Age of Information in Relativistic Communication Systems

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About the Presenter

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- Research interests: Age of Information, wireless networks, relativistic communication systems
- Background in telecommunications and signal processing

Motivation

- Age of Information (AoI) quantifies freshness of updates in communication systems
- Existing AoI analyses assume **shared time** between transmitter and receiver
- In satellite and space-based systems, **relativistic time dilation** distorts timestamps
- Naive timestamp comparison yields systematic errors in peak AoI (pAoI) evaluation

This talk:

1. Special Relativity: model & polynomial estimator
2. General Relativity: orbital model & estimator
3. Numerical validation across all regimes

Background: AoI and pAoI

Age of Information

Time elapsed since the generation of the latest received update:

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

where t_g is the generation time of the most recent update at time t.

Peak Age of Information (pAoI)

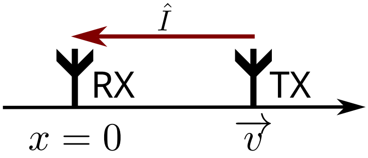
Maximum age immediately prior to reception of an update:

$$\Delta_{\text{peak}} = t_r - t_g$$

Key assumption in literature: TX and RX share the same time reference.

Our question: What happens when they don't?

Special Relativity: Model



- TX moves at constant speed v relative to RX
- Time dilation: $\tau = t/\gamma$
- Doppler factor:

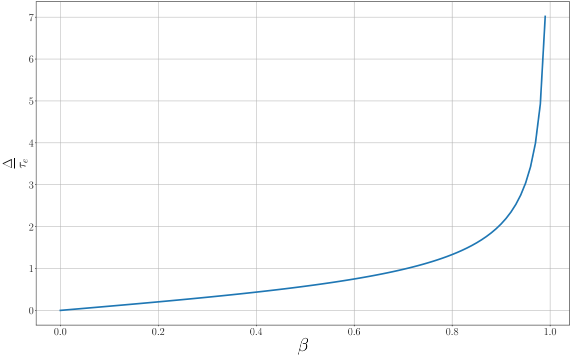
$$k_{\pm} = \sqrt{\frac{1 \pm \beta}{1 \mp \beta}}$$

- True pAoI:

$$\Delta = \gamma |\beta| \, \tau_g$$

- Naive approach $(t_r - \tau_g)$ gives **wrong** or even **negative** results

pAoI Grows with Relative Speed



- Normalized pAoI (Δ/τ_g) vs $\beta = v/c$
- pAoI diverges as TX approaches the speed of light
- Even at moderate β, naive evaluation introduces bias

Polynomial AoI Estimator (Special Relativity)

Idea: Approximate $t_r(\tau)$ locally by a polynomial using only timestamps.

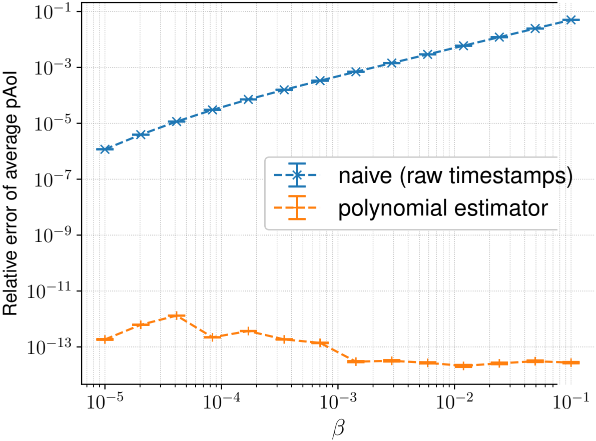
1. Collect sliding window of N pairs $\{(\tau_g^{(i)}, t_r^{(i)})\}$
2. Fit polynomial via OLS:

$$\hat{t}_r(\tau) = a_0 + a_1\tau + a_2\tau^2 + \dots$$

3. Extract Doppler factor from derivative $\hat{k}_n = \frac{d}{d\tau}\hat{t}_r\big|_{\tau_g^{(n)}}$
4. Recover $\hat{\gamma}_n$, then $\hat{t}_g = \hat{\gamma}_n\,\tau_g^{(n)}$
5. Compute pAoI: $\hat{\Delta}_n = t_r^{(n)} - \hat{t}_g$

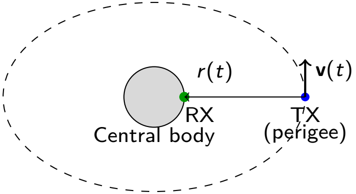
No carrier frequency needed – works purely on timestamped updates.

Special Relativity: Results



- Relative error of average pAoI vs true pAoI
- Naive approach: large systematic error across all β
- Polynomial estimator: consistently accurate

General Relativity: Orbital Model



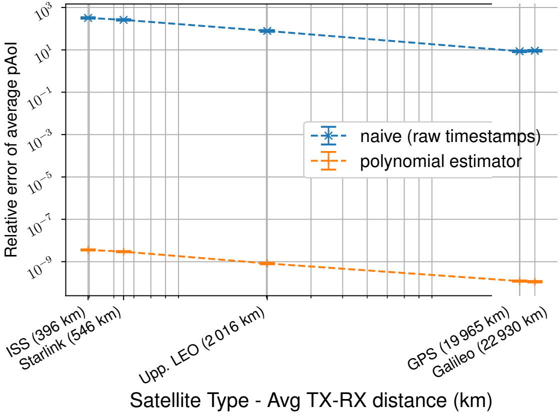
- TX on elliptical orbit, RX on surface
- Time-transfer mapping $t_r = \mathcal{T}(\tau_g)$: **no closed form**
- Weak-field approximation:

$$\frac{dt}{d\tau} \approx 1 + \frac{\mu}{rc^2} - \frac{v^2}{2c^2}$$

- Both gravitational and kinematic dilation

General Relativity: Estimator & Results

Approach: Local polynomial fit + recursive integration of clock rate.



- Tested from ISS altitude to Galileo GNSS
- Estimator outperforms naive by **orders of magnitude**

Why Do SR and GR Error Levels Differ?

Special Relativity

- Linear, closed-form mapping
- Well-conditioned estimation
- Naive error: **constant bias**

General Relativity

- Nonlinear, time-varying mapping
- Local approximation needed
- Naive error: **cumulative**, grows over time

Key insight

Under GR, time-varying distortions are integrated over the observation horizon, causing errors to accumulate – unlike the predictable bias in the SR case.

Conclusion & Future Work

Contributions:

- First relativistic formulation of pAoI
- Polynomial estimators for SR and GR settings
- Timestamp-only – no carrier or orbit knowledge needed
- Validated across all velocity and orbital regimes

Future directions:

- Strong gravitational fields (deep-space, compact objects)
- Full AoI distribution under relativistic distortions
- Velocities approaching c

Thank you!

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