Towards an "Effective Age" Concept

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Introduction: Effective Age

Beyond *Freshness* to *Real-Time Estimation*

In typical Age of Information (AoI) studies, the objective is for the monitor to observe the status with lowest age on average. However, the ultimate objective should be for the monitor to know the status at the source as best it can in real time or in the future. This is the problem of *real-time estimation* and *prediction*.

Need for an "Effective" Age

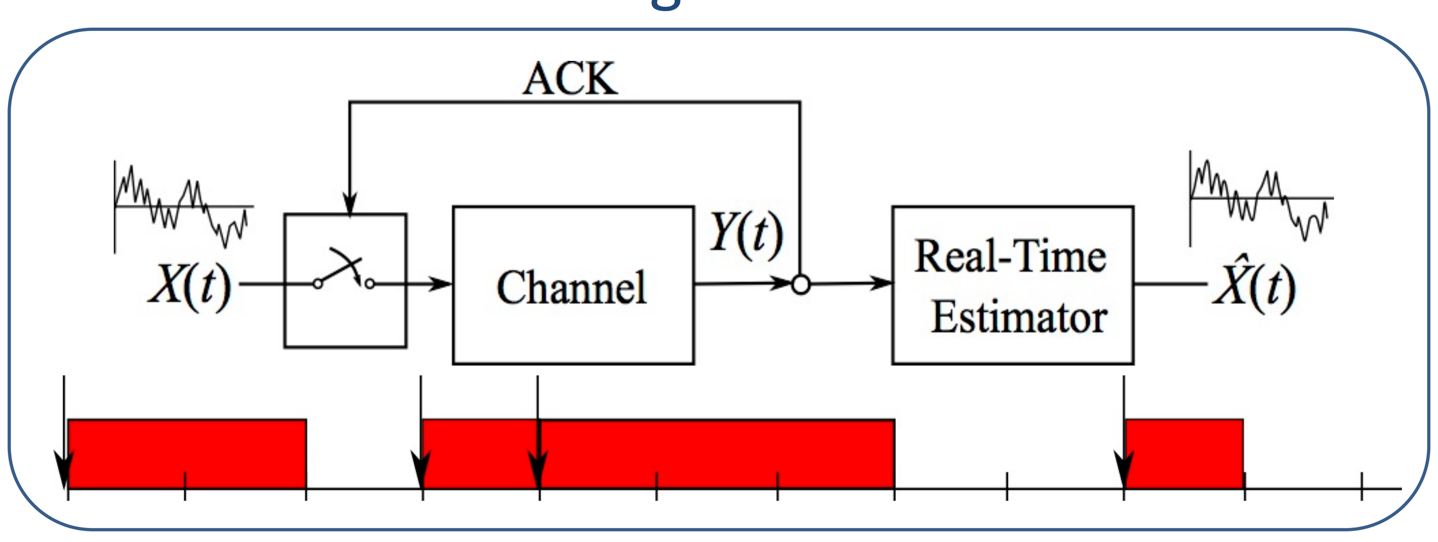
In general, minimizing average age does not minimize the average estimation error. We desire an *effective* age, an age-like metric that is reflective of the error performance.

Overarching goal: Understand the effect of sampling for *age* and *error* in different contexts towards defining an effective age.

This work: Study sampling for *age* and *error* for two vastly different cases where the time slot length is equal to the time to transmit 1) the entire state and 2) a single bit.

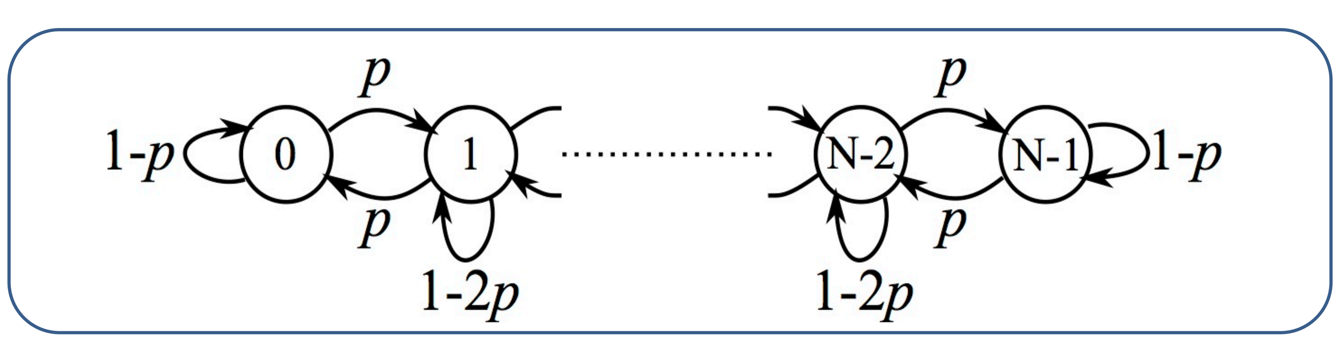
System Model

Communication System: Slotted time; state transition and sample just before slot boundary; immediate acknowledgement



N-State Markov Source: E.g.: Birth-death process with both rates equal to p

Error measure: Mean squared error (MSE)



Effective Age Metrics

Sampling Age:

$$\Delta_{samp}(t) = s(t) - g(t))$$

- $g(t)$: Most recent optimal sampling time
- $s(t)$: First actual sampling time after $g(t)$. If no sample exists, then $s(t) = t$.

Cumulative Marginal Error:

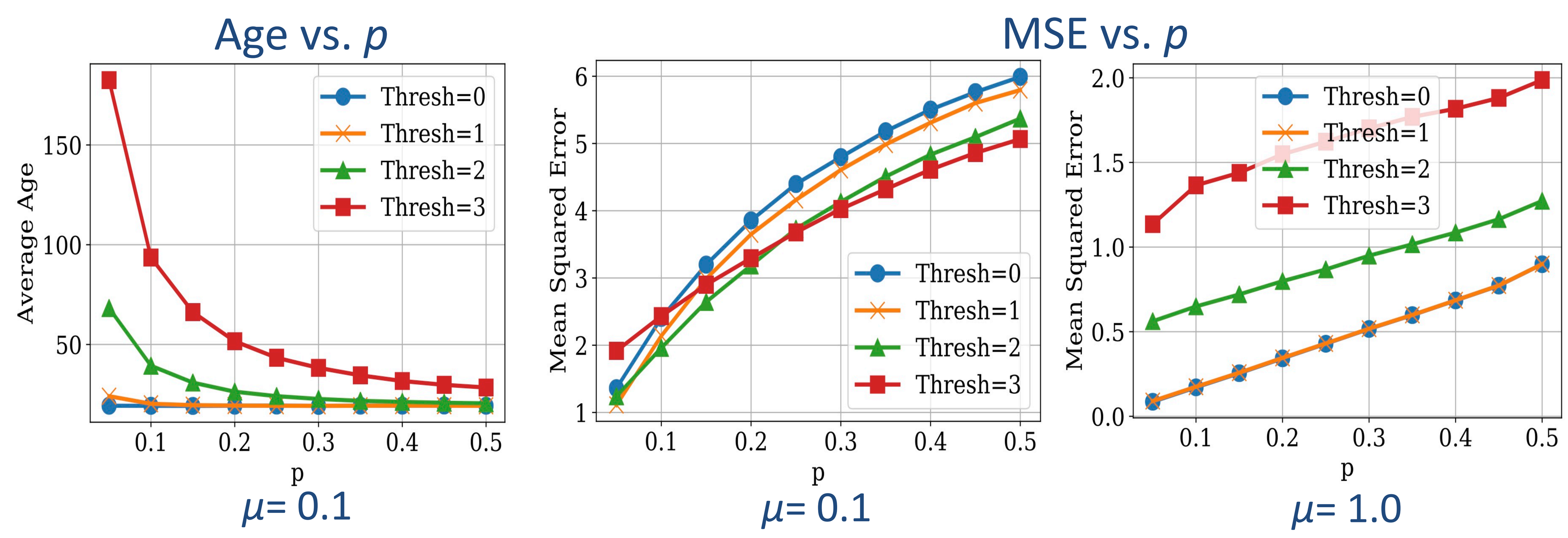
$$\Delta_{CME}(t) = \int_{r(t)}^{t} h(\tau)d\tau$$

- $r(t)$: Reception time of the packet received with the most recent timestamp
- $h(t)$: Penalty function (e.g., estimation error)

Problem 1: Time Slot Length = Entire State

Threshold sampling policy: Sample when the state differs from the last transmitted state by *Thresh*

Simulation: 7-State Markov Source, Geometric service time w/rate= μ



Observations:

- Age is larger for larger thresholds
- MSE does not follow same ordering as average age
- Higher thresholds tend to do better for lower μ (more value in transmitting larger change when reception takes longer)
- Lower p prefers lower thresholds

Problem 2: Time Slot Length = Single Bit

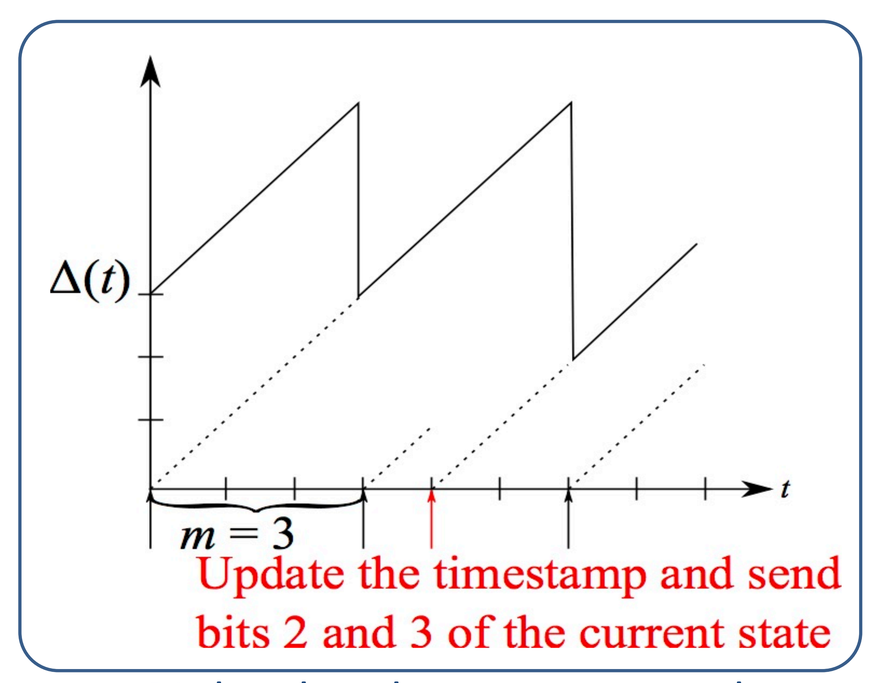
Transmission Model: Service time of each bit is 1 slot

Source Model: m-bits → 2^m states

Sampling Schemes:

- Full state: Sample every m bits
- Threshold sampling policy: *Thresh* = 1
- Bit level replacement scheme (BLR):

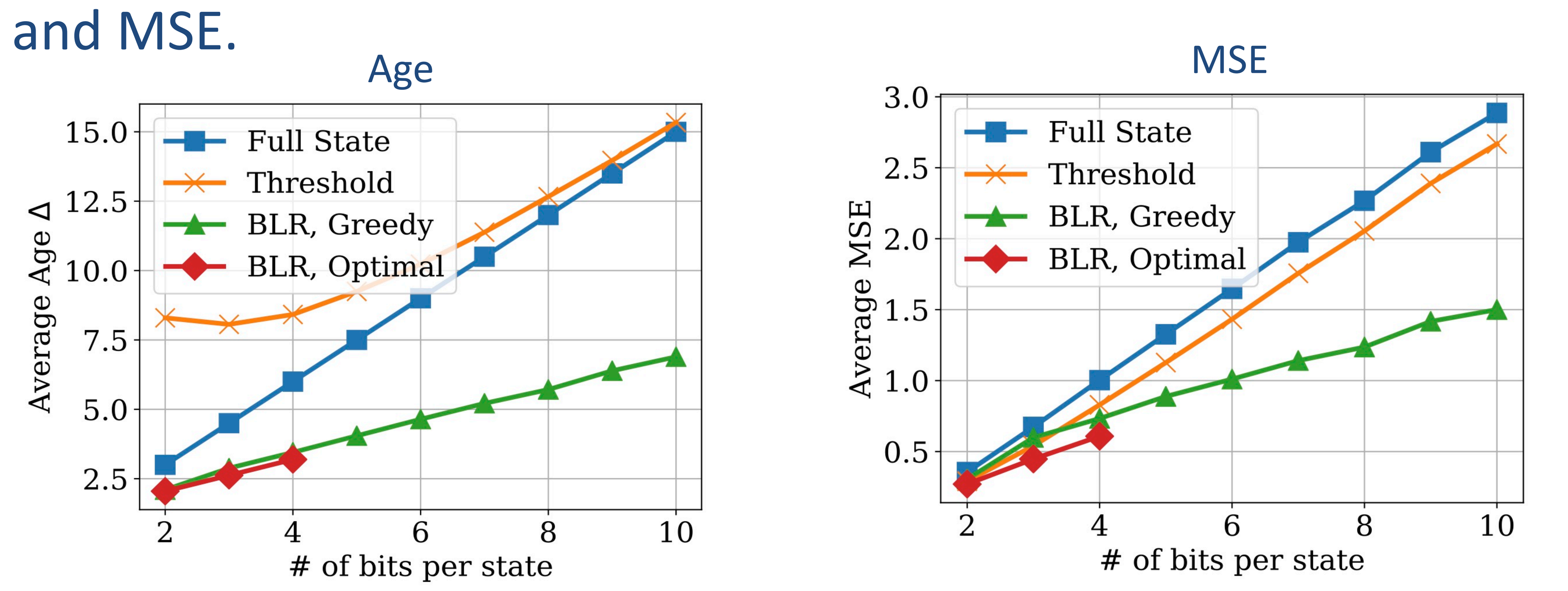
If the sent bits do not change, then resample (send remaining bits from the current state)



Bit level replacement example

Optimal Bit Encoding for BLR:

We have devised an algorithm for the *optimal* assignment of bits to states. Due to the complexity of the optimal algorithm, we devised a *greedy* algorithm that is more efficient and performs well in terms of age and MSE.



Conclusion

The problems studied in this work highlight the need for further investigation and refinement of the proposed metrics, so the search for an effective age continues…

Possible Future Work: Does maximizing the average mutual information ($^1/_T \int_0^T I(X(t); \hat{X}(t))\,dt$) minimize the average estimation error?