both are equivalent to the Greedy policy in symmetric networks
  - Both the Whittle's Index and Max-Weight policies have better performances

[Kadota'18] I. Kadota, A. Sinha, E. Uysal-Biyikoglu, R. Singh and E. Modiano, "Scheduling Policies for Minimizing Age of Information in Broadcast Wireless Networks," in IEEE/ACM Transactions on Networking, vol. 26, no. 6, pp. 2637-2650, Dec. 2018.

Heterogeneous Networks [Kadota'18] (8)

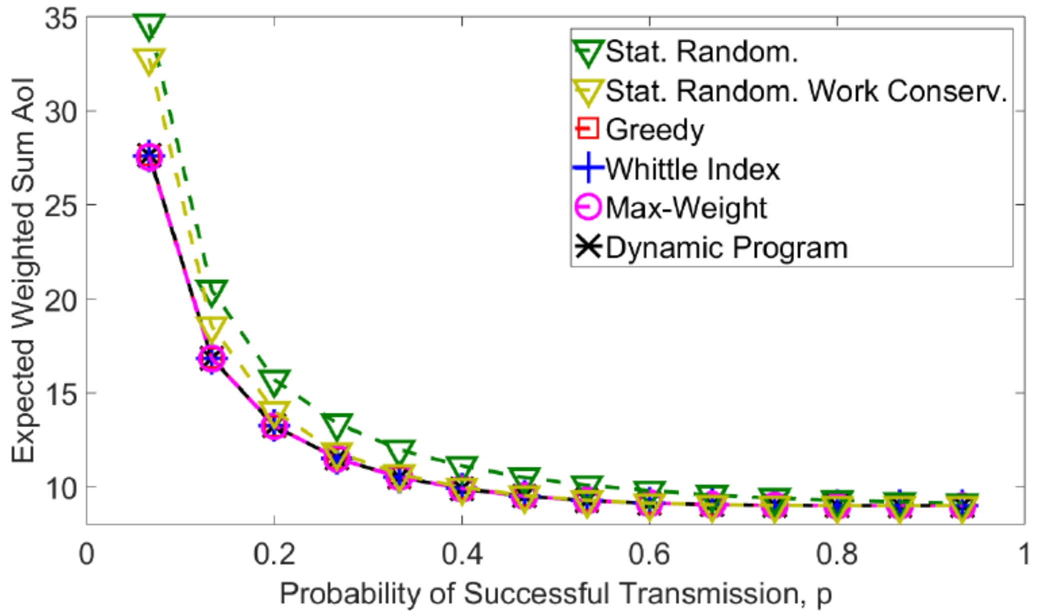


Fig. 5. Two-user symmetric network with $T = 6, K = 150, \alpha_i = 1, p_i = p, \forall i$. The simulation result for each policy and for each value of p is an average over 1,000 runs.

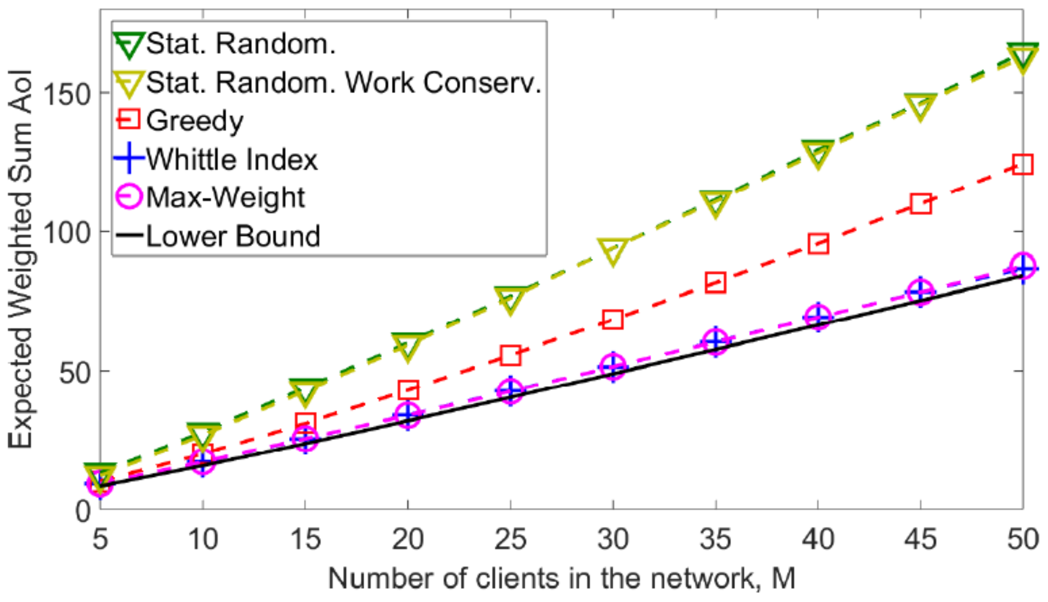
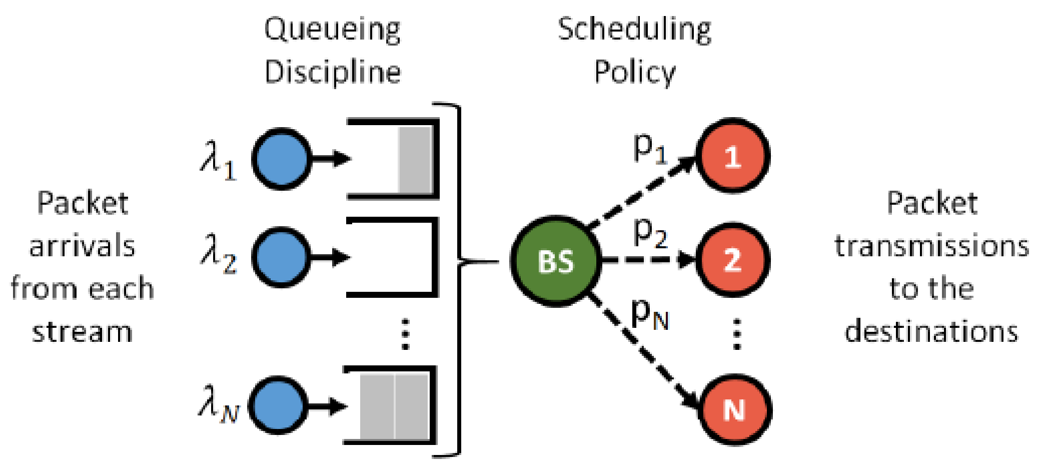


Fig. 7. Network with $T = 3, K = 50,000, \alpha_i = 1, p_i = i/M, \forall i$. The simulation result for each policy and for each value of M is an average over 10 runs.

[Kadota'18] I. Kadota, A. Sinha, E. Uysal-Biyikoglu, R. Singh and E. Modiano, "Scheduling Policies for Minimizing Age of Information in Broadcast Wireless Networks," in IEEE/ACM Transactions on Networking, vol. 26, no. 6, pp. 2637-2650, Dec. 2018.

Random arrival case [Kadota'19] (1)

- One BS, N users, downlink
- a new packet to user $i \in \{1, 2, \ldots, N\}$ arrives to the system with probability $\lambda_i \in (0, 1]$,
- Thee queueing disciplines
- Successful transmission probability p_i
- The BS can transmit at most one packet at any given timeslot t

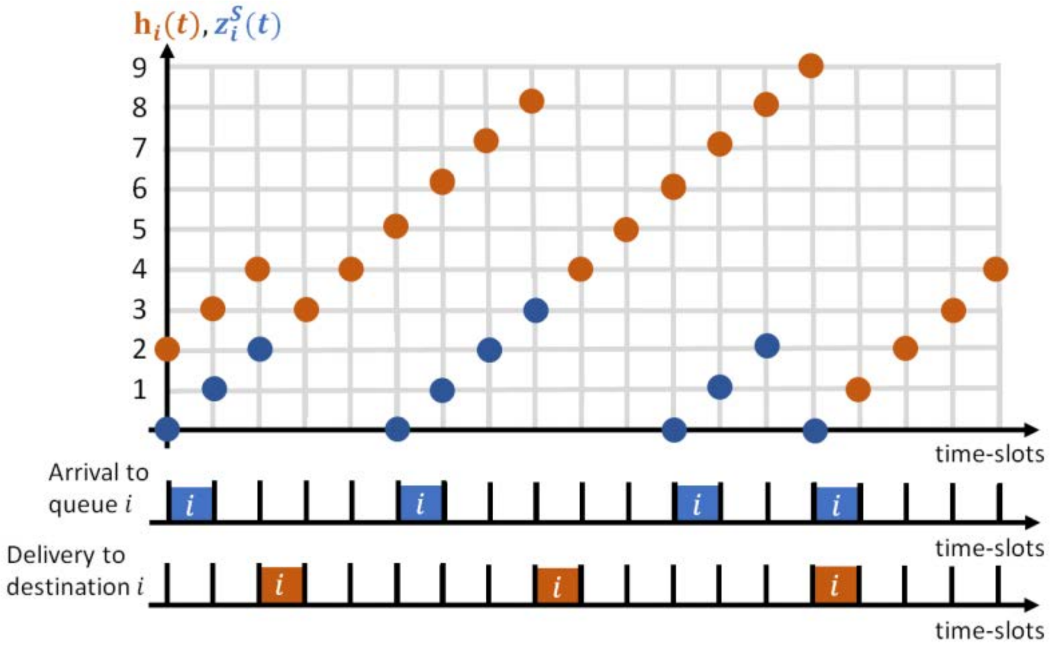


Three Queueing Discipline:
(1) First In First Out (FIFO) queues
(2) Single Packet queues
(3) No queues

[Kadota'19] I. Kadota and E. Modiano, "Minimizing the Age of Information in Wireless Networks with Stochastic Arrivals," in IEEE Transactions on Mobile Computing, early access, Dec. 2019.

Random arrival case [Kadota'19] (2)

- Key difference from the generate-at-will model: *The system time (local age) of the packets should be jointly considered together with the AoI*
- E.g., a packet that has waited for a long time may not worth a transmission
- h_i denotes AoI, z_i denotes the system time (local age)



[Kadota'19] I. Kadota and E. Modiano, "Minimizing the Age of Information in Wireless Networks with Stochastic Arrivals," in IEEE Transactions on Mobile Computing, early access, Dec. 2019.

Random arrival case [Kadota'19] (3)

- To minimize the Expected Weighted Sum AoI (EWSAoI)

$$\mathbb{E}\left[J^{\pi}\right] = \lim_{T\to\infty} \frac{1}{TN} \sum_{t=1}^{T} \sum_{i=1}^{N} w_i \mathbb{E}\left[h_i^{\pi}(t)\right]$$

- Max-Weight policy:

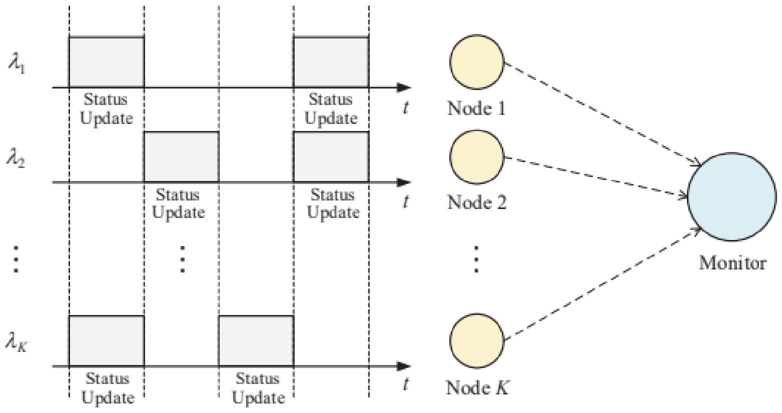
in each slot t, the stream i with a HoL packet and the highest value of $\beta_i p_i \left(h_i(t) - z_i(t)\right)$,

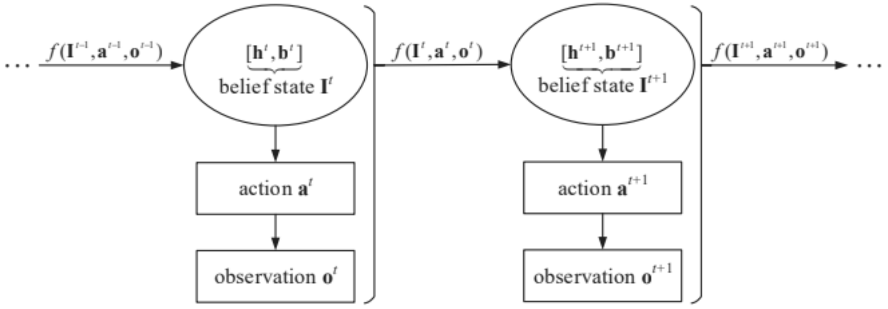
  - β_i is a positive hyperparameter that can be used to tune the Max-Weight policy to different network configurations and queueing disciplines.
  - the difference $h_i(t) - z_i(t)$ represents the AoI reduction accrued from a successful packet delivery to destination i

[Kadota'19] I. Kadota and E. Modiano, "Minimizing the Age of Information in Wireless Networks with Stochastic Arrivals," in IEEE Transactions on Mobile Computing, early access, Dec. 2019.

Uplink with Random Arrival [Gong'20]

- More complicated: the BS/monitor may not know whether new status updates arrive at end nodes ($z_i(t)$ is not exactly known)
- The BS/monitor needs to make a scheduling decision under partially observable system states (Instantaneous AoI is known)
- [Gong'20] addressed the EWSAoI minimization by formulating it as a partially observable Markov decision process (POMDP)
- Belief state characterizes the fully observable AoI and the partially observable status update arrivals of end nodes at the monitor

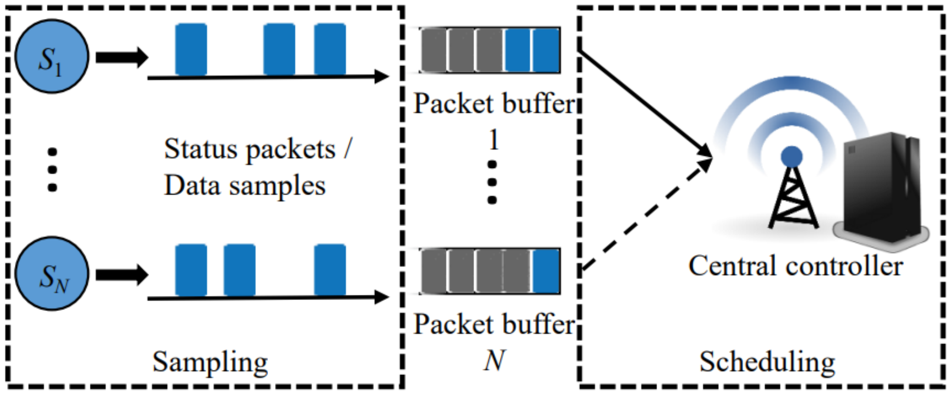




[Gong'20] A. Gong, T. Zhang, H. Chen, Y. Zhang, "Age-of-Information-based Scheduling in Multiuser Uplinks with Stochastic Arrivals: A POMDP Approach," accepted to appear in GLOBECOM 2020, available: https://arxiv.org/abs/2005.05443

Joint Design of Sampling and Scheduling

- Sampling cost (e.g., energy consumption) is considered
- Generate-at-will becomes no longer optimal
- When to sample and when to transmit need to be jointly optimized

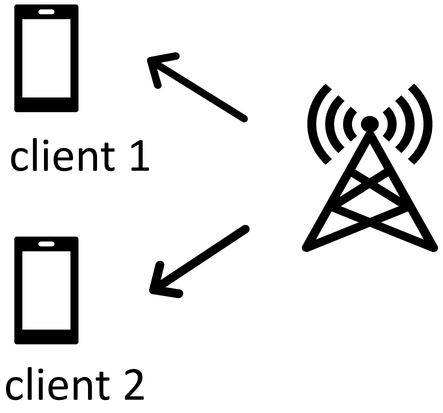


[Jiang'19] Z. Jiang, S. Zhou, Z. Niu and C. Yu, "A Unified Sampling and Scheduling Approach for Status Update in Multiaccess Wireless Networks," IEEE INFOCOM 2019 - IEEE Conference on Computer Communications, Paris, France, 2019.

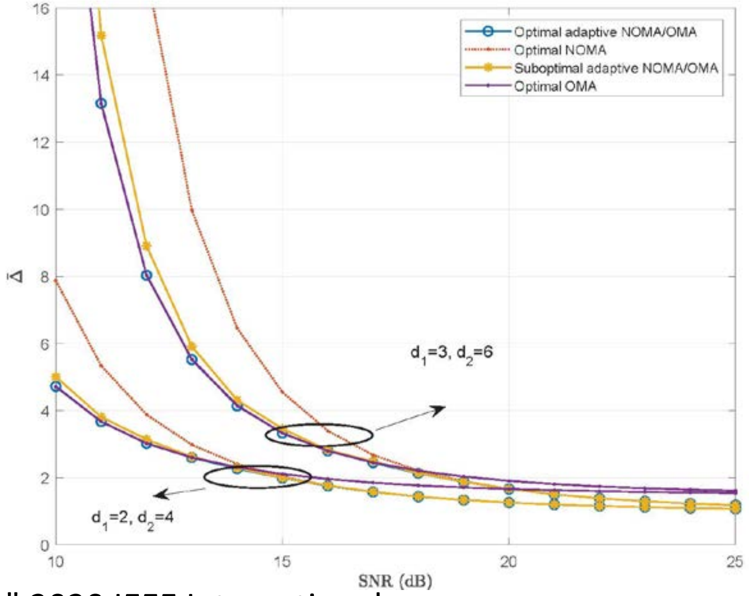
[Abd-Elmagid'20] M. A. Abd-Elmagid, H. S. Dhillon, N. Pappas, "AoI-optimal Joint Sampling and Updating for Wireless Powered Communication Systems", IEEE Transactions on Vehicular Technology, vol. 69, no. 11, pp. 14110-14115, Nov. 2020.

[Fountoulakis'20] E. Fountoulakis, N. Pappas, M. Codreanu, A. Ephremides, "Optimal Sampling Cost in Wireless Networks with Age of Information Constraints", IEEE INFOCOM - 3rd AoI Workshop 2020.

Scheduling 1+ users per timeslot [Wang'20] (1)



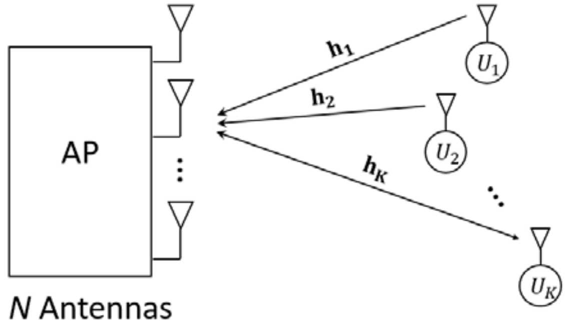
- Users can update more frequently → lower average AoI
- [Wang'20] proposed to apply adaptive NOMA/OMA
- A base station (BS) conducting timely transmission to two clients in a slotted manner via adaptive NOMA/OMA.
- generate-at-will model
- In OMA, the BS decides which client to conduct transmission.
- In NOMA, the BS should determine power allocated to each client
- Decision to make: power allocation between the two users
- Formulated as a Markov decision process (MDP) problem
- Low-complexity max-weight policy was derived

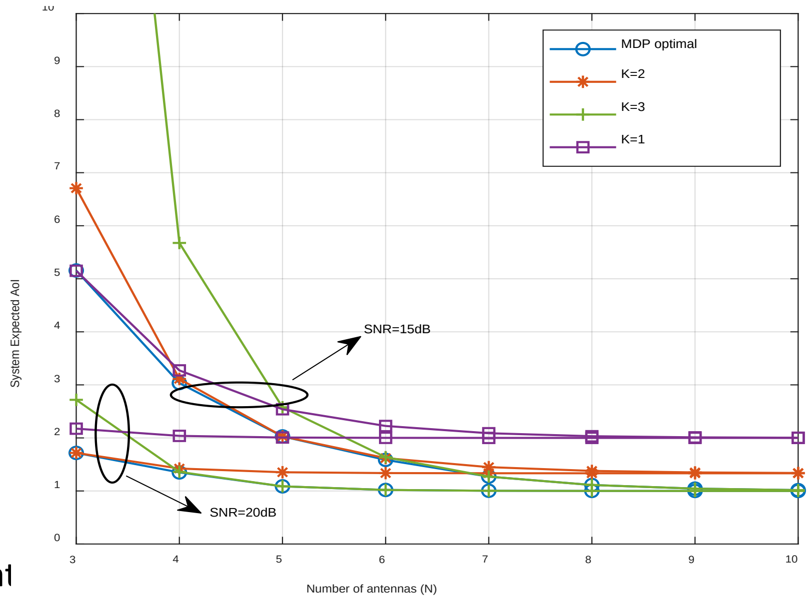


[Wang'20] Q. Wang, H. Chen, Y. Li and B. Vucetic, "Minimizing Age of Information via Hybrid NOMA/OMA," 2020 IEEE International Symposium on Information Theory (ISIT), Los Angeles, CA, USA, 2020, pp. 1753-1758, available: https://arxiv.org/abs/2001.04042

Scheduling 1+ users per timeslot [Chen'20] (2)

- [Chen'20] proposed to use multi-antenna techniques
- Uplink, generate-at-will
- K users, one AP with N antennas
- Can schedule N users in each time slot
- An inherent trade-off exists in multiuser MIMO systems: *scheduling more users to transmit in the same time slot will lead to a higher transmission error probability for each scheduled user*.
- Decision to make: which user or a group of users to schedule in each time slot → MDP problem
- Max-weight policy was also studied





[Chen'20] H Chen, Q Wang, Z Dong, N Zhang, "Multiuser Scheduling for Minimizing Age of Informat
accepted to appear in IEEE/CIC ICCC 2020, available: https://arxiv.org/pdf/2002.00403.pdf

[Feng'20] S. Feng and J. Yang, "Precoding and Scheduling for AoI Minimization in MIMO Broadcast Channels"
https://arxiv.org/pdf/2009.00171.pdf.

Other topics (1)

- Scheduling under other constraints
  - [Kadota’19] I. Kadota, A. Sinha and E. Modiano, "Optimizing Age of Information in Wireless Networks with Throughput Constraints," *IEEE INFOCOM 2018 - IEEE Conference on Computer Communications*, Honolulu, HI, 2018
  - [Tang’20] H. Tang, J. Wang, L. Song and J. Song, "Minimizing Age of Information With Power Constraints: Multi-User Opportunistic Scheduling in Multi-State Time-Varying Channels," in *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 5, pp. 854-868, May 2020
  - [Talak’19] R. Talak, S. Karaman and E. Modiano, "Optimizing Information Freshness in Wireless Networks Under General Interference Constraints," in *IEEE/ACM Transactions on Networking*, vol. 28, no. 1, pp. 15-28, Feb. 2020.
- Scheduling with instantaneous CSI
  - [Zhou’19] Bo Zhou and Walid Saad, "Joint Status Sampling and Updating for Minimizing Age of Information in the Internet of Things", IEEE Transactions on Communications, vol. 67, no. 11, pp. 7468-7482, Nov. 2019.
  - [Talak’20] R. Talak, S. Karaman and E. Modiano, "Improving Age of Information in Wireless Networks With Perfect Channel State Information," in IEEE/ACM Transactions on Networking, vol. 28, no. 4, pp. 1765-1778, Aug. 2020

Other topics (2)

- Non-linear age
  - [Yin'18] Bo Yin, Shuai Zhang, Yu Cheng, Lin X. Cai, Zhiyuan Jiang, Sheng Zhou, Zhisheng Niu. Only Those Requested Count: Proactive Scheduling Polices for Minimizing Effective Age-of-Information. In IEEE INFOCOM, 2018.
  - [Tang'20] H. Tang, J. Wang, Z. Tang and J. Song, "Scheduling to Minimize Age of Synchronization in Wireless Broadcast Networks With Random Updates," in *IEEE Transactions on Wireless Communications*, vol. 19, no. 6, pp. 4023-4037, June 2020
- Multi-channel
  - [Sombabu'20] B. Sombabu and S. Moharir, "Age-of-Information Based Scheduling for Multi-Channel Systems," in *IEEE Transactions on Wireless Communications*, vol. 19, no. 7, pp. 4439-4448, July 2020.
  - [Qian'20] Z. Qian, F. Wu, J. Pan, K. Srinivasan and N. B. Shroff, "Minimizing Age of Information in Multi-channel Time-sensitive Information Update Systems," *IEEE INFOCOM 2020 - IEEE Conference on Computer Communications*, Toronto, ON, Canada, 2020.
  - [Moltafet'20] M. Moltafet, M. Leinonen, M. Codreanu, N. Pappas, "Power Minimization for Age of Information Constrained Dynamic Control in Wireless Sensor Networks", Submitted, IEEE Transactions on Communications, Oct. 2020.

Other topics (3)

- Scheduling in multi-hop networks
  - [Talak'17] R. Talak, S. Karaman and E. Modiano, "Minimizing age-of-information in multi-hop wireless networks," 2017 55th Annual Allerton Conference on Communication, Control, and Computing (Allerton), Monticello, IL, 2017, pp. 486-493.
  - [Li'20] B. Li, H. Chen, Y. Zhou, and Y. Li, "Age-oriented opportunistic relaying in cooperative status update systems with stochastic arrivals," https://arxiv.org/pdf/2001.04084.pdf, IEEE GLOBECOM 2020, accepted in Aug. 2020..
  - [Gu'20] Y Gu, Q Wang, H Chen, Y Li, and B Vucetic, "Optimizing Information Freshness in Two-Hop Status Update Systems under a Resource Constraint", submitted, July 2020. See https://arxiv.org/pdf/2007.02531.pdf

AoI-Oriented Random Access

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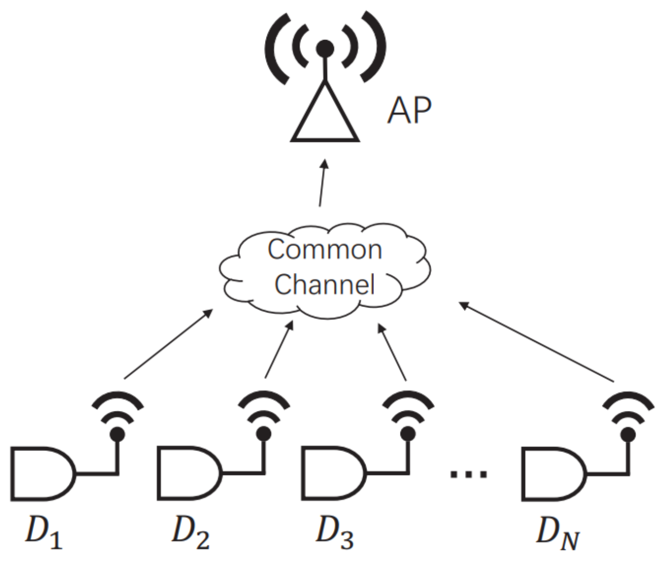
Why random access?

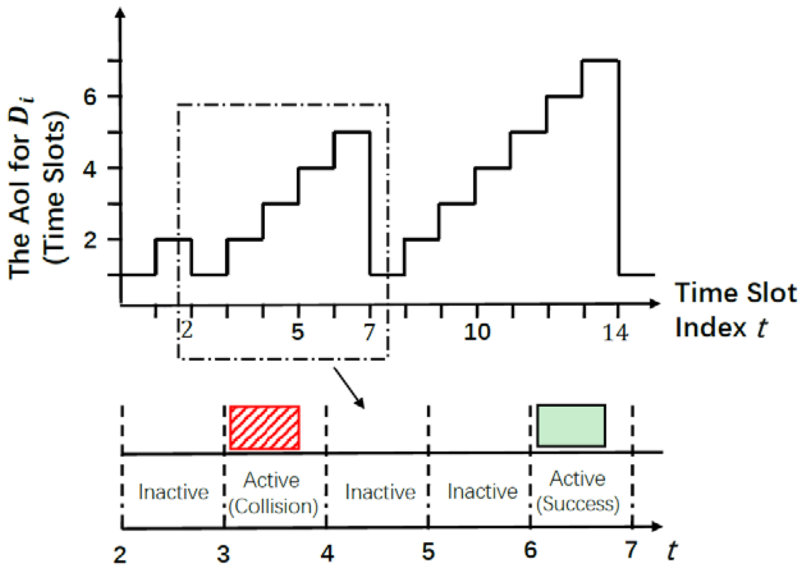
- Massive connectivity is coming → Ericsson foresaw that by 2021, there will be around 28 billion IoT devices
- Centralized scheduling → overhead is excessive for a large-scale network
- Decentralized scheduling (random access) is more preferred

How to schedule the status updates of massive IoT devices to achieve a low network-wide AoI?

Generic Model

- Consider an uplink network consisting of one access point (AP) and N IoT devices (N can be large)
- Time is divided into slots of equal durations
- the transmission of each status update packet takes one time slot





Age-independent random access (AIRA)

- Slotted ALOHA-like random access
- The active probability for each IoT device p’ is independent of its instantaneous AoI
- Generate-at-will model
- Let q denote the successful status update probability when an IoT device becomes active

$$q = (1 - p')^{N-1}$$

- Average AoI (collision channel)

$$\bar{\Delta}' = \frac{1}{p'q} = \frac{1}{p'\left(1 - p'\right)^{N-1}}.$$

[Yates-Kaul’17] R. D. Yates and S. K. Kaul, "Status updates over unreliable multiaccess channels," 2017 IEEE International Symposium on Information Theory (ISIT), Aachen, 2017, pp. 331-335.

Age-Dependent Random Access (ADRA)

- [Chen-Gu'20] proposed age-dependent random access
- Intuition: those devices with relatively smaller AoI should access the channel with a lower probability
  - such that other devices with larger AoI can achieve a higher success probability to update their statuses by encountering less collisions
- For simplicity, we consider a threshold-based ADRA protocol: if the instantaneous AoI is no less than a threshold δ, the IoT device becomes activate with a fixed probability of p. Otherwise, the IoT device will stay inactive with probability 1

[Chen-Gu'20] H. Chen, Y. Gu, and S. C. Liew, "Age-of-Information Dependent Random Access for Massive IoT Networks," presented in IEEE INFOCOM 2020 workshop on Age of information, July 2020, avaliable: https://arxiv.org/pdf/2001.04780.pdf.

Age-Dependent Random Access (ADRA)

- Different from the AIRA policy, the active probability of each IoT device (i.e., p) in the ADRA protocol depends on its instantaneous AoI.
  - q depends on the instantaneous AoI of all IoT devices and thus the AoI evolutions of all devices tangle together
  - Multi-dimension Markov Chain (MC) is a possible solution, however the computational complexity is very high
- We managed to derived an approximated closed-from expression of the average AoI of ADRA so that threshold δ and transmission probability p can be optimized
- [Chen-Gatsis'19] considered a similar threshold policy with applying the conventional back-off channel access probability

[Chen-Gu'20] H. Chen, Y. Gu, and S. C. Liew, "Age-of-Information Dependent Random Access for Massive IoT Networks," presented in IEEE INFOCOM 2020 workshop on Age of information, July 2020, avaliable: https://arxiv.org/pdf/2001.04780.pdf.

[Chen-Gatsis'20] X. Chen, K. Gatsis, H. Hassani and S. S. Bidokhti, "Age of Information in Random Access Channels," 2020 IEEE International Symposium on Information Theory (ISIT), Los Angeles, CA, USA, 2020, pp. 1770-1775

Performance Comparison

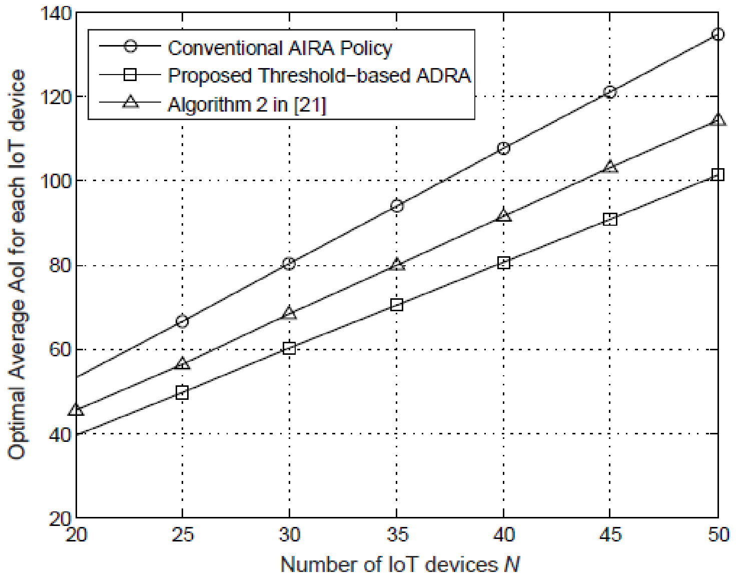


Fig. 5. The average AoI versus the number of IoT devices N for the proposed threshold-based ADRA, the existing AIRA schemes and Algorithm 2 in [21].

[Chen-Gu'20] H. Chen, Y. Gu, and S. C. Liew, "Age-of-Information Dependent Random Access for Massive IoT Networks," presented in IEEE INFOCOM 2020 workshop on Age of information, July 2020, available: https://arxiv.org/pdf/2001.04780.pdf.

[Chen-Gatsis'19] X. Chen, K. Gatsis, H. Hassani, and S. S. Bidokhti, "Age of information in random access channels," arXiv preprint arXiv:1912.01473, 2019.

Threshold-ALOHA

- Threshold-ALOHA [Yavascan'20] :
  - sources will wait until their age reaches a certain threshold Γ, before they turn on their slotted ALOHA mechanism, and
  - only then start to attempt transmission with a fixed probability τ at each time slot
- Derived time-average expected Age of Information (AoI) attained by this policy, and explored its scaling with network size, n
- the optimal age threshold and transmission probability are 2.2n and 4.69/n, respectively
- the optimal AoI scales with the network size as 1.4169n (almost half the minimum AoI achievable using slotted ALOHA)
- while the loss from the maximum achievable throughput of e^(-1) remains below 1%.

[Yavascan'20] O. T. Yavascan, E. Uysal, "Analysis of Slotted ALOHA with an Age Threshold, July 2020, available: https://arxiv.org/abs/2007.09197.

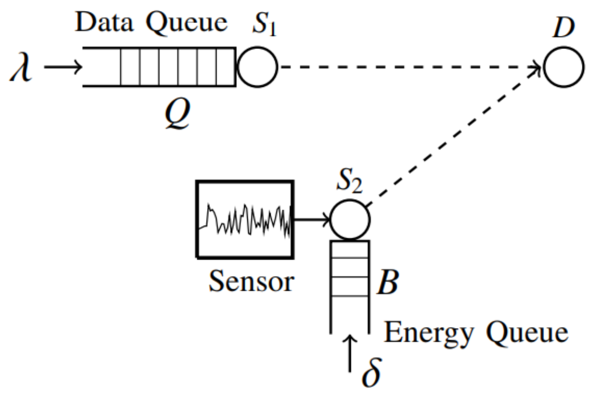
Index-Prioritized Random Access

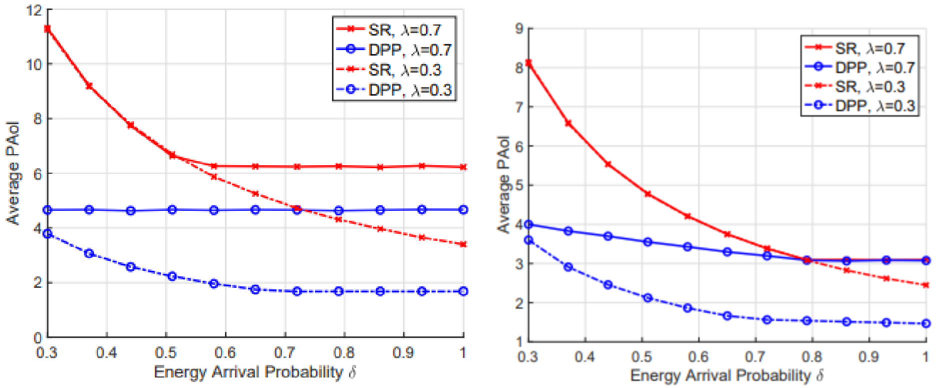
- Whittle index scheduling policies can achieve near-optimal AoI but require heavy signalling overhead
- [Sun-Jiang'20] proposed a contention-based random-access scheme, namely Index-Prioritized Random Access (IPRA)
- Each terminal can calculate its own index
- This individual index can be mapped to a transmission probability
    - based on a public mapping function which captures the idea that only valuable packets (packets with high index values) are transmitted
- A single-threshold function was used in [Sun-Jiang'20]

[Sun-Jiang'20] J. Sun, Z. Jiang, B. Krishnamachari, S. Zhou and Z. Niu, "Closed-Form Whittle's Index-Enabled Random Access for Timely Status Update," in IEEE Transactions on Communications, vol. 68, no. 3, pp. 1538-1551, March 2020

Random Access vs Scheduling

- Two-user multiple access channel with multipacket reception (MPR) capabilities
- a stationary randomized (SR) policy where both nodes make independent transmission decisions based on some fixed probability distributions
- a Drift-Plus-Penalty (DPP) policy for AoI-optimal and peak-AoI-optimal scheduling algorithms using the Lyapunov optimization theory
- Simulation results show that the DPP policy always outperforms the SR policy





(a) Weak MPR (b) Strong MPR

[Chen-Pappas'20] Z. Chen, N. Pappas, E. Björnson, E. G. Larsson, "Optimizing Information Freshness in a Multiple Access Channel with Heterogeneous Devices", arXiv:1910.05144v2, July 2020.

Carrier sensing multiple access (CSMA)

- [Wang'19] studied the broadcast Age of Information of CSMA/CA networks
- [Maatouk'20] analyzed the average AoI of CSMA for both generate-at-will and stochastic arrival models, optimized the CSMA scheme and proposed a modification to it by giving each link the freedom to transition to SLEEP mode
- [Bedewy'20] optimized the sleep-wake parameters for minimizing the weighted-sum peak AoI of the sources, subject to per-source battery lifetime constraints

[Wang'19] M. Wang and Y. Dong, "Broadcast Age of Information in CSMA/CA Based Wireless Networks," 2019 15th International Wireless Communications & Mobile Computing Conference (IWCMC), Tangier, Morocco, 2019, pp. 1102-1107

[Maatouk'20] A. Maatouk, M. Assaad and A. Ephremides, "On the Age of Information in a CSMA Environment," in IEEE/ACM Transactions on Networking, vol. 28, no. 2, pp. 818-831, April 2020, doi: 10.1109/TNET.2020.2971350.

[Bedewy'20] Ahmed M. Bedewy, Yin Sun, Rahul Singh, and Ness B. Shroff, "Optimizing Information Freshness using Low-Power Status Updates via Sleep-Wake Scheduling", accepted by ACM MobiHoc, 2020.

Part V Prototype for Experimental Study of AoI-oriented Designs

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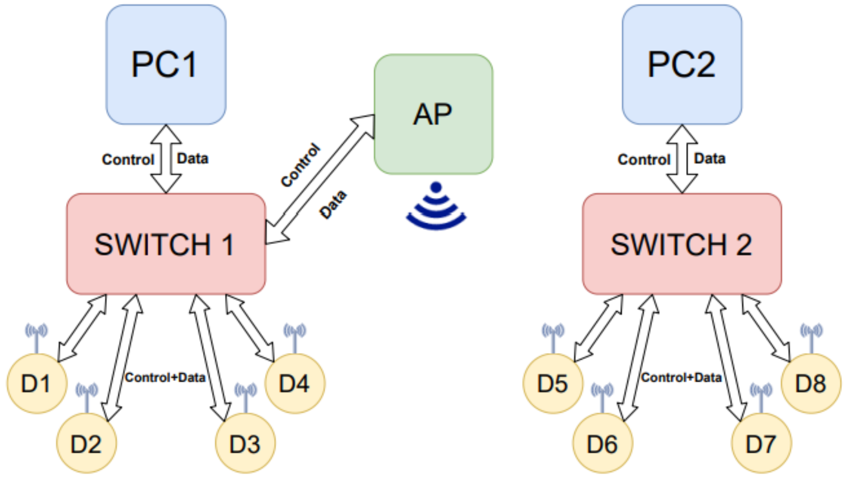
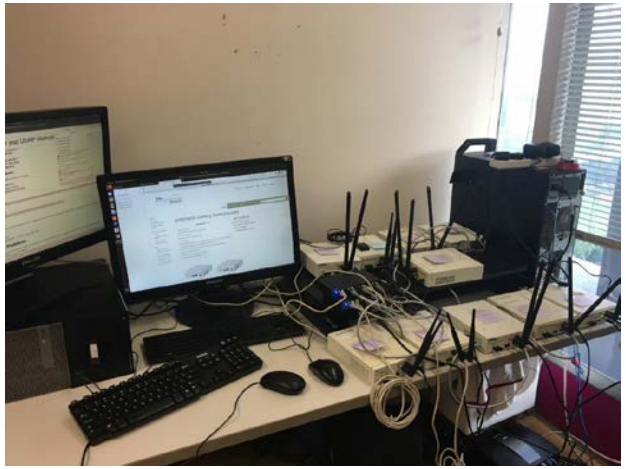
SDR-based proof-of-concept prototype

- Ettus USRP N210's as transceivers: One USRP N210 serves as the AP and eight USRP N210s serve as end devices
- All of them are connected to two powerful PCs through multiple 1 Gigabit Ethernet cables and two Ethernet switches
- though some USRPs are connected to the same PC, they use individual local clocks on their motherboards
- The SBX RF frontboards embedded in USRPs are used to transmit RF signals, working at 1 GHz with 500 kHz channel bandwidth.
- We use the GNURadio platform to define the signal generation and data processing in our SDR prototype





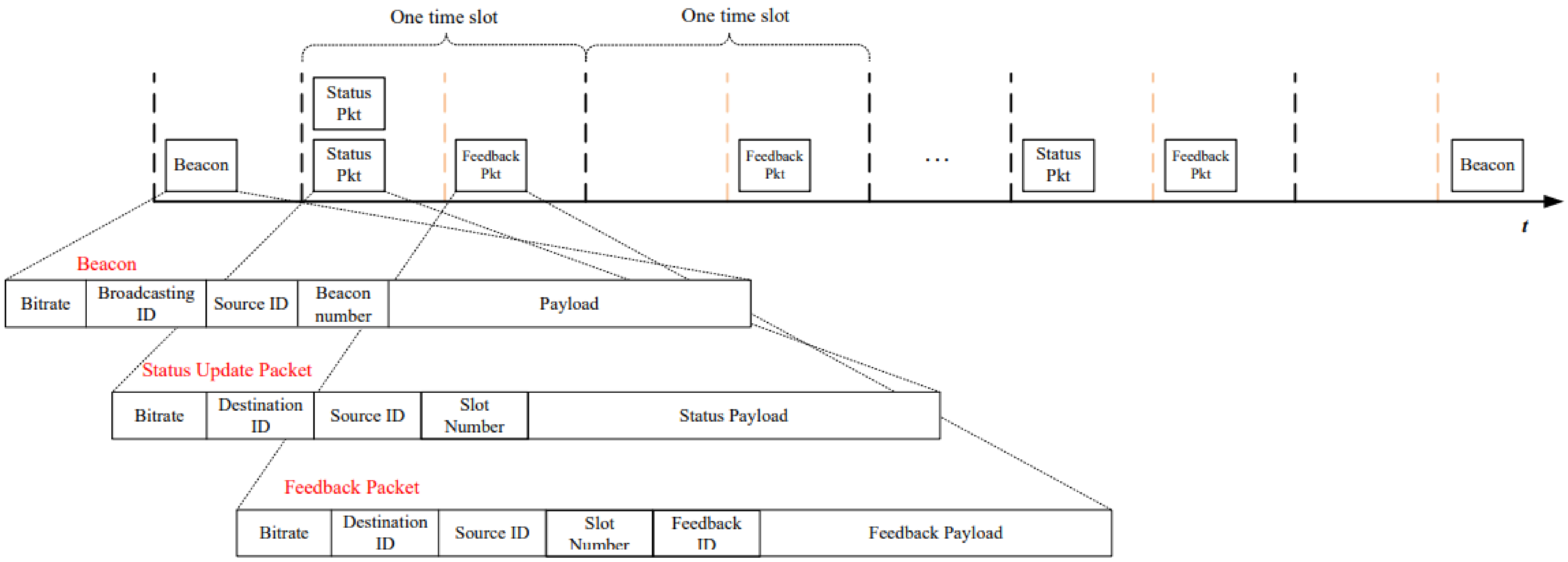
[Han'20] Z. Han, J. Liang, Y. Gu, H. Chen, "Software-Defined Radio Implementation of Age-of-Information-Oriented Random Access," in IEEE IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society, July 2020.

SDR-based proof-of-concept prototype

- We implemented the ADRA protocol and tested it in office environments
- To mimic the collision channel, we implement the convolutional code in the physical layer. Orthogonal frequency duplex modulation (OFDM) is used for higher frequency efficiency
- A simple yet effective synchronized transmission scheme for time-slotted transmission
  - (1) beacon broadcasting: aims to achieve the time synchronization (the USRP that acts as the AP broadcasts a Beacon, which contains timing information to serve as a time reference, the inter-beacon period is set as 100 time slots in our experiments)
  - Each time slot is further split to two parts for channel access and feedback
  - (2) channel access: status update by end devices
  - (3) feedback: AP broadcasts a Feedback Packet indicating the successful reception of a Status Update Packet

[Han'20] Z. Han, J. Liang, Y. Gu, H. Chen, "Software-Defined Radio Implementation of Age-of-Information-Oriented Random Access," in IEEE IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society, July 2020.

SDR-based proof-of-concept prototype



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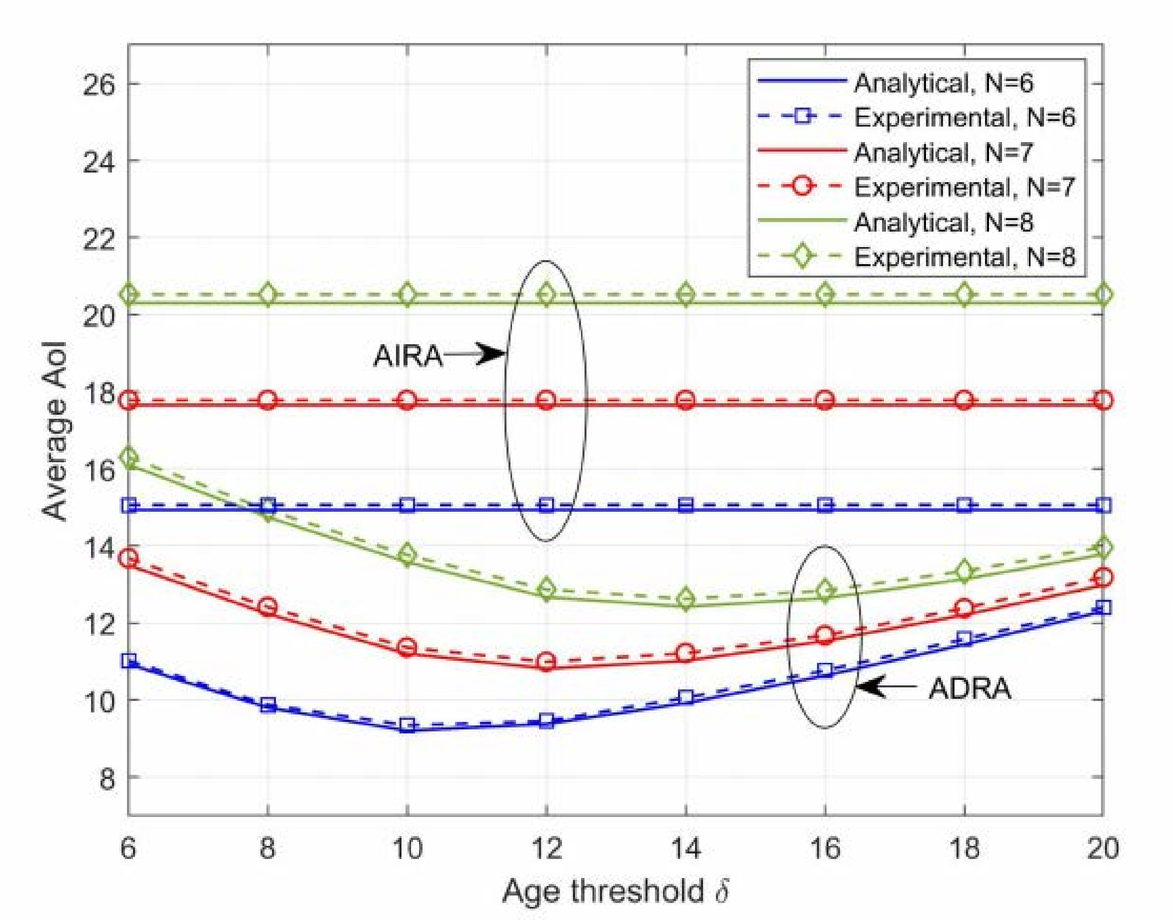

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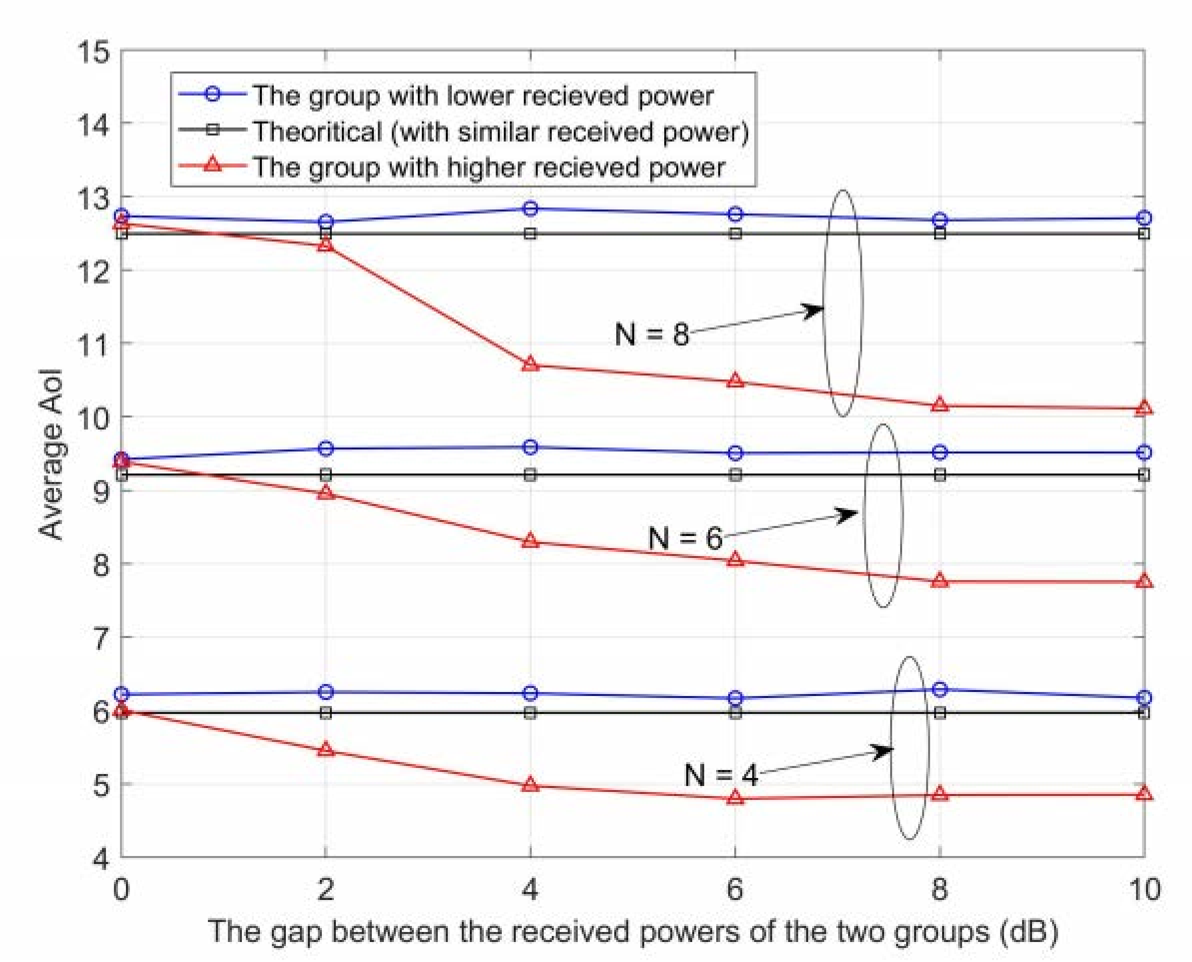
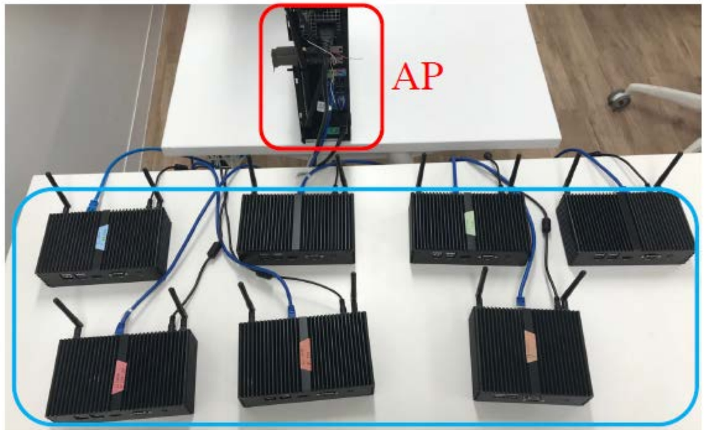
SDR-based proof-of-concept prototype

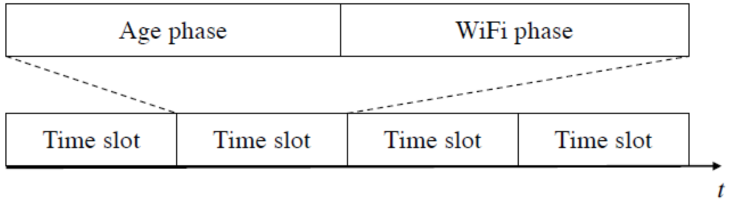


[Han'20] Z. Han, J. Liang, Y. Gu, H. Chen, "Software-Defined Radio Implementation of Age-of-Information-Oriented Random Access," in IEEE IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society, July 2020.

Commercial WiFi network cards-based prototype

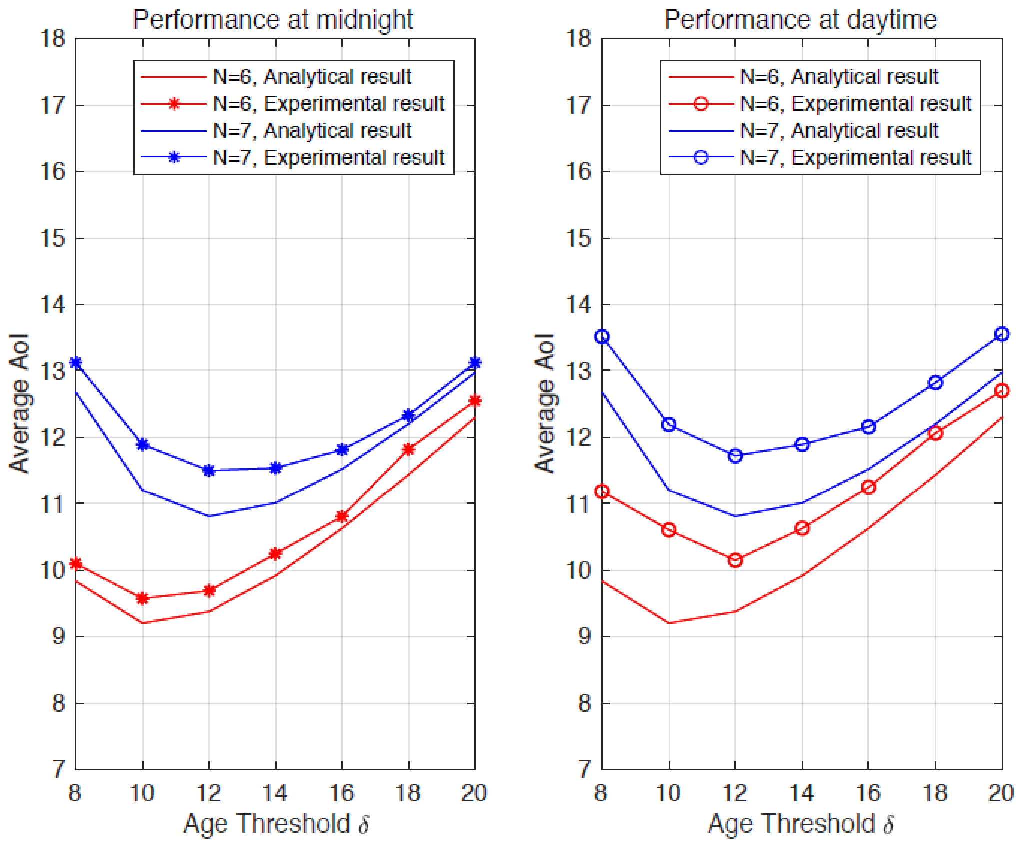
- Atheros AR9285 chips
- Modify the driver of AR9285, e.g., the module ath9k in the Linux kernel (built on RT-WiFi)
- CSMA → TDMA
- Frame design
- Coexistence between AoI data traffic and WiFi network maintenance traffic





Commercial WiFi network cards-based prototype

- Performance of ADRA



Pass to Dr. Nikolaos PAPPAS

Concluding remarks

Concluding 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.

Concluding remarks and future directions

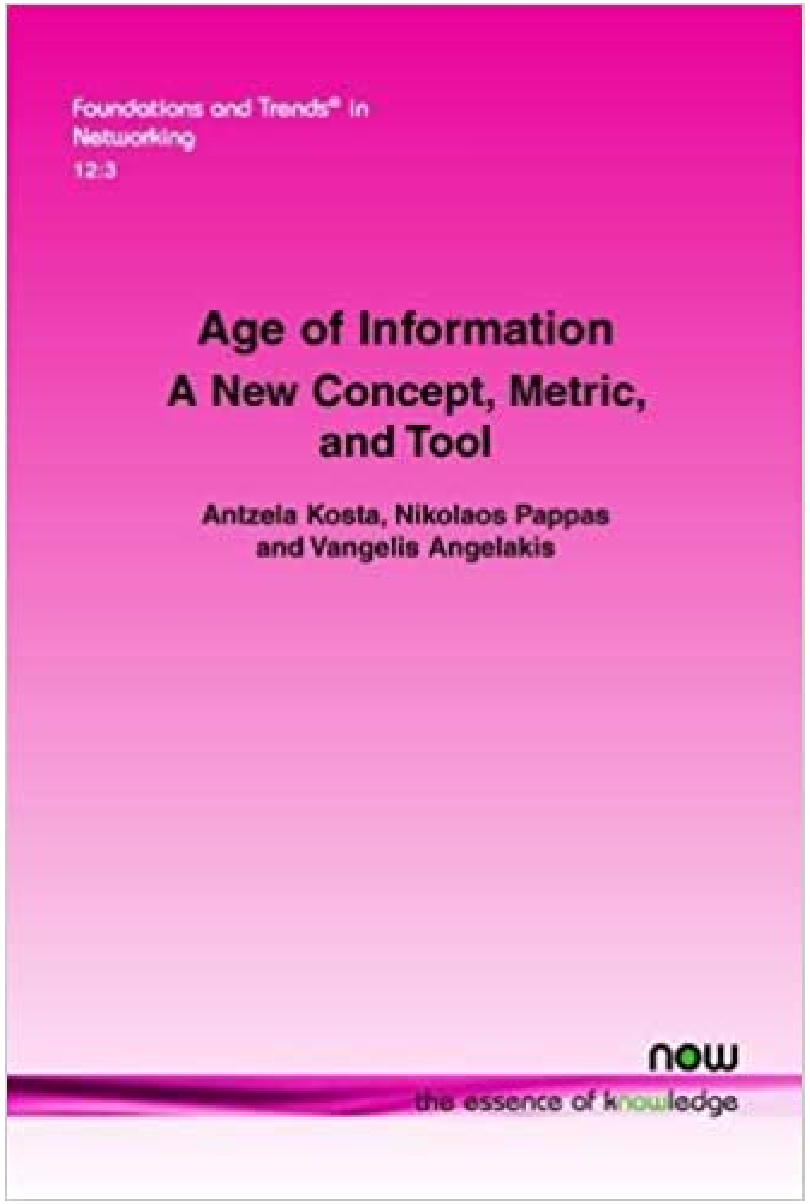
- There are still many interesting research directions
  - Definition of effective age (term coined by Prof. Ephremides in ITA 2015)
  - Sampling and remote reconstruction
  - Deploying of AoI in machine learning

- 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

M. Kountouris, N. Pappas, "Semantics-Empowered Communication for Networked Intelligent Systems", *arxiv*, July 2020.

Monographs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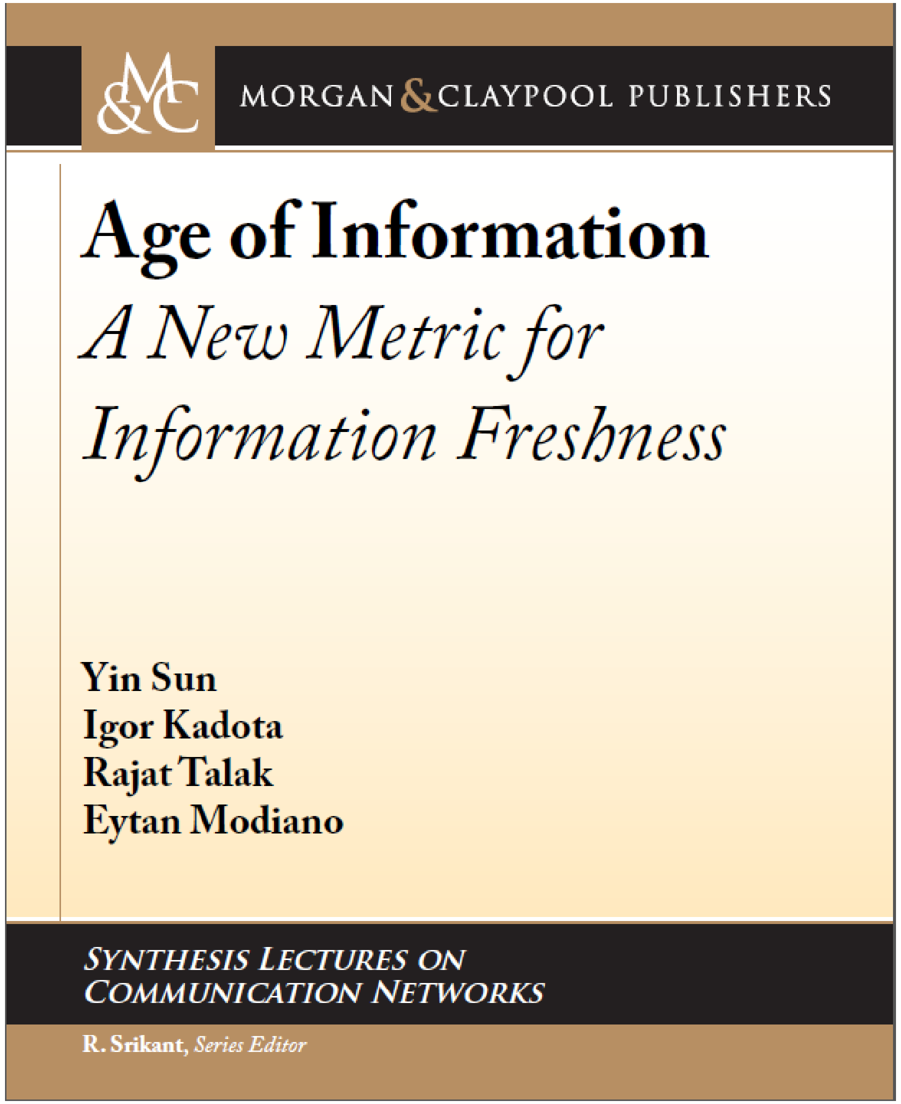
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