High Accuracy Wireless Time Synchronization for Distributed Antenna Arrays

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Outline

1. Distributed Antenna Arrays Overview
2. High Accuracy Time Transfer
3. Experimental Results

Distributed Array Applications and Benefits

Reduced Cost

- Smaller, low-cost platforms
- Cost distributed over many nodes

Reconfigurable

- Adaptable sub-arrays to meet *bandwidth* and *spatial* requirements

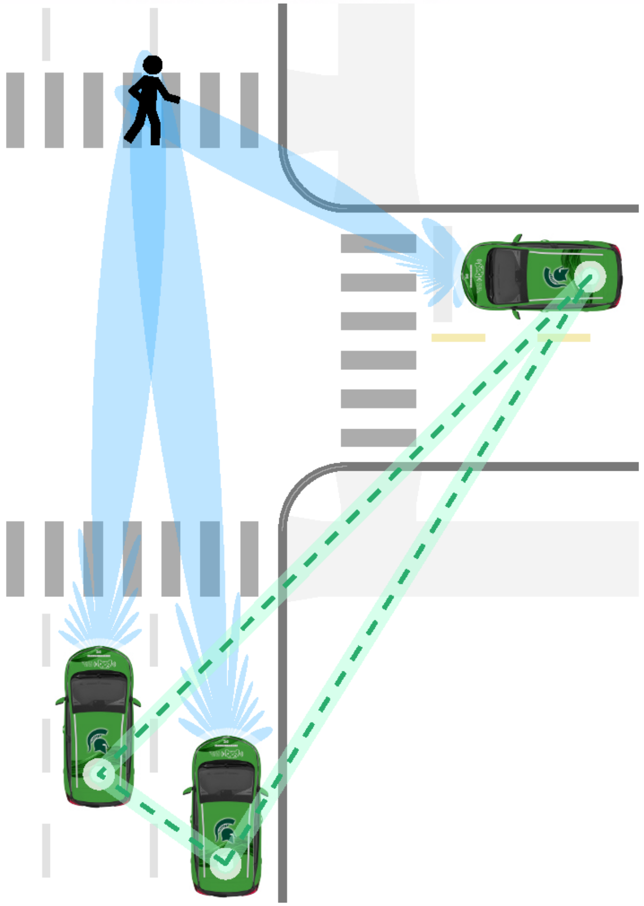
Increased Robustness

- Nodes may be added or removed without failure of array

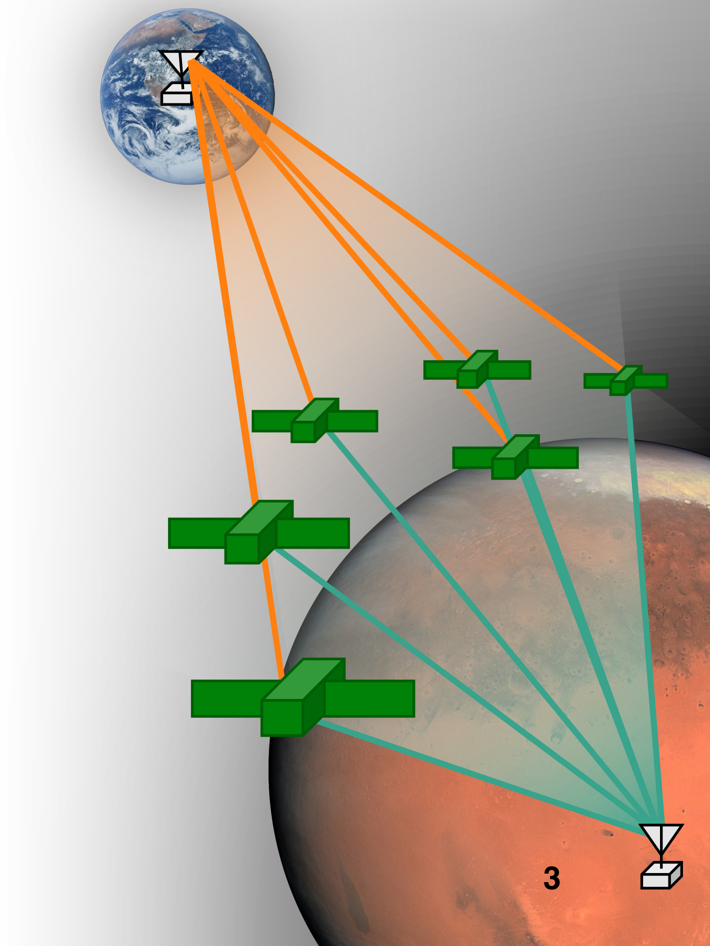
Increased Gain

- Transmission gain $\propto N^2$
- Reception gain $\propto M$
- Total gain $\propto N^2 M$

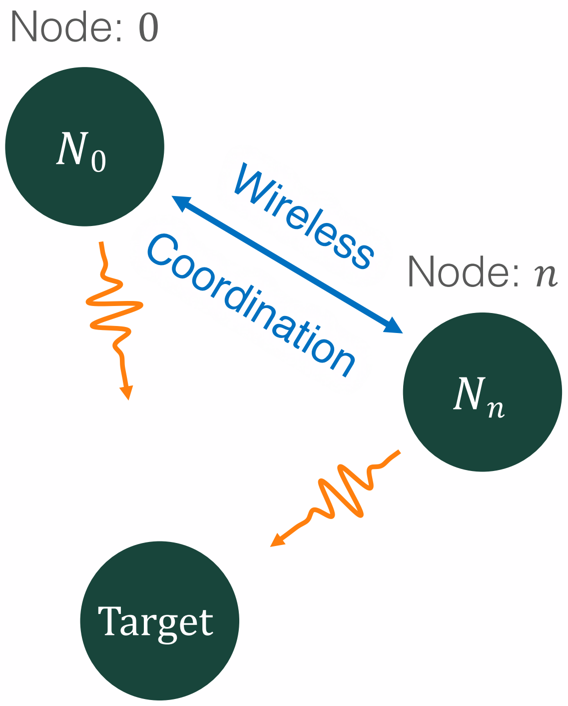
V2X Distributed Sensing



Space Communication and Sensing



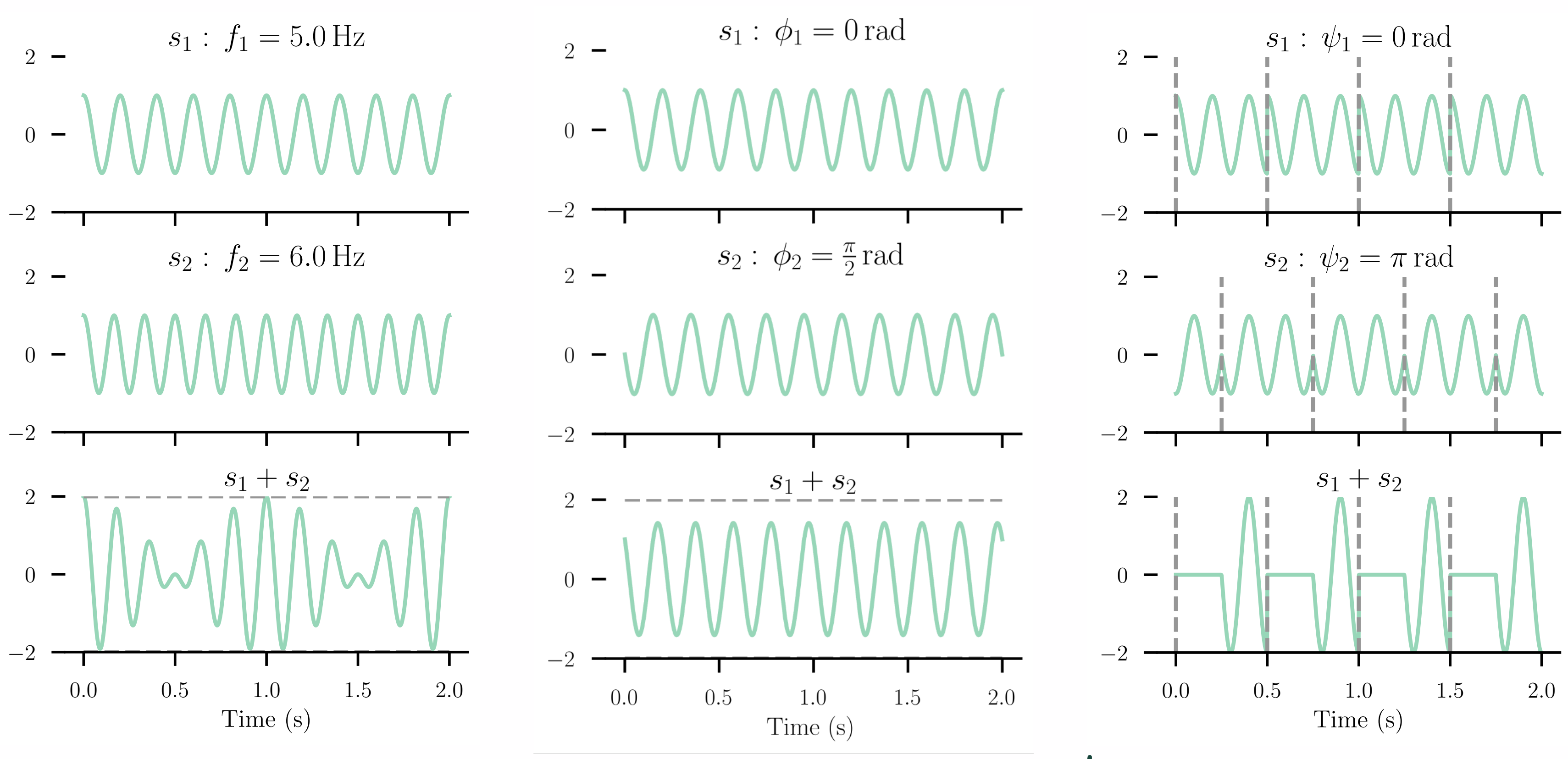
Distributed Array Coordination Challenges



Frequency Syntonization

Phase Alignment

Time Synchronization



Focus of this work

Distributed Array Time Error Tolerance

Probability of coherent gain:

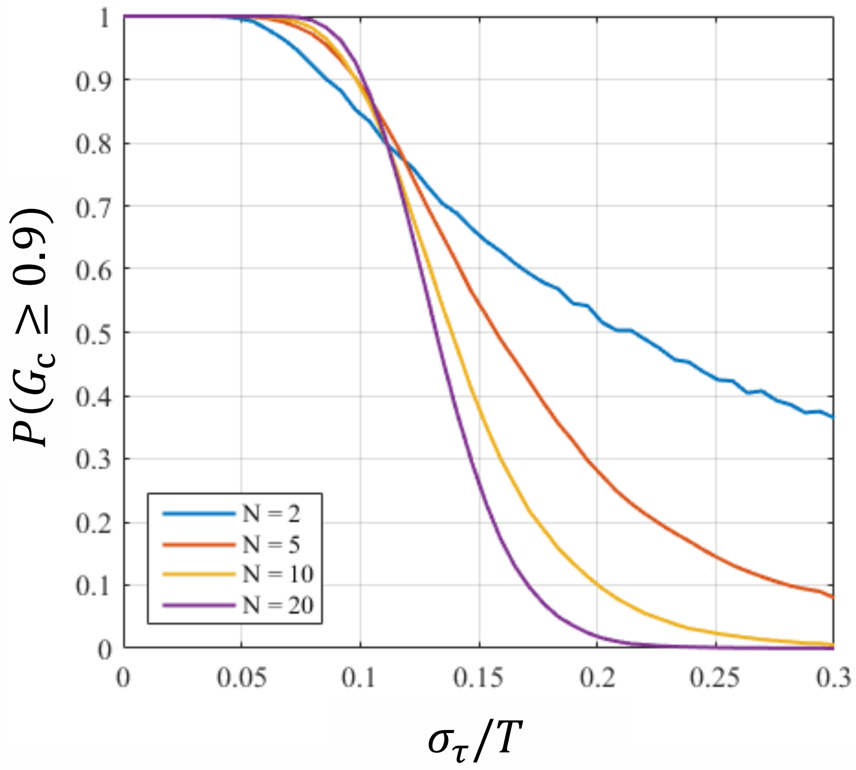
$$P(G_c \geq X)$$

where

$$G_c = \frac{|s_r s_r^*|}{|s_i s_i^*|}$$

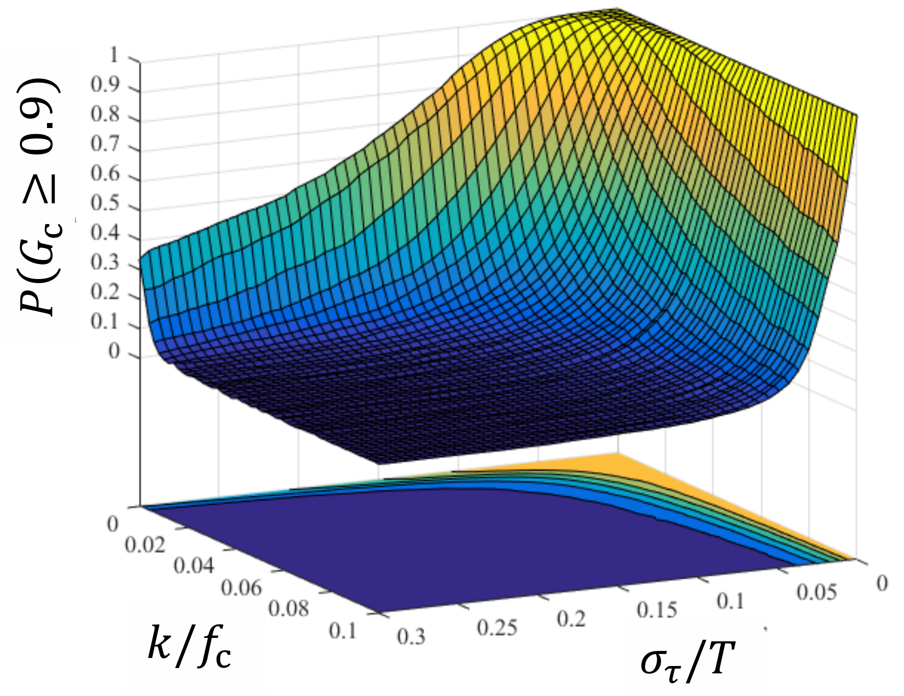
- s_r: received signal
- s_i: ideal signal

Monotone Pulse



Timing error <10% pulse duration

LFM Pulse



Modulation requires stricter timing

[1] J. A. Nanzer, R. L. Schmid, T. M. Comberiate and J. E. Hodkin, "Open-Loop Coherent Distributed Arrays," in IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 5, pp. 1662-1672, May 2017, doi: 10.1109/TMTT.2016.2637899.

[2] S. Mghabghab, S. M. Ellison, J. A. Nanzer, arXiv:2010.10396, 2020

Distributed Array Coordination Topologies

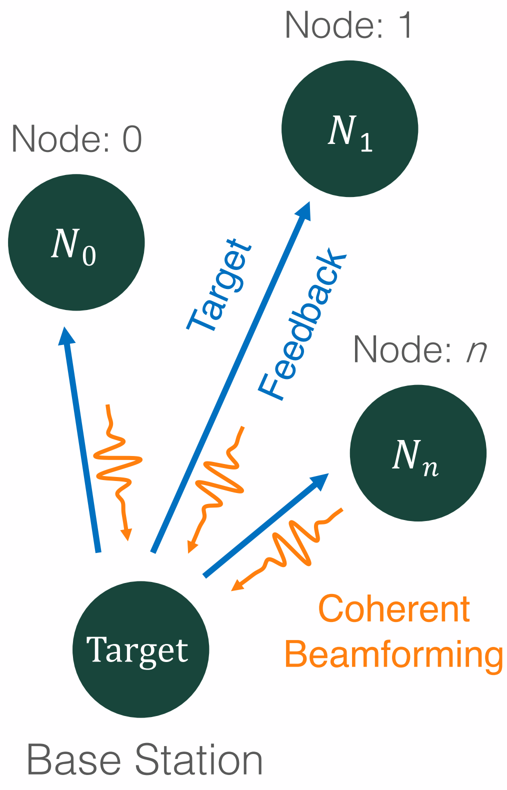
Closed-Loop

Pros

- Minimal information sharing required
- Channel errors corrected implicitly

Cons

- Can only transmit to base station (no beamsteering)
- Time consuming due to potentially large number of iterations



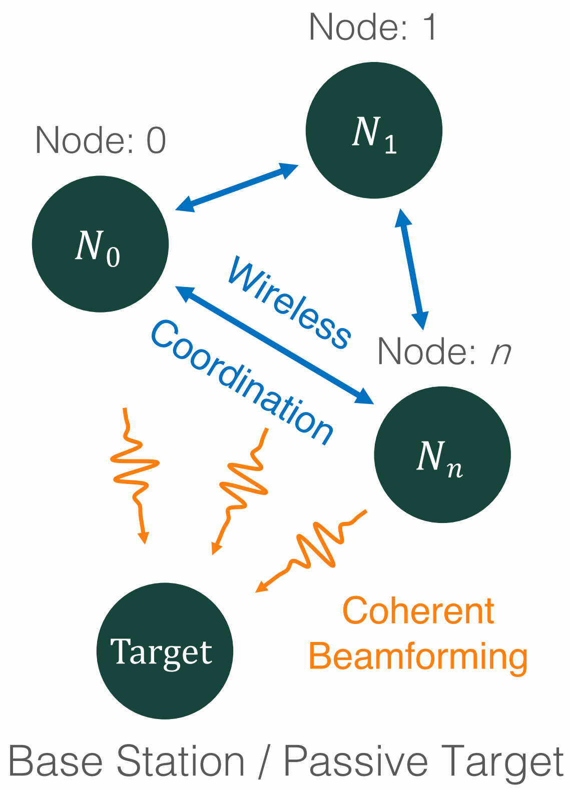
Open-Loop

Pros

- Compatible with noncooperative/ passive targets
- Arbitrary beamforming capability

Cons

- Stringent inter-node coordination requirements
- Channel errors to target location not inherently corrected

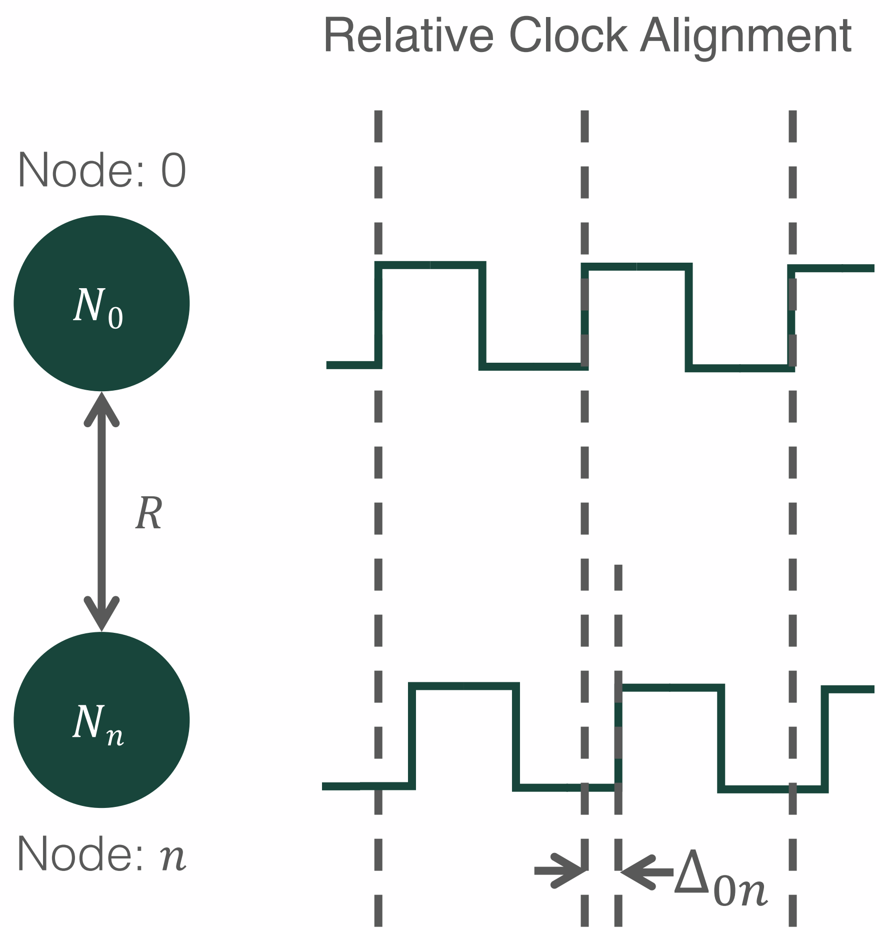


System Time Model

- Time at node n:

$$T_n(t) = t + \delta_n(t) + \nu_n(t)$$

  - t : true time
  - $\delta_n(t)$: time-varying bias
    - Assumed quasi-static over synchronization epoch
    - No further assumptions on distribution of δ_n
  - $\nu_n(t)$: other zero-mean noise sources
  - $\Delta_{0n}(t) = \delta_0(t) - \delta_n(t)$
- Goal: estimate and compensate for δ_n



Time Transfer Techniques

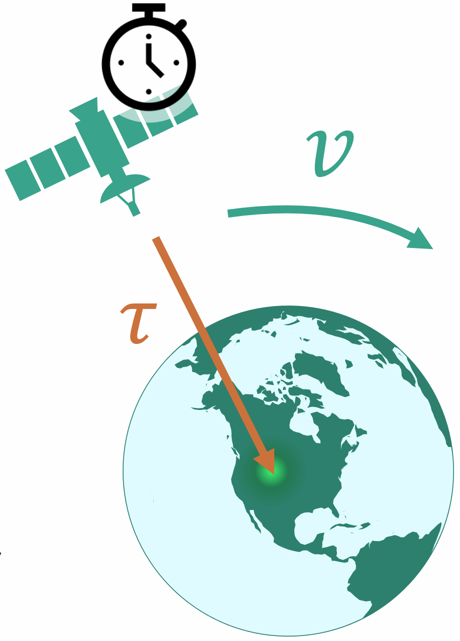
One-Way Time Transfer

Pros

- Receiver nodes do not need to transmit
- One node can provide time to many anonymous receivers

Cons

- Channel must be well characterized to accurately determine and subtract propagation delay
- Positions and trajectories of nodes must be known



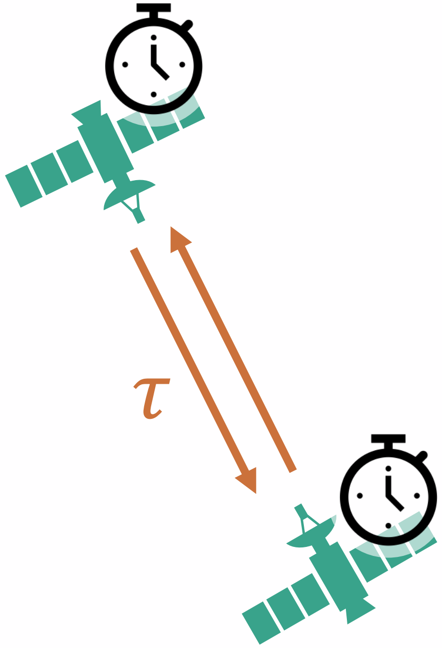
Two-Way Time Transfer

Pros

- Both nodes implicitly estimate channel delay
- Both nodes determine their relative offset

Cons

- Requires all nodes to have transmitters
- Time transfer must be performed pairwise
  - N orthogonal channels required to synchronize N nodes



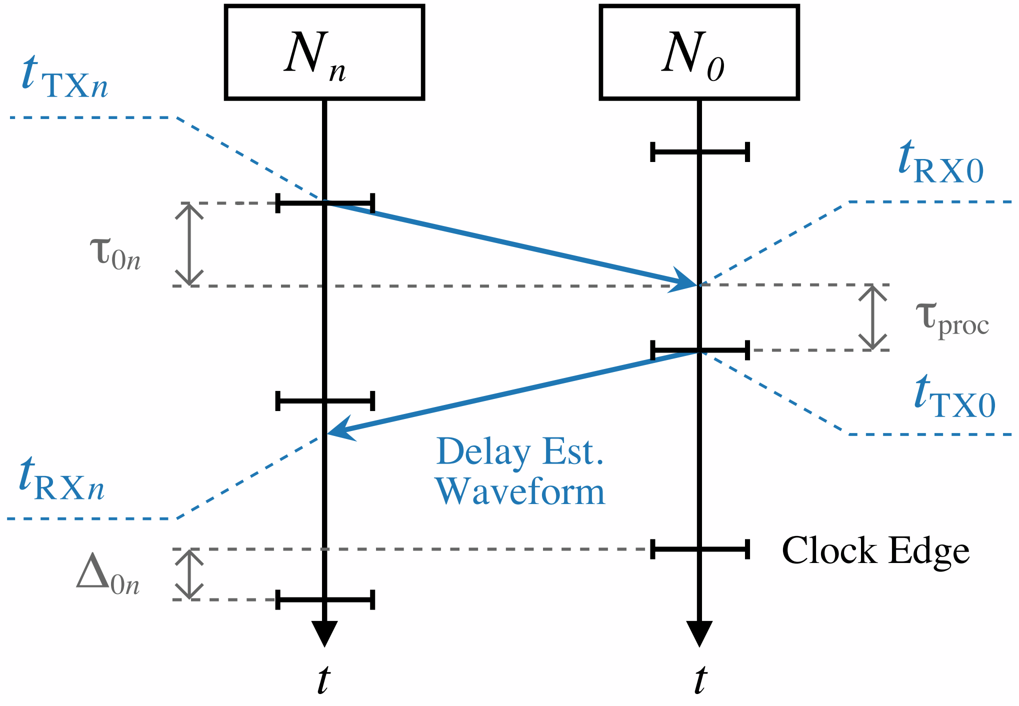
Two-Way Time Transfer Synchronization

- Assumptions
  - Channel is quasi-static over synchronization epoch
- Propagation delay estimate:

$$\tau_{0n} = \frac{(t_{RX0} - t_{TXn}) + (t_{TX0} - t_{RXn})}{2}$$

- Timing skew estimate:

$$\Delta_{0n} = \frac{(t_{RX0} - t_{TXn}) - (t_{TX0} - t_{RXn})}{2}$$



[3] Merlo, J. M., Mghabghab, S. R., and Nanzer, J. A., "Wireless Picosecond Time Synchronization for Distributed Antenna Arrays", *arXiv e-prints*, 2022.

High Accuracy Time Delay Waveform

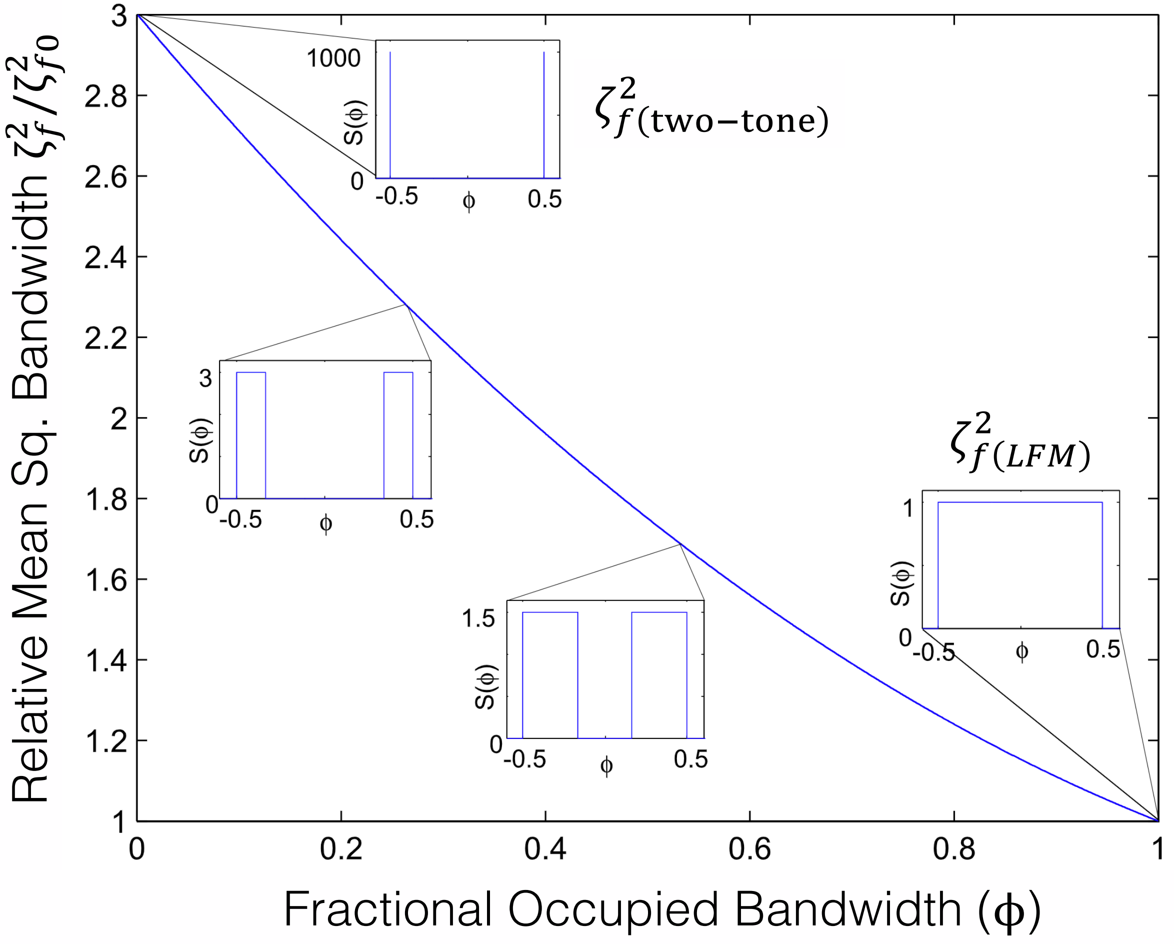
- The delay accuracy lower bound (CRLB) for time is given by

$$\mathrm{var}(\hat{\tau} - \tau) \geq \frac{1}{2\zeta_f^2} \cdot \frac{N_0}{E_s}$$

  - ζ_f^2: mean-squared bandwidth
  - N_0: noise power spectral density
  - E_s: signal energy

$$\frac{E_s}{N_0} = \tau_p \cdot \mathrm{SNR} \cdot \mathrm{NBW}$$

  - τ_p: integration time
  - SNR: signal-to-noise ratio
  - NBW: noise bandwidth



[3] J. A. Nanzer and M. D. Sharp, "On the Estimation of Angle Rate in Radar," *IEEE T Antenn Propag*, vol. 65, no. 3, pp. 1339–1348, 2017, doi: 10.1109/tap.2016.2645785.

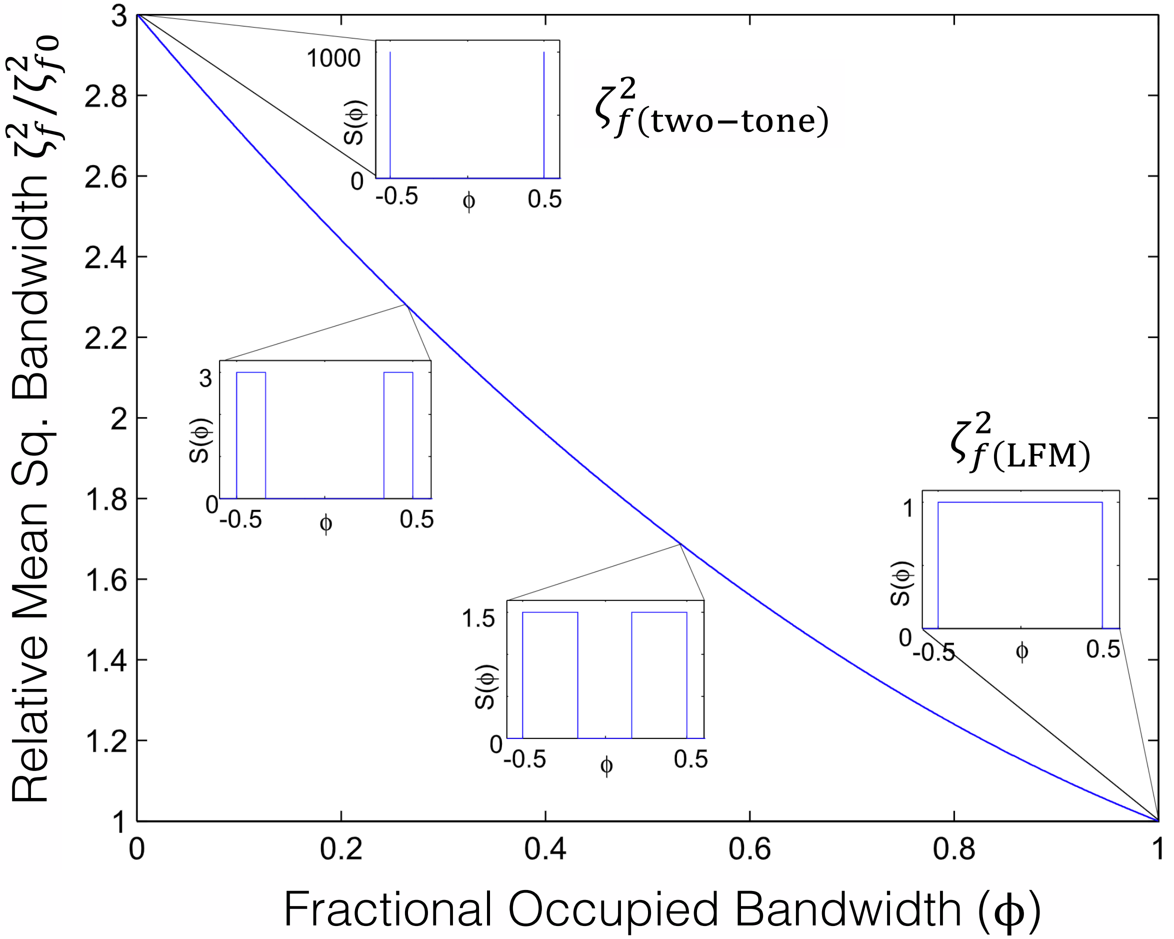
High Accuracy Time Delay Waveform

$$\mathrm{var}(\hat{\tau} - \tau) \geq \frac{1}{2\zeta_f^2} \cdot \frac{N_0}{E_s}$$

- For constant-SNR, maximizing ζ_f^2 will yield improved delay estimation

$$\zeta_f^2 = \int_{-\infty}^{\infty} (2\pi f)^2 |G(f)|^2 df$$

- $\zeta_{f(\mathrm{LFM})}^2 = (\pi \cdot \mathrm{BW})^2 / 3$
- $\zeta_{f(\mathrm{two-tone})}^2 = (\pi \cdot \mathrm{BW})^2$



[4] J. A. Nanzer and M. D. Sharp, "On the Estimation of Angle Rate in Radar," *IEEE T Antenn Propag*, vol. 65, no. 3, pp. 1339–1348, 2017, doi: 10.1109/tap.2016.2645785.

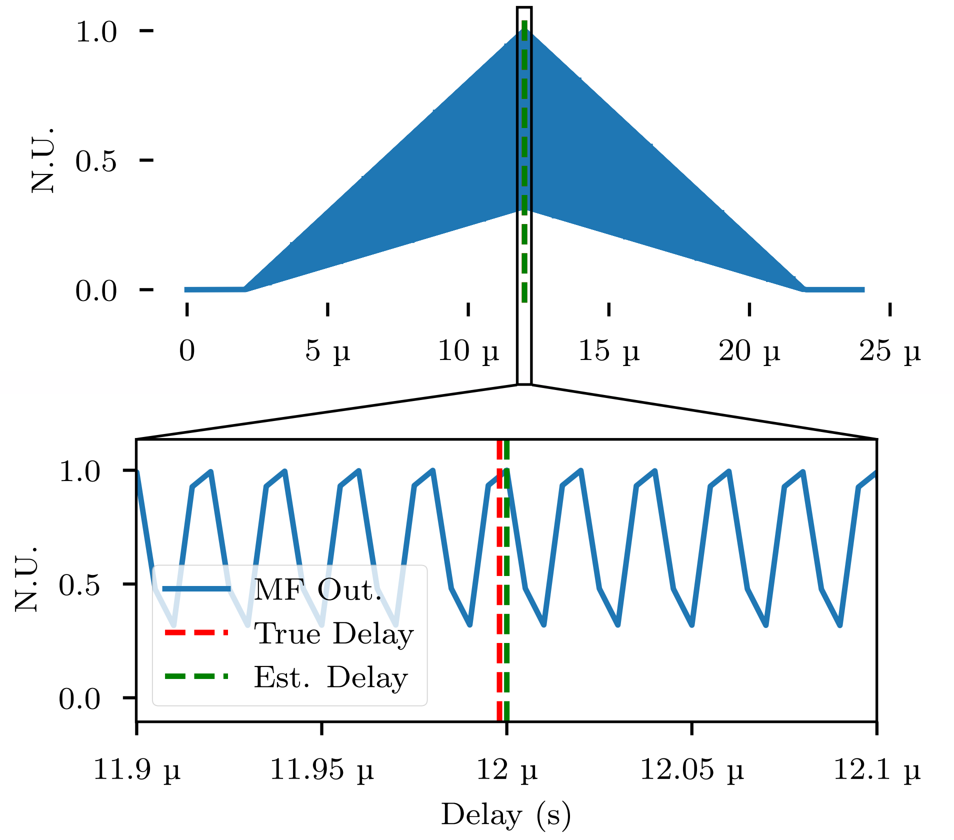
Delay Estimation and Refinement

- Discrete matched filter (MF) used in initial time delay estimate

$$s_{\mathrm{MF}}[n] = s_{\mathrm{RX}}[n] \circledast s_{\mathrm{TX}}^{*}[-n]$$
$$= \mathcal{F}^{-1}\{S_{\mathrm{RX}} S_{\mathrm{TX}}^{*}\}$$

- Two-tone matched filter waveform is highly ambiguous

- High SNR or narrow-band pulse required to disambiguate peaks



[5] T. M. Comberiate, K. S. Zilevu, J. E. Hodkin and J. A. Nanzer, "A Coherent RF repeater for distributed communications," 2015 USNC-URSI Radio Science Meeting (Joint with AP-S Symposium), 2015, pp. 211-211, doi: 10.1109/USNC-URSI.2015.7303495.

Delay Estimation and Refinement

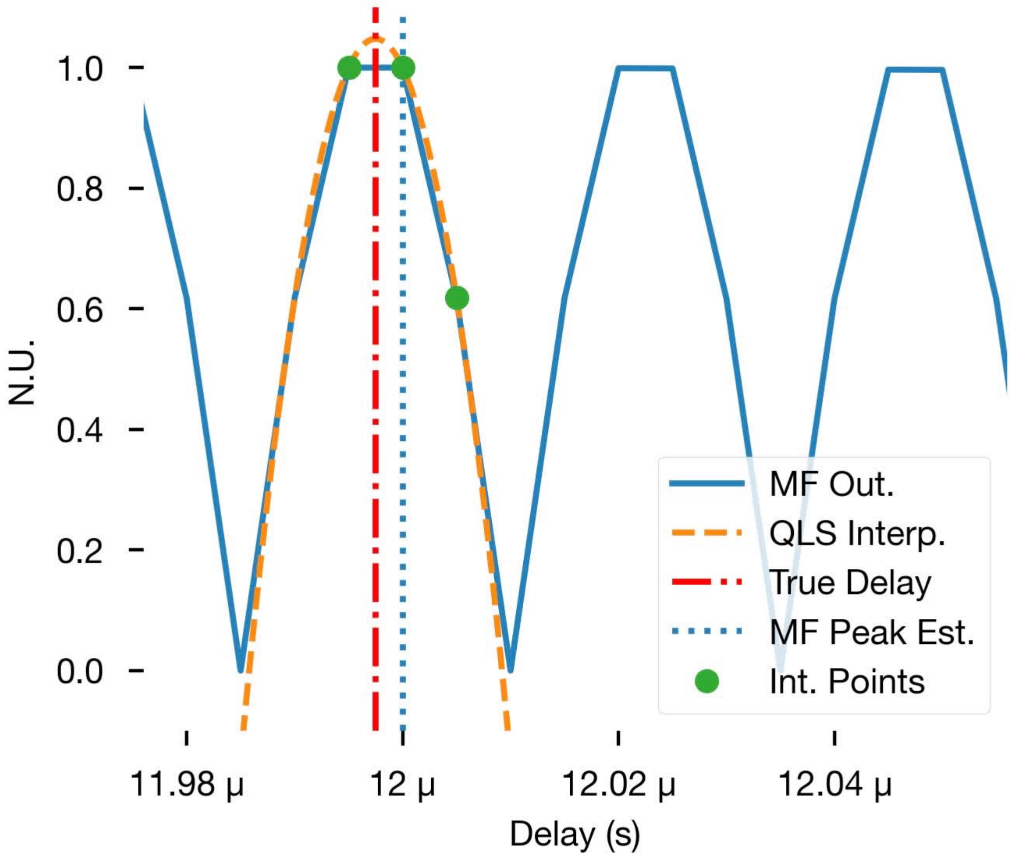
- MF causes estimator bias due to time discretization

- Refinement of MF obtained using Quadratic Least Squares (QLS) fitting to find true delay based on three sample points

$$\hat{\tau} = \frac{T_s}{2} \frac{s_{\mathrm{MF}}[n_{\max} - 1] - s_{\mathrm{MF}}[n_{\max} + 1]}{s_{\mathrm{MF}}[n_{\max} - 1] - 2s_{\mathrm{MF}}[n_{\max}] + s_{\mathrm{MF}}[n_{\max} + 1]}$$

where

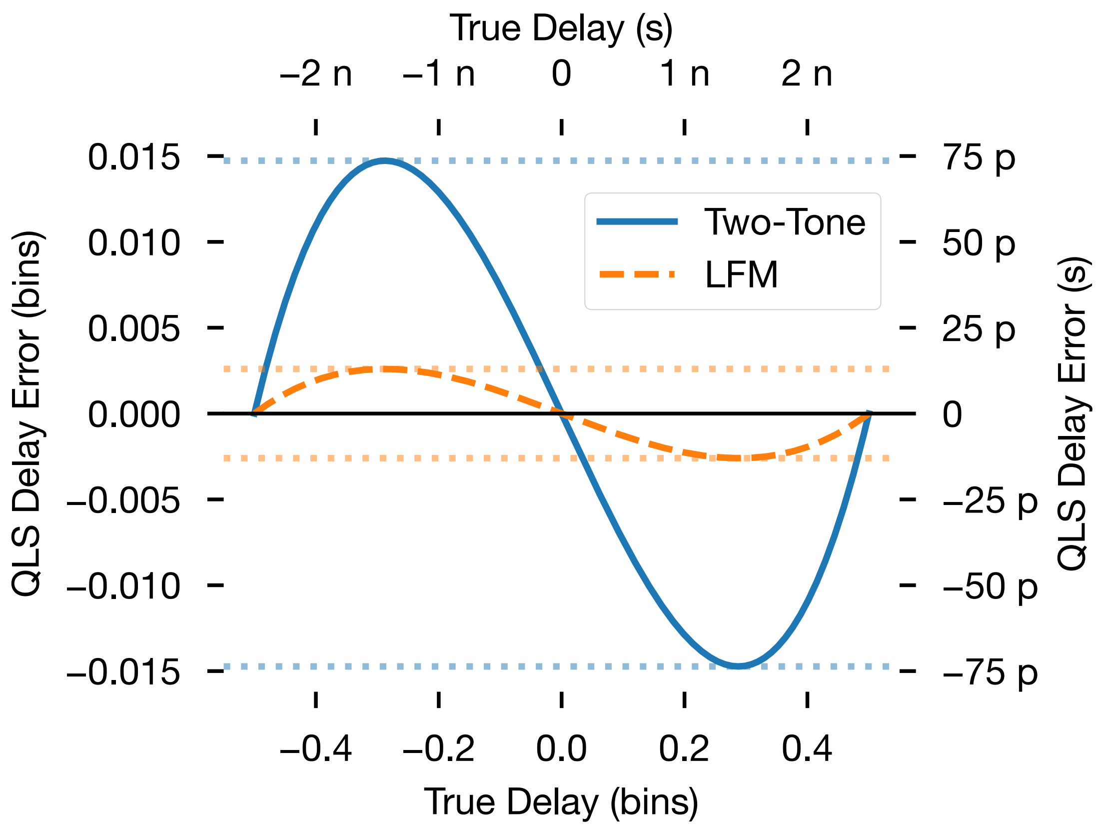
$$n_{\max} = \underset{n}{\operatorname{argmax}}\{s_{\mathrm{MF}}[n]\}$$



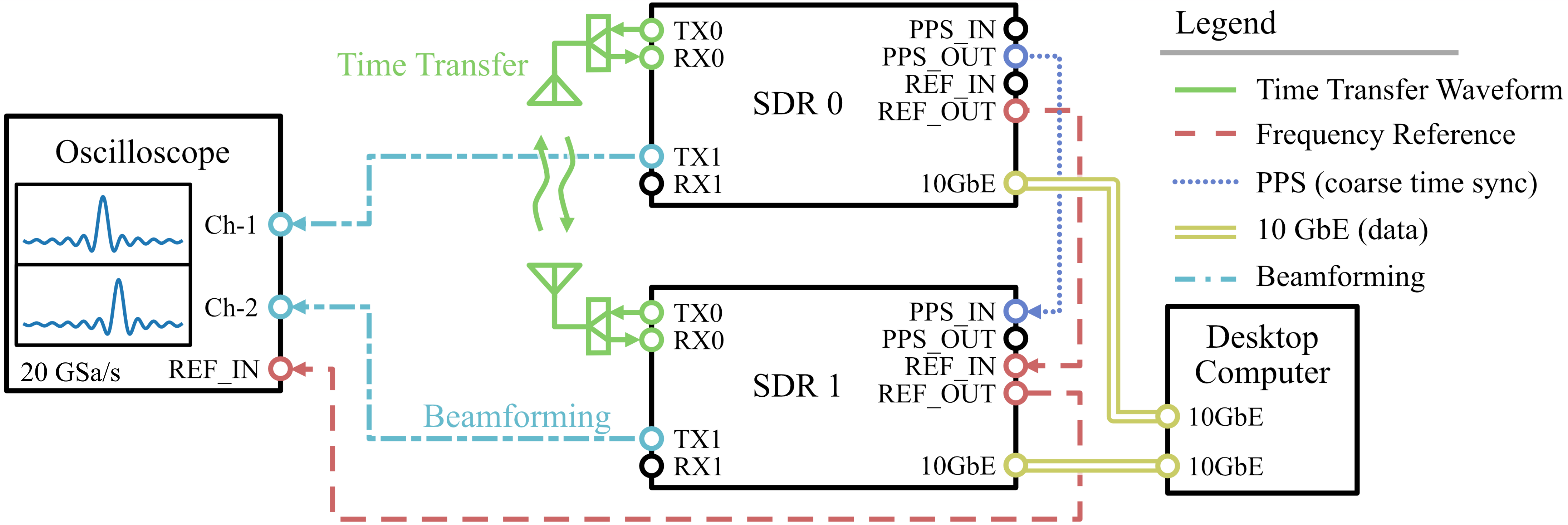
[6] R. Moddemeijer, "On the determination of the position of extrema of sampled correlators," *IEEE Transactions on Signal Processing*, vol. 39, no. 1, pp. 216–219, 1991.

Delay Estimation and Refinement

- QLS results in small residual bias due to an imperfect representation of the underlying MF output
- Residual bias is a function of waveform and sample rate
- Can be easily corrected via lookup table



Experimental Time Synchronization Setup

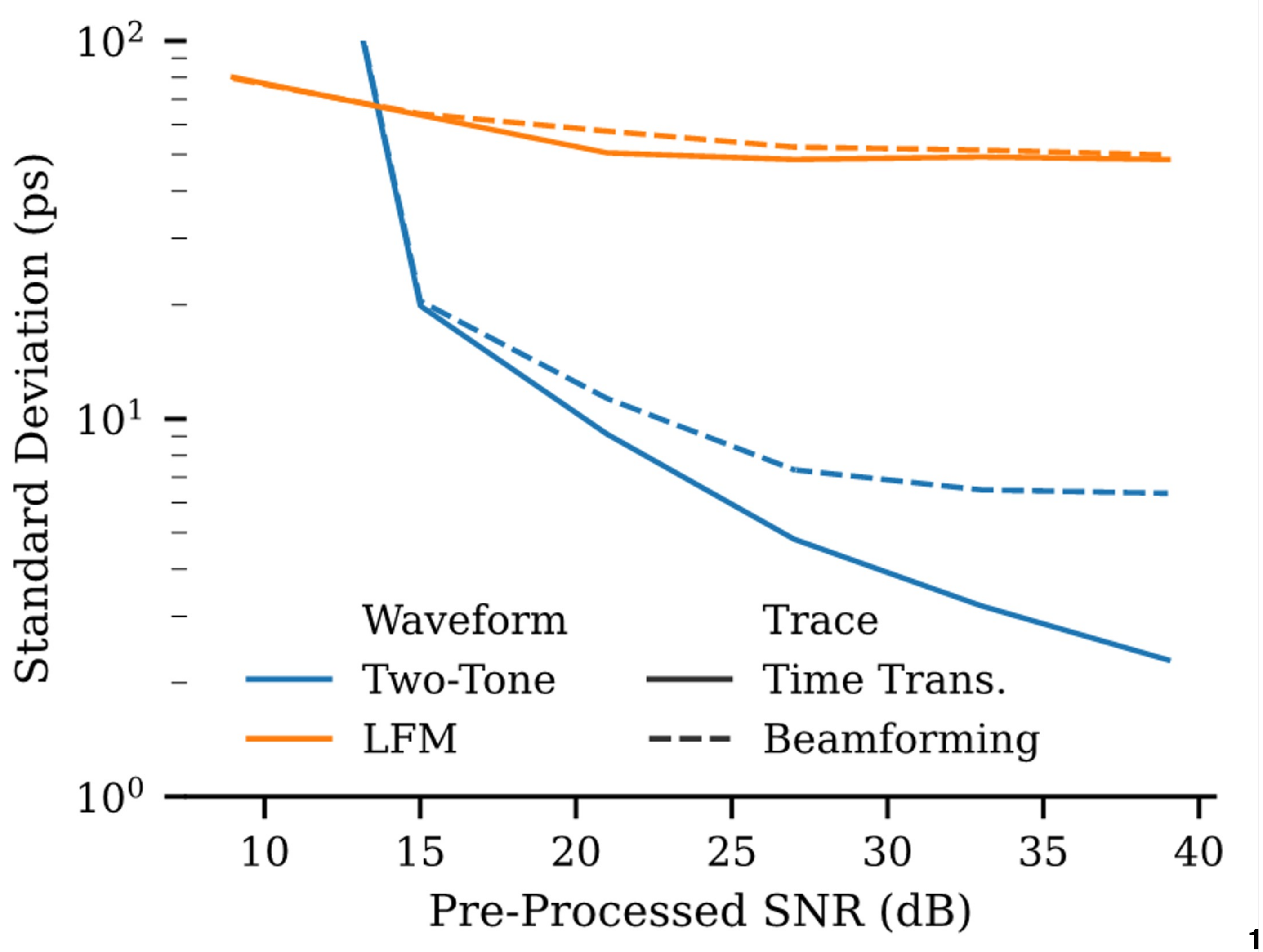


- Time Transfer Waveform
  - $f_c = 5.9$ GHz
  - BW = 50 MHz (tone separation)
  - $\tau_{\text{rise-fall}} = 50$ ns (rise-fall time)
  - $\tau_p = 10\ \mu s$ (pulse duration)
  - $\tau_{\text{sync}} = 50.01$ ms (synchronization epoch)
- Antenna
  - 5.9 GHz, 13.2 dBi Yagi-Uda antennas
- SDR
  - $f_s = 200$ MSa/s (sample rate)

Experimental Time Synchronization Setup

Time-Transfer and Beamforming Precision

- Time transfer st. dev. was estimated on SDR using time update deltas
- Beamforming st. dev. was estimated by cross-correlating received waveforms on oscilloscope
- Inter-channel bias was <10 ps after calibration



Conclusions

- Using spectrally-sparse two-tone pulses, theoretical maximum time-delay estimation may be achieved
- Approach experimentally validated using two-way time synchronization on software-defined radios
- Using a 50 MHz signal bandwidth, precisions of
  - ~2 ps for two-way time transfer
  - ~7 ps for beamforming

  are achieved

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Questions?

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