Towards an “Effective Age” Concept

**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.

**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

**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:**

\[ \Delta_{CME}(t) = \int_0^t h(\tau) d\tau \]

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

**Problem 2: Time Slot Length = Single Bit**

**Transmission Model:** Service time of each bit is 1 slot

**Source Model:** \( m \)-bits \( \rightarrow \) 2\(^m \) states

**Sampling Schemes:**
- Full state: Sample every \( m \) bits
- Threshold sampling policy: \( \text{Thresh} = 1 \)
- Bit level replacement scheme (BLR):
  - If the sent bits do not change, then resample (send remaining bits from the current state)

**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

\[ \frac{1}{T} \int_0^T I(X(t); \hat{X}(t)) dt \]

minimize the average estimation error?