Delft University of Technology

Data Freshness in Mixed-Memory Intermittently-Powered Systems

James Scott Broadhead

and

Przemysław Pawełczak

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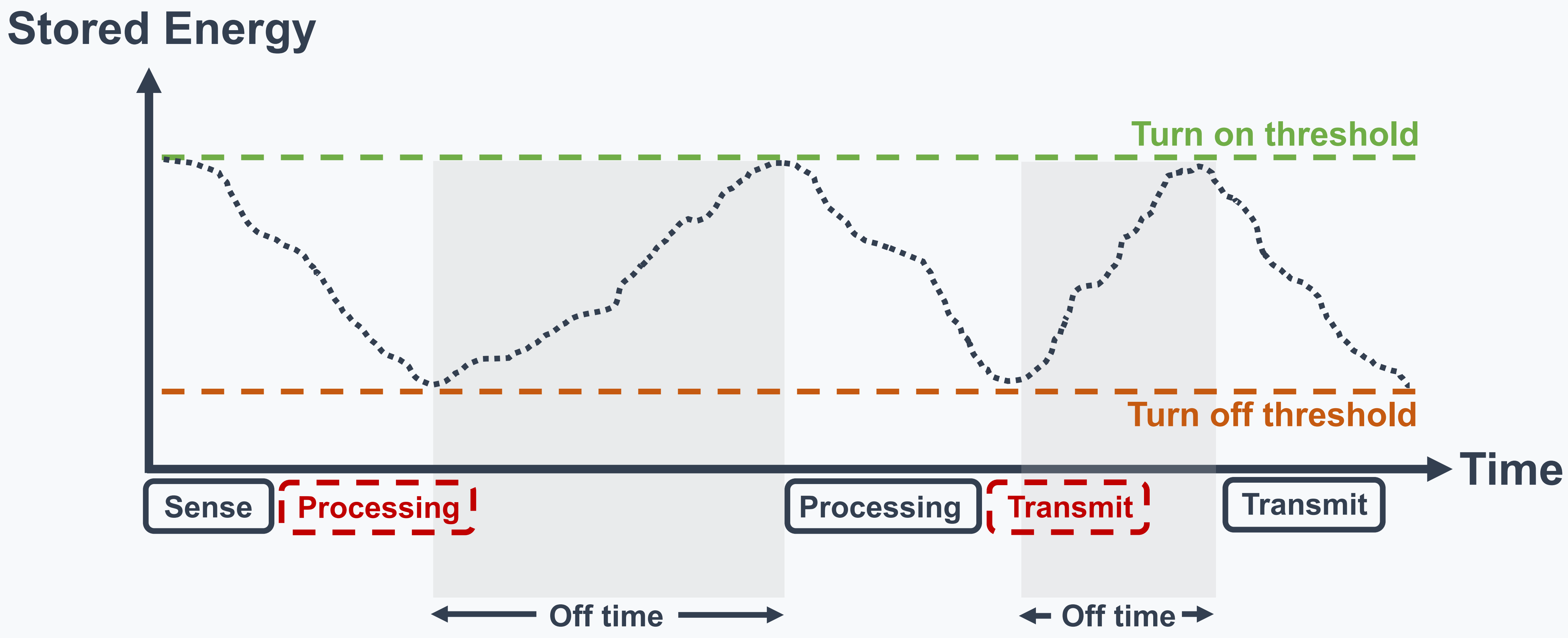
29,300,000,000

Networked devices by 2023*

Removing batteries to make a more sustainable IoT

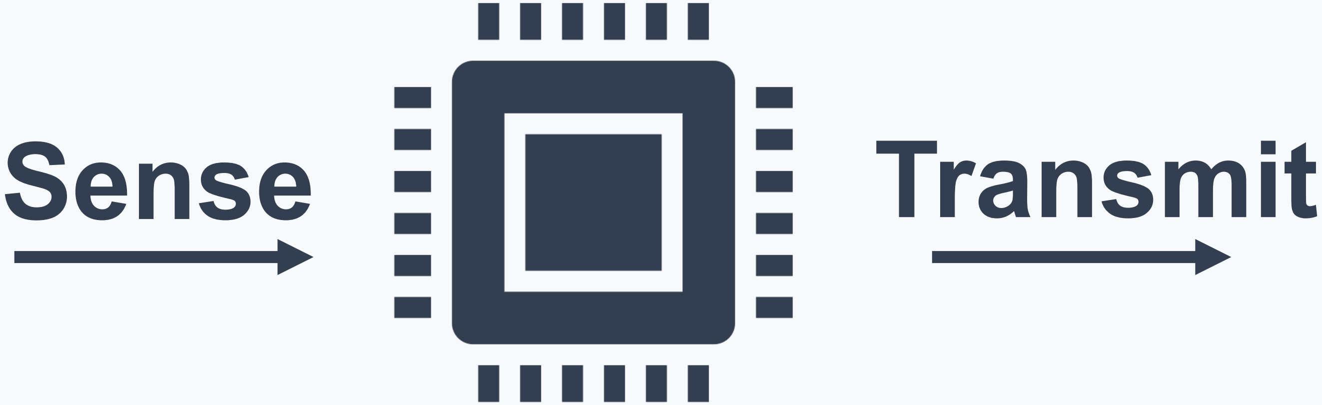
* Source: Cisco Annual Internet Report (2018–2023) White Paper. Available: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/ white-paper-c11-741490.html

Intermittent Computing



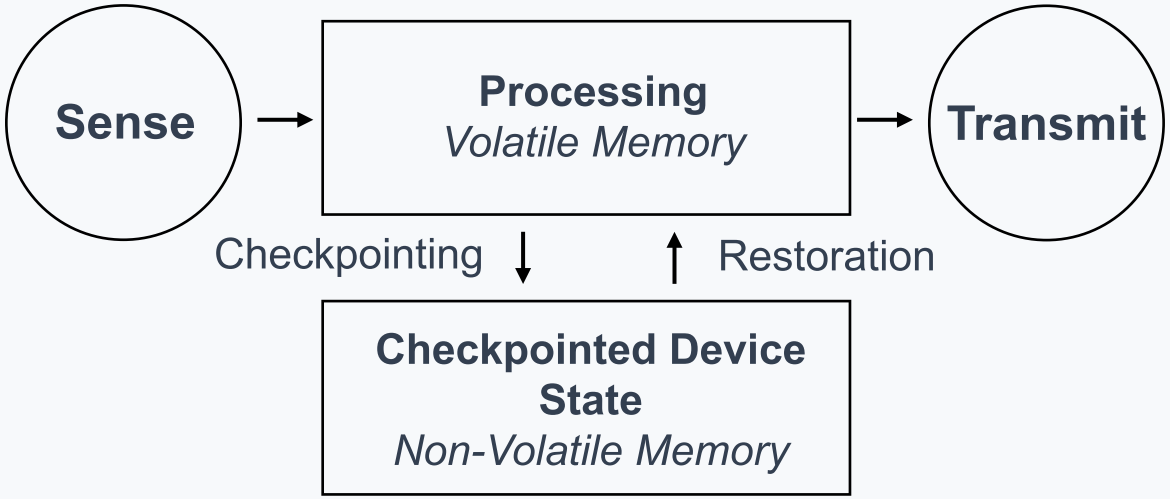
Intermittently Operating Sensor

Often have **mixed-memory** structure



Checkpointing between memory types common to reduce impact of failure

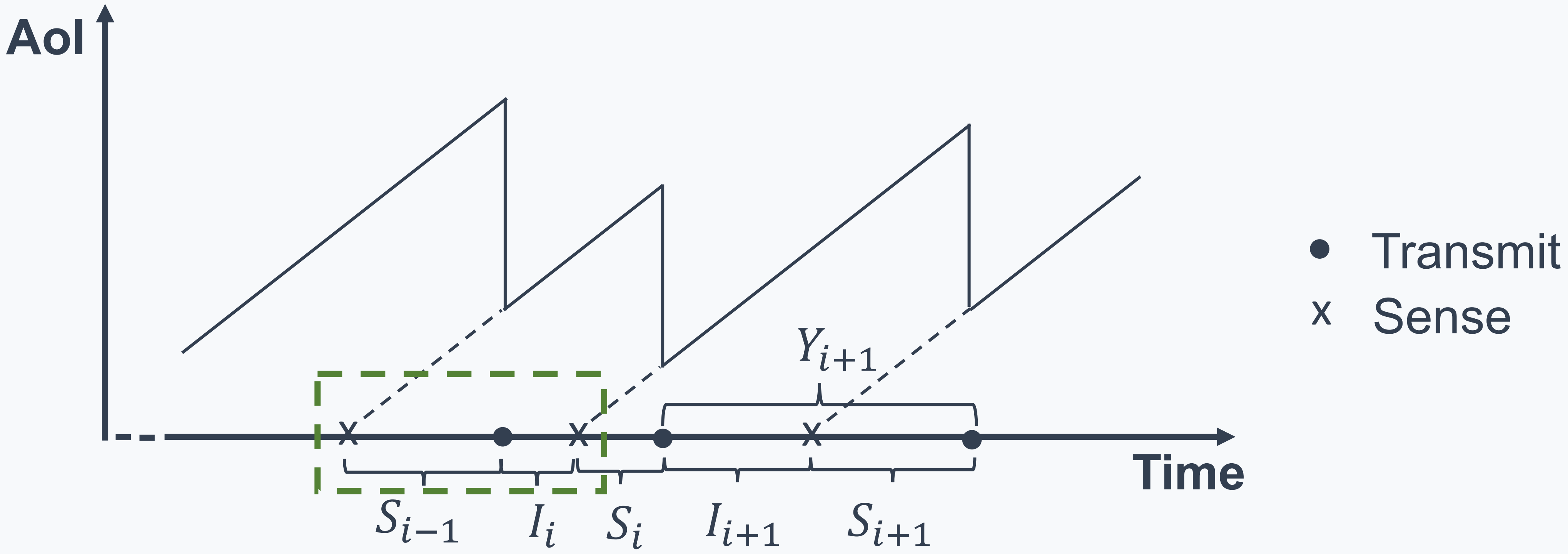
Mixed-Memory System Model



How does **checkpointing** affect the **freshness** of data generated by the sensor?

We can use the apparatus of **Age of Information (AoI)**

AoI Evolution of the System



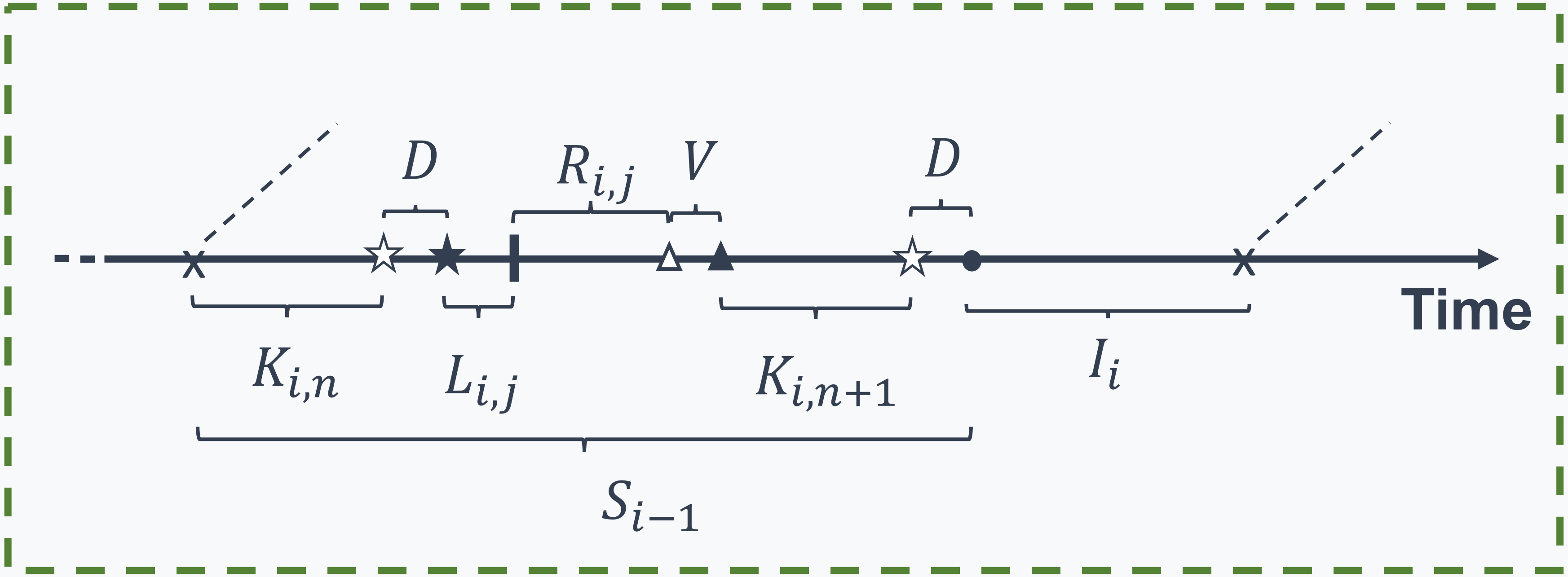
Average Peak AoI

$$\mathbb{E}[\Delta^{\text{Peak}}] = \mathbb{E}[Y] + \mathbb{E}[S]$$

Average AoI

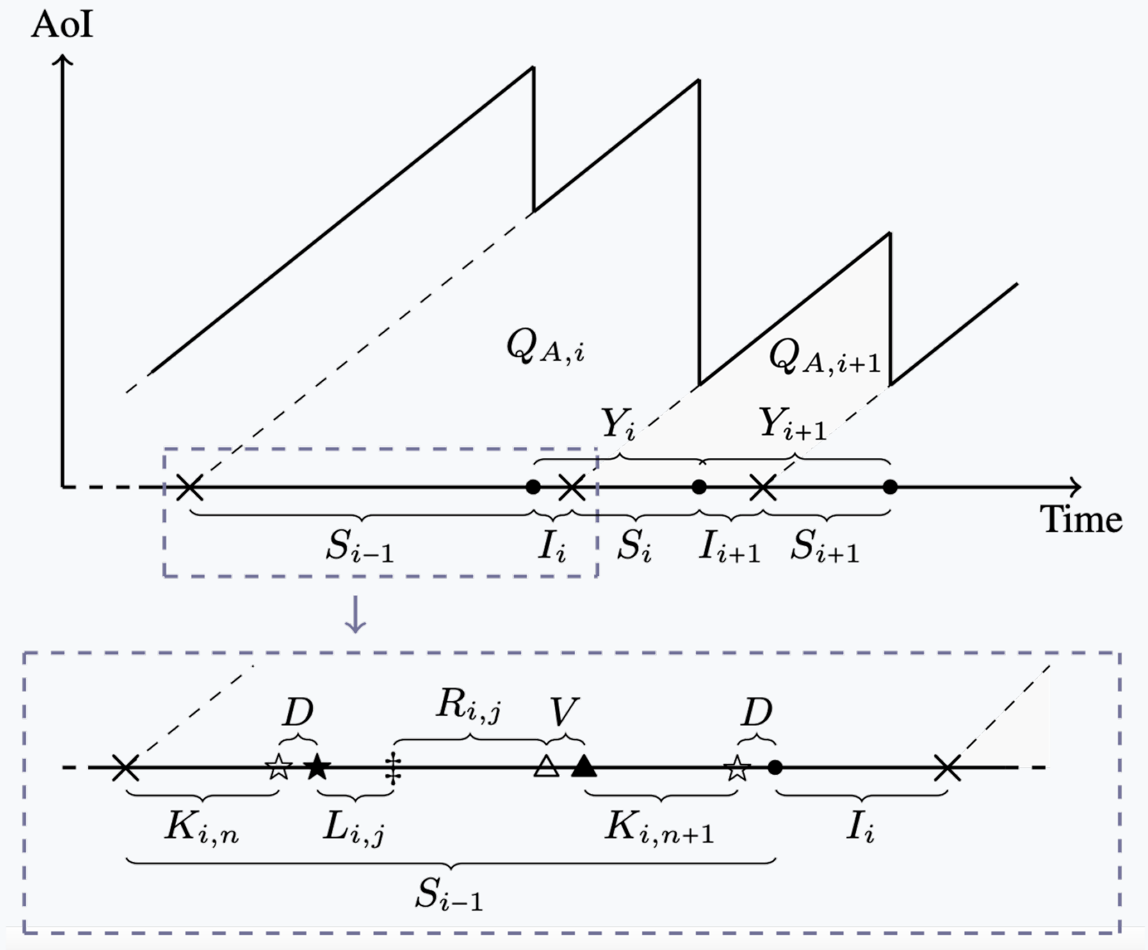
$$\mathbb{E}[\Delta] = \frac{\mathbb{E}[Y^2]}{2\,\mathbb{E}[Y]} + \mathbb{E}[S]$$

AoI Evolution of the System



- $K_{i,n}$ Inter-checkpointing time
- D Time to checkpoint
- $L_{i,j}$ Wasted processing time
- $R_{i,j}$ System down time
- V Restoration time
- S_{i-1} Completion time
- I_i Idle time

AoI Evolution of the System



Inter-completion time:

$$Y_i = \underbrace{I_i}_{\text{Idle time}} + \underbrace{\sum_{j=1}^{f} (L_{i,j} + R_{i,j} + V)}_{\text{Events associated with failure}} + \underbrace{\sum_{n=1}^{h} K_{i,n}}_{\text{Processing} \triangleq P_i} + \underbrace{Dh}_{\text{Checkpointing}},$$

Completion time:

$$S_i = Y_i - I_i$$

Problems Evaluated in the Paper

1) **Optimise** checkpointing strategies to **improve the freshness** of data produced by the system

2) Compare the data freshness produced by **alternative memory** arrangements to mixed-memory

3) Compare **alternative time-dependent checkpointing** strategies to improve system resilience to variable environmental conditions

Expectation of Peak AoI

$$Y_i = \underbrace{I_i}_{\text{Idle time}} + \underbrace{\sum_{j=1}^{f} (L_{i,j} + R_{i,j} + V)}_{\text{Events associated with failure}} + \underbrace{\sum_{n=1}^{h} K_{i,n}}_{\text{Processing} \triangleq P_i} + \underbrace{Dh}_{\text{Checkpointing}},$$

$$S_i = Y_i - I_i$$

By applying Wald's identity

Expectation of inter-completion time

$$\mathbb{E}[Y] = \mathbb{E}[I] + \mathbb{E}[f]\left(\mathbb{E}[L] + \mathbb{E}[R] + V\right) + \mathbb{E}[h]\,\mathbb{E}[K] + D\,\mathbb{E}[h],$$

Expectation of Peak AoI

$$\mathbb{E}[\Delta^{\text{Peak}}] = \mathbb{E}[Y] + \mathbb{E}[S]$$

Expectation of completion time

$$\mathbb{E}[S] = \mathbb{E}[Y] - \mathbb{E}[I],$$

Expectation of Peak AoI

Expectation of Peak AoI

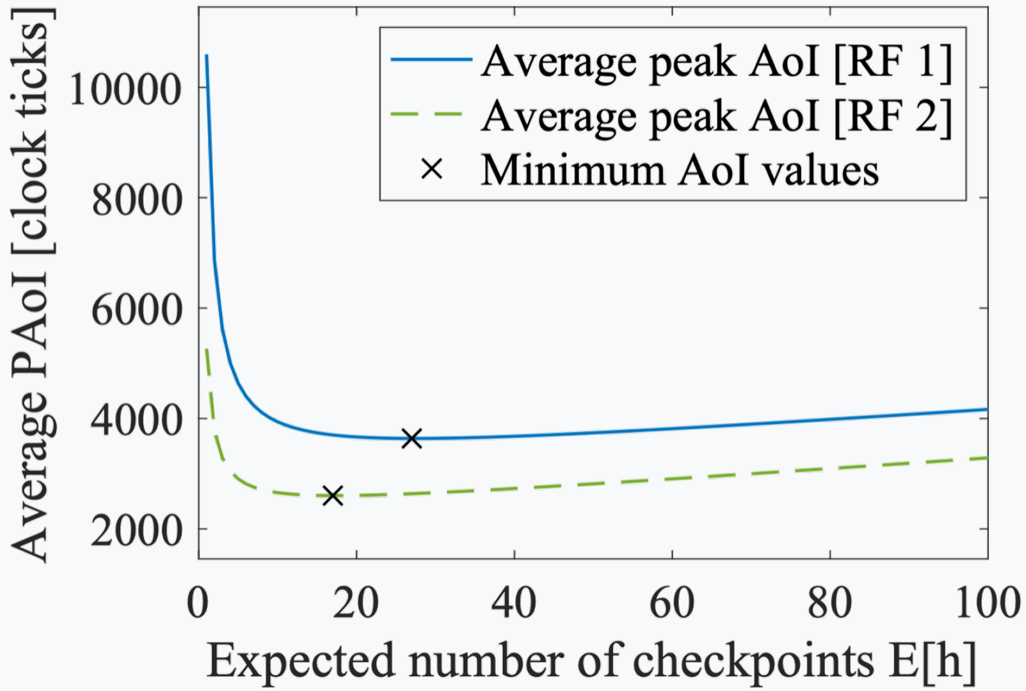
$$\mathbb{E}[\Delta^{\text{Peak}}]_{\text{MM}} = 2\,\mathbb{E}[f]\left(C_1 + \frac{\mathbb{E}[P]}{2\,\mathbb{E}[h]}\right) + C_2 + \mathbb{E}[P] + 2D\,\mathbb{E}[h]$$

Minimising Peak AoI

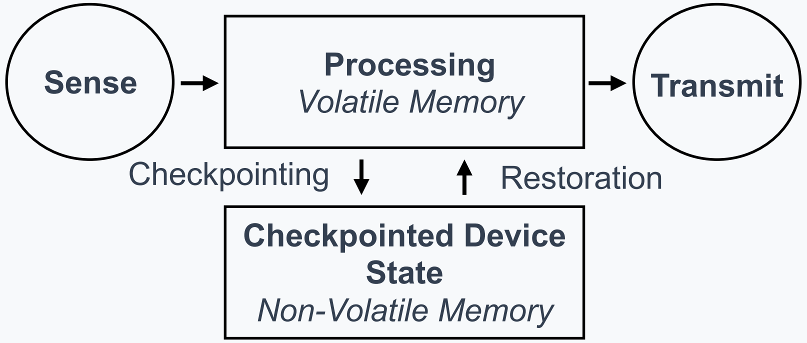
$$\frac{d\,\mathbb{E}[\Delta^{\text{Peak}}]_{\text{MM}}}{d\,\mathbb{E}[h]} = 2D - \frac{\mathbb{E}[f]\,\mathbb{E}[P]}{\mathbb{E}[h]^2}$$

Optimum checkpointing

$$\mathbb{E}[h] = \sqrt{\frac{\mathbb{E}[f]\,\mathbb{E}[P]}{2D}}$$



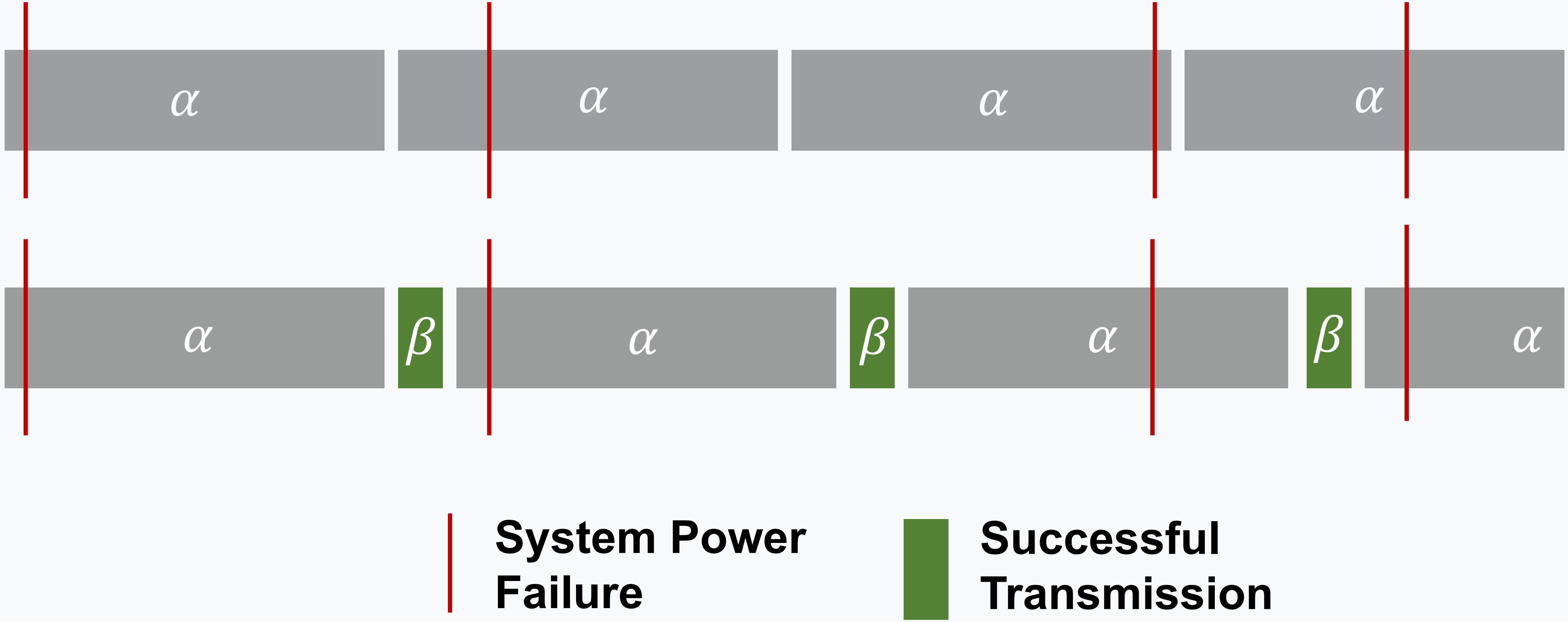
Memory Structure and Data Freshness



Lemma 1. An entirely NVM IPD will have a lower or equal average PAoI than a checkpointing mixed-memory IPD

Lemma 2. Under certain environmental conditions a mixed-memory IPD will have a lower average PAoI than a single-memory VM IPD

Improving Resilience in Variable Environmental Conditions



TU Delft
Delft University of Technology

James Scott Broadhead

j.s.broadhead@tudelft.nl

Przemysław Pawełczak

p.pawelczak@tudelft.nl