



**METU**



Communication Networks  
Research Group  
<http://cng-eee.metu.edu.tr>

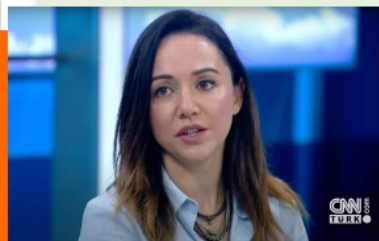
# Goal Oriented Communication for the Scale-up of MTC

**Elif Uysal**

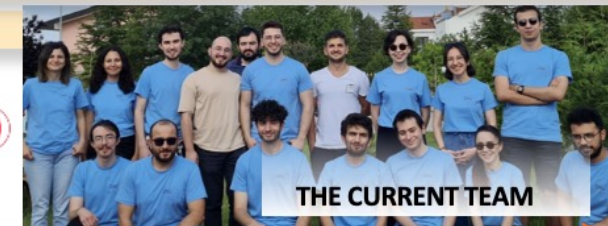
Middle East Technical University (METU), Turkey

**CS Distinguished Seminar  
Chalmers University, Sweden  
November 10, 2023**

# Where do I come from



PROF. ELİF UYSAL  
Fellow, IEEE Fellow, AAIA

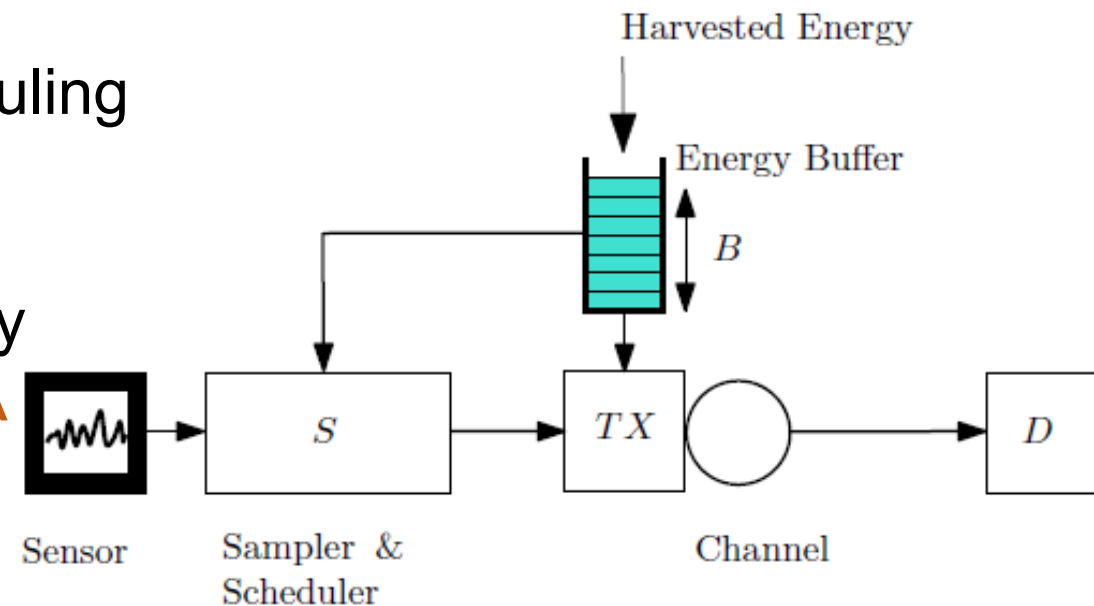


THE CURRENT TEAM

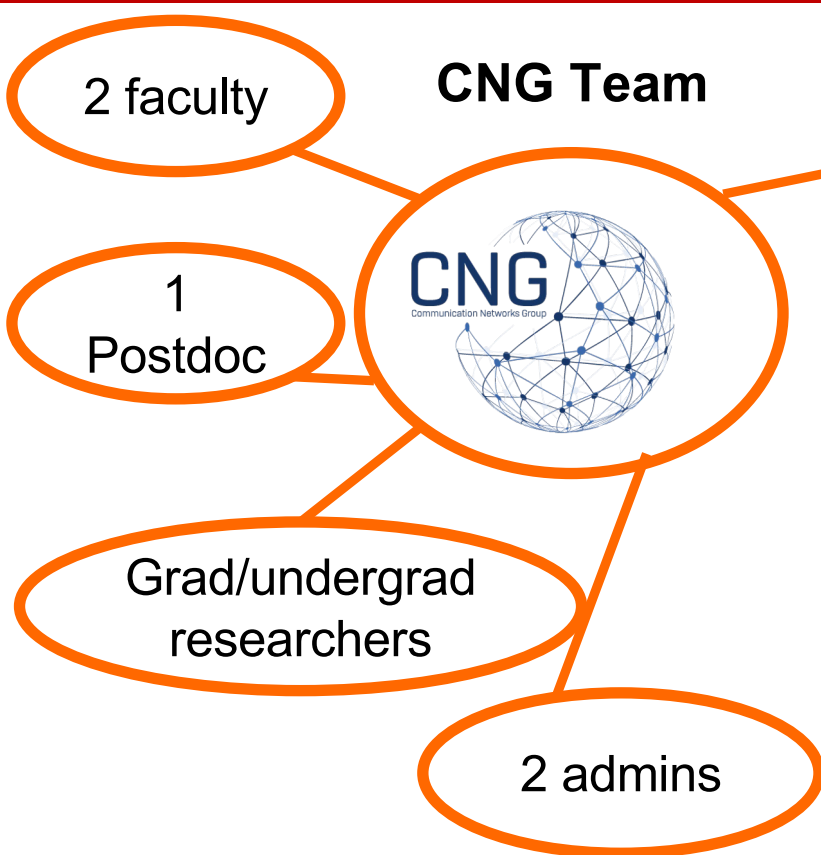
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## Our exploration of Machine Type Communication:

- 2000s: Energy Efficient Transmission Scheduling
  - Exogeneous “bursty” arrivals of data
- 2010s: Energy-harvesting, “Zero-Energy”
  - Exogeneous “bursty” arrivals of energy
- 2015-2020: Age of Information **FRESHDATA**
  - “Generate-at-will”
- 2021-today: **Goal-Oriented Communication**
  - “Selection-from-buffer”



# Communication Networks Research Group (CNG)



**FRESHDATA Technologies**

**Spin-off, 2022**



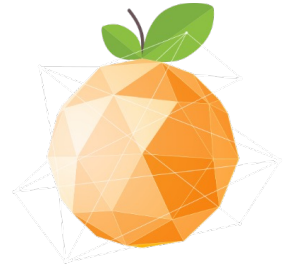
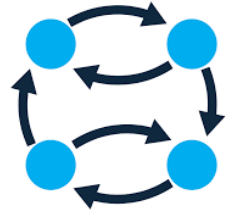
- SUIT (Sustainable Urbanization through Innovative Technologies) (2022)

- Consortium of universities, research labs, companies



# General Outline

- Why **Goal-oriented Communication**?
- What are some goal-oriented KPIs that can guide **the design of protocols today**
- **Re-design of networks** through these metrics

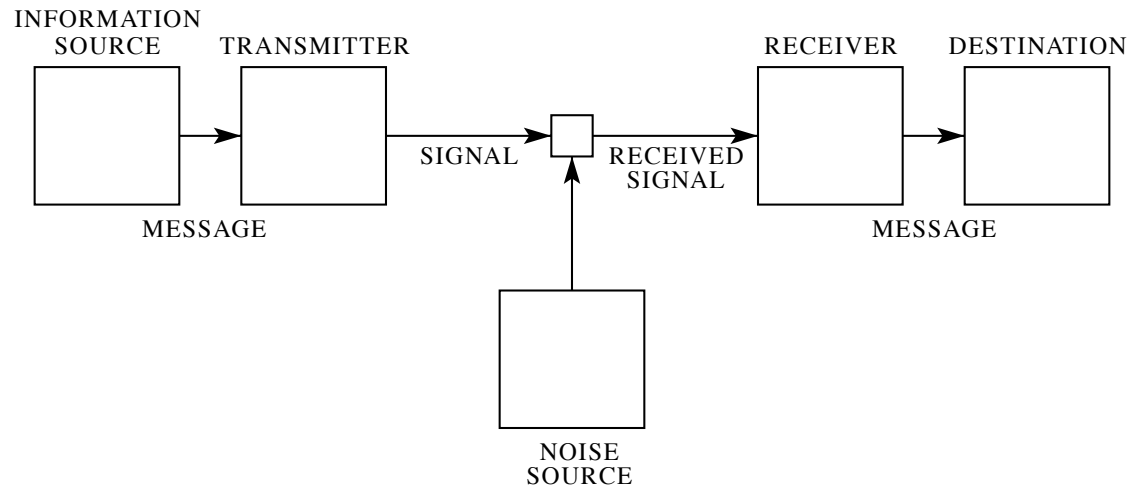


# Classical Communication Systems

vs

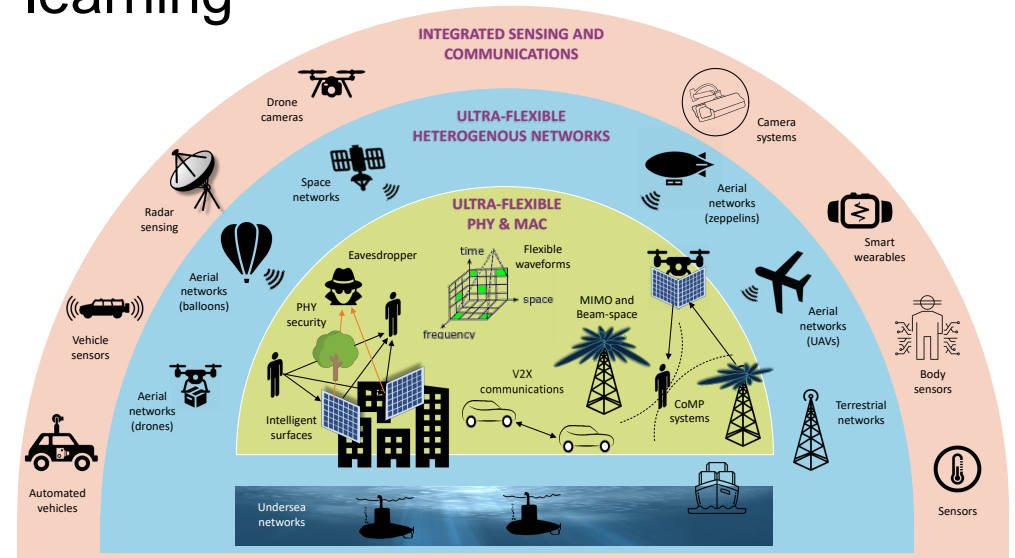
# Machine Type Communications

- Humans choose the data
- The network ensures its correct, to some extent timely delivery



Shannon's point to point communication model

- *Networked applications*, machine-type data.
- Real-time systems; automated decisions in a sense-compute-actuate cycle.
- Massive access e.g. IoT
- Learning for communications/communications for learning



Source: Yazar et al, 6G Vision: An ultra flexible perspective.

# Transmission Problem vs Effective Communication

## Recent Contributions to The Mathematical Theory of Communication

Warren Weaver

September, 1949



Claude Shannon



Warren Weaver

## Foundations of the Theory of Signs

Charles W. Morris



Charles W. Morris

## 1.2 Three Levels of Communications Problems

Relative to the broad subject of communication, there seem to be problems at three levels. Thus it seems reasonable to ask, serially:

**LEVEL A.** How accurately can the symbols of communication be transmitted? (The technical problem.)

**LEVEL B.** How precisely do the transmitted symbols convey the desired meaning? (The semantic problem.)

**LEVEL C.** How effectively does the received meaning affect conduct in the desired way? (The effectiveness problem.)

### Semiosis and Semiotic

- 1) syntactics – the study of the methods by which signs may be combined to form compound signs,
- 2) semantics – the study of the signification of signs,
- 3) pragmatics – the study of the origins, uses, and effects of signs.

The science of relation of signs to their interpreters

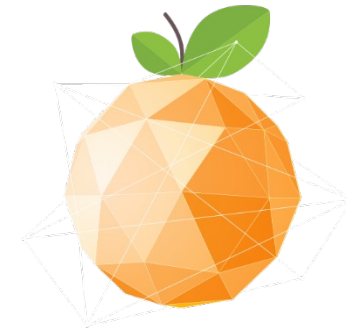
# GAP current protocols and effective communication



## Available Communication Protocols



## Semantic/Effective Communication



### Traditional protocols

Optimized for high throughput/low delay,  
Low loss (transmit all the data)

### Real time monitoring/decision making

Goal-oriented performance criteria

- **MTC is Loss resilient !**

e.g. irrelevant data can be dropped from queues

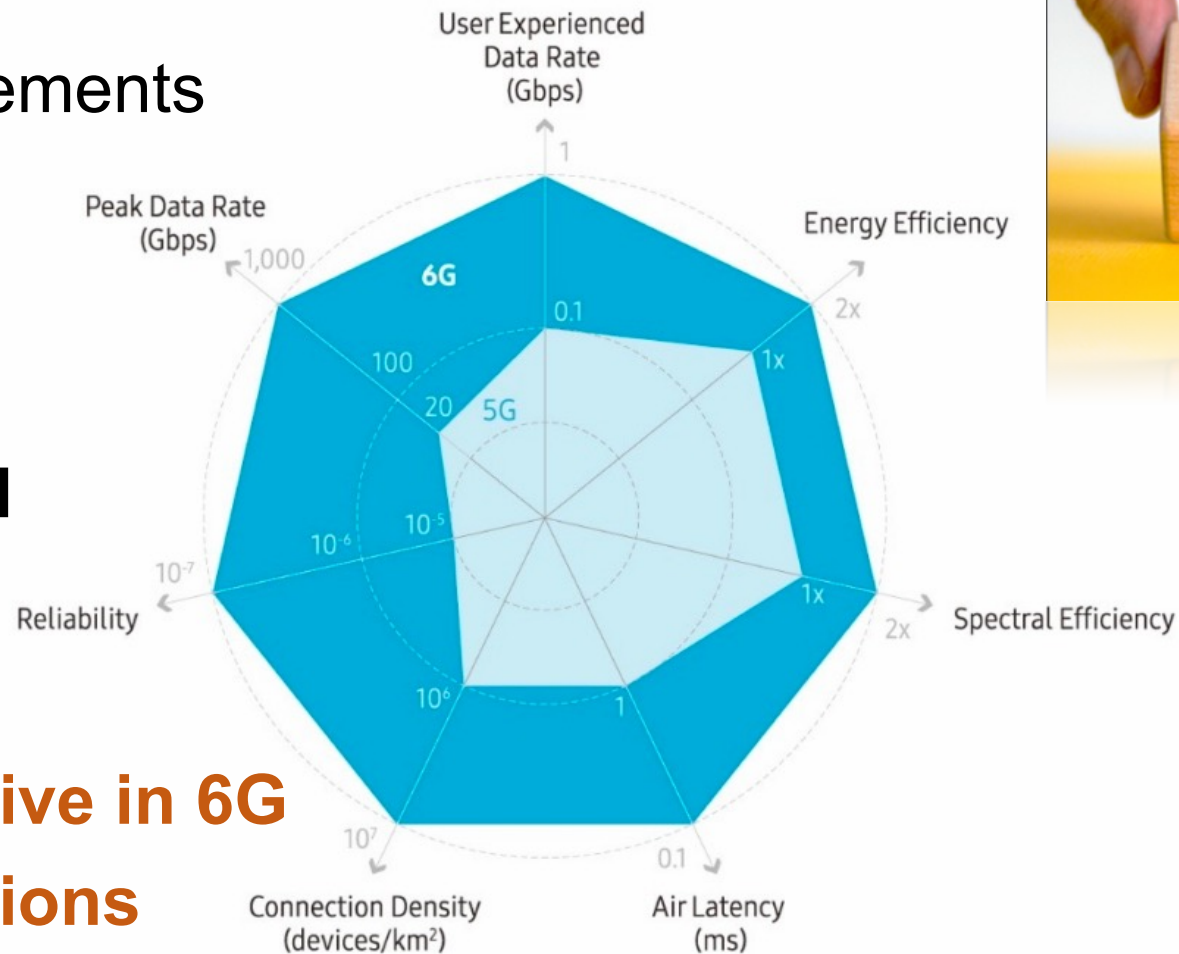
- **Future networks: AI-native**

Exploit cognition introduced into the communication system for resilient and robust networking

# MTC in 6G: we cannot ignore the gap

- Conflicting ambitious requirements
- One size fits all not possible
- Must rethink the **end-to-end** communication system design

**Sensing and NTN will be native in 6G**  
**Further: Space Communications**





# Effectiveness KPI Example: Age of Information



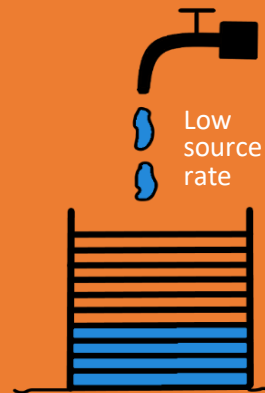
## Traditional Approach

### Throughput Maximization



Minimum idling: full buffers

### Delay Minimization



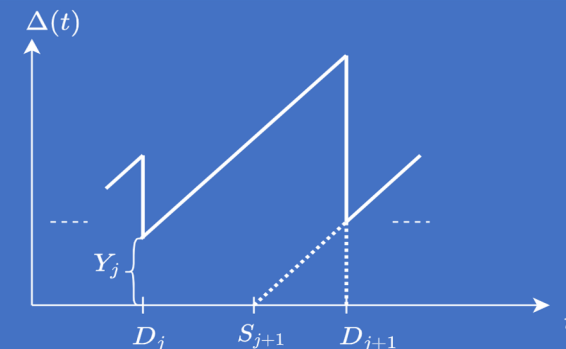
No congestion  
Minimum queuing: light buffers

Age is a composite measure of Throughput and Delay.

## Age of Information

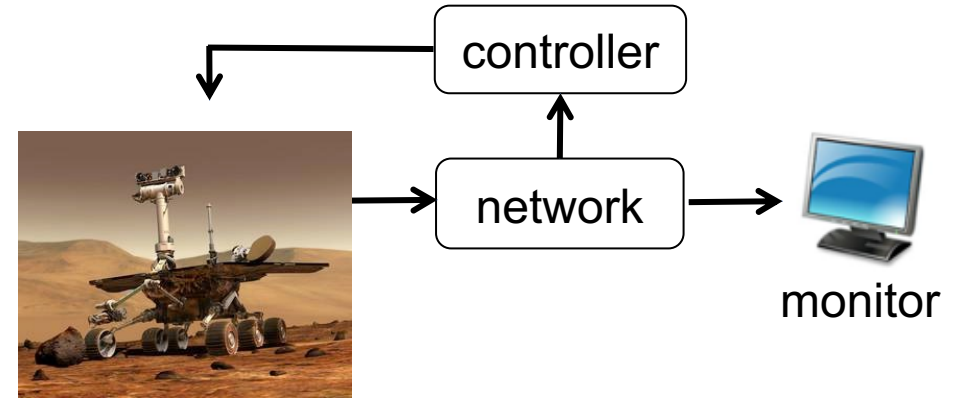
- A measure of freshness for an information flow
- Let  $u(t)$  be the timestamp of the newest packet that the destination has received by time  $t$ .
- The age of this flow at  $t$  is

$$\Delta(t) = t - u(t)$$

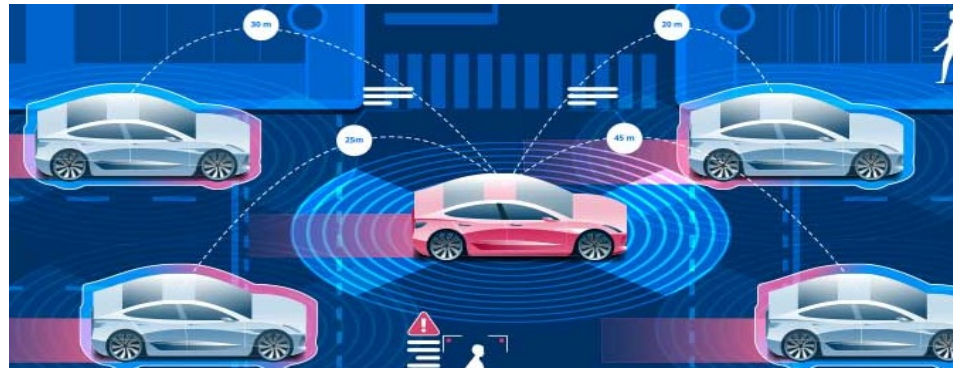


# Effectiveness KPI Example: Age of Information

Satellite IoT



Remote Monitoring and Control

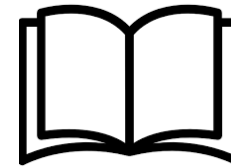
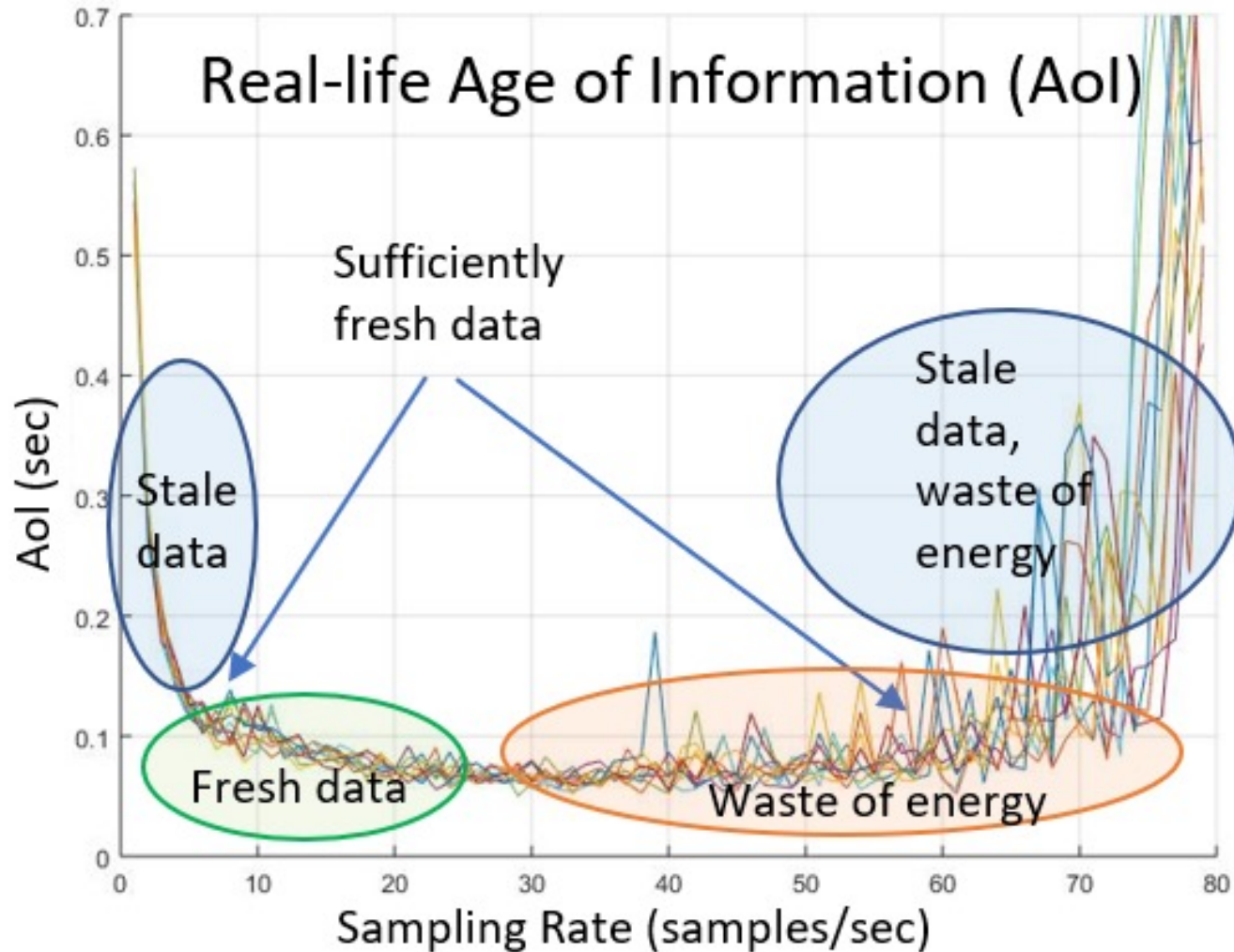


Automated Vehicles

Terrestrial localization and tracking



# Effectiveness KPI example: Age of Information



**Book Chapter:**

***Age of Information In Practice***

[Uysal, Kaya, Baghaee, Beytur, 2023]



**Conference presentations:**

[Guloglu, Baghaee, Uysal 2021]

[Beytur, Baghaee, Uysal 2020]

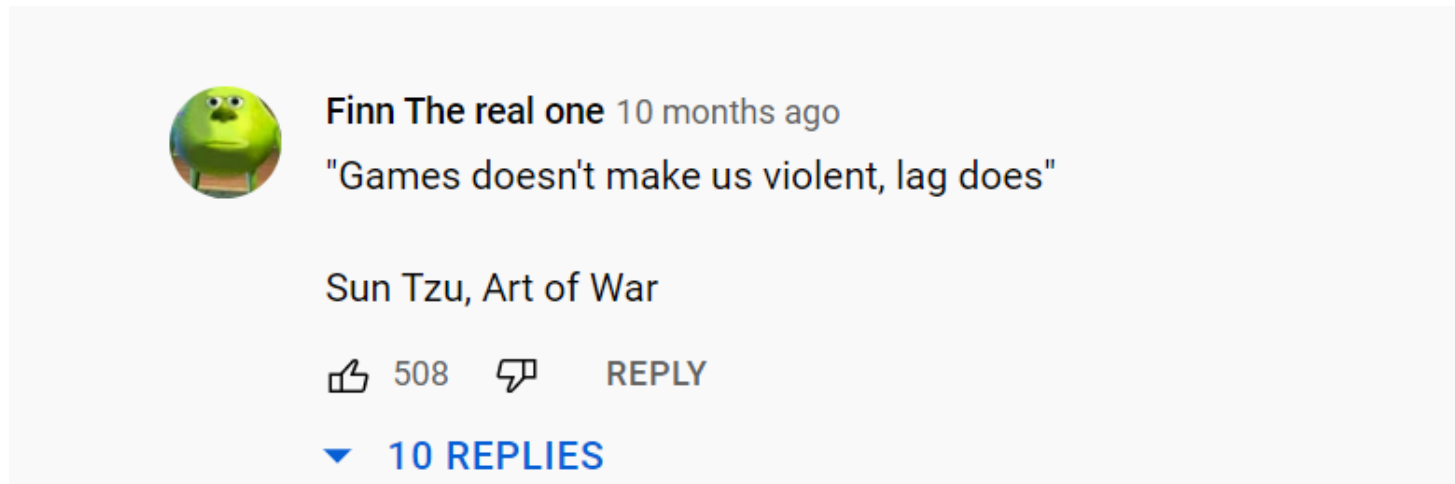
[Beytur, Baghaee, Uysal 2019]

[Sonmez, Baghaee, Ergisi, Uysal 2018]

[Sert, Sönmez, Baghaee, Uysal 2018]

[Baghaee, Beytur, Uysal 2019]

# URLLC – The Right Approach?



- Ultra-Reliable Low Latency Communication (URLLC) :
  - high reliability (e.g., > 99.999%)
  - 1 ms delay
- One “umbrella” to satisfy almost all MTC applications currently envisioned
- Same requirements to be followed in 6G?

# Low Latency: Neither necessary nor sufficient!

Latency	1.1 ms	1.1 ms
Sampling period	1 ms	0.1 ms
Peak Age	2.1 ms	1.2 ms

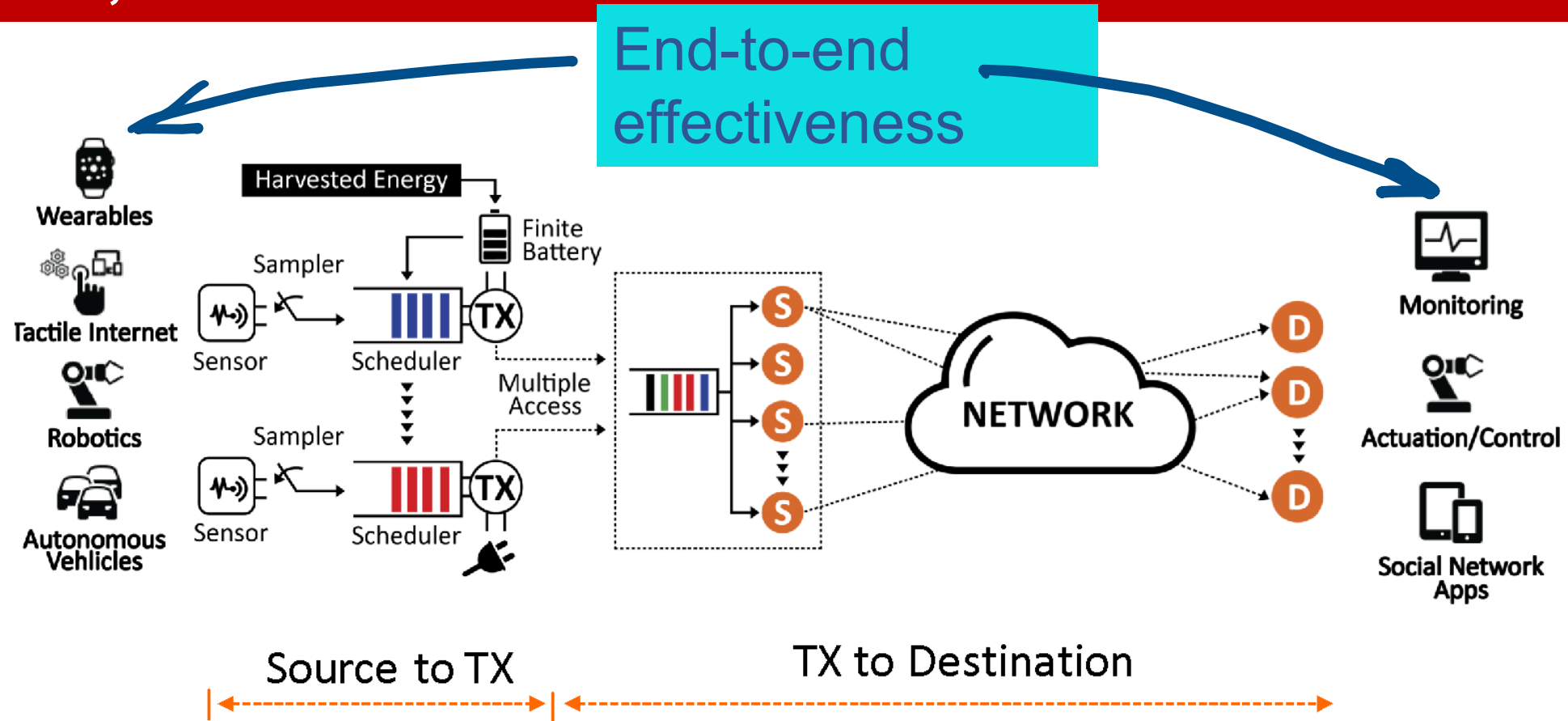
Not  
sufficient!

- In cyber-physical systems timeliness cannot be captured with low latency alone

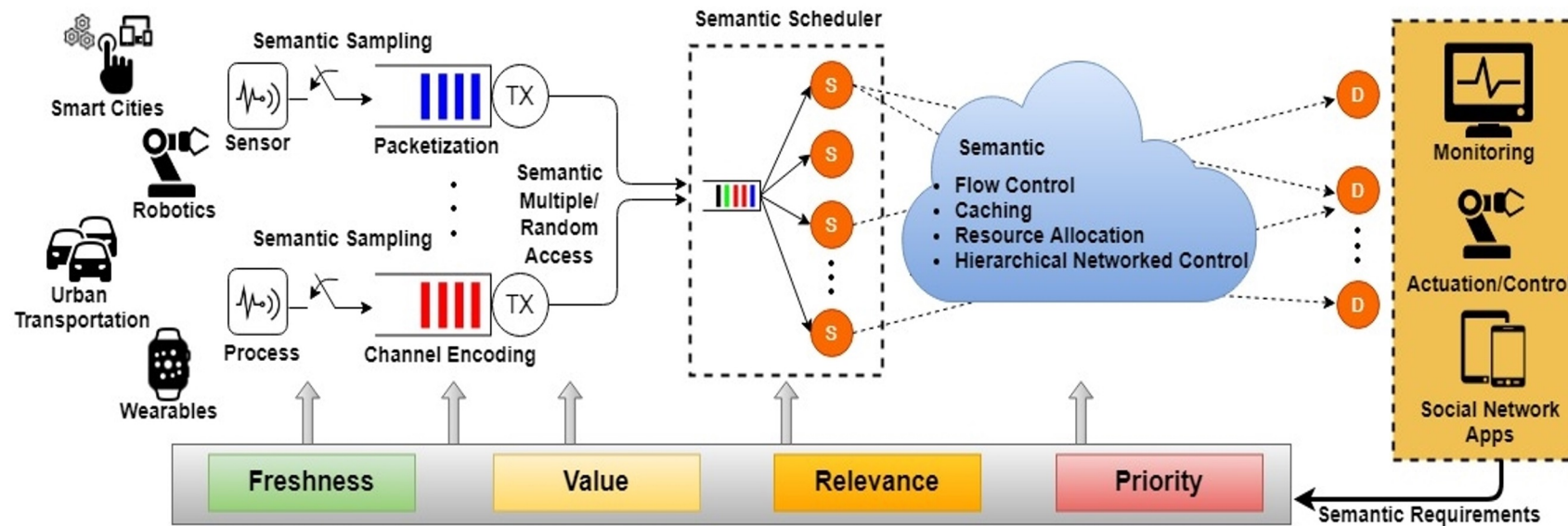
Unnecessary!

- Consider eMBB and URLLC coexistence
- High rate vs intermittent critical updates
- Low latency  $\Rightarrow$  reserved slots  $\Rightarrow$  **over-provisioning**

# Semantic communication: a data significance perspective, Uysal et al., IEEE Network 2022



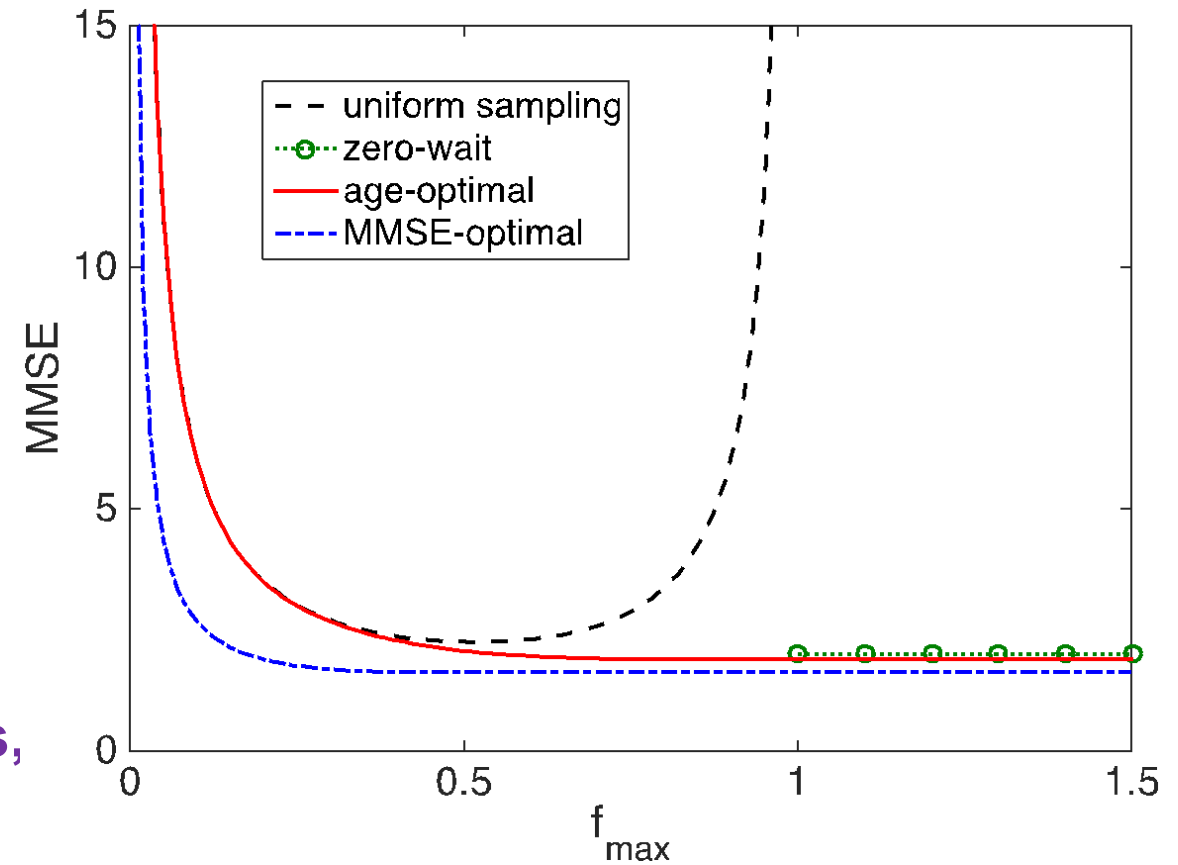
# End-to-end Goal-Oriented Communication Architecture



- New effectiveness measures and metrics that define them.
- Develop goal-oriented link, transport and application layer principles in concert
- Relax the exogeneous data arrival assumption
  - **Non-uniform process-aware sampling.**
- New communication protocol principles tailored for information flow in networked **control systems.**

# Semantic Attribute: Relevance

- Remote Tracking from Samples sent over a network with delay
- Measurements of a process/images/video sent for remote estimation/ AI, etc
- Separate handling of sampling, encoding and transmission -> highly suboptimal
- **Optimal sampling and transmission:**  
**Generate At Will, based on Age, delay statistics, and the state of the process**

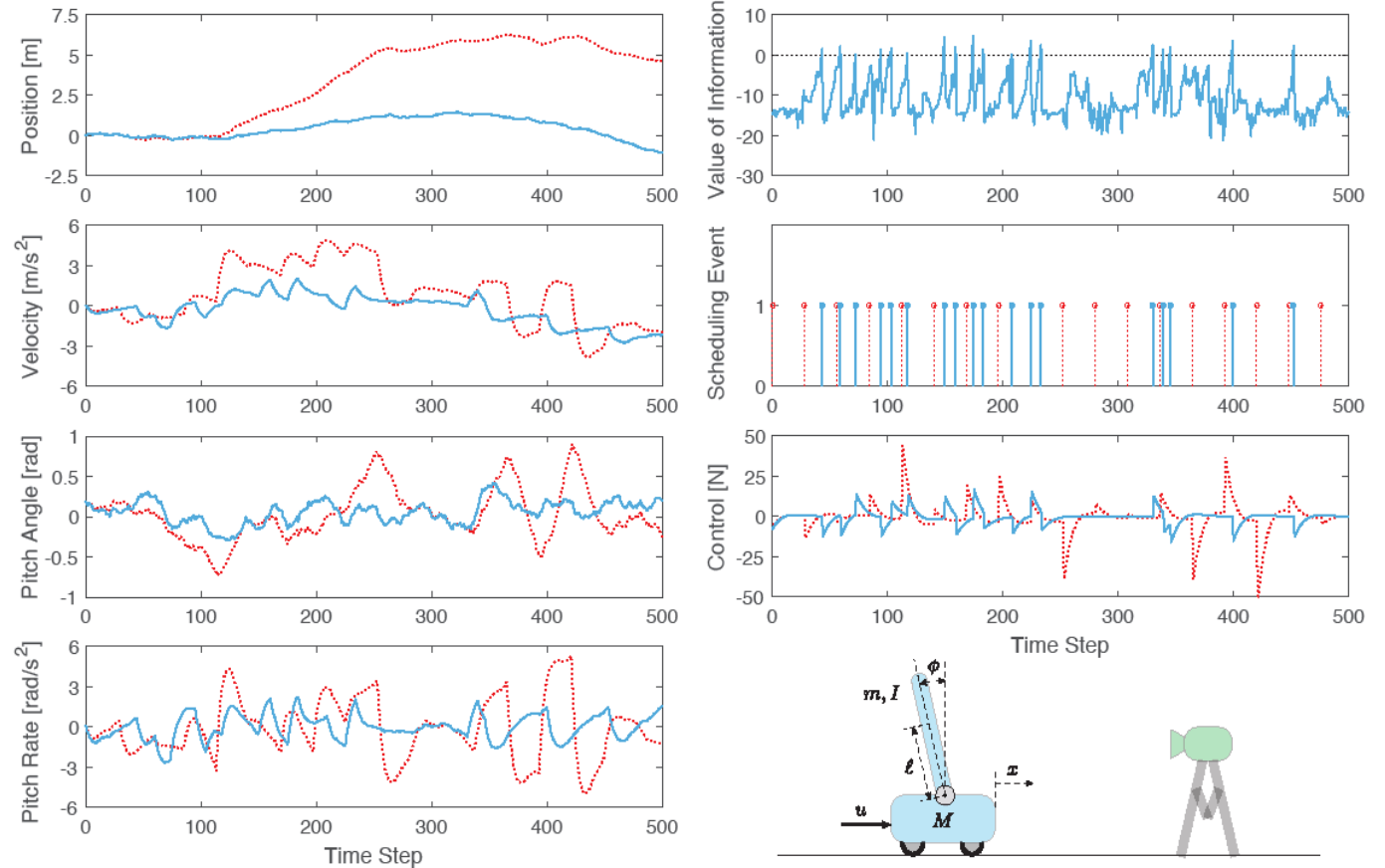


[Sun Polyanskiy Uysal 2019]



# Semantic Attribute: Value- Vol

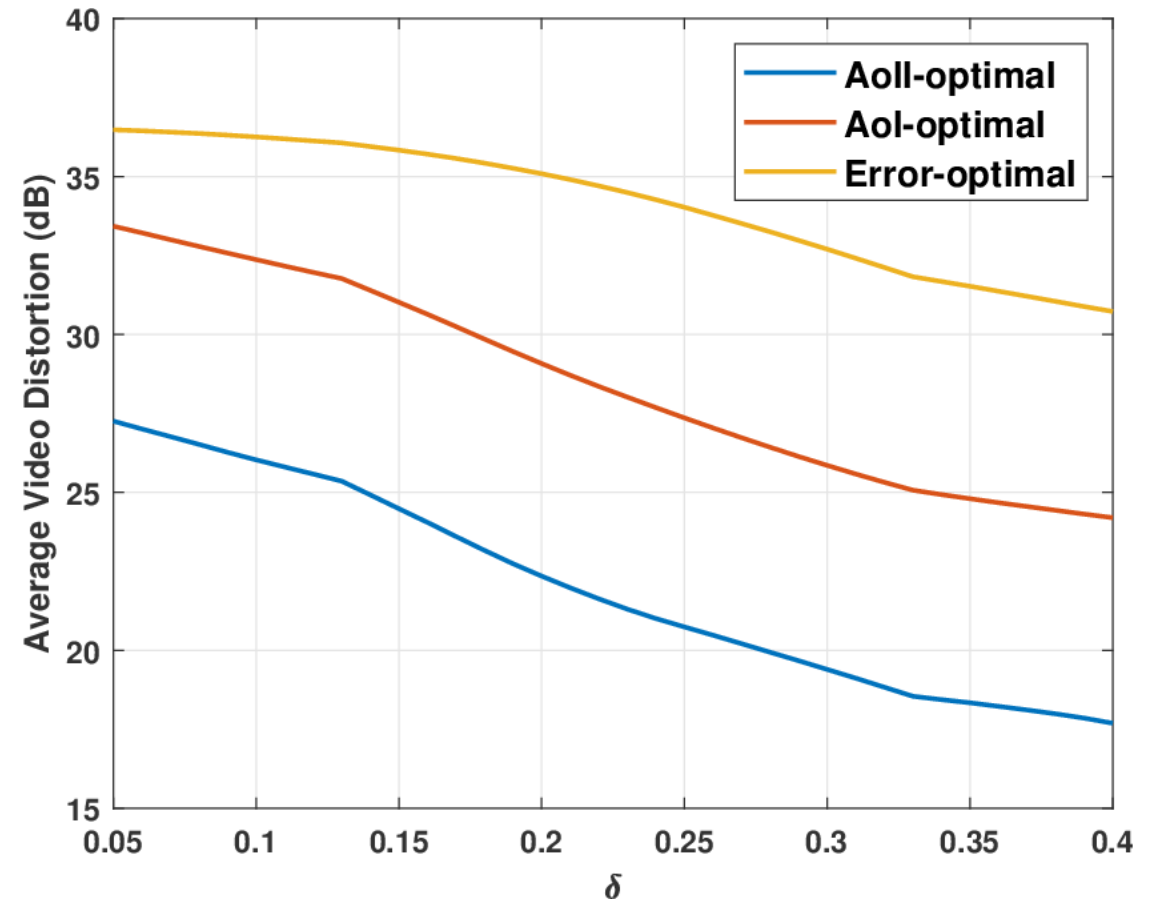
- Relevance: source based
- Value: the *value* of the next source sample to the point of computation.
- (Vol) : difference between the benefit of having this sample and the cost of its transmission.



- Vol > 0 18 times out of 500 -> transmit control signal.
- Vol based (blue), periodic with same number of transmissions (red).

# Semantic Attribute: Freshness & Relevance -Aoll

- Combines aging and accuracy
- E.g. application in video streaming: an Aoll-based transmission policy reduces the distortion with respect to Aol-based and conventional error-based policies.



A. Maatouk, M. Assaad, T. Ephremides. The Age of Incorrect Information: an Enabler of Semantics-Empowered Communication, 2020

# Semantic Attribute: Freshness & Value: QAol

➤ Query Age of Information (QAol): Aol at query instants  $Q_k$  (Chiarotti et. al. 2021)

- Pull based systems.
- Eg. Satellite IoT
  - GEO: Periodic Query instants, constant coverage
  - LEO: Intermittent connectivity with some blind slots, yet predictable query times.
  - Best to send right before query time, but perhaps allowing enough time for retransmission.

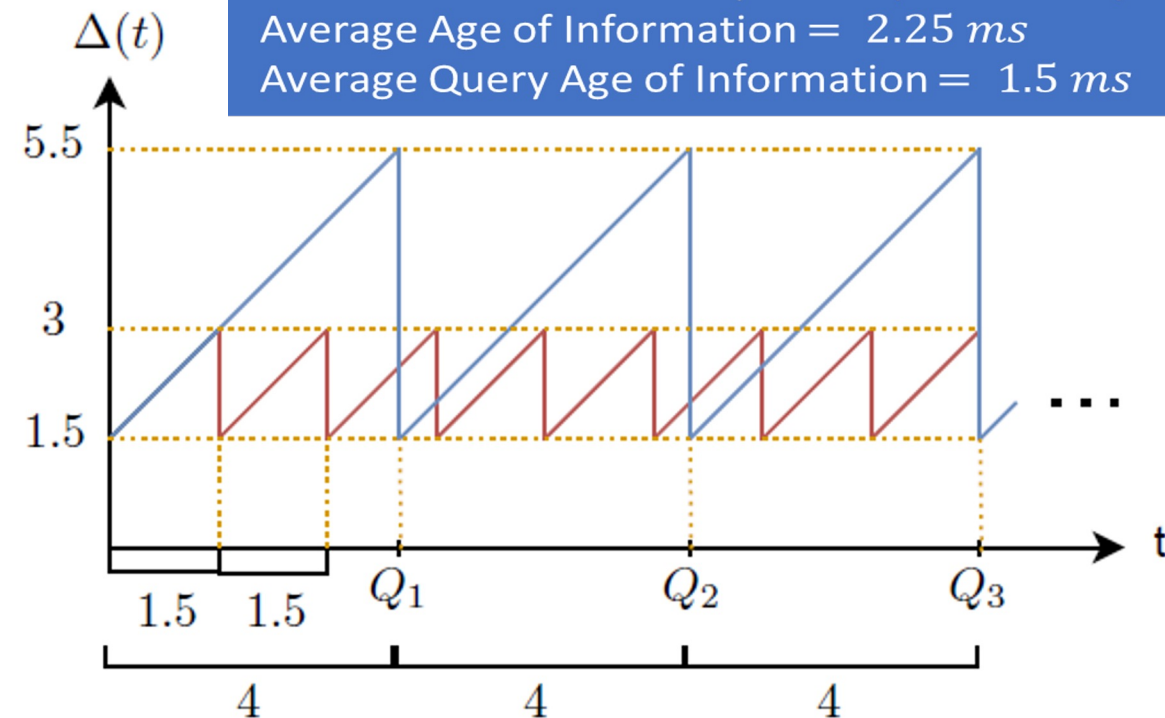
## Aol Optimization

- Worse Performance
- Wasteful

## QAol Optimization

- Better freshness
- Fewer transmissions

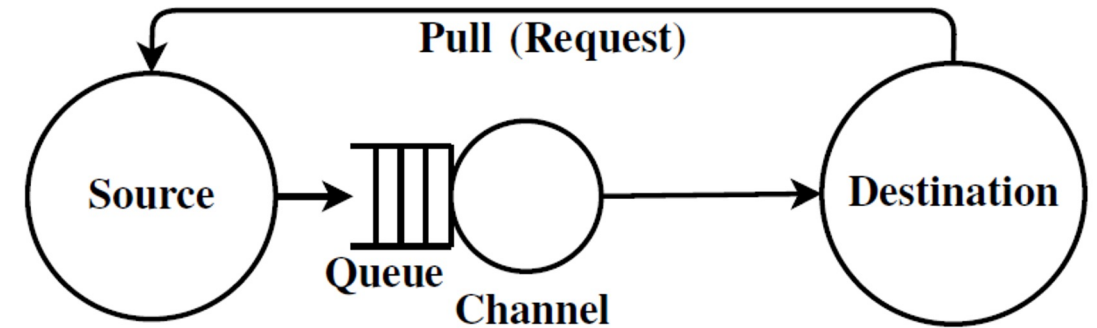
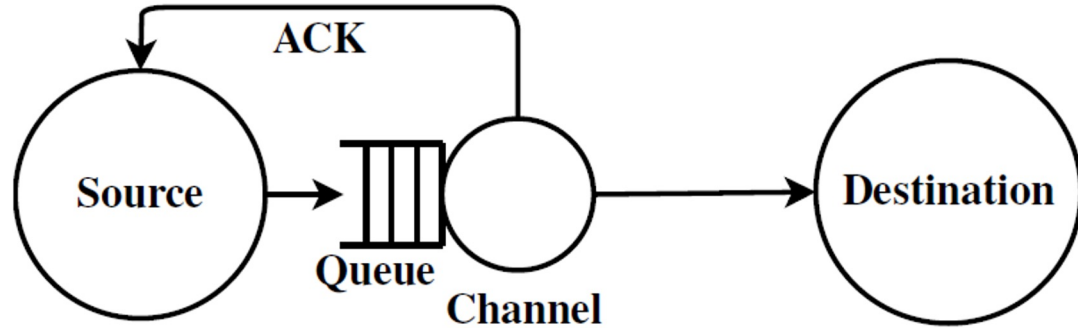
[Ildiz et al 2021]



# “Update-or-Wait”

vs

# “Pull-or-Wait”



$$\bar{g}_{opt} = \min_{\pi \in \Pi} \limsup_{n \rightarrow \infty} \frac{E[\int_0^{D_n} g(\Delta(t)) dt]}{E[D_n]}$$

$$s. t. \liminf_{n \rightarrow \infty} \frac{1}{n} E\left[\sum_{i=1}^n (Y_j + Z_j)\right] \geq \frac{1}{f_{max}}$$

$$*\bar{h}_{opt} = \min_{\pi \in \Pi} \limsup_{n \rightarrow \infty} \frac{1}{n} E\left[\sum_{k=1}^n g(\Delta(Q_k))\right]$$

$$s. t. \liminf_{n \rightarrow \infty} \frac{1}{n} E\left[\sum_{i=1}^n (Y_j + Z_j)\right] \geq \frac{1}{f_{max}}$$

- Equal, for Poisson queries (Ildiz et al 2021)
- PoW dominates (Ildiz et al 2022) for
  - periodic queries, or
  - Constant delay
- General problem open

with the assumptions

- The penalty function  $g$  is continuous.
- $Y_j$  and  $Z_j$  is lower and upper bounded i.e.

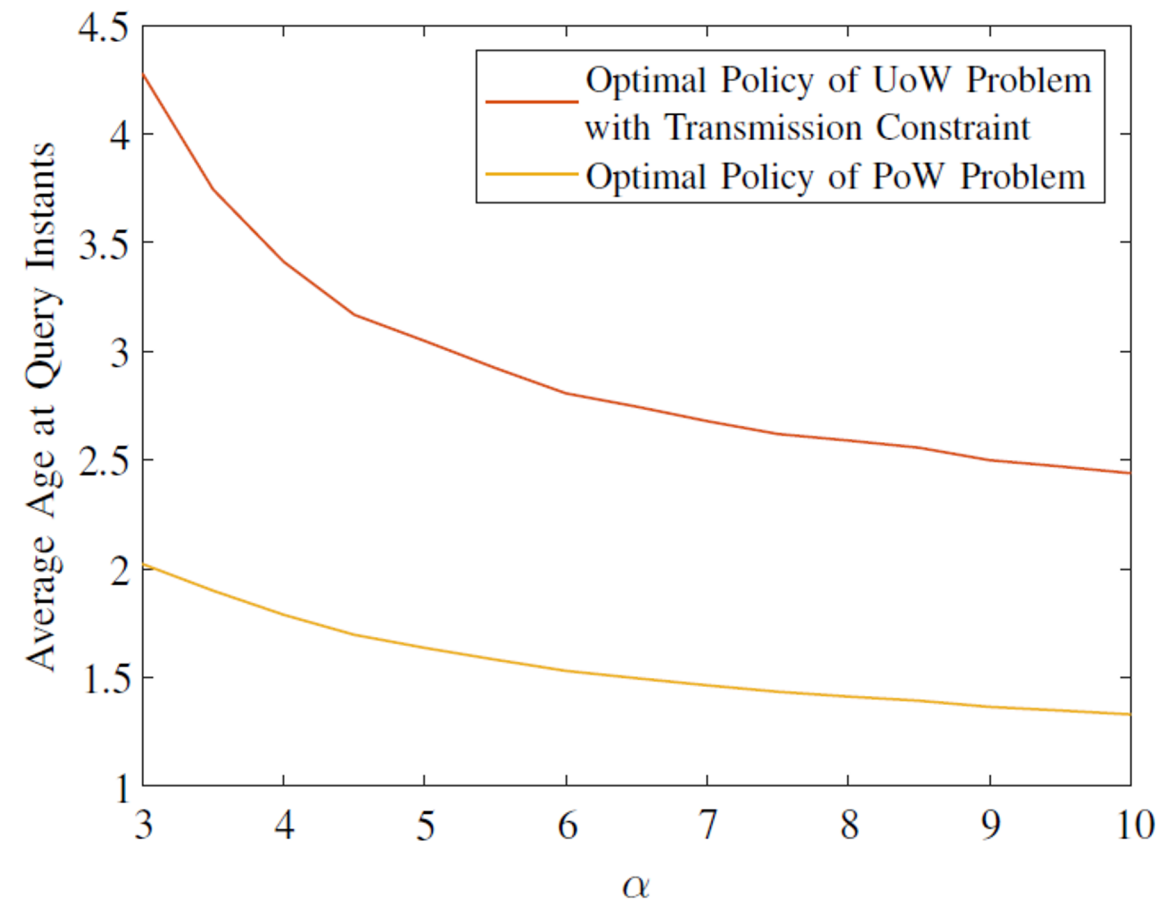
$$P(Y_j \in [B_L, B_U]) = 1$$

$$Z_j \in [0, M]$$

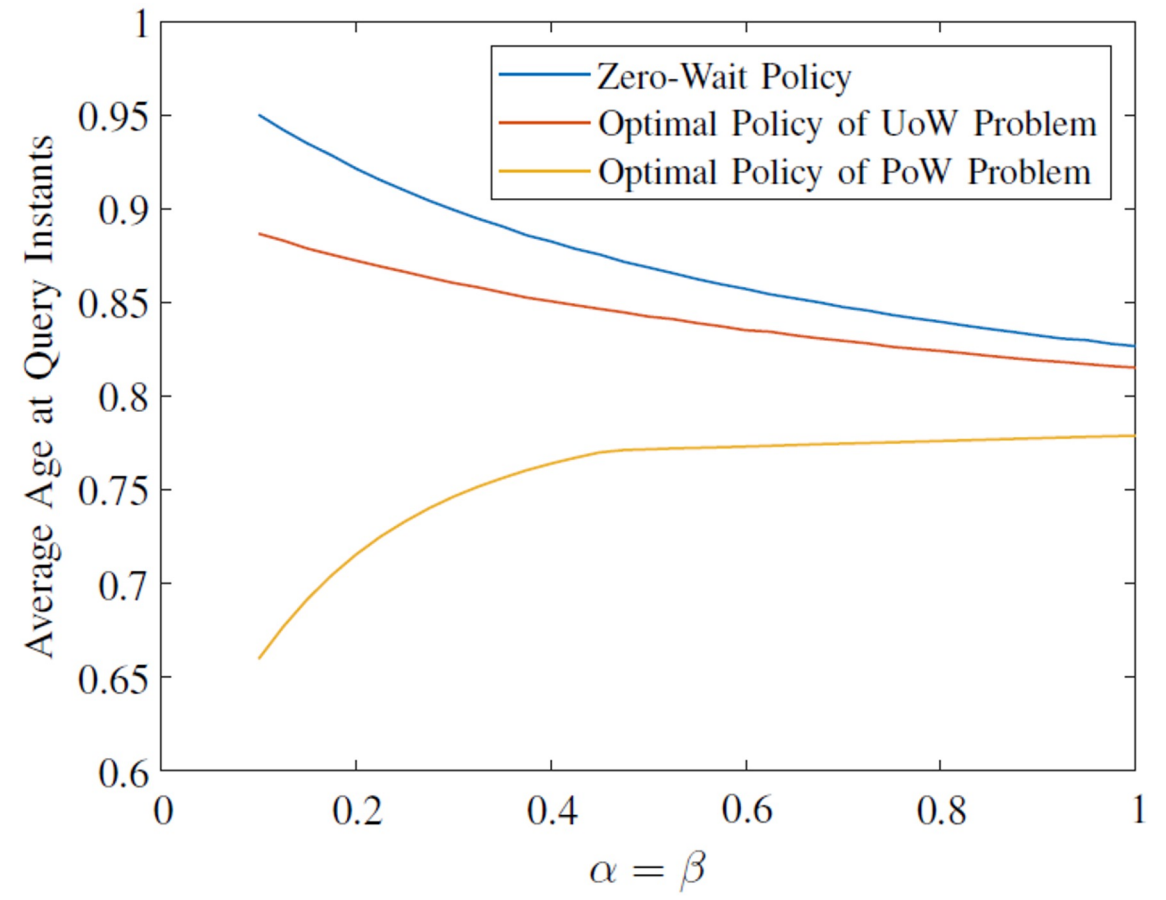


# PoW dominates UoW in terms of performance

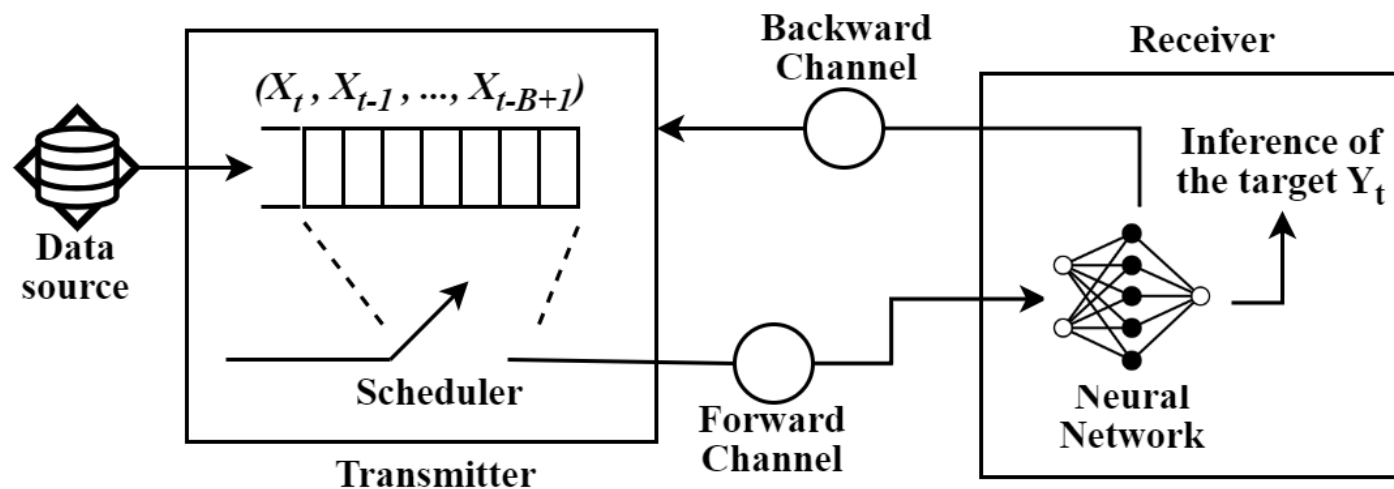
Pareto distributed transmission delays  
(IID with parameters  $x_m = 1$  and  $\alpha$ )



Transmission delays are i.i.d. beta random variables  
with parameters  $(\alpha, \beta)$ .



# Selection From Buffer (Shisher & Sun 2022)

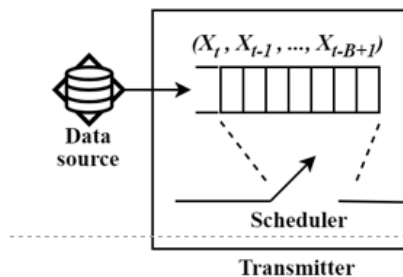


$$h_{opt} = \inf_{(f,g) \in \Pi} \limsup_{T \rightarrow \infty} \frac{1}{T} \mathbb{E}_{(f,g)} \left[ \sum_{t=0}^{T-1} h(\Delta(t)) \right]$$

The function  $h$  is **task-specific** and not necessarily monotone

Scheduling policy optimizes inference performance using Aol as an **intermediate parameter**.

# Selection from Buffer (SFB)

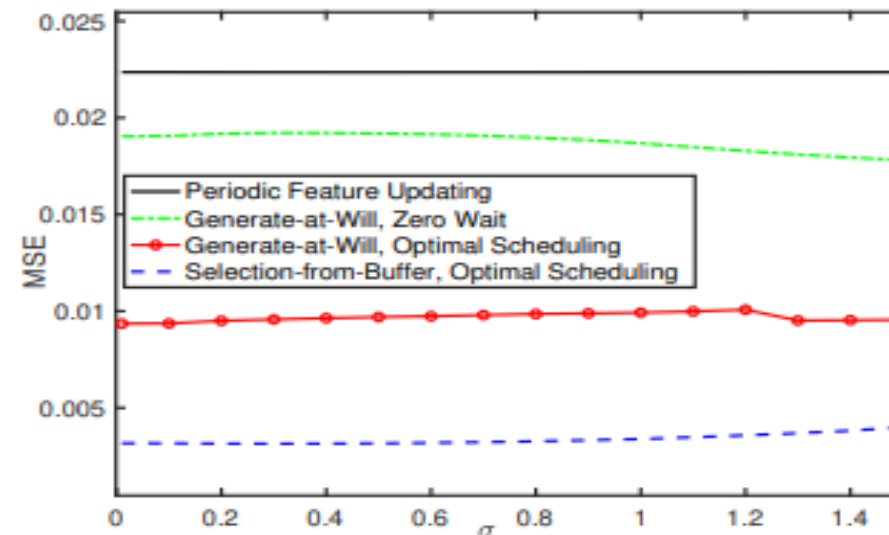


Buffer contains the most recently sampled  $B$  packets

$(X_t, X_{t-1}, \dots, X_{t-B+1})$  at any time slot  $t$ .

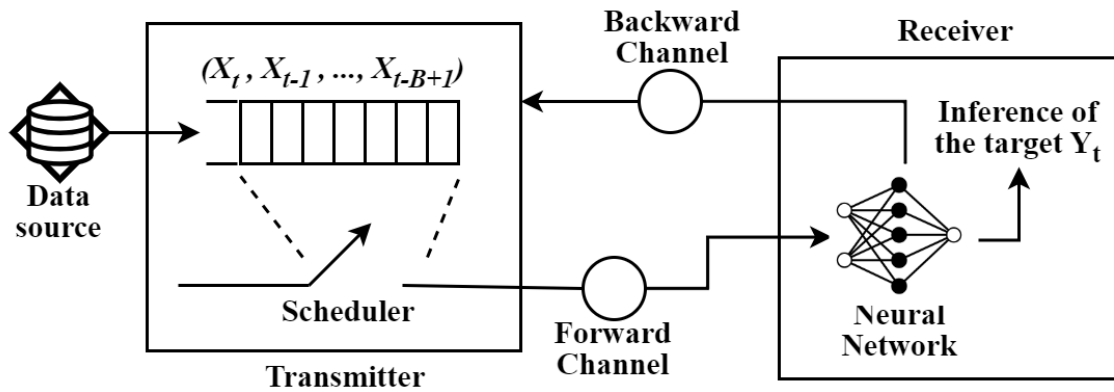
An optimal scheduler on the transmitter side must determine (i) when to submit a packet to the forward channel and (ii) which packet in the buffer to submit.

In case of IID transmission delay and immediate feedback, index-based threshold policy:



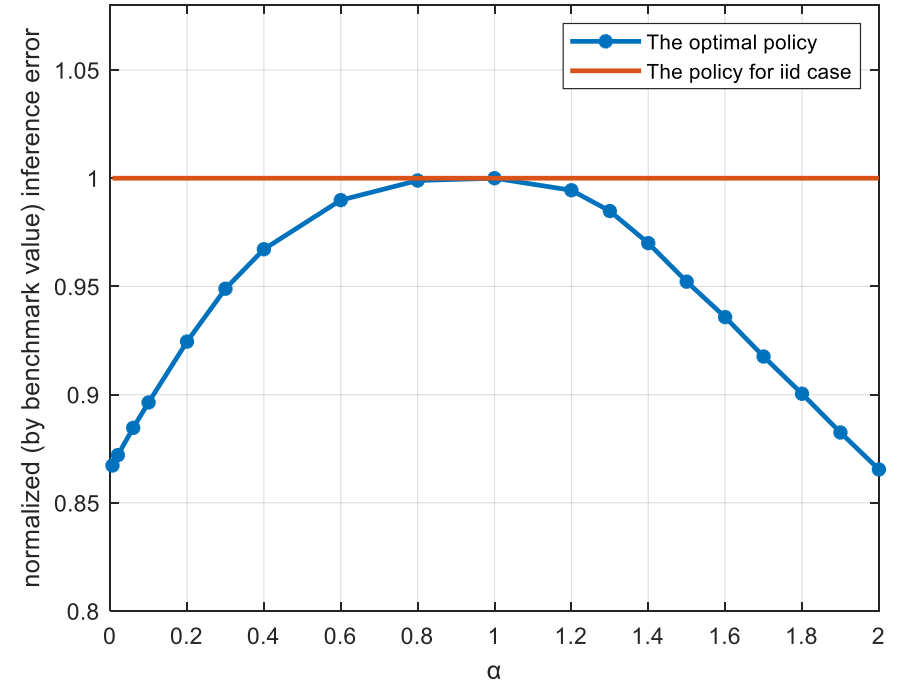
**Figure 5: Time average inference error (MSE) vs. the scale parameter  $\sigma$  of discretized i.i.d. log-normal transmission time distribution for single-source scheduling (in robot state prediction task).**

# SFB under variable delay [Ari, Shisher, Uysal, Sun 2023]



In this case, the solution is an index-based threshold policy where the index varies based on the scheduler's knowledge of the memory of the delay:

$$\gamma(\delta, c) = \inf_{\nu \in \mathbb{Z}^+} \frac{1}{\nu} \sum_{k=0}^{\nu-1} \mathbb{E} \left[ h(\delta + k + T_{i+1}) \mid c_i = c \right]$$



$$\alpha = p_{01} + p_{10}$$

$$p_{01} = p_{10}$$

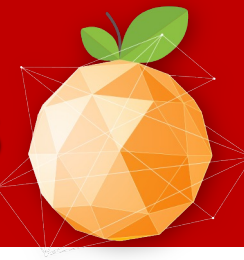
$\alpha = 1$  implies that the forward channel is iid.

Two forward channel states 0 and 1.

As  $\alpha$  gets away from 1, the memory increases.

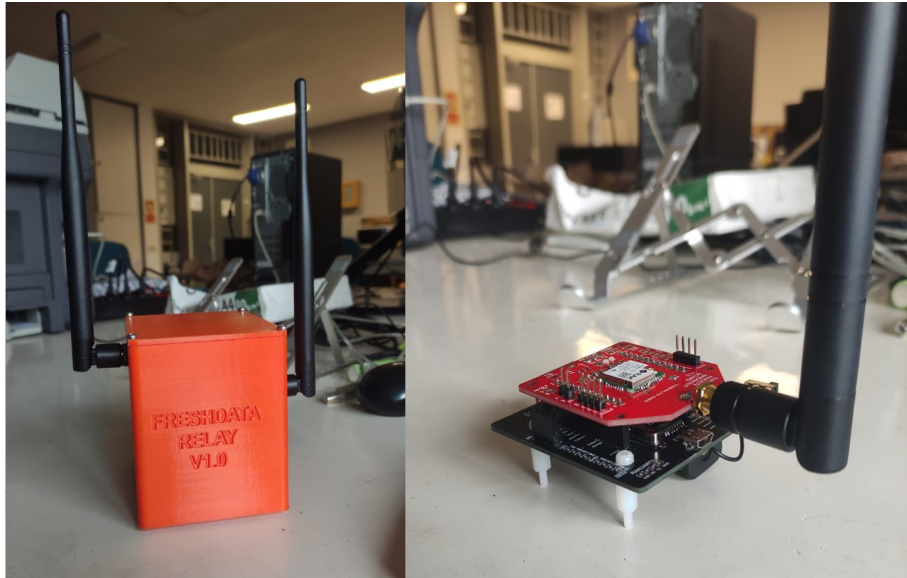


# Goal Oriented Communication entering products



• Startup: FRESHDATA Technology

• Products and IPR development targeting LoRa Alliance, 3GPP



Satellite IoT



NTN



Terrestrial IoT

# Broader Applications: Sustainable Urbanization

- SUIT (Sustainable Urbanization through Innovative Technologies)  
<http://suit.metu.edu.tr/>
- Consortium of universities, research labs, companies
- 11 projects – all spinning off from FRESHDATA



# Thank you, from the CNG team



Est. 2007



<http://cng-eee.metu.edu.tr>