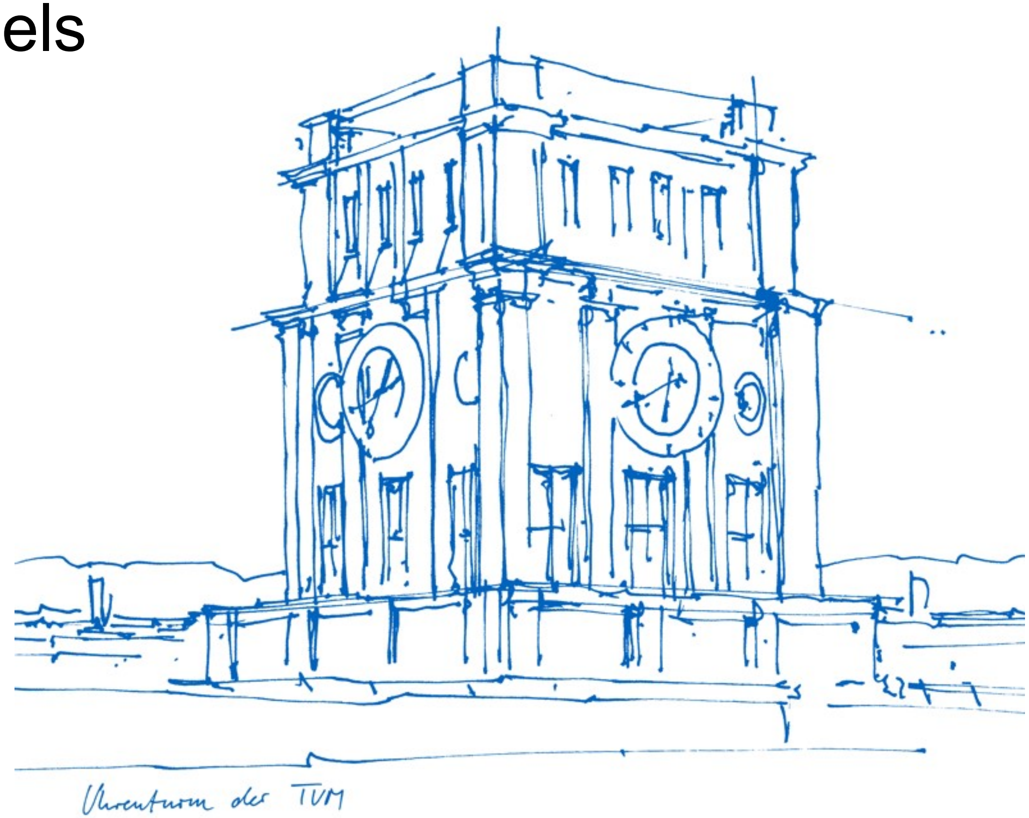
Chair of Communication Networks
Department of Electrical and Computer Engineering
Technical University of Munich

AoI-based Scheduling for Networked Control Systems over Gilbert-Elliot Channels

Bachelor Thesis

Final Presentation



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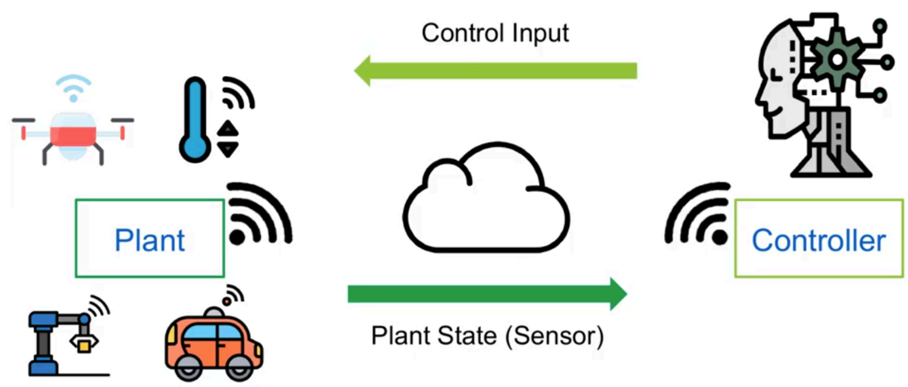
Networked Control Systems:

Feedback control loops closed over a communication network

- How to schedule NCS efficiently?
- Solution: *Application-aware* scheduler for MAC



Agenda

- Preliminaries
  - Problem Statement
  - Gilbert-Elliot Channel Model
  - State of the Art

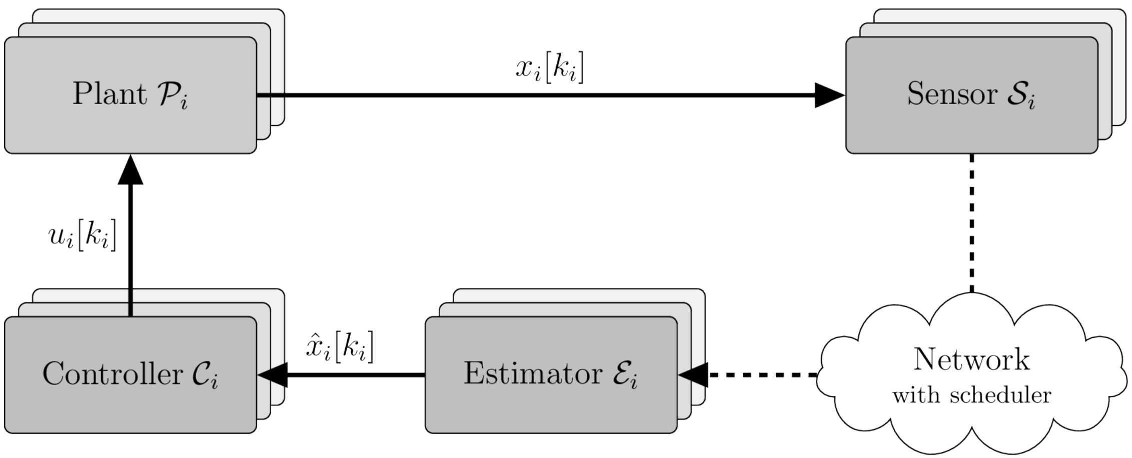
- Methodology
  - Simulation Setting

- Evaluation
  - Performance Metric
  - Results
  - Conclusion

Preliminaries

Problem Statement

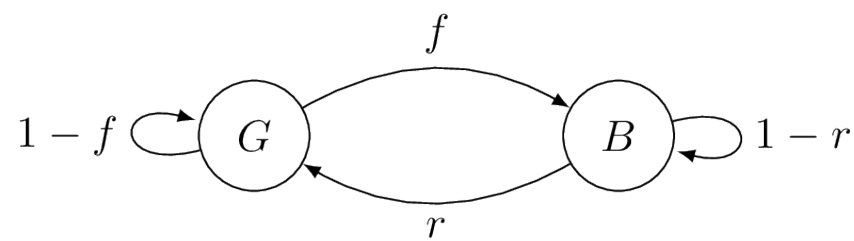
- Centralized resource scheduling problem for a single wireless link shared by multiple heterogeneous NCS with time-varying channel conditions
- Remote estimation process between each sensor-controller pair



- Goal: Optimal *control-aware* scheduler which takes the Gilbert-Elliot Channel Model fully into account

Gilbert-Elliot (GE) Channel Model

- Simple model for burst errors typical in wireless networks
- Two state Markov Chain
  - Good & Bad states
  - State transition probabilities



$$f = \Pr[B|G] \quad \text{failure rate}$$
$$r = \Pr[G|B] \quad \text{recovery rate}$$

- Statistical properties
  - Stationary state probabilities
  - Average error probability
  - Mean sojourn time

$$\pi_G = \frac{r}{f+r} \qquad \pi_B = \frac{f}{f+r}$$

$$p_E = \pi_G p_G + \pi_B p_B$$

$$T_G = \frac{1}{f} \qquad T_B = \frac{1}{r}$$

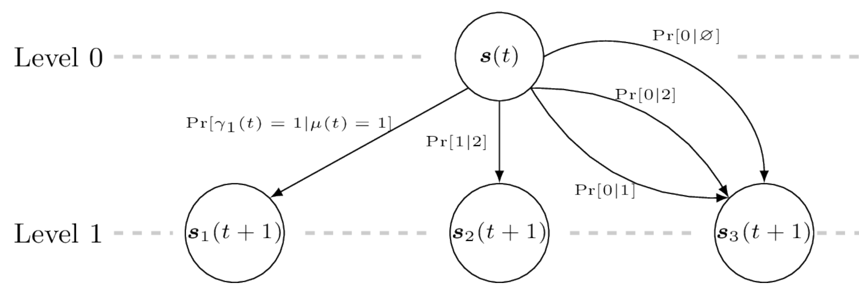
State of the Art: Finite Horizon Scheduler (FHS) [2]

- Employ AoI [1] as intermediate metric for age-penalty functions
- Tree with every possible future outcome for the next H steps => finite horizon age-penalty minimization problem
- Complexity: $O(N^H)$
- Open Issue:
  - Assumes constant channel

System dynamics

$$g(\Delta_i[k_i]) = \sum_{r=1}^{\Delta_i[k_i]-1} \mathrm{tr}\left(\left(\boldsymbol{A}_i^T\right)^r \left(\boldsymbol{A}_i\right)^r \boldsymbol{\Sigma}_i \right)$$

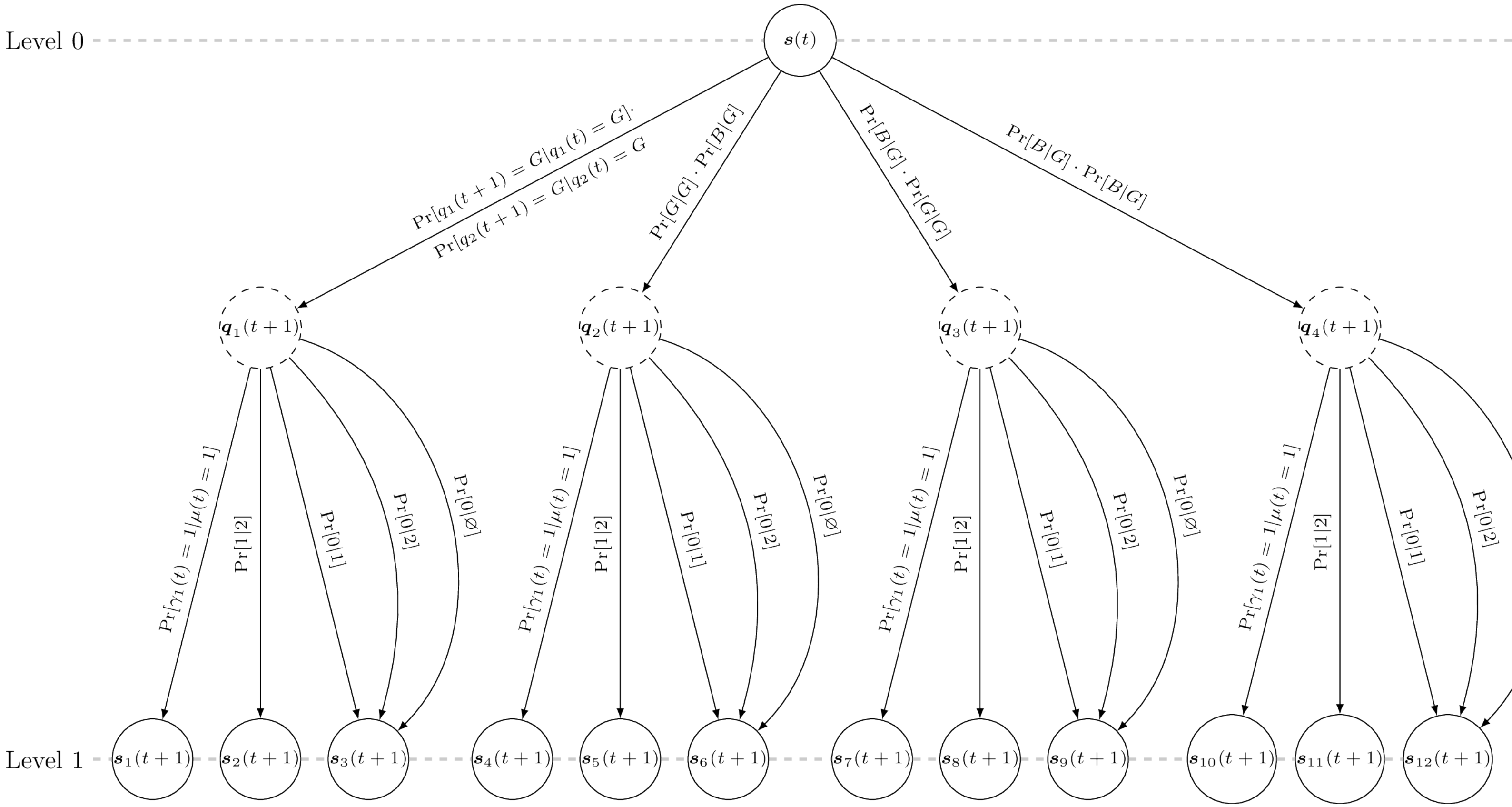
$$C(\boldsymbol{s}(t)) = \sum_{i=1}^{N} g(\Delta_i[k_{i(t)}]),$$



Example tree structure of FHS for $N = 2$ sub-systems and finite horizon $H = 1$

GE Channel-aware Finite Horizon Scheduler (GES)

- 2^N times more possible network states for one level due to GE channel transitions => Complexity: $O(2^{NH})$



Methodology

Objective and Approach

- Objective
  - How does FHS perform in a Gilbert-Elliot channel?
  - How does the GES perform in comparison?
  - Extra: Why does simulation result differ between Linux, Mac, Windows?

- Approach
  - Modeling of *GE Channel* in a simulation network
  - Implementation / Extension of control and channel aware scheduler
  - Simulation using NCS_framework_cpp
  - Evaluating AoI, MSE, complexity vs. finite horizon H

Simulation Setting

- $N = 3$ scalar sub-systems
  - $A_{1,2,3} = \{1.0, 1.25, 1.5\}$
- FHS: $H = \{1, \ldots, 10\}$
- GES: $H = \{1, \ldots, 4\}$
- Simulated for $D = 20000$ time slots and repeated $R = 200$ times

Channel model parameters		**Scenario 1**
Loss in Good	p_G	0.25
Loss in Bad	p_B	0.75
Failure rate	f	0.3
Recovery rate	r	0.3
Stationary probability Good	π_G	0.5
Stationary probability Bad	π_B	0.5
Average error probability	p_E	0.5
Mean sojourn time in Good	T_G	3.33
Mean sojourn time in Bad	T_B	3.33

Evaluation

Performance Metric

- Mean Squared Error (MSE)

$$MSE_i = \frac{1}{D}\sum_{t=1}^{D} \boldsymbol{e}_i(t)^T \boldsymbol{e}_i(t)\,, \qquad \overline{MSE} = \frac{1}{N}\sum_{i=1}^{N} MSE_i$$

- Reflects estimation accuracy

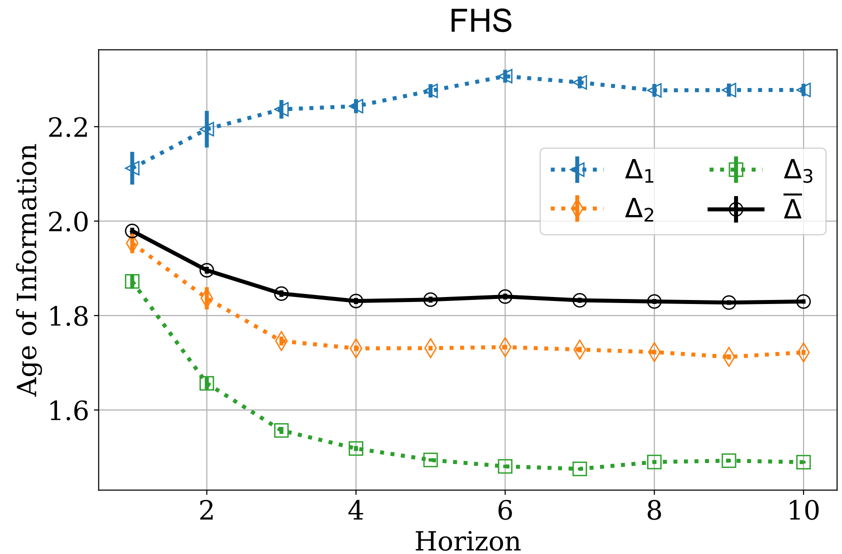
AoI Performance

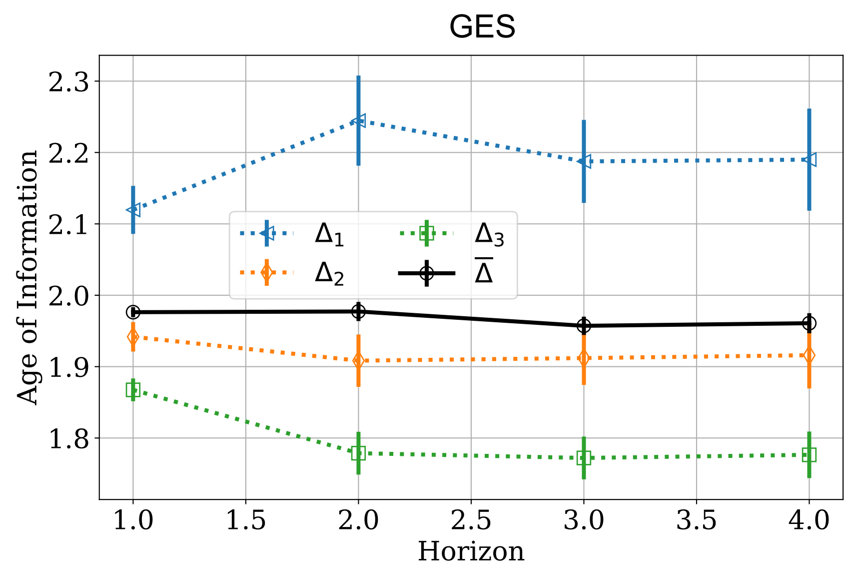
- Age-of-Information (AoI)

$$\Delta_i = \frac{1}{D}\sum_{t=1}^{D}\Delta(t), \qquad \overline{\Delta} = \frac{1}{N}\sum_{i=1}^{N}\Delta_i$$

Reflects the scheduler decisions

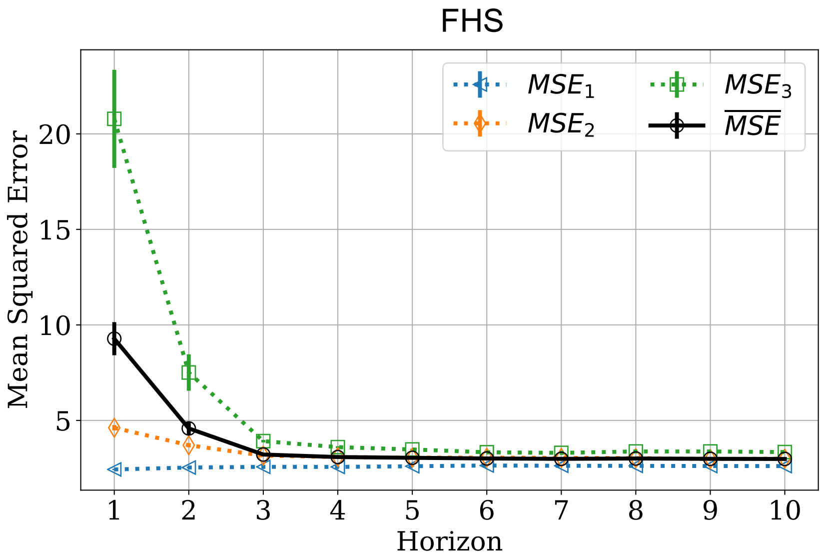
  - Low AoI indicates a more frequent update rate
- Average AoI differs for each sub-system
  - Scheduler grants more medium access to sub-systems expected to produce high costs
  - Falling trend for Δ_2, Δ_3 as H increases
  - Rising trend for Δ_1

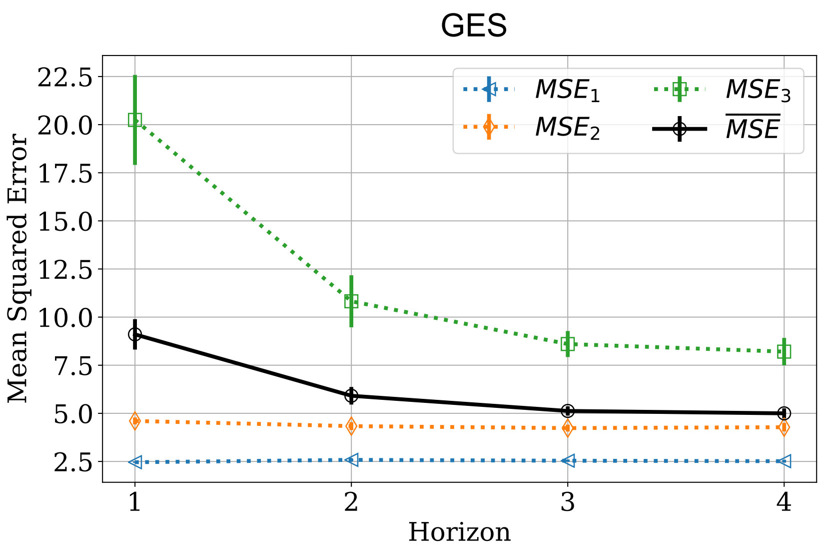




MSE Performance

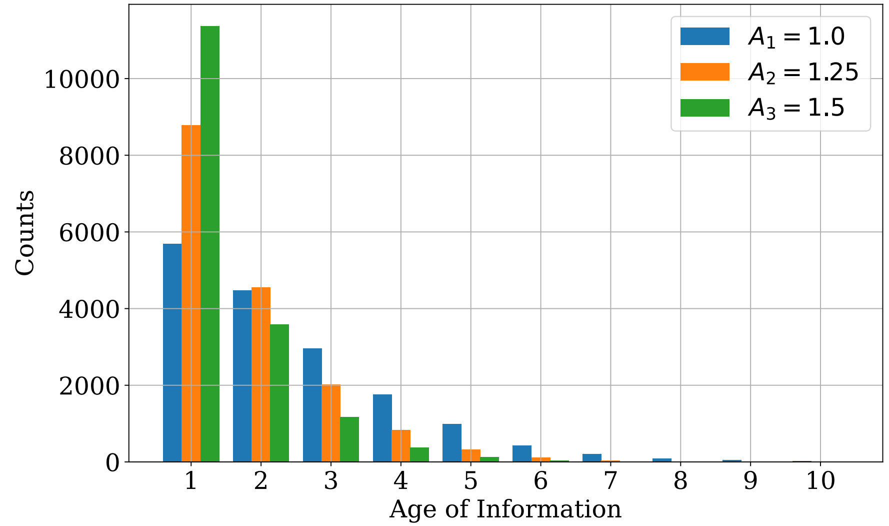
- Significant reduction of $\overline{MSE}$ from $H = 1$ to $H = 2$ afterwards performance gain diminishes
- FHS: No increase in MSE beyond $H = 4$
- GES does not outperform FHS although being aware of GE channel transitions

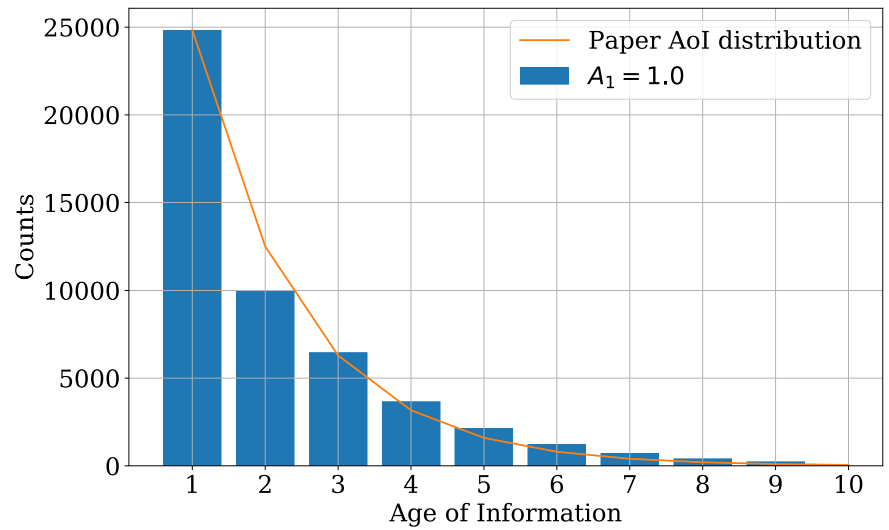




AoI Distribution

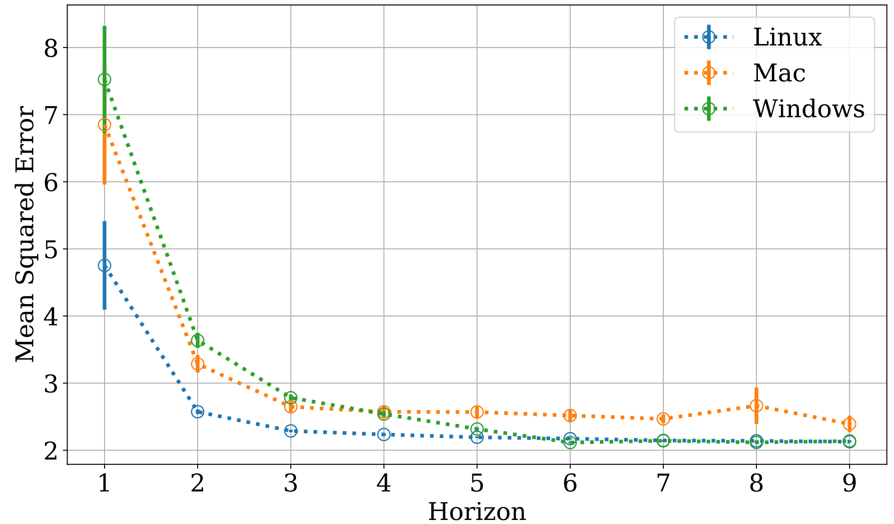
- Most up-to-date plant measurements are available to task-critical sub-systems
  - $A_3 = 1.5$ has highest 1 AoI count
  - Shift for higher AoI values
- Similar geometrical AoI distribution to the derived AoI pmf from [3]





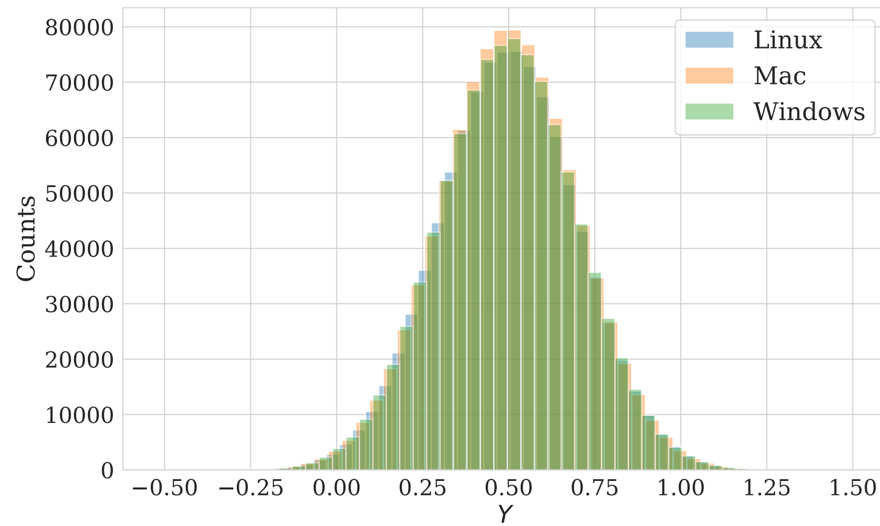
Effect of OS on Simulation Results

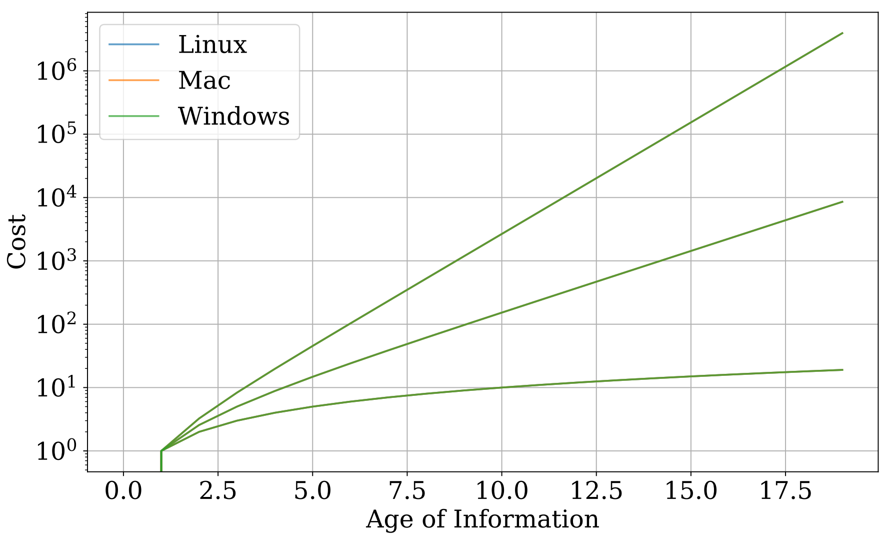
- For the same setting MSE differ among OSs
  - MSE: Almost 50% deviation between Linux and Windows
- Deviating scheduler decisions can be caused by
  - Inconsistent Random Number Generators
  - Inconsistent Cost Maps from where the total cost is taken from
  - Inconsistent floating point operations

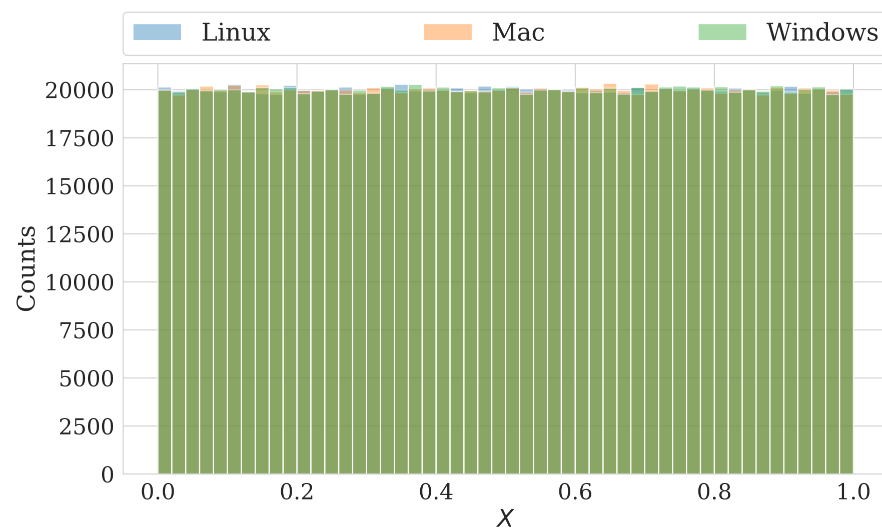


Numerical effects on Scheduler

- Realizations of normal and uniform distributions show consistent Random number generators
- Cost are obtained from the same cost maps







Summary of Thesis Results

- Contribution
  - Implemented channel state dependent scheduling algorithm
  - Performance gain of FHS diminishes after a certain H
  - GES does not lead to improved scheduler performance compared to FHS
  - Being fully GE channel-aware is not scalable -> Trade-off between optimality and complexity must be found
  - Root cause of varying OS performance is not found in the algorithm

- Future Work
  - FHS tree with GES transition probabilities
  - Evaluating efficiency of finite horizon scheduling in real-life use-cases
  - Further investigation on possible numerical errors of floating point operations among different OSs

References

- [1] Kaul, Sanjit, Roy Yates, and Marco Gruteser. "Real-time status: How often should one update?." *2012 Proceedings IEEE INFOCOM*. IEEE, 2012.
- [2] Ayan, Onur, et al. "AoI-based Finite Horizon Scheduling for Heterogeneous Networked Control Systems." *arXiv preprint arXiv:2005.02037* (2020).
- [3] Ayan, Onur, et al. "Probability Analysis of Age of Information in Multi-hop Networks." *IEEE Networking Letters* 2.2 (2020): 76-80.

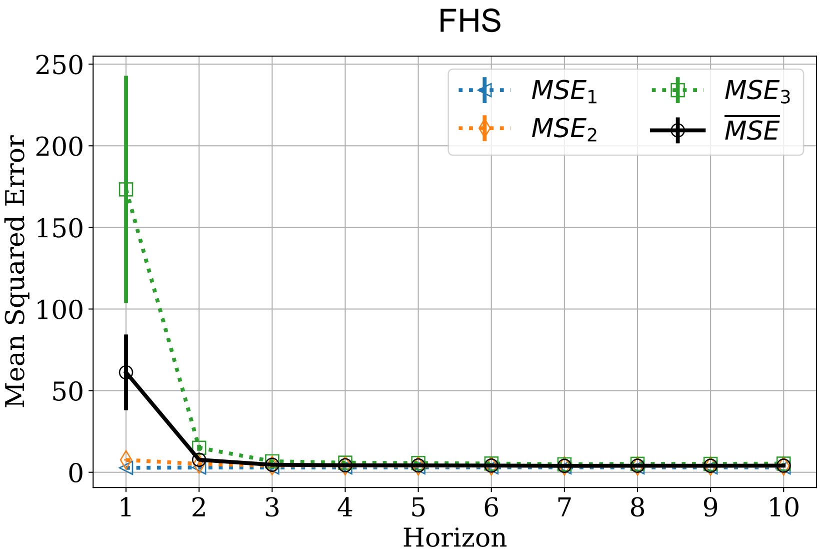
Questions?

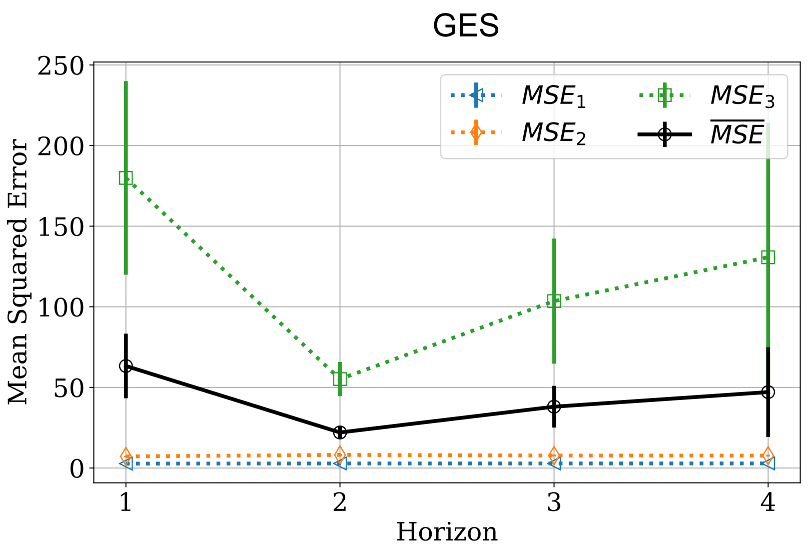
Appendix

Scenario 2

Longer burst errors

Channel model parameters		Scenario 2
Loss in Good	p_G	0.25
Loss in Bad	p_B	0.75
Failure rate	f	0.1
Recovery rate	r	0.1
Stationary probability Good	π_G	0.5
Stationary probability Bad	π_B	0.5
Average error probability	p_E	0.5
Mean sojourn time in Good	T_G	10
Mean sojourn time in Bad	T_B	10





Scenario 3

Real-life channel

Channel model parameters		Scenario 3
Loss in Good	p_G	0.0011
Loss in Bad	p_B	0.7734
Failure rate	f	0.0024
Recovery rate	r	0.0832
Stationary probability Good	π_G	0.972
Stationary probability Bad	π_B	0.028
Average error probability	p_E	0.0227
Mean sojourn time in Good	T_G	416.66
Mean sojourn time in Bad	T_B	12