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TUT-01: Age of Information as a New Data Freshness Metric in the IoT Era: From Theory to Implementation

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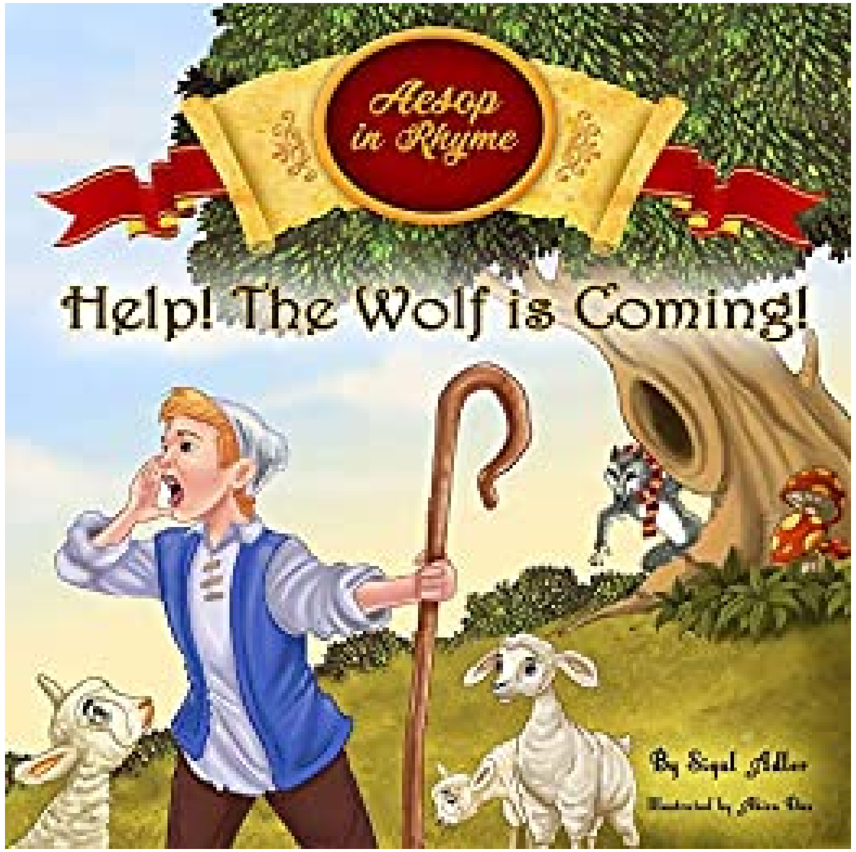
Outline of the Tutorial

- Overview
- Modeling and Optimization of AoI
- AoI-oriented Multiuser Scheduling
- AoI-oriented Random Access
- Prototyping Testbed for Validation and Evaluation of AoI-oriented Designs
- Concluding remarks

Internet of Things (IoT)

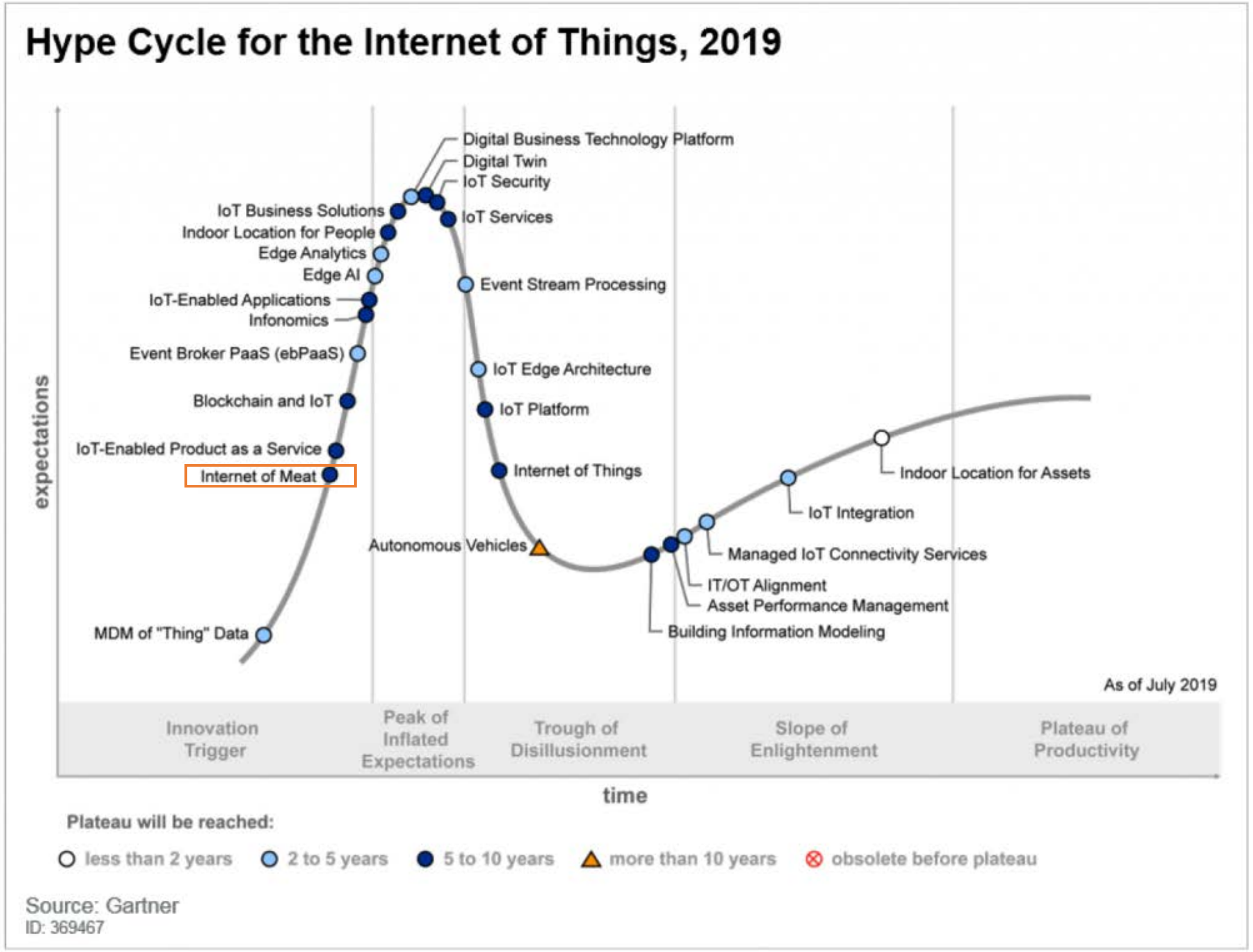


“Wolf is coming”

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

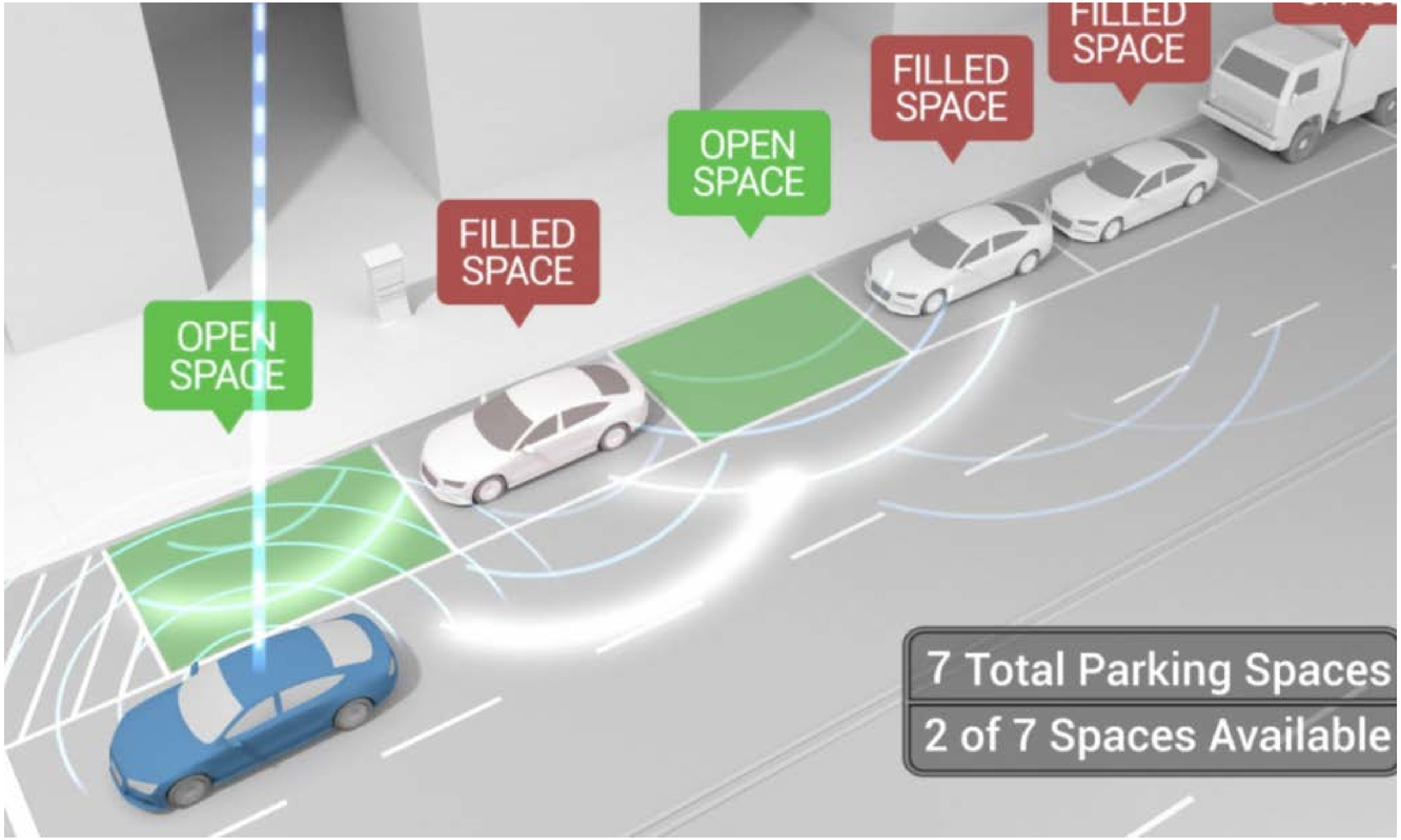
IoT is really coming



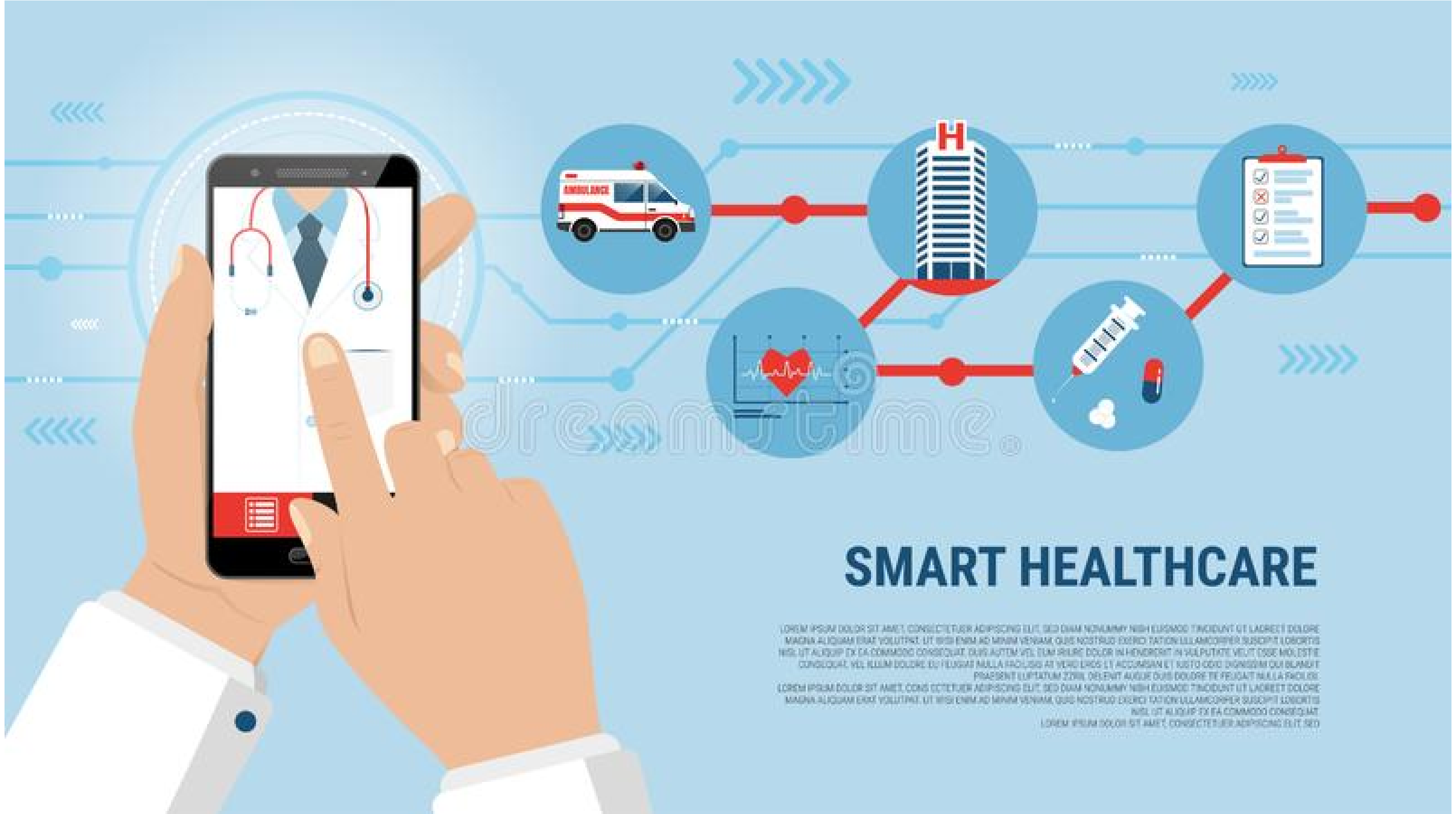
Source: https://www.gartner.com/smarterwithgartner/3-major-trends-drive-gartner-hype-cycle-midsize-enterprises-2019/

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 to a remote monitor --- status update system
- Information usually has the highest value when it is fresh.
- How to quantify information freshness?

Age of Information as a New Data Freshness Metric in the IoT Era: From Theory to 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 status updates 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.
    - On the other hand, 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

Modeling and Optimization of AoI

Nikolaos Pappas

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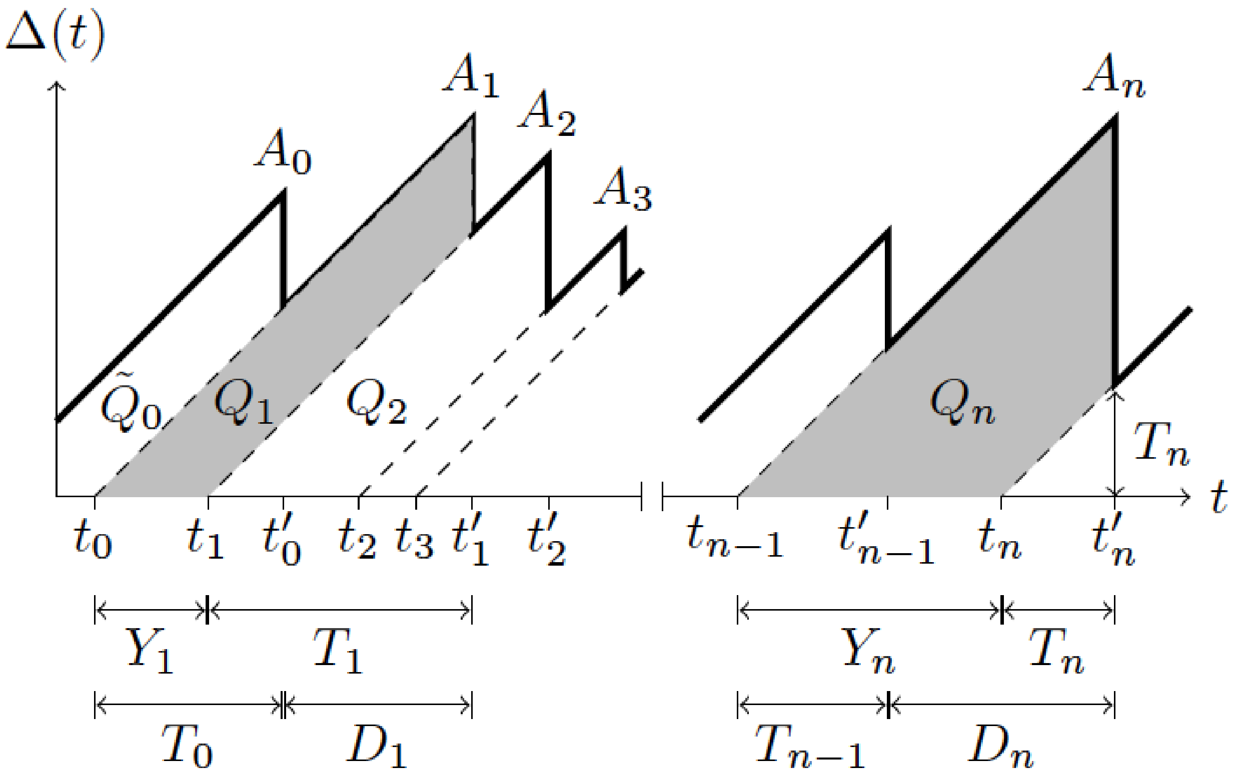
Definition of Age of Information (AoI)

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

Time Average AoI – Sawtooth Sample path



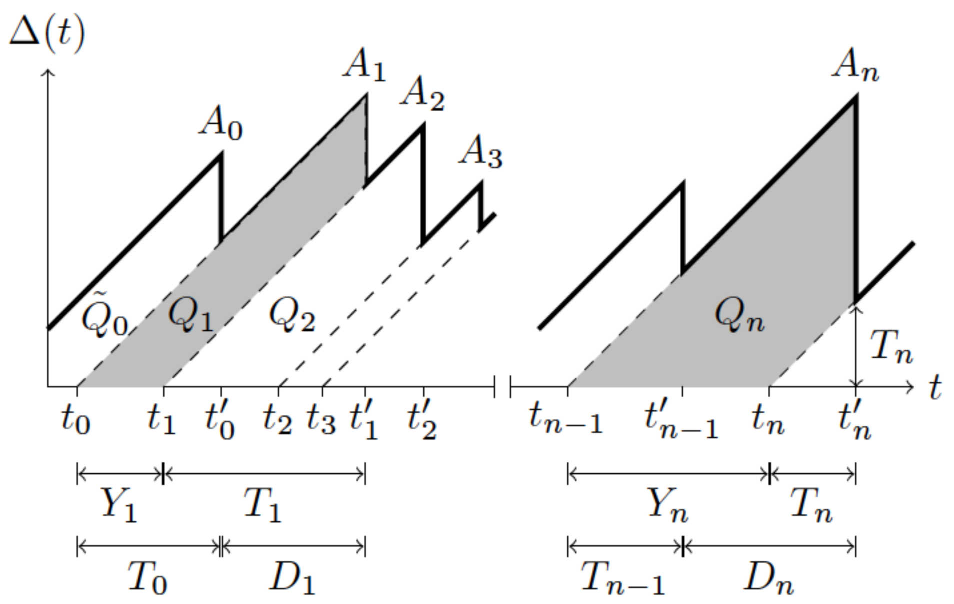
- $t_0, t_1, t_2, \ldots$ times that are updates are generated
- $t_o', t_1', t_2', \ldots$ times that updates are received at the monitor

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



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

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

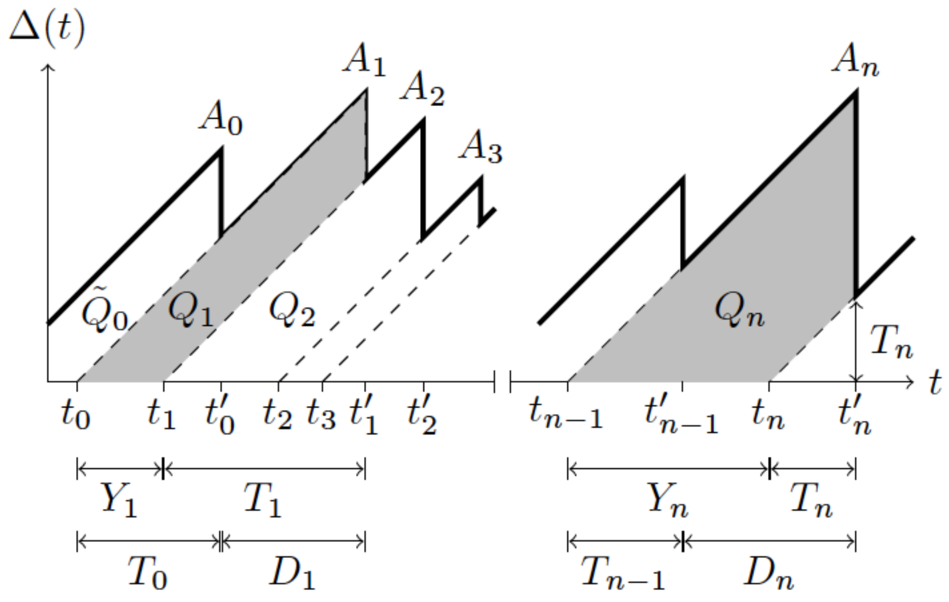
$$\frac{1}{N(\mathcal{T})}\sum_{j=1}^{N(\mathcal{T})} Q_j \;\to\; \mathrm{E}[Q] \quad \mathcal{T} \to \infty$$

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

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

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

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



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

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

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 $E[Y_n T_n]$

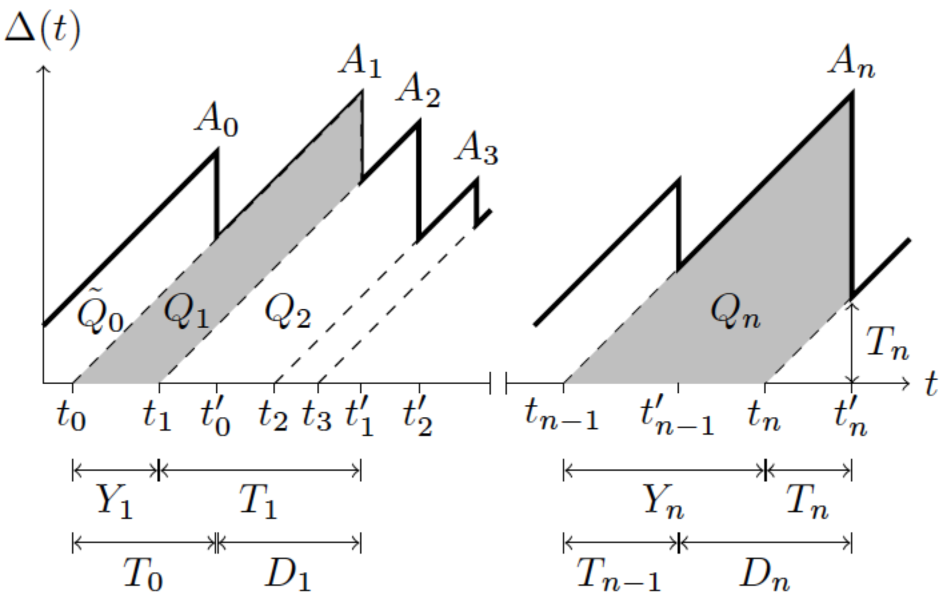
Peak AoI

- 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.

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. This requirement is aligned with the fact that 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,” JCN 2019.
A. Kosta, N. Pappas, A. Ephremides, and V. Angelakis, “The cost of delay in status updates and their value: Non-linear ageing,” Accepted, IEEE TCOM 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

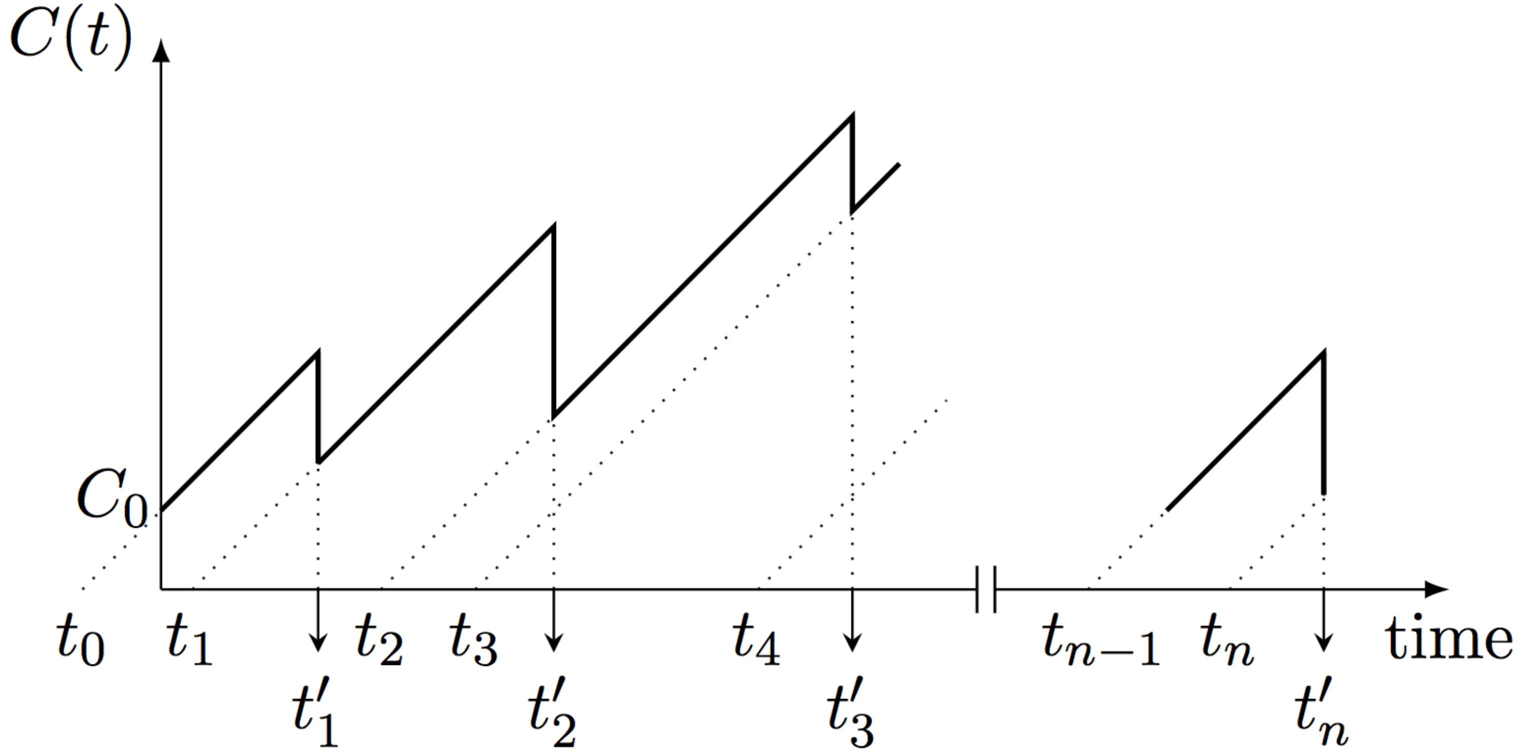
A. Kosta, N. Pappas, A. Ephremides, V. Angelakis, "Age and Value of Information: Non-linear Age Case", *IEEE ISIT* 2017.

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

Cost of Update Delay (CoUD): The linear case

$$f_s(t) = \alpha t$$

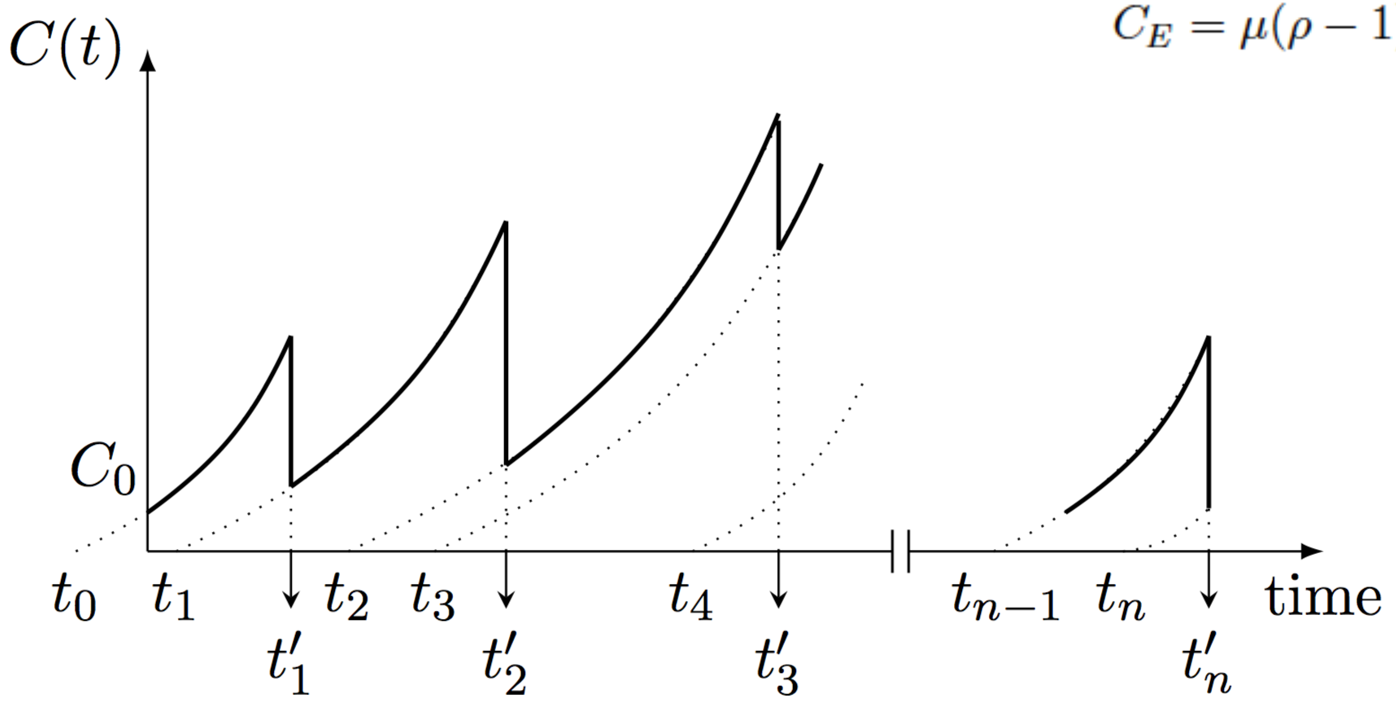
$$C_P = \alpha \frac{1}{\mu} \left(1 + \frac{1}{\rho} + \frac{\rho^2}{1-\rho} \right)$$



Cost of Update Delay (CoUD): The exponential case

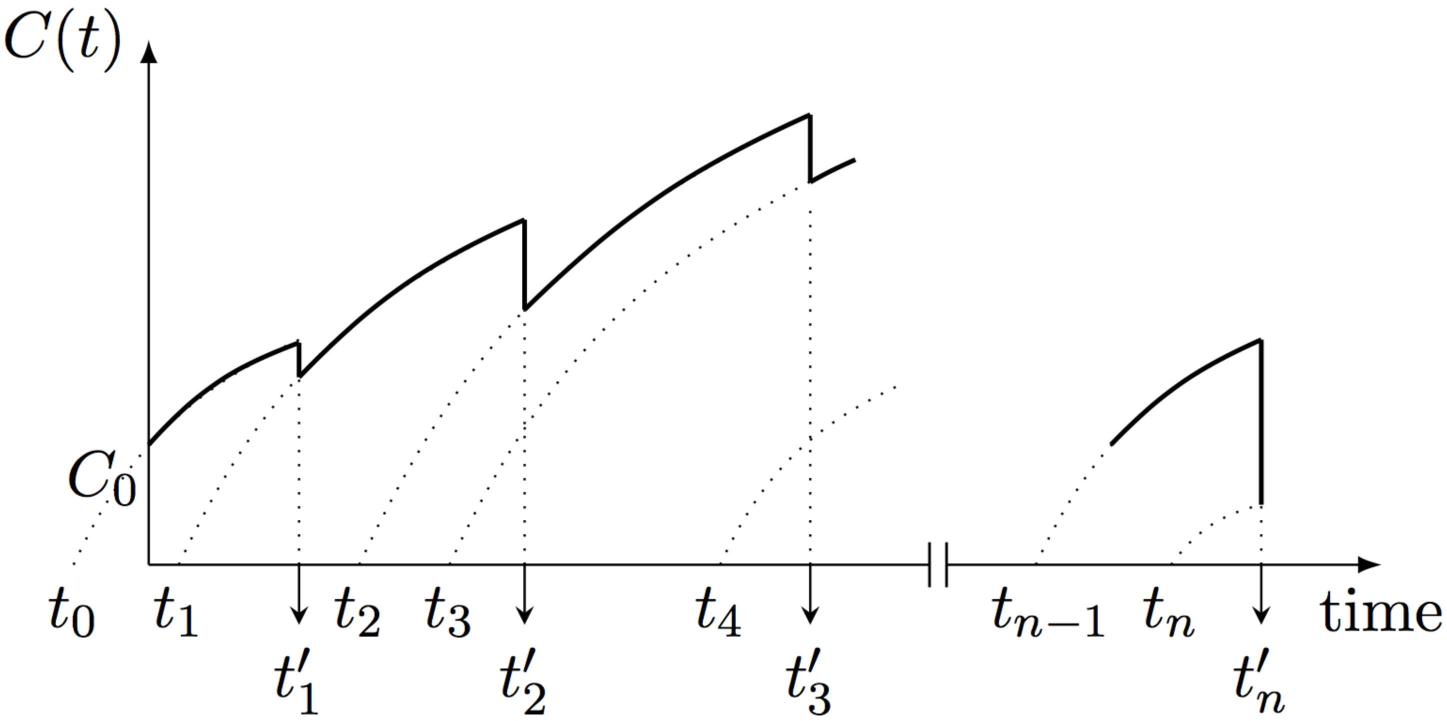
$$f_s(t) = e^{\alpha t} - 1 \longleftrightarrow \text{low autocorrelation}$$

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



Cost of Update Delay (CoUD): The logarithmic case

$$f_s(t) = \log(\alpha t + 1) \longleftrightarrow \text{high autocorrelation}$$



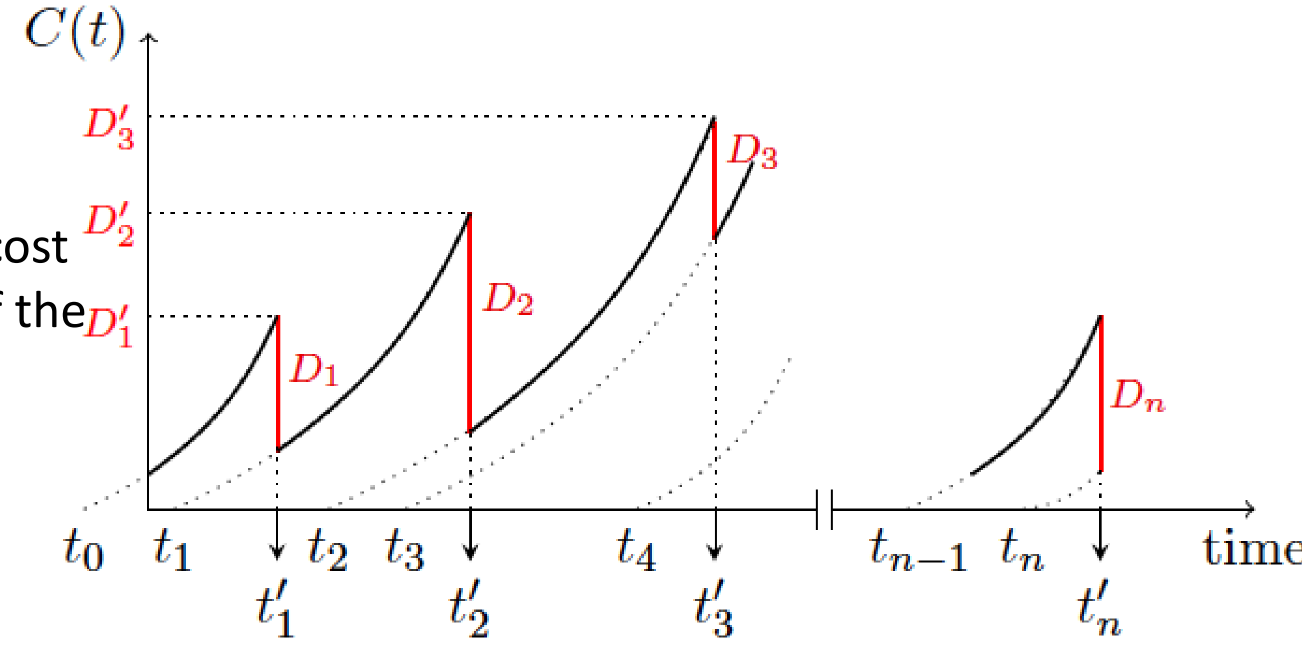
$$C_L = \frac{1}{\alpha(\lambda-\mu)^2}\left(e^{-\frac{\mu\rho}{\alpha}}\left(\mu(1-\rho)Ei\left[-\frac{\mu}{a}\right](\alpha\mu+\lambda^2-\lambda\mu)\,e^{\frac{\mu(\rho+1)}{\alpha}} - \alpha\mu^2(1-\rho)Ei\left[-\frac{\lambda}{\alpha}\right]e^{\frac{\lambda+\mu\rho}{\alpha}} - \alpha e^{\mu/\alpha}(\lambda-\mu)^2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

Value of Information of update (VoIU)

- It captures the degree of importance of an update

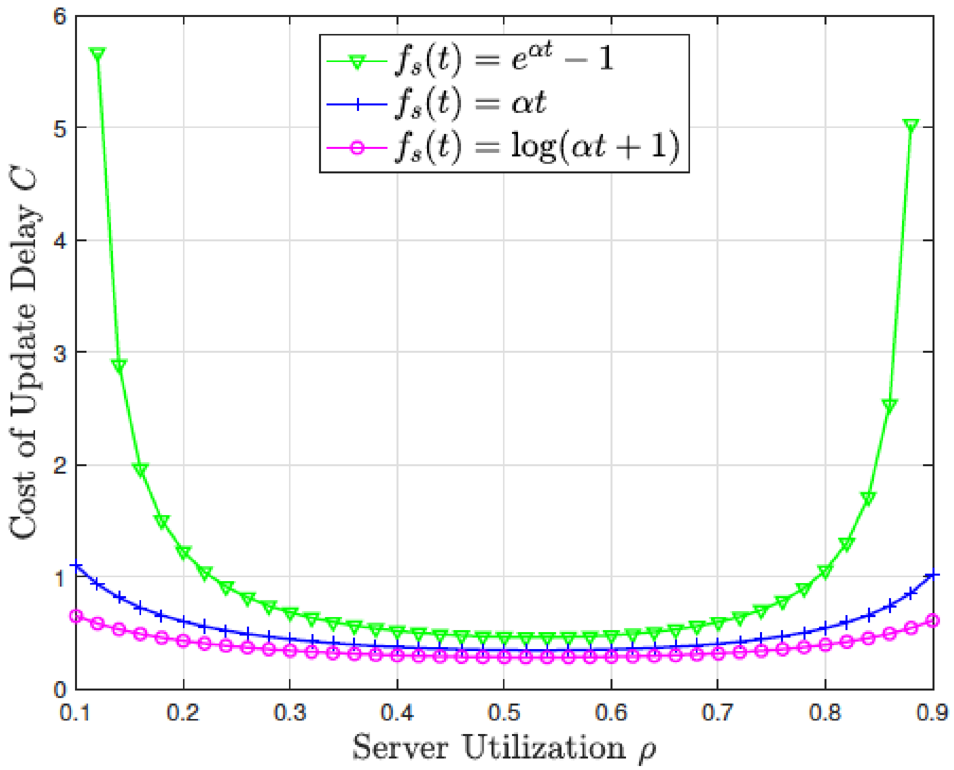
$$V_i = \frac{f_s(t'_i - t_{i-1}) - f_s(t'_i - t_i)}{f_s(t'_i - t_{i-1})} = \frac{D_i}{D'_i}.$$

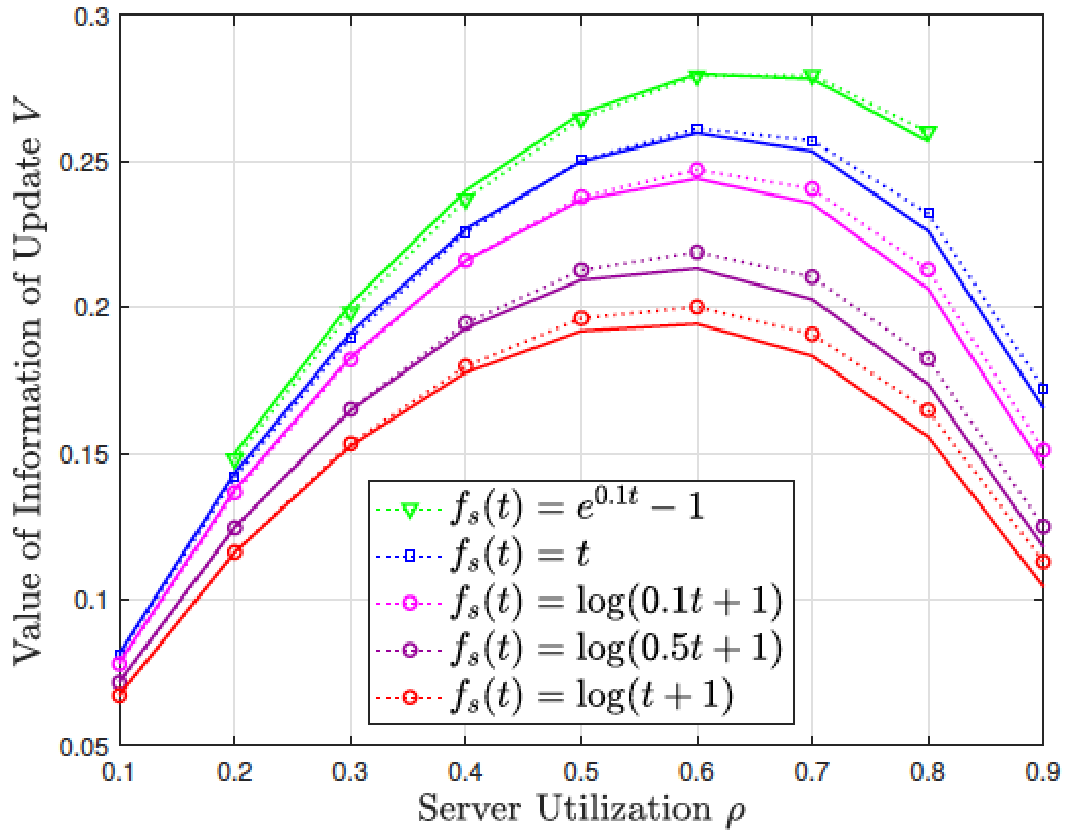
In the linear CoUD case, VoIU is independent of the cost assigned per time unit →the Value is independent of the slope.



$$V_i = \lim_{t'_i \to t_i} \frac{f_s(t'_i - t_{i-1}) - f_s(t'_i - t_i)}{f_s(t'_i - t_{i-1})} = 1$$

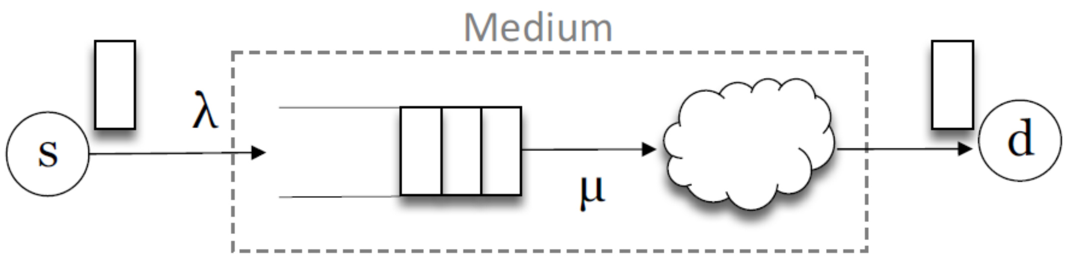
Numerical evaluation





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 $\rho^* \approx 0.53$

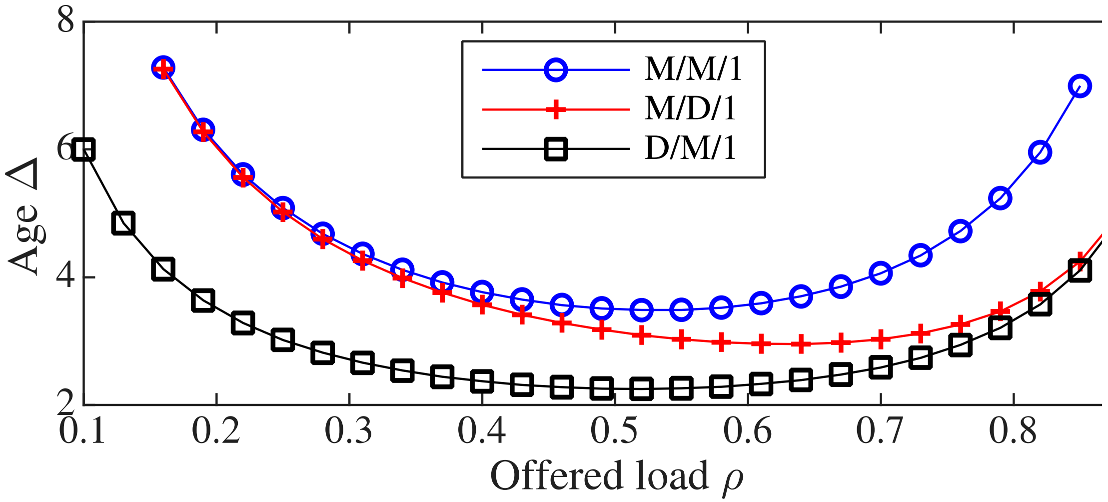
- Optimal age is achieved by choosing a λ which makes the server being slightly busy than being idle.
- If ρ is close to 1 we maximize the throughput, which is the number of packets delivered to the destination per time.
- If ρ is close to 0, we minimize the delay.

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

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



- At low load, randomness in the interarrivals dominates the average age.
- At high load, M/D/1 and D/M/1 substantially outperform M/M/1 because the determinism in either arrivals or service helps to reduce the average queue length.
- For each queue, we observe a 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.
- Packet management:
  - M/M/1/1 queue that blocks and clears a new arrival while the server is busy,
  - M/M/1/2 queue that will queue one waiting packet but blocks an arrival when the waiting space is occupied,
  - M/M/1/2* queue

S. Kaul, R. Yates, and 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, and 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

Each source *i* generates updates as an independent Poisson process of rate λ_i and the service time *S* of an update has expected value $1/\mu$. The total offered load is $\rho=\Sigma_i \lambda_i/\mu$.

R. D. Yates and S. K. Kaul, “The age of information: Real-time status updating by multiple sources,” IEEE Trans. Info. Theory, 2019.
L. Huang and E. Modiano, “Optimizing age-of-information in a multiclass queueing system,” IEEE ISIT 21015.
E. Najm and E. Telatar, “Status updates in a multi-stream M/G/1/1 preemptive queue,” IEEE INFOCOM Workshops 2018.
M. Moltafet, M. Leinonen, and M. Codreanu, “On the age of information in multi-source queueing models,” IEEE TCOM 2020.

$$P_\lambda = \mathrm{E}\left[e^{-\lambda S}\right] \quad \text{Laplace transform of service time } S$$

$$\lambda = \lambda_1 + \cdots + \lambda_N$$

For the user i in an M/G/1/1 system the average AoI is $\Delta_i = \frac{1}{\lambda_i P_\lambda}$ and Peak AoI is

$$\Delta_i^{(p)} = \frac{1}{\lambda_i P_\lambda} + \frac{\mathrm{E}\left[S e^{-\lambda S}\right]}{P_\lambda}$$

Multiple sources at a single server source

Each source *i* generates updates as an independent Poisson process of rate λ_i and the service time *S* of an update has expected value $1/\mu$. The total offered load is $\rho=\Sigma_i \lambda_i/\mu$.

R. D. Yates and S. K. Kaul, "The age of information: Real-time status updating by multiple sources," IEEE Trans. Info. Theory, 2019.
L. Huang and E. Modiano, "Optimizing age-of-information in a multiclass queueing system," IEEE ISIT 21015.
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$P_\lambda = \mathrm{E}\left[e^{-\lambda S}\right]$ Laplace transform of service time S

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$$\Delta_i^{(p)} = \frac{1}{\lambda_i P_\lambda} + \frac{\mathrm{E}\left[S e^{-\lambda S}\right]}{P_\lambda}$$

A case of heterogeneous traffic sharing the same queue will be discussed a bit later.

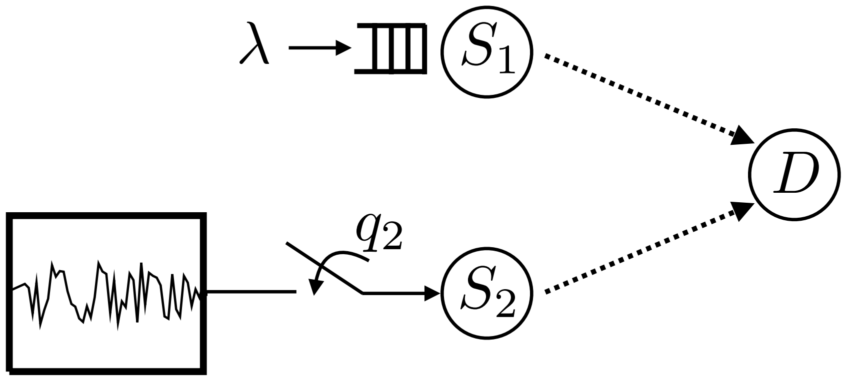
Towards a complete characterization of the AoI distribution

- 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.
- The AoI distribution in bufferless systems
  - G. Kesidis, T. Konstantopoulos, and M. Zazanis, “The distribution of age-of-information performance measures for message processing systems,” arXiv:1904.05924, 2019.

- The complete characterization of the AoI stationary distribution in a discrete time queueing system for three cases: FCFS, preemptive LCFS, a bufferless system with packet dropping. *We provide 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", arxiv, June 2020. (shorter version in IEEE ICC 2020)

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

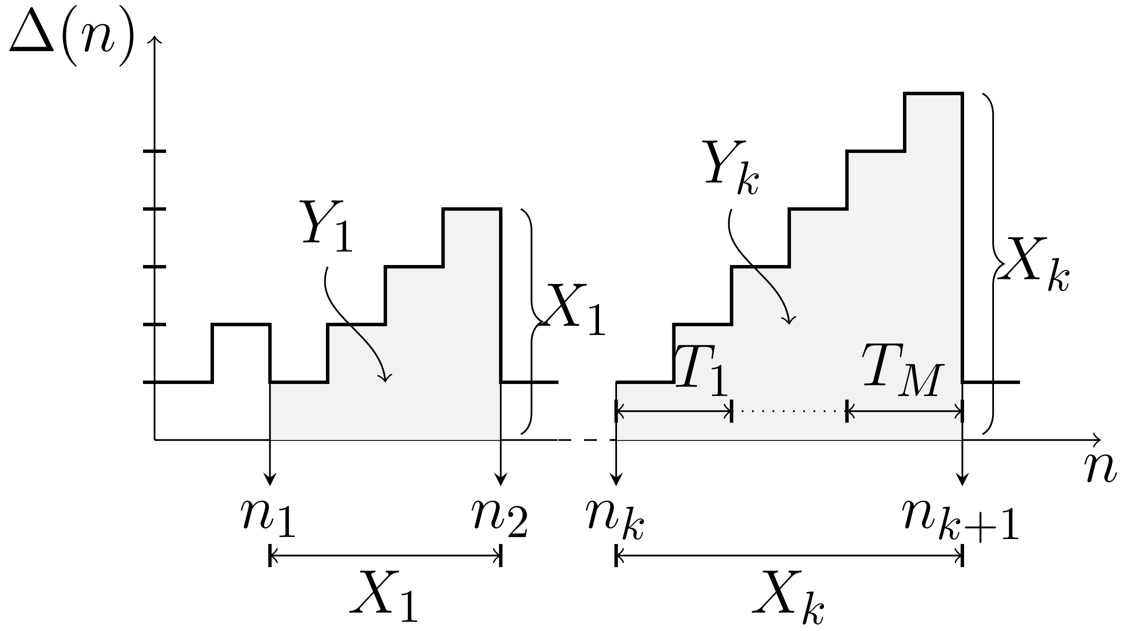
- Two sources sending packets to a common destination.
- Source S_1 has external traffic with stringent delay requirements.
- Source S_2 monitors a sensor and samples a status update on each slot w. p. q_2. Then, transmits the update to the destination through a channel with success probability p_2. If the transmission of a status update fails, then it is dropped.
- Time is slotted, fixed rate R transmissions, Rayleigh fading,
- Instantaneous and error-free ACK/NACK.
- S_i transmits with power P_i, $i=1,2$.



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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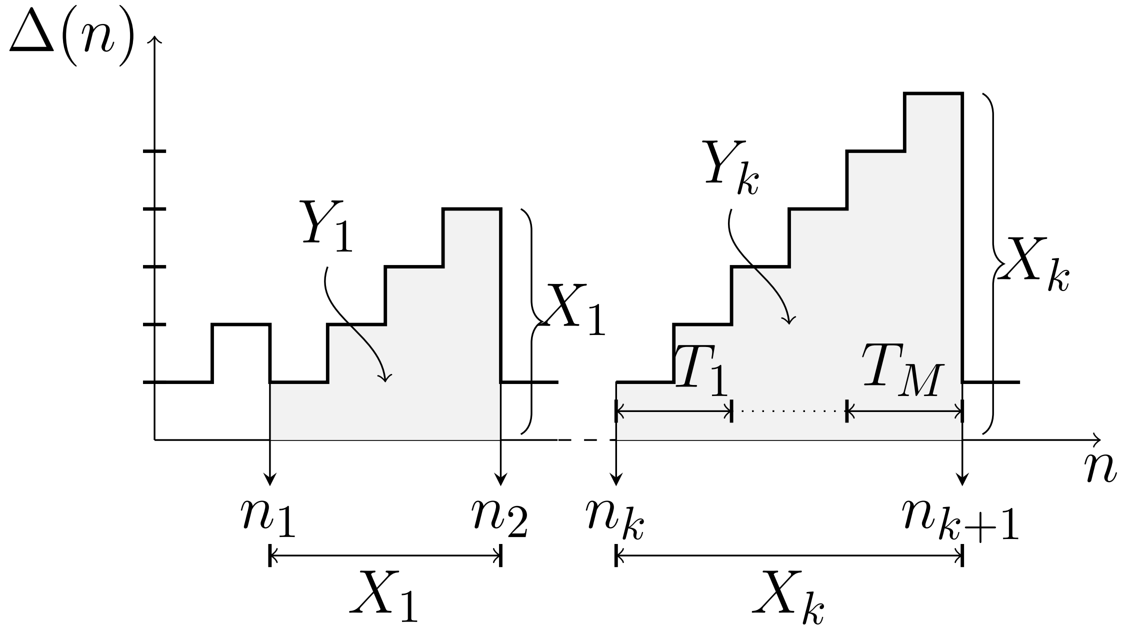

$$X_k = \sum_{i=1}^{M} T_i$$

$$\Delta_N = \frac{1}{N}\sum_{n=1}^{N}\Delta(n) = \frac{1}{N}\sum_{k=1}^{K} Y_k = \frac{K}{N}\frac{1}{K}\sum_{k=1}^{K} Y_k$$

$$\Delta = \lim_{N\to\infty}\Delta_N = \frac{\mathbb{E}[Y]}{\mathbb{E}[X]}$$

$$Y_k = \sum_{m=1}^{X_k} m = \frac{X_k(X_k+1)}{2}$$

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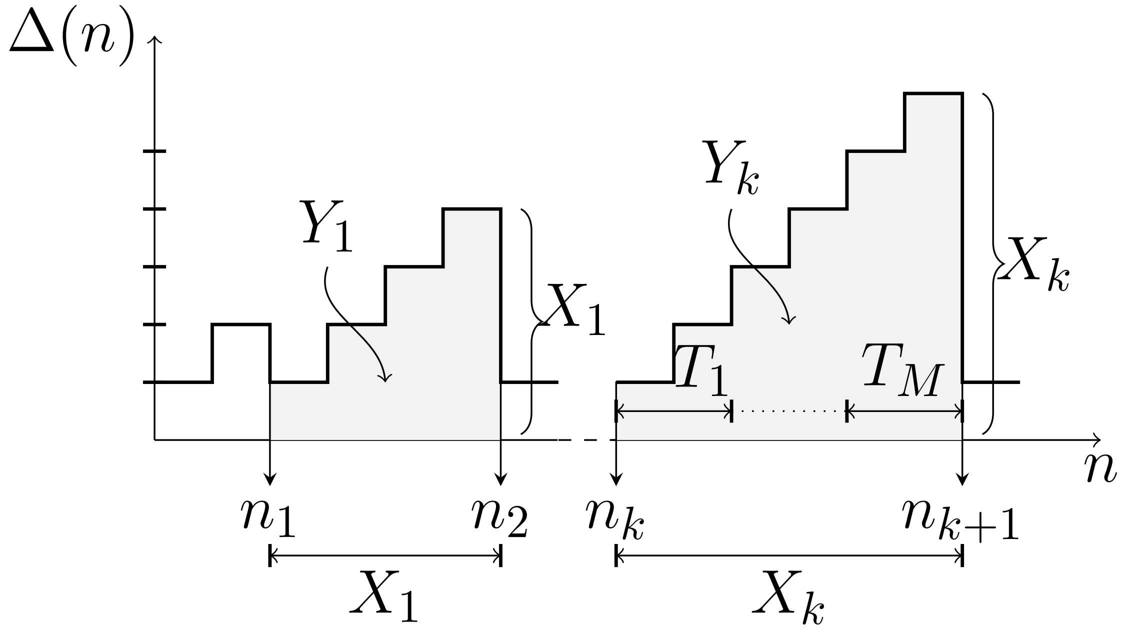

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$$\Delta = \lim_{N\to\infty}\Delta_N = \frac{\mathbb{E}[Y]}{\mathbb{E}[X]}$$

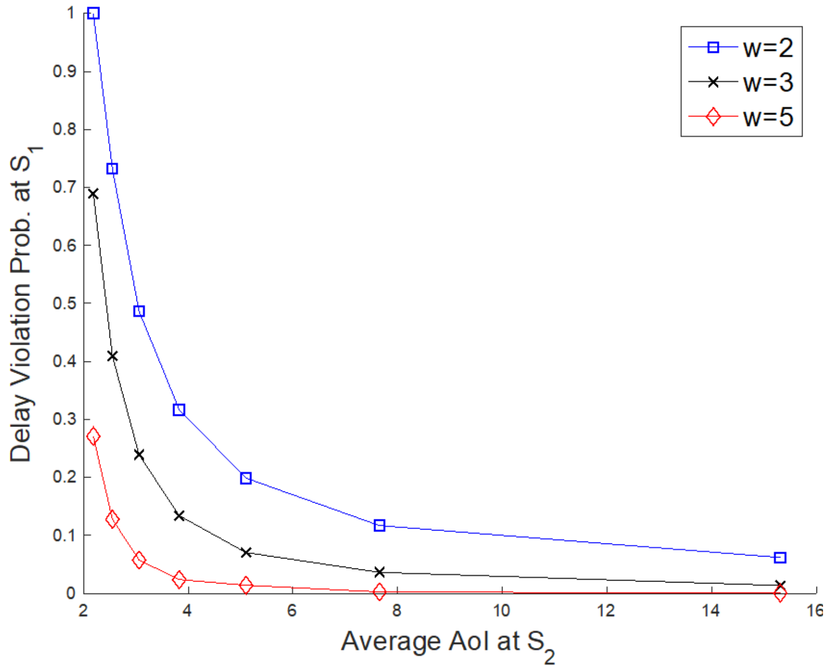
$$Y_k = \sum_{m=1}^{X_k} m = \frac{X_k(X_k+1)}{2}$$

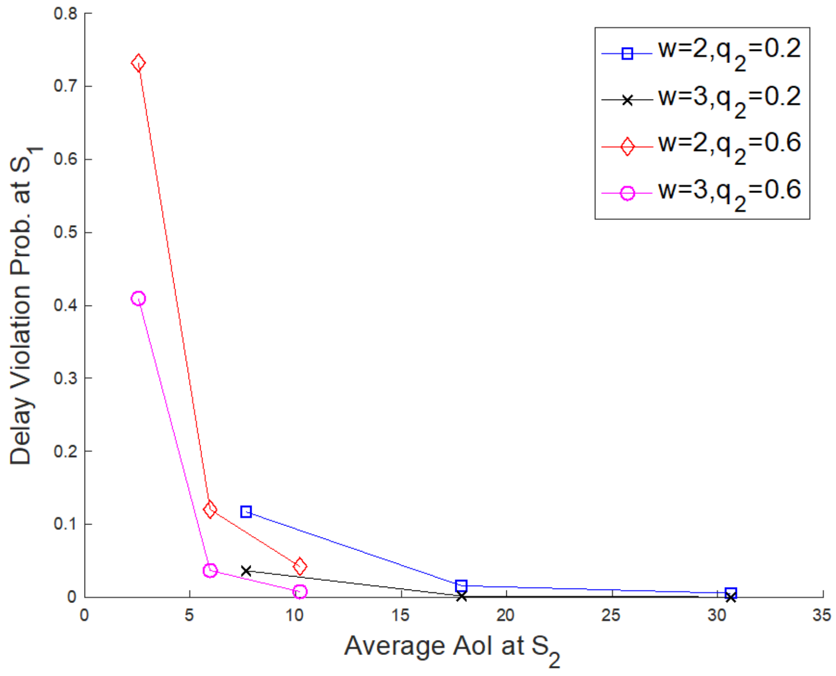
$$\Delta_N = \frac{K}{N}\frac{1}{K}\sum_{k=1}^{K} Y_k = \frac{\mathbb{E}\left[\frac{X_k^2}{2}+\frac{X_k}{2}\right]}{\mathbb{E}[X]} = \frac{\mathbb{E}[X^2]}{2\mathbb{E}[X]}+\frac{1}{2}$$

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

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

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





- The latency constraint *w* does not affect the average AoI.
- 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.

Main takeaway

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

Other systems

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

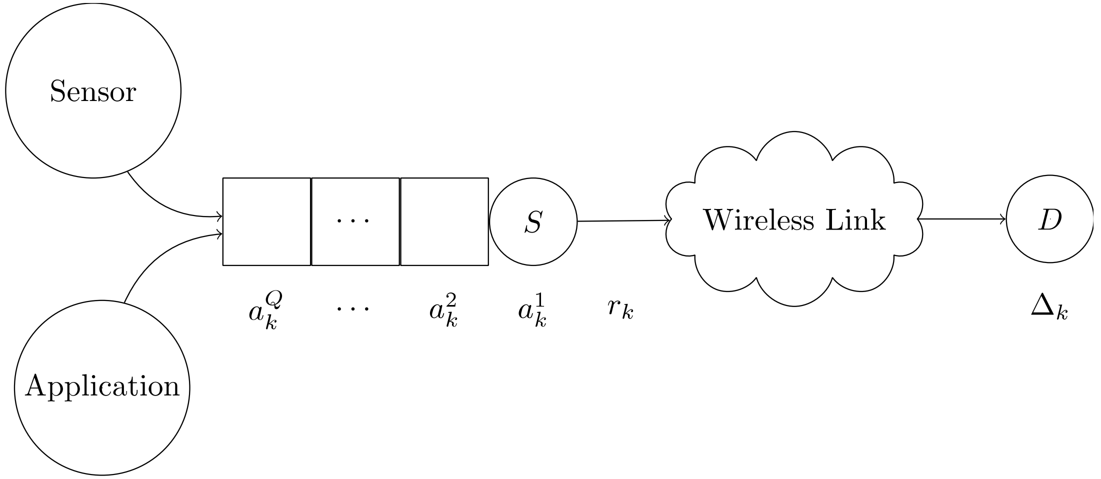
C. Kam, S. Kompella, and A. Ephremides, "Age of information under random updates," IEEE ISIT 2013.

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.

Optimal status update generation in a device with heterogeneous traffic

- A source node transmitting data to a destination through a wireless link.
- Source node consists of a sensor and an application and has a finite capacity queue
  - Sensor is generating status updates in forms of packets
  - Application generates data packets
- Discrete time
- Wireless link with success probability P_s and the number of retransmissions is fixed, equal to r_{max}
- Application generates a data packet in each slot with prob. P_α



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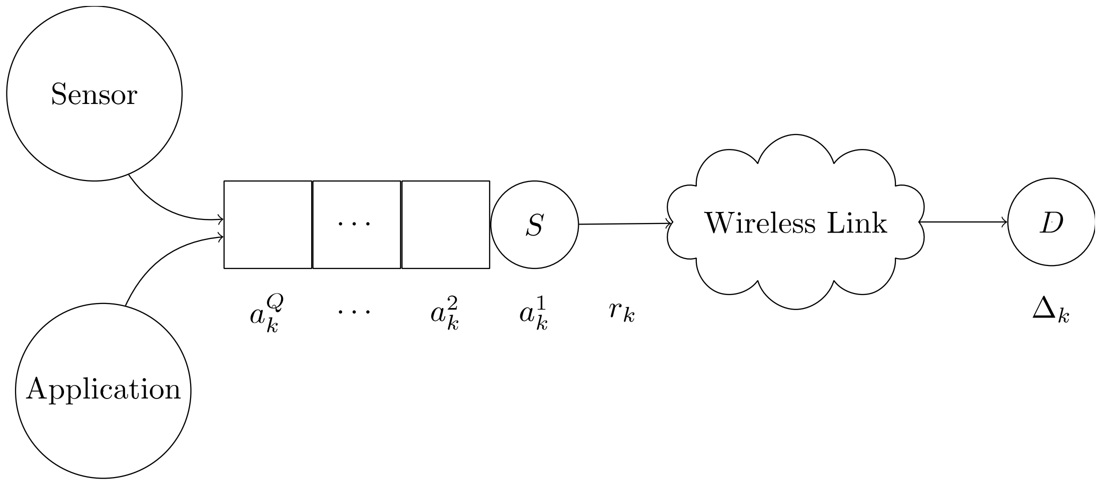
G. Stamatakis, N. Pappas, A. Traganitis, "Optimal Policies for Status Update Generation in an IoT Device with Heterogeneous Traffic", IEEE IoT Journal, June 2020. (shorter version in IEEE GLOBECOM 2019)

Optimal status update generation in a device with heterogeneous traffic

- The source decides in each slot if a status update from the sensor is generated or not
- All packets generated in a slot are enqueued unless the queue is full
- The source must satisfy a hard constraint Δ_{max} on age of information for the sensor
- When the age reaches the value Δ_{max} then
  - All status update packets currently in the queue are dropped as outdated.
  - A fresh status update packet is sampled and transmitted via a URLLC link (expensive) by the transmitter.
- URLLC link has success probability 1



G. Stamatakis, N. Pappas, A. Traganitis, "Optimal Policies for Status Update Generation in an IoT Device with Heterogeneous Traffic", IEEE IoT Journal, June 2020.

Heuristics Policies

Zero-wait

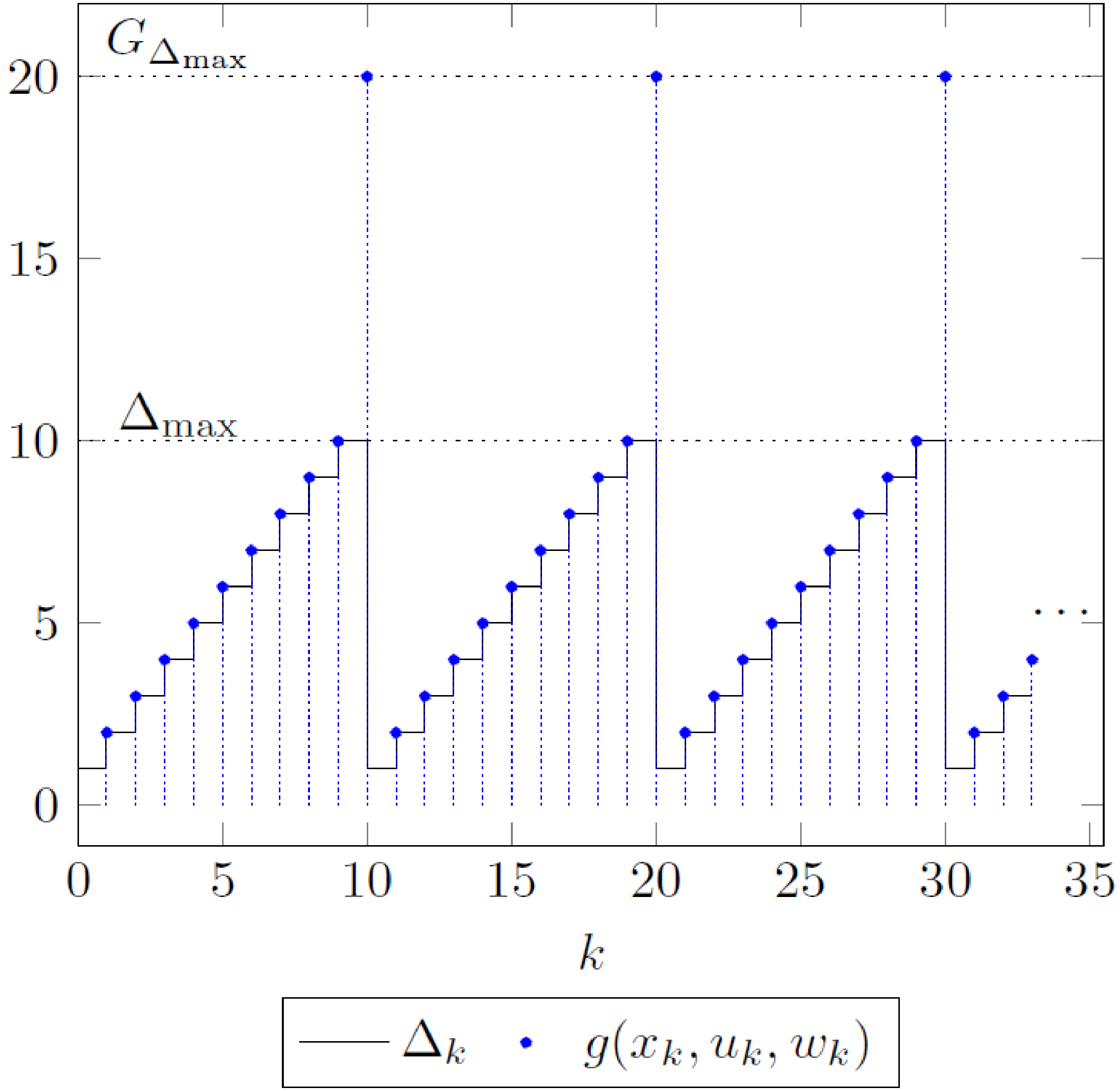
- To achieve zero-waiting in the queue both status update and application packets must have been served prior to generating a new status update.
- The arrival rate of application packets in the queue will determine how often the queue and the server will be idle.

Max-sampling policy

- Generate a status update at **every** time-slot
- Is meaningful when the application generates packets with a very high rate.
- Queueing delay may result in increased AoI
    - If the application does not generate packets frequently.

3rd heuristic policy: Never sample policy

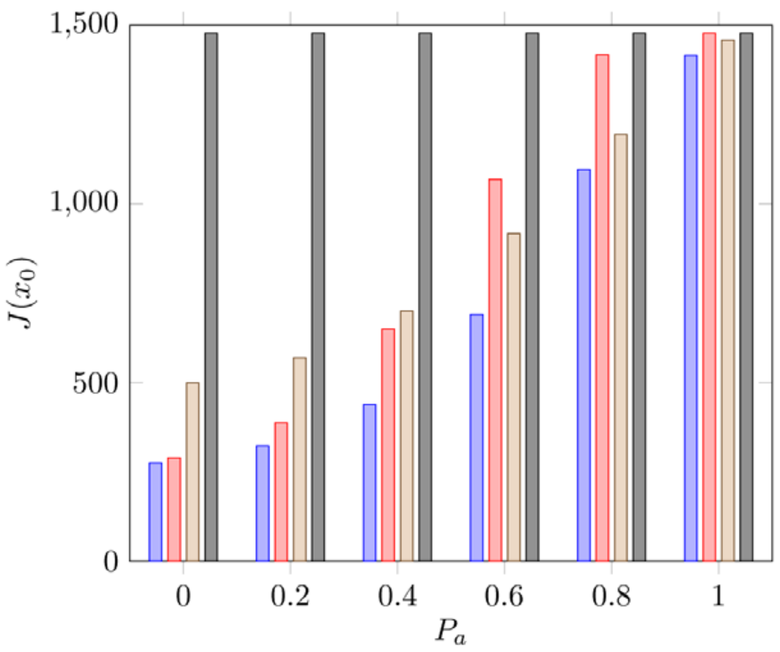
- It never samples the stochastic process unless the upper bound on AoI is violated.
- Subsequently it uses the URLLC mechanism to send a status update.
- This is the worst-performing policy.
  - Complete lack of control over the status update generation process
  - Used to indicate the worst possible performance



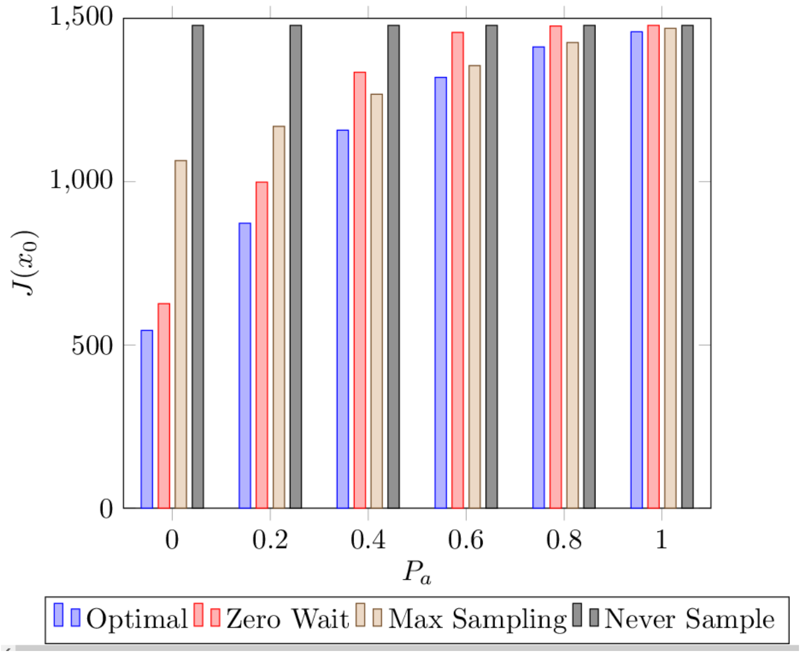
AoI and transition cost for the never-sample policy when the upper bound on AoI is 10 and the cost related to using the URLLC is 20.

Results

- System Parameters
  - Queue Size = 4
  - AoI Threshold = 10
  - Max. Retransmission Number = 4
  - URLLC channel cost = 100
  - Discount factor = 0.99
- For low values of P_a the performance of the zero-wait policy is close to the optimal.
- For higher values of P_a the performance of the max-sampling policy is close to the optimal policy.
- The never-sample policy has the same performance irrespective of the P_a value since it only uses the URLLC channel when the AoI threshold is violated.



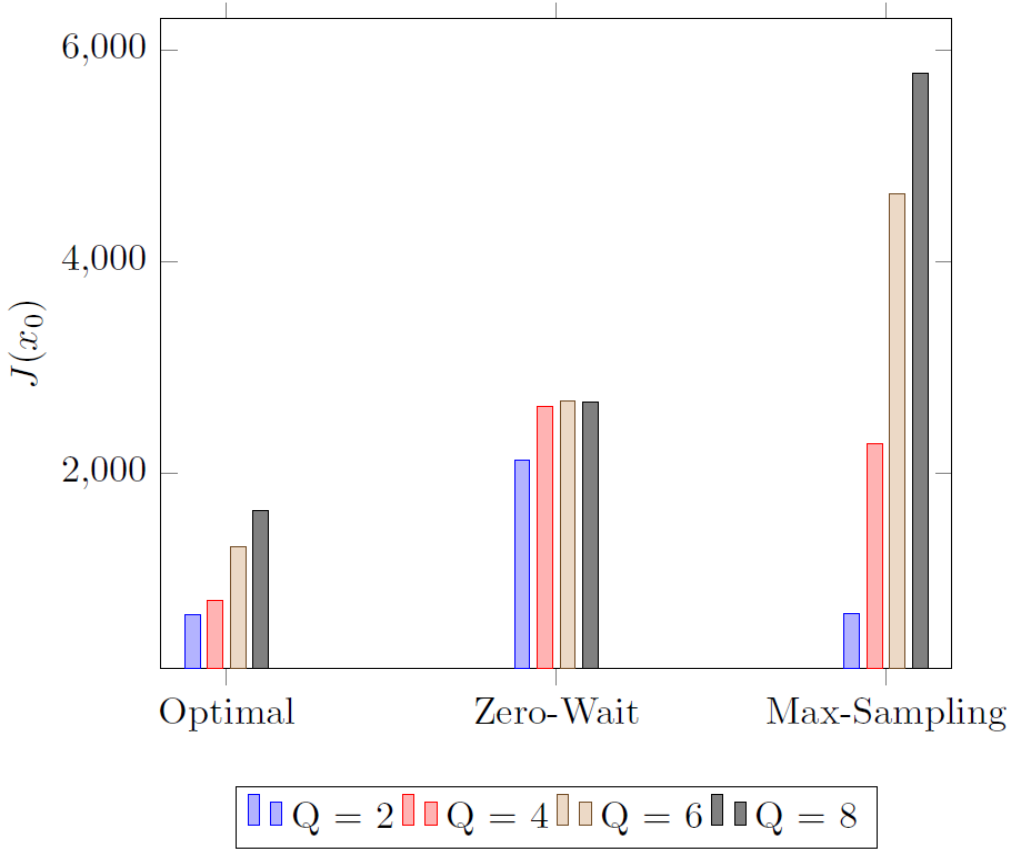
Transmission success probability = 0.8



Transmission success probability = 0.4

Effect of queue size on cost

- System Parameters
  - Queue Size = 2, 4, 6 and 8
  - URLLC channel cost = 1000
  - Transmission success probability = 0.8
  - Application packets arrival probability = 0.4
- The cost for the optimal policy increases with the queue size
  - Increased queueing delays for status updates.
- The max-sampling policy cost increases with queue size
  - Large number of status updates stored in the queue result in increased queueing delay.
- The zero-wait policy is remains unaffected by increasing the size of the queue beyond 4.
  - Increasing the queue size beyond a certain value has no effect on the probability distribution of the number of application packets in the queue.



Part III AoI-Oriented Multiuser Scheduling

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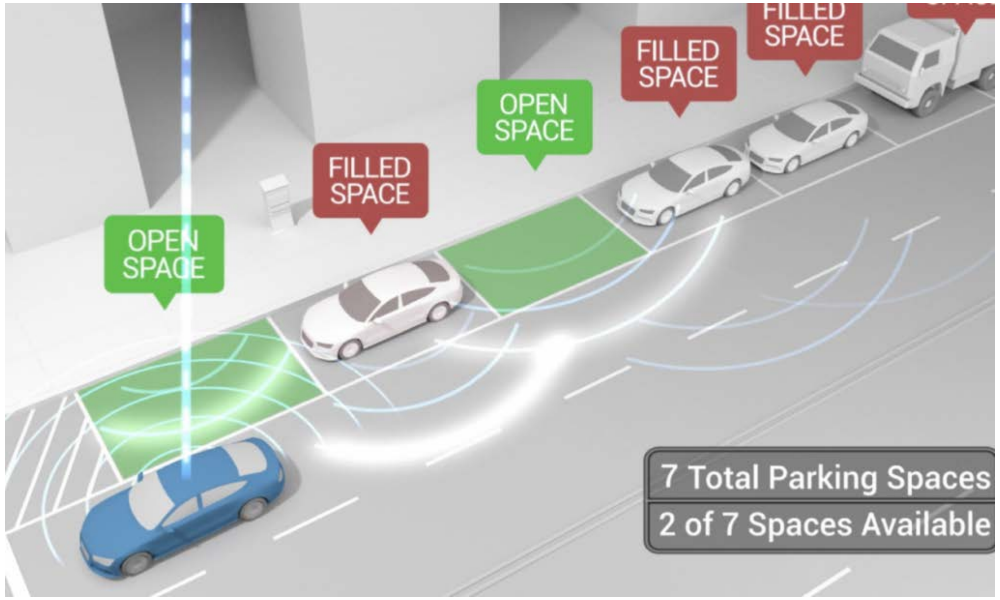
Multiuser Scheduling

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

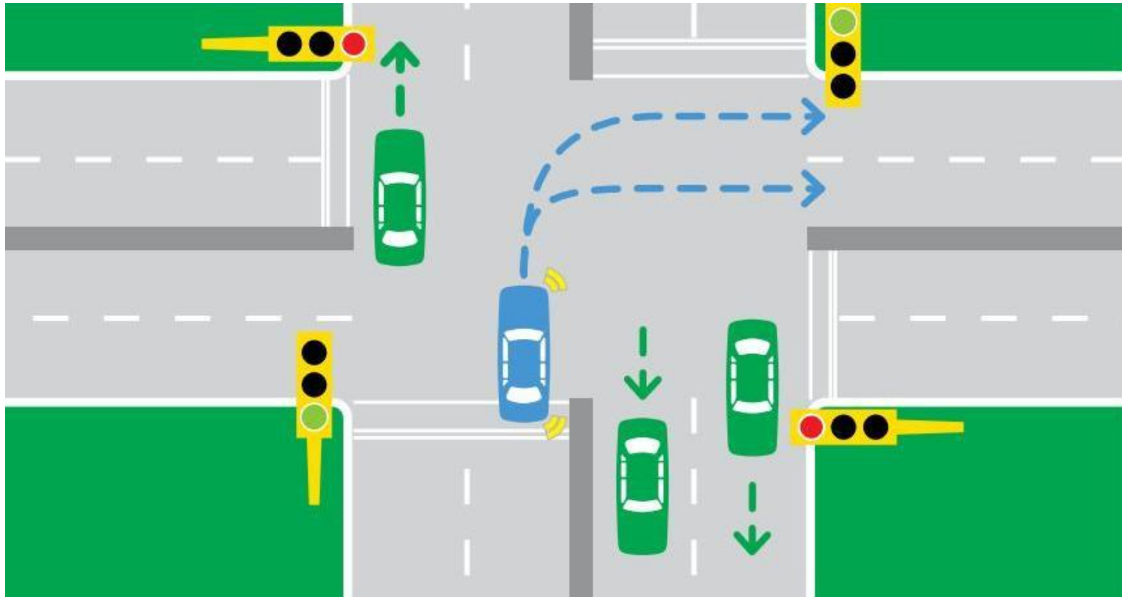
How to schedule the status updates of multiple users to minimize the expected (weighted) sum AoI of the whole system?

Status update arrival model

- Generate-at-will

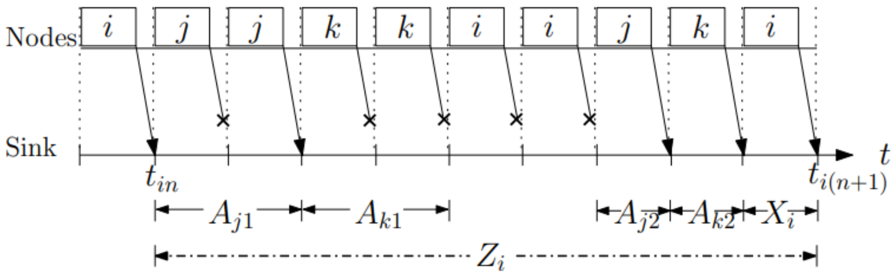


- Random (stochastic) Arrival



Homogenous Networks

- The channel error probability (when no collision) of all links are identical
- Generate-at-will model
- 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 (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 $p_i \in (0, 1]$

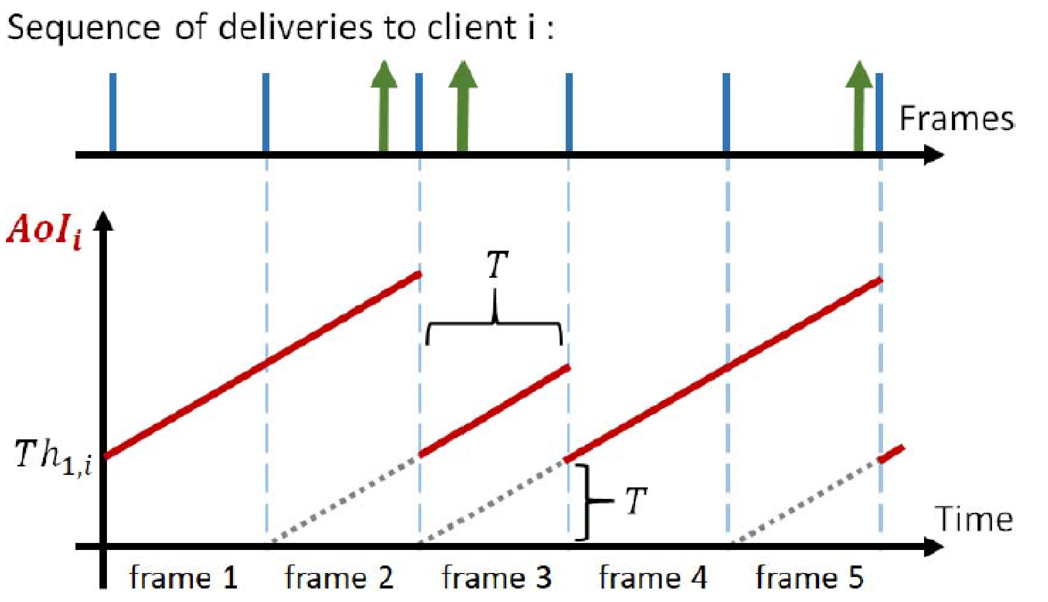
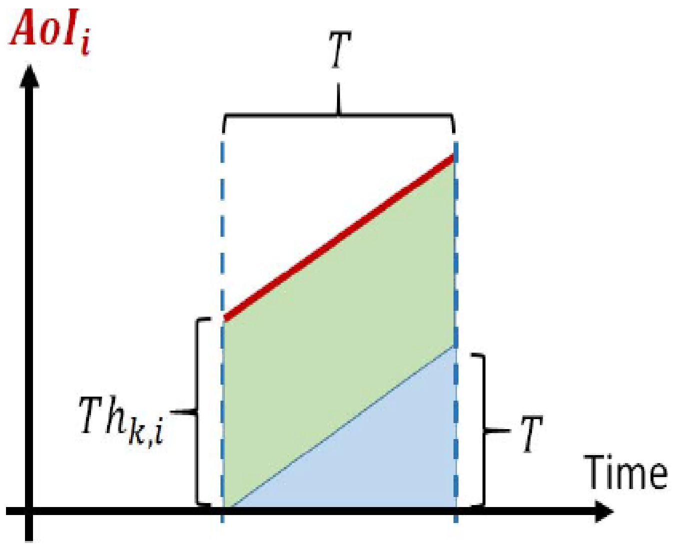


Fig. 2. On the top, a sample sequence of deliveries to client i during five frames. The upward arrows represent the times of packet deliveries. On the bottom, the associated evolution of the AoI_i.

[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 (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.

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

$h_{k,i}$: 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 (3)

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

- 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 (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

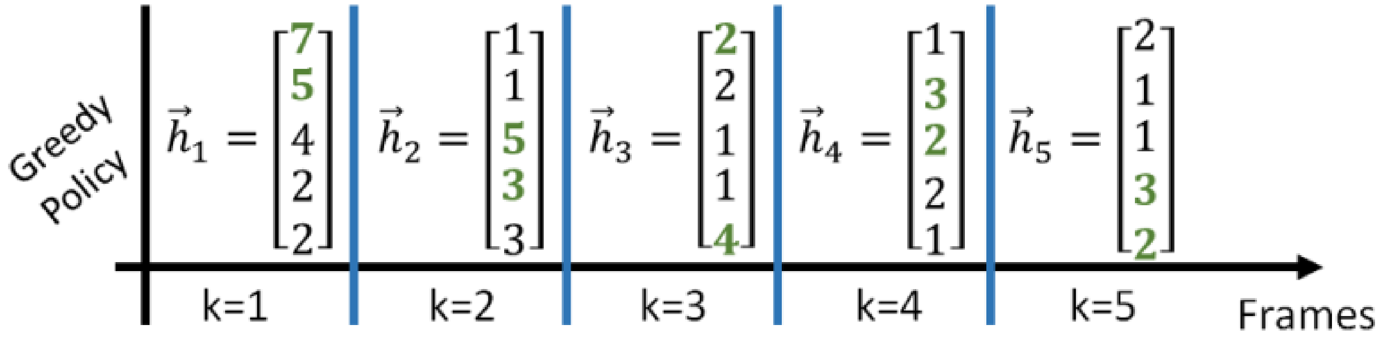


Fig. 4. Evolution of $\vec{h}_k$ when the Greedy policy is employed in a network with $M = 5$ clients, $T = 2$ slots per frame, error-free channels, $p_i = 1, \forall i$, and $\vec{h}_1 = [7\ 5\ 4\ 2\ 2]^T$. In each frame, the Greedy policy transmits packets of two clients. The elements of $\vec{h}_k$ associated with the clients that received a packet during frame k are depicted in bold green.

[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 (5)

- Properties of Greedy policy
  - It switches scheduling decisions only after a successful packet delivery
  - 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 (6)

- 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 (7)

- 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 (8)

- Whittle's Index policy
  - the optimal solution to a relaxation of the Restless Multi-Armed Bandit (RMAB) problem
  - First step is to realize that each client in the AoI problem evolves as a restless bandit
  - Next step is to consider the relaxed version of the RMAB problem, called the Decoupled Model, in which clients are examined separately.
  - The Decoupled Model associated with each client i adheres to the network model with M = 1, except for the addition of a service charge C.
  - The service charge is a fixed cost per transmission C > 0 that is incurred by the network every time the BS transmits a packet.
  - The final step is to prove that the AoI problem is indexable and derive the Whittle's Index 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 (9)

- Whittle's Index policy

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 strong 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 (10)

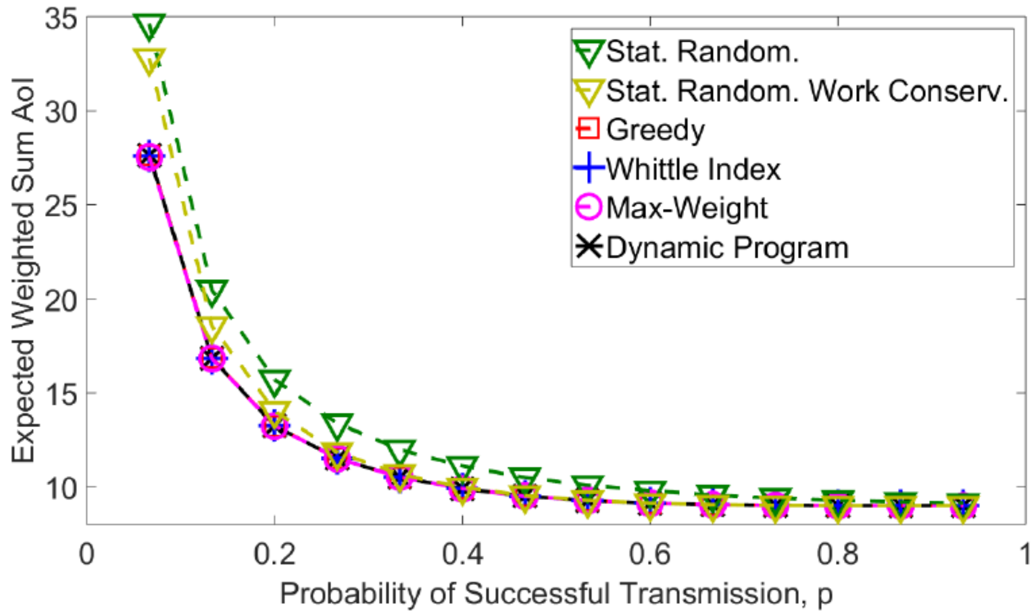


Fig. 5. Two-user symmetric network with $T = 6, K = 150, \alpha_i = 1, p_i = p, \forall i$. The simulation result for each policy and for each value of p is an average over 1,000 runs.

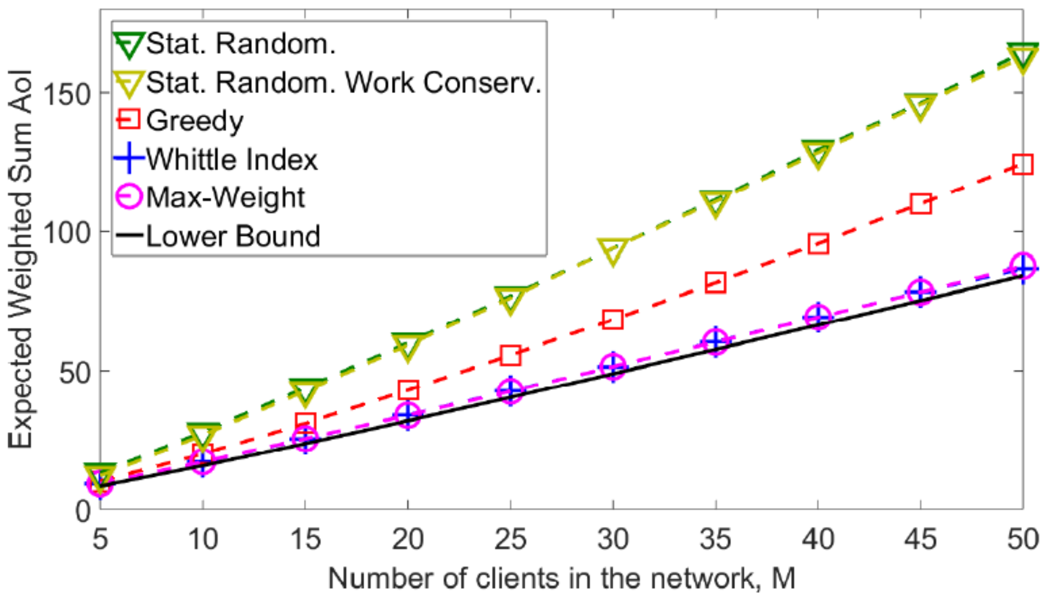
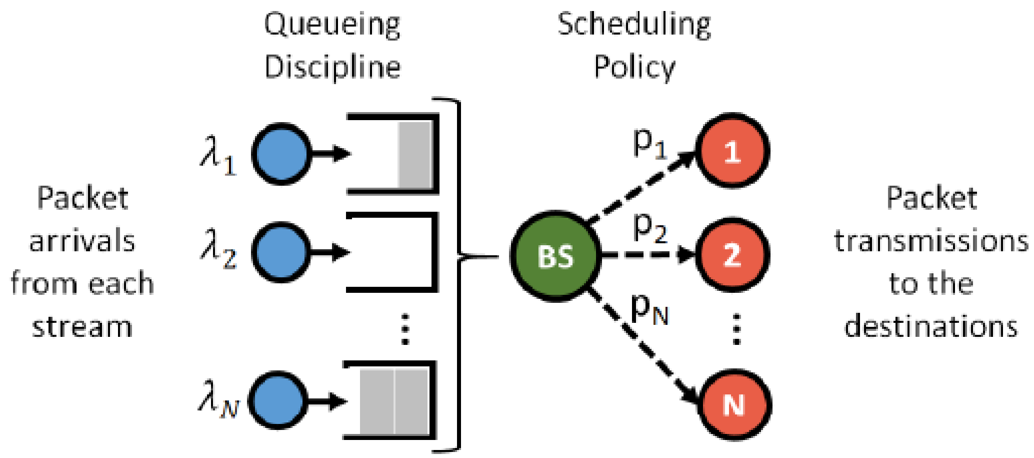


Fig. 7. Network with $T = 3, K = 50,000, \alpha_i = 1, p_i = i/M, \forall i$. The simulation result for each policy and for each value of M is an average over 10 runs.

[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 (1)

- One BS, N users, downlink
- a new packet to user i ∈ {1, 2, …, 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



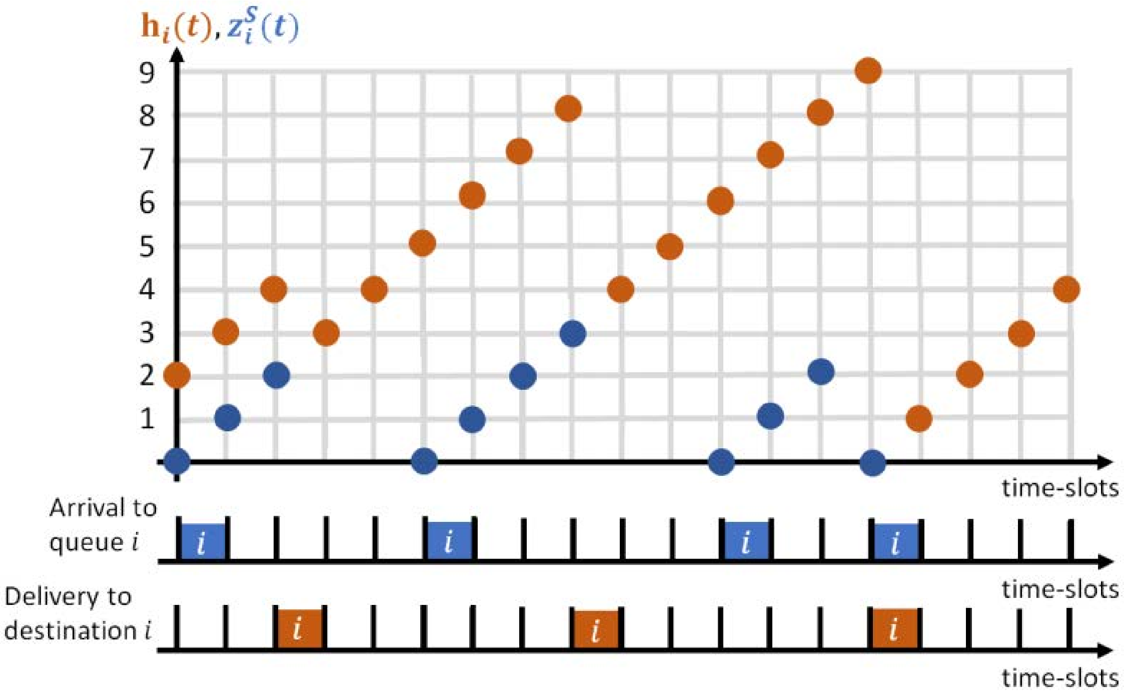
Three Queueing Discipline:

(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 (2)

- Key difference from the generate-at-will model: *The system time 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



[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 (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 policies:

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.

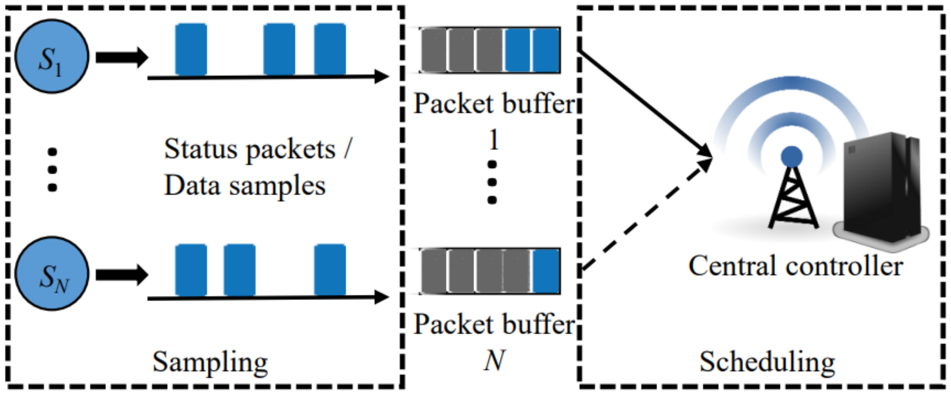
Random arrival case in the uplink

- 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," submitted, May 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 is no longer age-optimal
- When to sample and when to transmit need to be jointly optimized

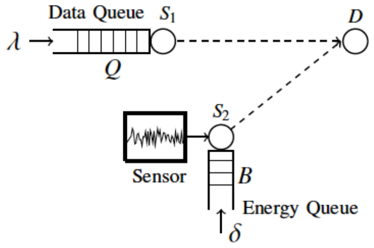


[Zhou’19] Bo Zhou and Walid Saad, "Joint Status Sampling and Updating for Minimizing Age of Information in the Internet of Things", IEEE Transactions on Communications, vol. 67, no. 11, pp. 7468-7482, Nov. 2019.

[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.

[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.

Hybrid Systems



- Time-slotted multiple access channel (MAC).
- S_1: connected to a power grid, Bernoulli data arrivals with arrival probability λ, queue backlog Q.
- S_2: energy harvesting (EH) sensor, Bernoulli energy arrivals with probability δ, battery level (energy queue) B.
- Multi-packet reception (MPR) capabilities at the destination node D.

Transmission and Re-transmission Policy

Transmission policy
- S_1: First In, First Out (FIFO);
- S_2: always generates a fresh sample before attempted transmission.

In case of failed transmission
- S_1: re-transmits the same packet in the next slot;
- S_2: drops that packet and generates a new sample before the next attempted transmission.

- Stationary randomized policy: random access decisions based on some stationary probability distribution.
- Drift-Plus-Penalty policy: Lyapunov optimization, virtual queue, drift-plus-penalty.

Simulation Results

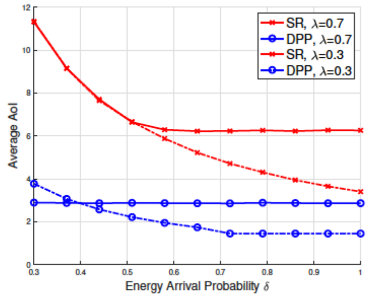


Figure: Weak MPR.

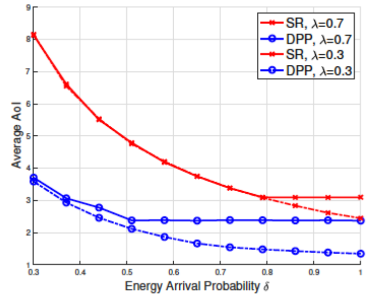


Figure: Strong MPR.

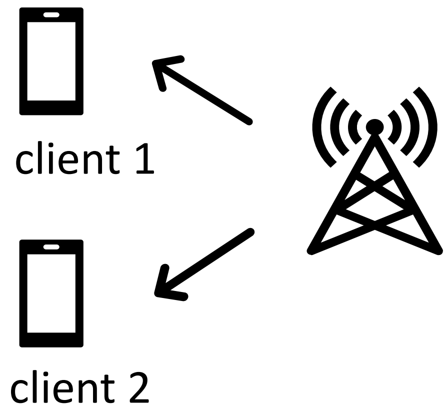
- DPP policy performs significantly better than the SR policy, especially when the destination node has weak MPR capabilities.

[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.

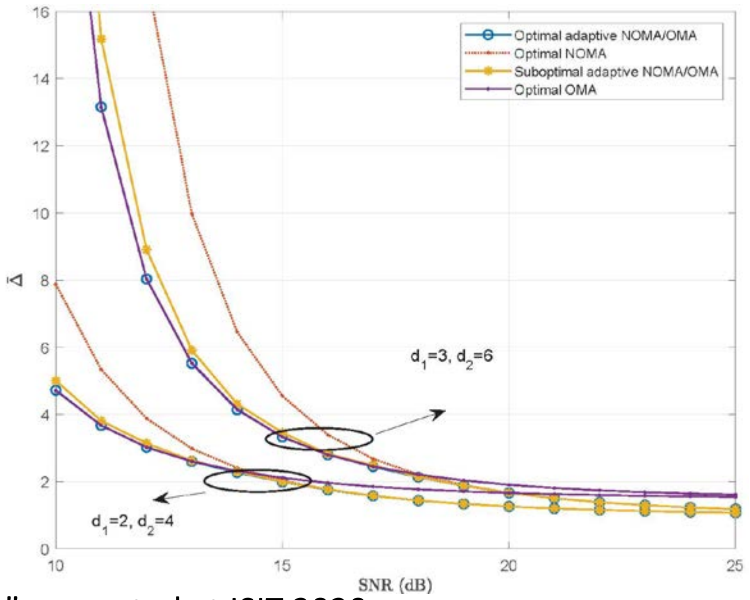
[Wang'20] Q. Wang, **H. Chen**, Y. Gu, Y. Li, and B. Vucetic, "Minimizing the age of information of cognitive radio-based IoT systems under a collision constraint," https://arxiv.org/pdf/2001.02482.pdf, Jan. 2020.

[Moltafet'20] M. Moltafet, M. Leinonen, M. Codreanu, N. Pappas, "Power Minimization for Age of Information Constrained Dynamic Control in Wireless Sensor Networks", arXiv:2007.05364, July 2020.

Scheduling 1+ users per timeslot (1)



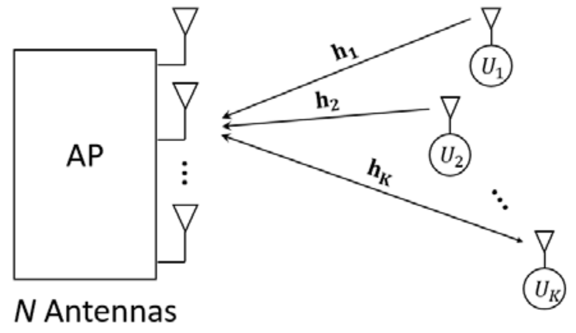
- Users can update more frequently → lower average AoI
- [Wang'20] proposed to apply adaptive NOMA/OMA
- A base station (BS) conducting timely transmission to two clients in a slotted manner via adaptive NOMA/OMA.
- generate-at-will model was considered
- In OMA, the BS decides which client to conduct 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

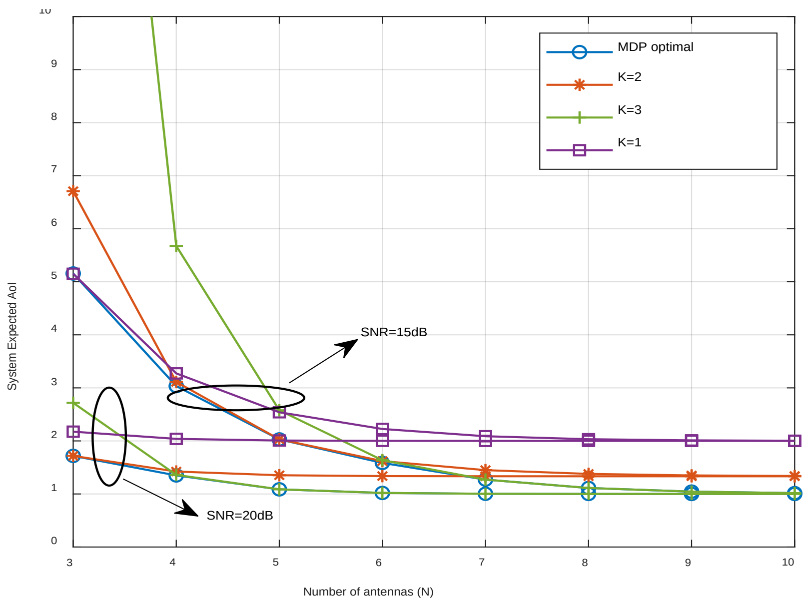


[Wang'20] Q. Wang, H. Chen, Y. Li, and B. Vucetic, "Minimizing age of information via hybrid NOMA/OMA," presented at ISIT 2020, available: https://arxiv.org/abs/2001.04042

Scheduling 1+ users per timeslot (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
- Formulated as an MDP problem
- Max-weight policy was also studied





[Chen'20] **H Chen**, Q Wang, Z Dong, N Zhang, "Multiuser Scheduling for Minimizing Age of Information in Uplink MIMO Systems," IEEE/CIC ICCC 2020, accepted in June, available: https://arxiv.org/pdf/2002.00403.pdf

Part IV AoI-Oriented Random Access

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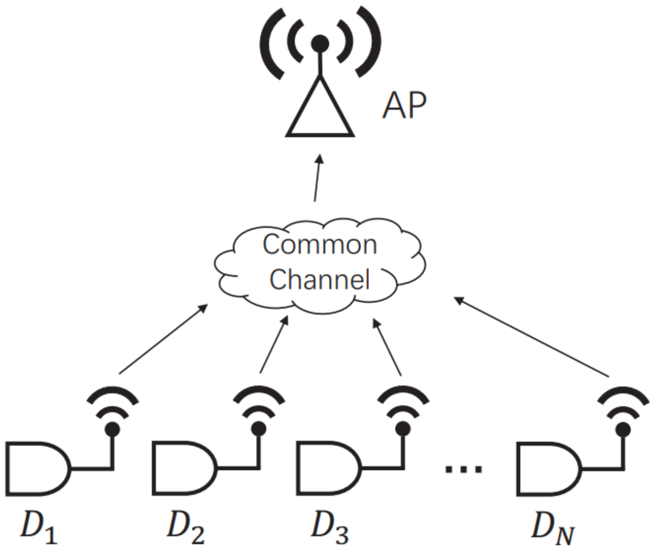
Why random access?

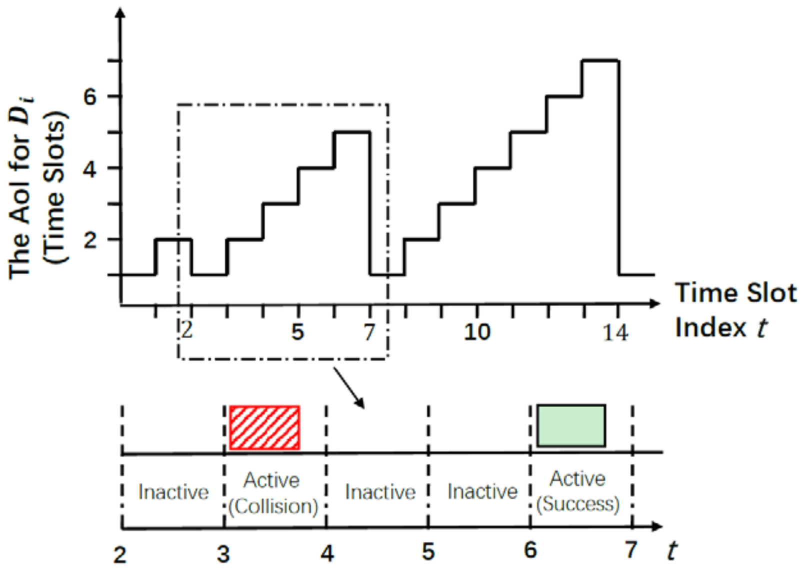
- Massive connectivity is coming → Ericsson foresaw that by 2021, there will be around 28 billion IoT devices
- Centralized scheduling → overhead is excessive for a large-scale network
- Decentralized scheduling (random access) is more preferred

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)

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

[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.

Average AoI Analysis for ADRA (1)

- In the AIRA policy, the successful status update probability q of one device is independent of the instantaneous AoI of all other devices

- In the proposed ADRA protocol, the active probability of each IoT device (i.e., p) 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

[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.

Average AoI Analysis for ADRA (2)

- Key approximation to decouple the tangled evolution of the AoI for all IoT devices:

The successful probability q for all IoT devices is a constant when they decide to transmit a status update.

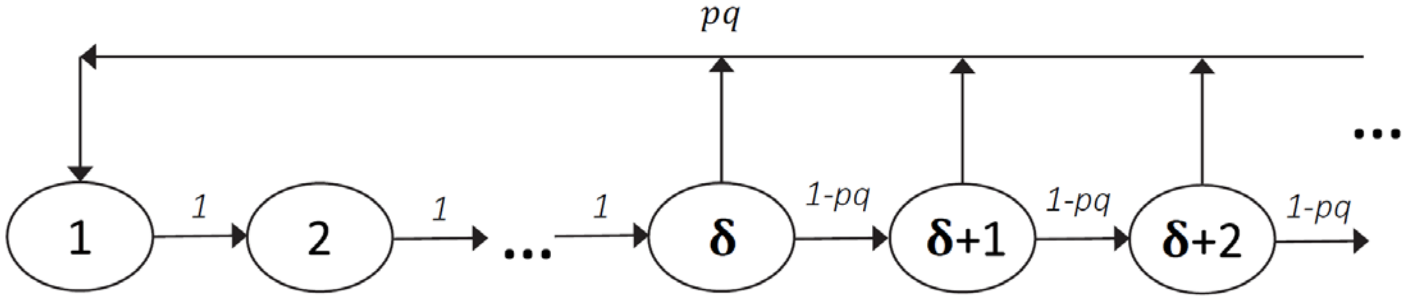
- The value of q is independent of the instantaneous AoI of all other IoT devices, but still a function of the age threshold δ and the active probability p.

- The accuracy of such approximation has been proved in the literature

[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.

Average AoI Analysis for ADRA (3)

- All devices follow an identical state transition process, which can be described by a Discrete-Time Markov Chain



Given p, δ, q ⇒ Stationary Distribution of the AoI, π_l ⇒ stationary probability of an IoT device transmitting in a randomly chosen time slot

$$\eta = \sum_{l=\delta}^{\infty} \pi_l p$$

⇐ $q = (1-\eta)^{N-1}$

[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.

ADRA with random arrival

- Local AoI needs to be considered
- M identical source nodes, collision channel model
- New status update arrives with probability θ in each time slot and replace the staled one in the buffer
- slotted ALOHA: At every time slot k, transmitters send their packets immediately upon arrival unless they are "backlogged" after a collision in which case they transmit with a back-off probability
- Rivest's stabilized slotted ALOHA: all arrivals are regarded as backlogged nodes that transmit with the backoff probability $p_b(k)$
- Let c(k) = 1 denote the event that collision occurred at time k and c(k) = 0 denote the complementary event

$$p_b(k) = \min\left(1, \frac{1}{n(k)}\right)$$

$$n(k) = \begin{cases} \min\Big(n(k-1) + M\theta + (e-2)^{-1}, M\Big) & \text{if } c(k) = 1 \\ \min\Big(\max\left(M\theta, n(k-1) + M\theta - 1\right), M\Big) & \text{if } c(k) = 0 \end{cases}.$$

- Conventional slotted ALOHA is asymptotically optimal in terms of the Normalized Expected Weighted Sum AoI (NEWSAoI) when θ < 1/(eM)
- When θ > 1/(eM), local AoI-aware (threshold-based) schemes were designed.

[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.

Performance Comparison

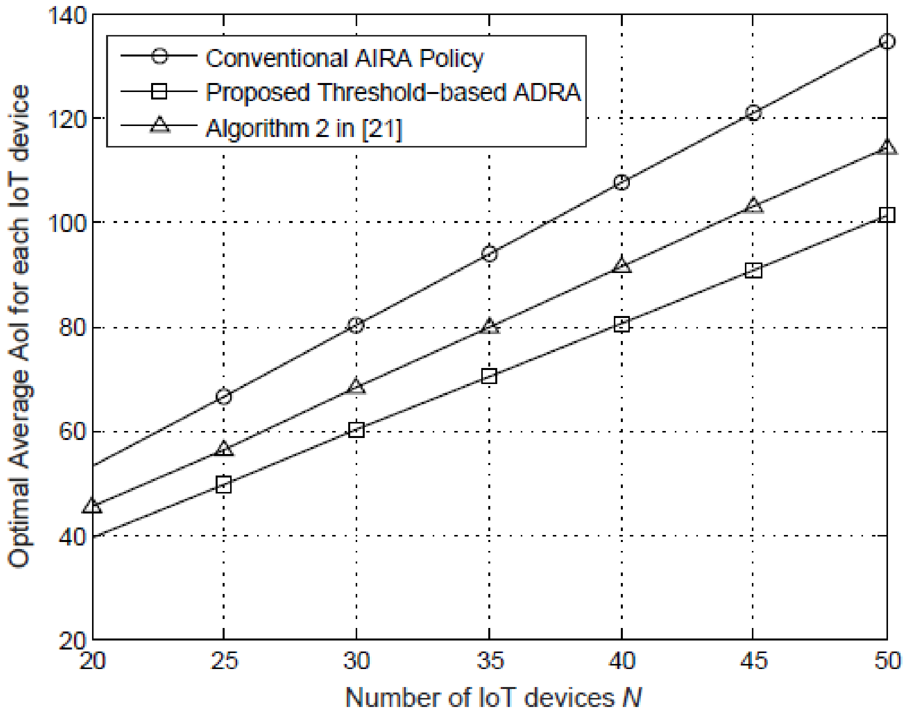


Fig. 5. The average AoI versus the number of IoT devices N for the proposed threshold-based ADRA, the existing AIRA schemes and Algorithm 2 in [21].

[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, avaliable: https://arxiv.org/pdf/2001.04780.pdf.

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, which is 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

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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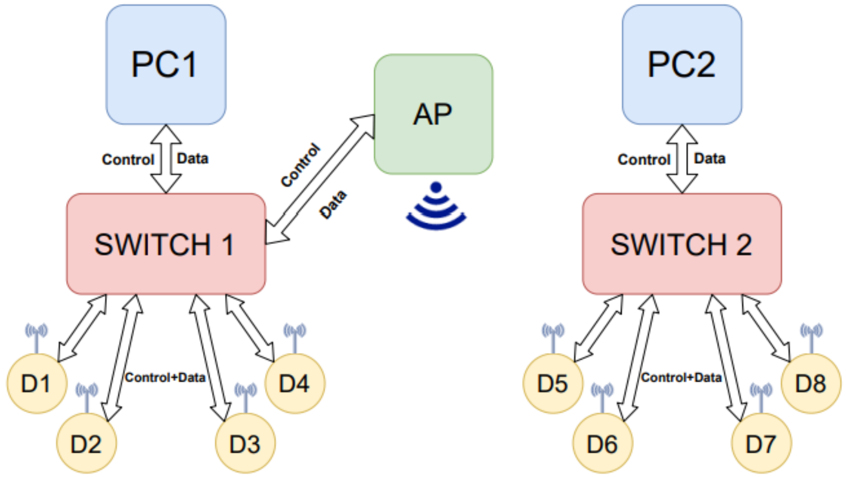
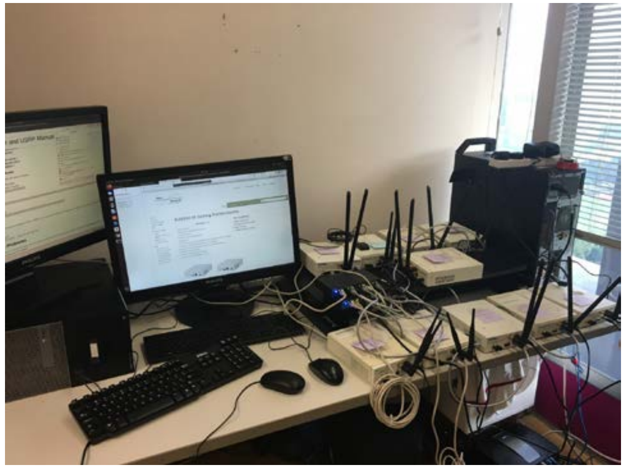
SDR-based proof-of-concept prototype

- 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





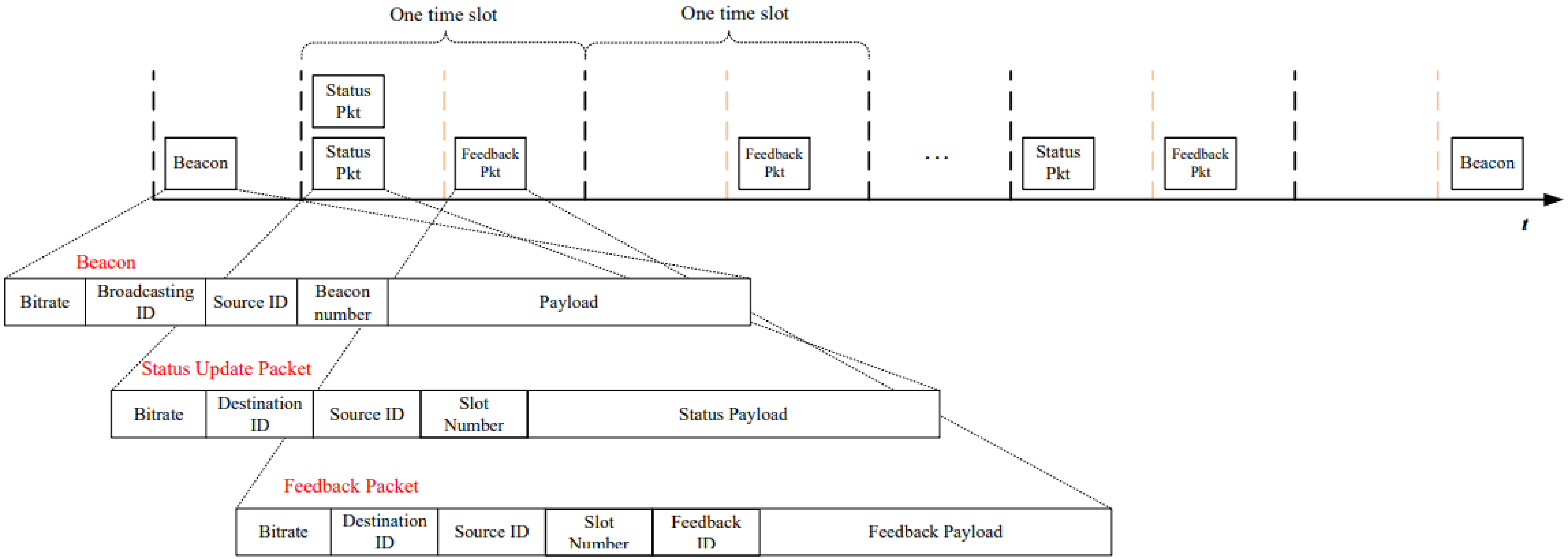
[Han'20] Z. Han, J. Liang, Y. Gu, **H. Chen**, "Software-Defined Radio Implementation of Age-of-Information-Oriented Random Access," accepted to appear in IEEE IECON, July 2020.

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,” accepted to appear in IEEE IECON, July 2020.

SDR-based proof-of-concept prototype



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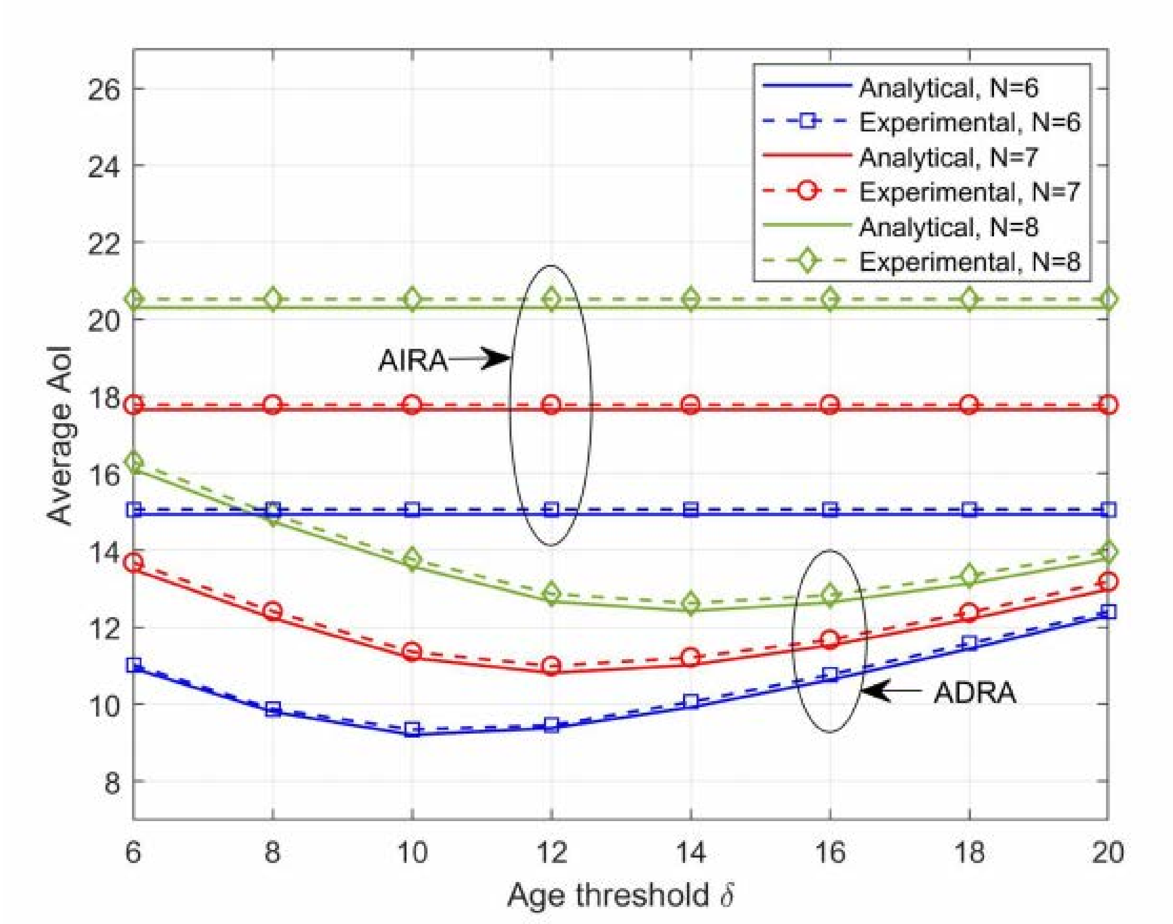

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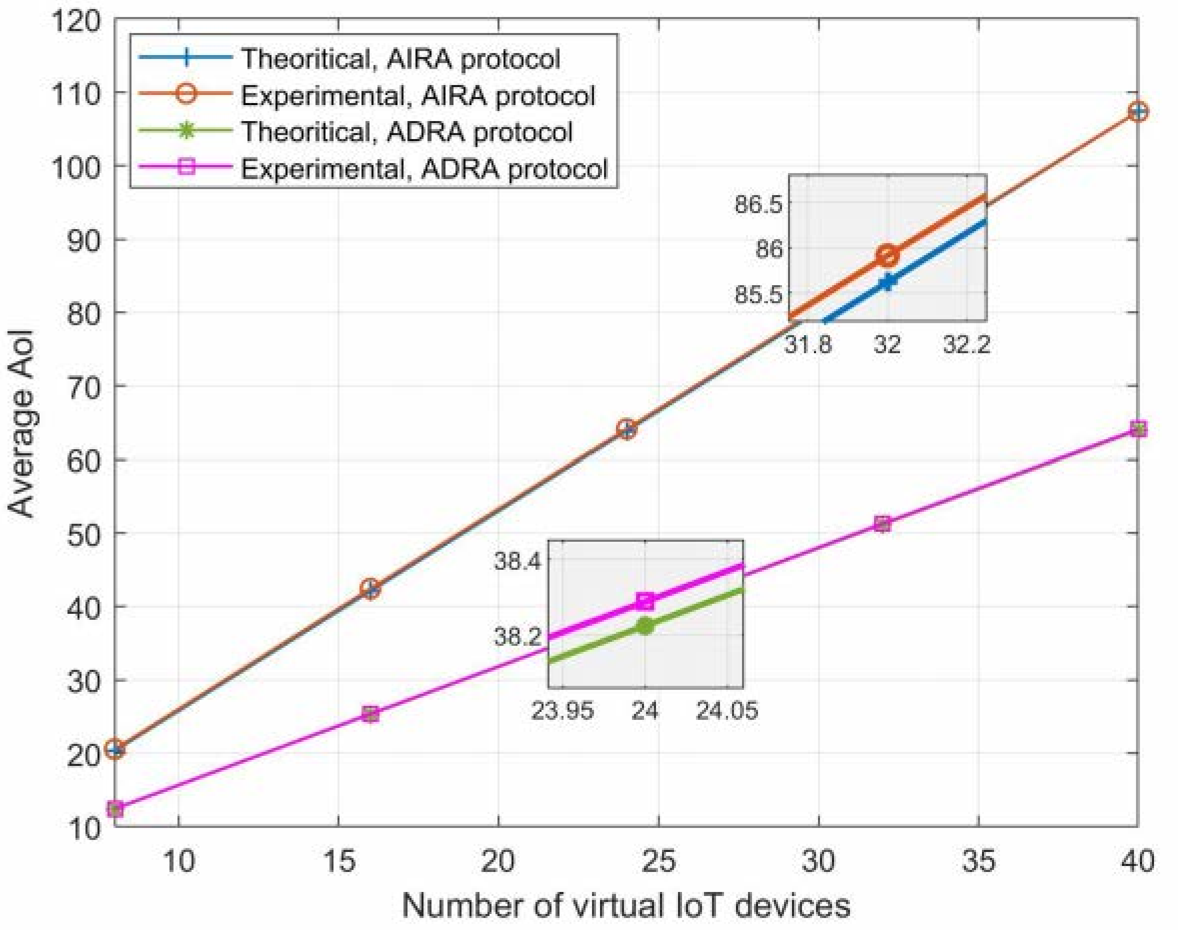

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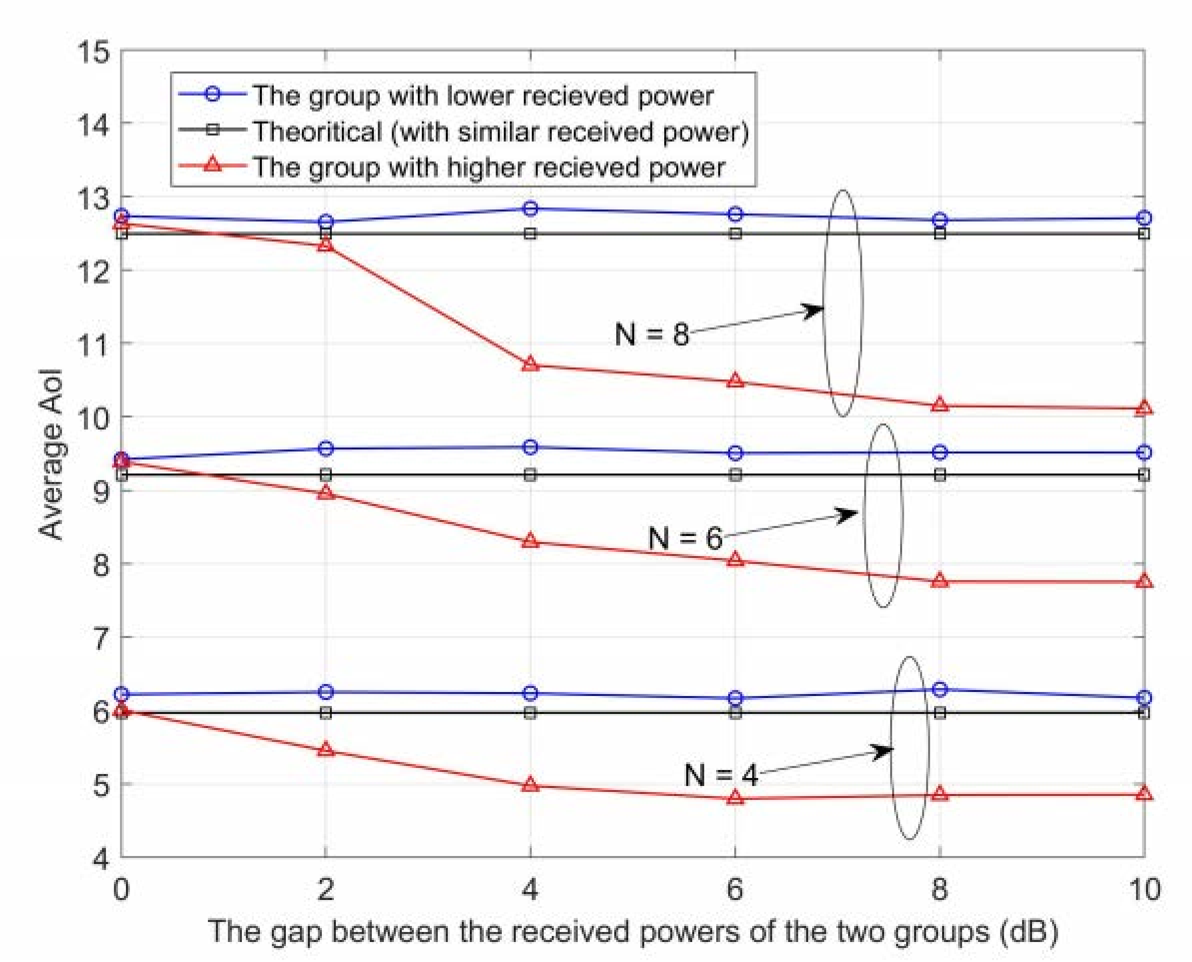

[Han'20] Z. Han, J. Liang, Y. Gu, **H. Chen**, "Software-Defined Radio Implementation of Age-of-Information-Oriented Random Access," accepted to appear in IEEE IECON, July 2020.

Thanks to my students and RAs: Qian, Zixiao, Bob, Jingwei, Tong Zhang

Thanks to my collaborators for many insightful discussions: Dr Yifan Gu, Prof Yong Zhou, Prof Soung Liew, Nikos, etc.

Pass to Nikolaos PAPPAS

Concluding remarks

Nikolaos PAPPAS

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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

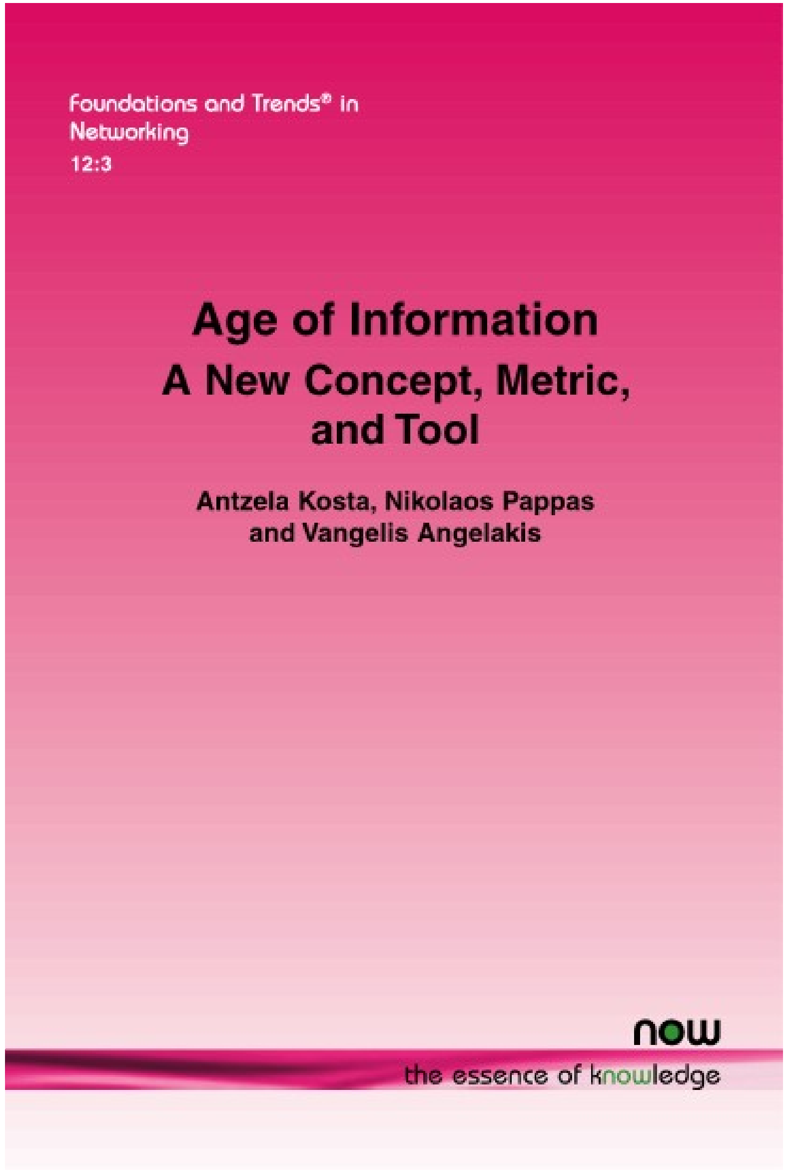
- There are still many interesting research directions
  - Definition of effective age (term coined by Prof. Ephremides in ITA 2015)
  - Sampling and remote reconstruction
  - Deploying of AoI in machine learning

- 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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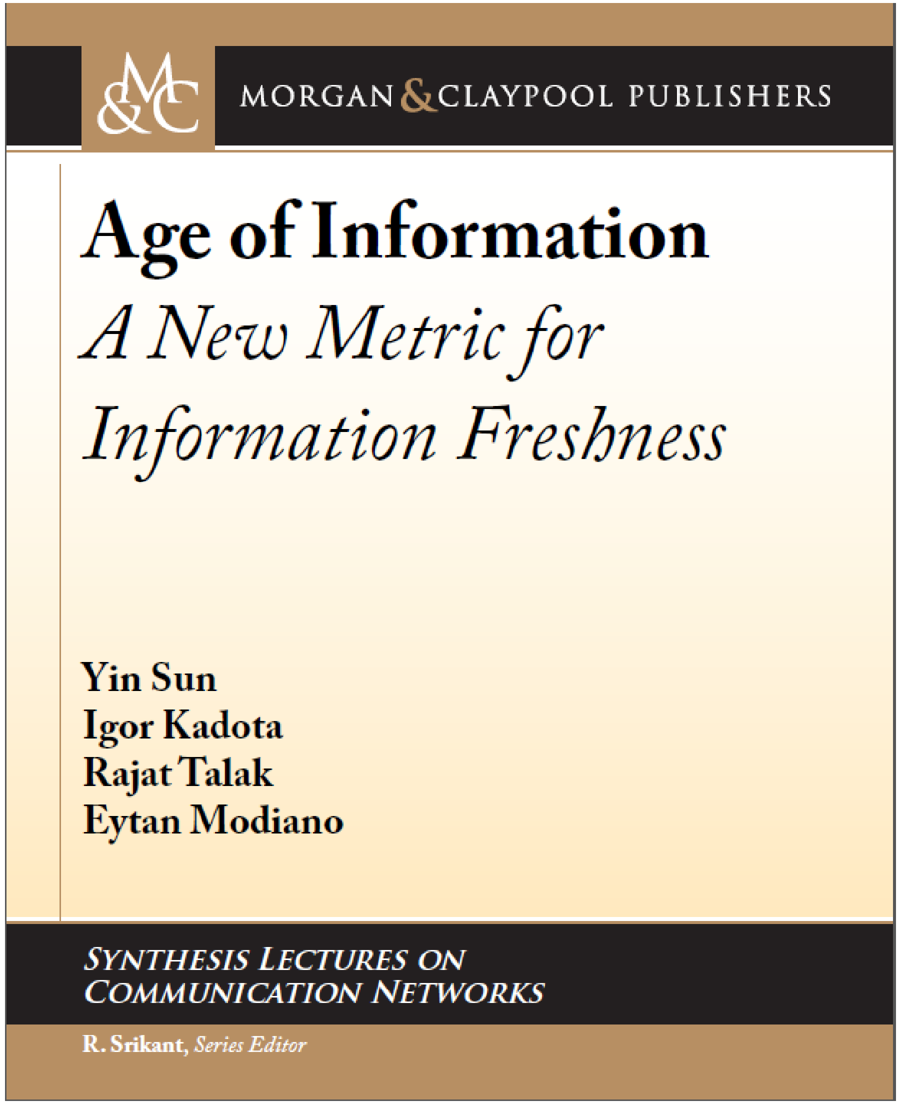
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Upcoming workshop in IEEE GLOBECOM 2020

IEEE Globecom 2020 Workshop 7: Information Freshness, Communications, Control, and Computing for Industrial IoT
Date: Monday, 7 December 2020

Call for Workshop Papers

Industrial Internet of Things (IIoT) integrates advanced digital computing, communications, and control technology. Within the Industry 4.0 framework, IIoT aims to tackle a set of new technological challenges in industrial control, automation, and intelligence. Since most of the IIoT applications, such as intelligent transportation, telesurgery, industry automation, power systems automation, and power electronics control, are mission-critical and demand real-time communications and computation capabilities for successful closed-loop operation, IIoT requires the joint design and optimization of communications, control and computing (3C). Moreover, the freshness and value of information is significant in real-time IIoT applications.
Age of Information (AoI) has emerged as a concept that has recently gained increasing attention as a performance metric for quantifying information freshness at the destination. It is important to note that improving first-order metrics (e.g., for providing high throughput and low delay) that render enhanced performance in traditional communication networks, are inadequate when it comes to improving the information freshness. Therefore, there is an urgent need to re-examine existing metrics and develop new ones for emerging time-critical applications.
The workshop is expected to bring together academic and industrial researchers to identify and discuss the major technical challenges and recent breakthroughs related to AoI, communications, control, and computing in IIoT.

- AoI analysis and optimization
- Multiuser scheduling for optimizing information freshness
- Cooperative status update for improved information freshness
- The application of emerging technologies (e.g., cloud and edge computing, machine learning) for improving AoI performance
- AoI approaches for industrial control applications
- Fundamental tradeoffs between communications, control and computing in IIoT
- Resource allocation for next generation wireless sensing and control applications in IIoT
- MAC layer and network layer design for supporting multi-loop control applications
- Edge computing for low-latency control
- Cyber-physical security in IIoT
- Prototypes and testbeds for validating AoI and communications-control-computing codesign protocols.

Workshop Organizers

- Yonghui Li, The University of Sydney, Australia (yonghui.li@sydney.edu.au)
- He (Henry) Chen, The Chinese University of Hong Kong, Hong Kong SAR, China (he.chen@ie.cuhk.edu.hk)
- Nikolaos Pappas, Linköping University, Sweden (nikolaos.pappas@liu.se)
- Sheng Zhou, Tsinghua University, China (sheng.zhou@tsinghua.edu.cn)
- Zhibo Pang, ABB AB, Corporate Research, Sweden (pang.zhibo@se.abb.com)

IMPORTANT DATES

Paper Submission Deadline: ~~1 August 2020~~ 14 August 2020 (Firm)
Paper Acceptance Notification: 15 September 2020
Camera-Ready: 1 October 2020

Thanks for your attention.

Q&A

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