Picosecond Non-Line-of-Sight Wireless Time and Frequency Synchronization for Coherent Distributed Aperture Antenna Arrays

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C03-4 | Emerging Technologies for Radar & Communications

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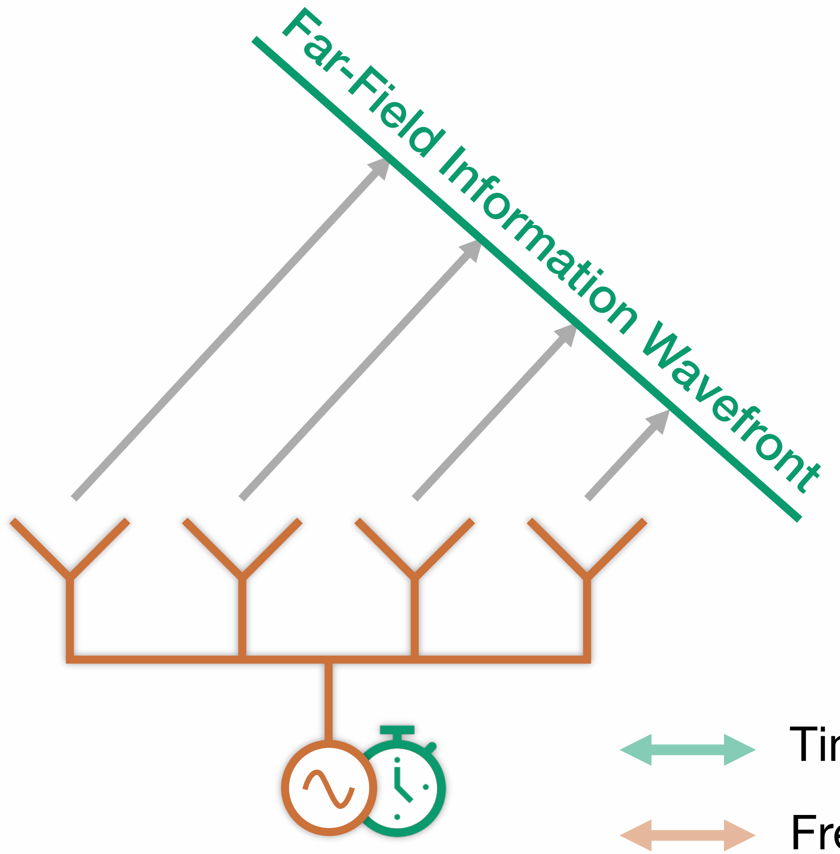
Jason M. Merlo and Jeffrey A. Nanzer
Michigan State University, East Lansing, MI, USA

delta
Distributed Electromagnetics Theory and Applications

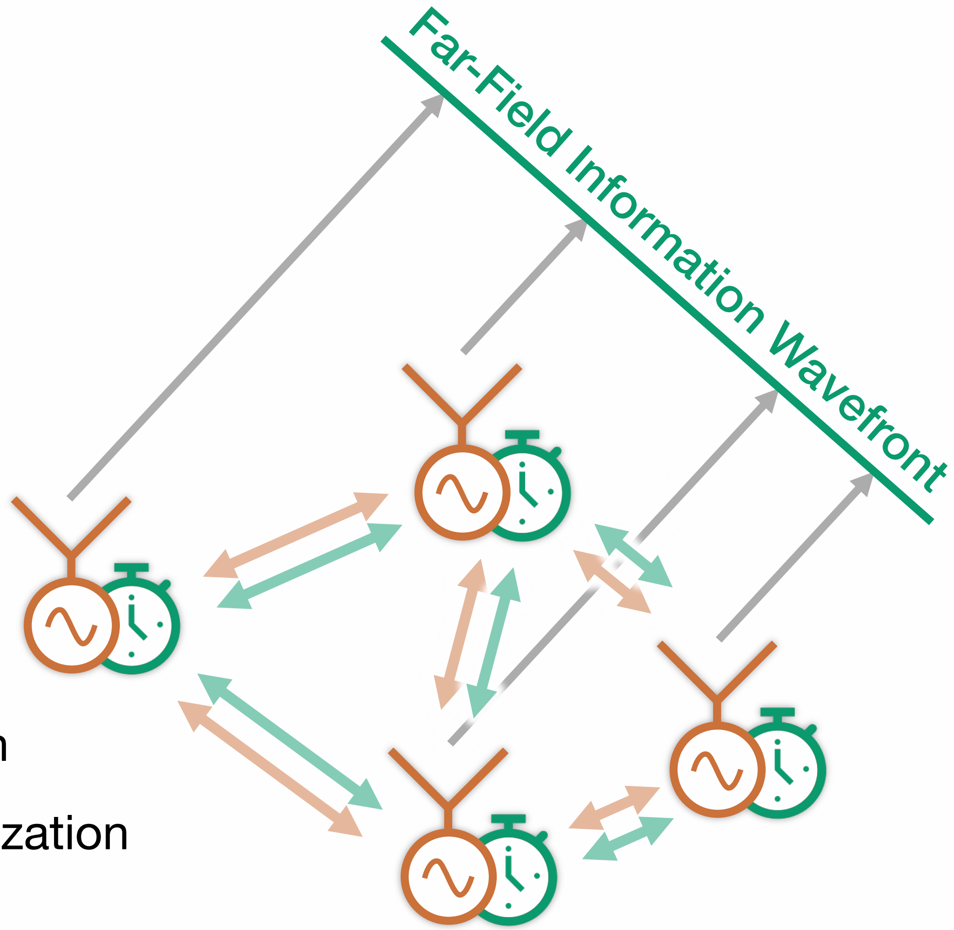
emrg
Electromagnetics Research Group
Michigan State University

Coherent Distributed Array Overview

Traditional Phased Array



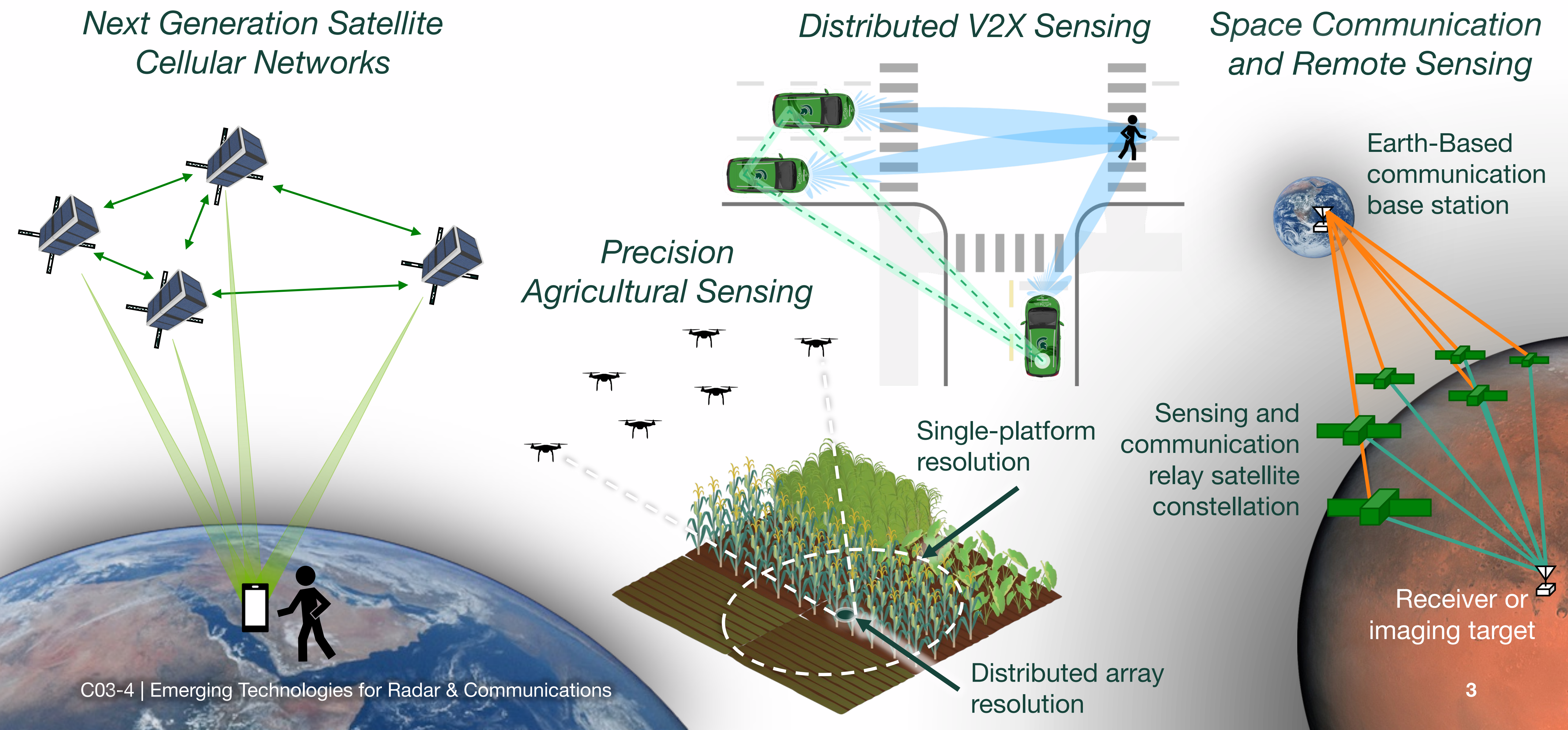
Distributed Phased Array



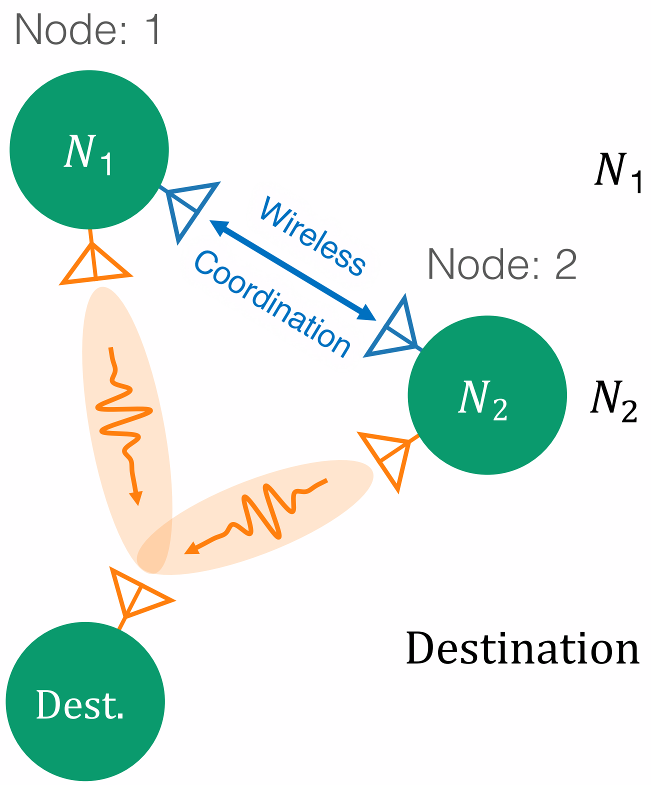
Time Synchronization

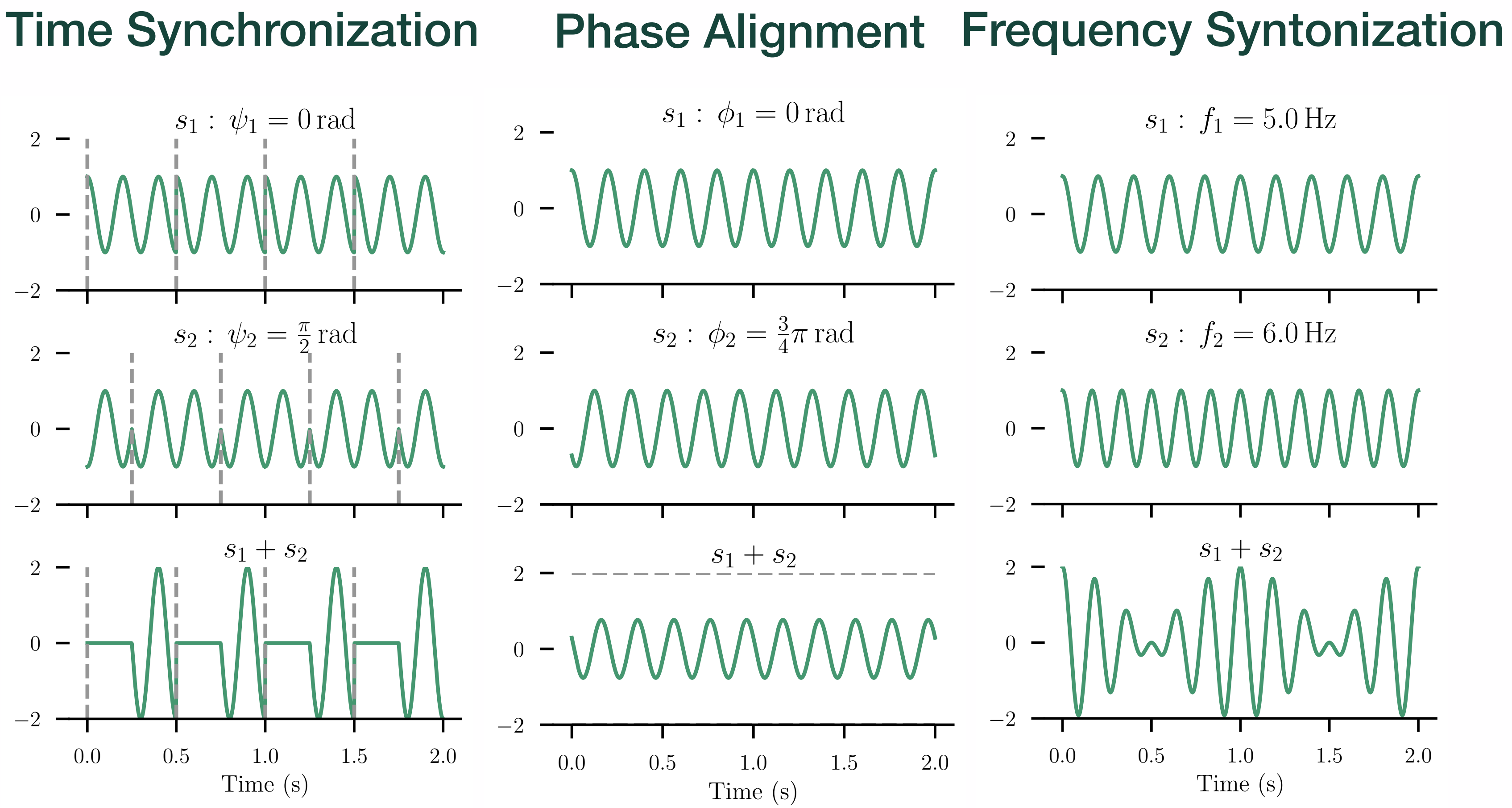
Frequency Synchronization

Coherent Distributed Array Applications



Coherent Distributed Array Synchronization





$$s_1 + s_2 = \sum_{n=1}^{2} \alpha_n(t - \delta t_n) \exp\{j[2\pi(f + \delta f_n) + \phi_n]\}$$

Coherent Distributed Array Performance

Probability of coherent gain:

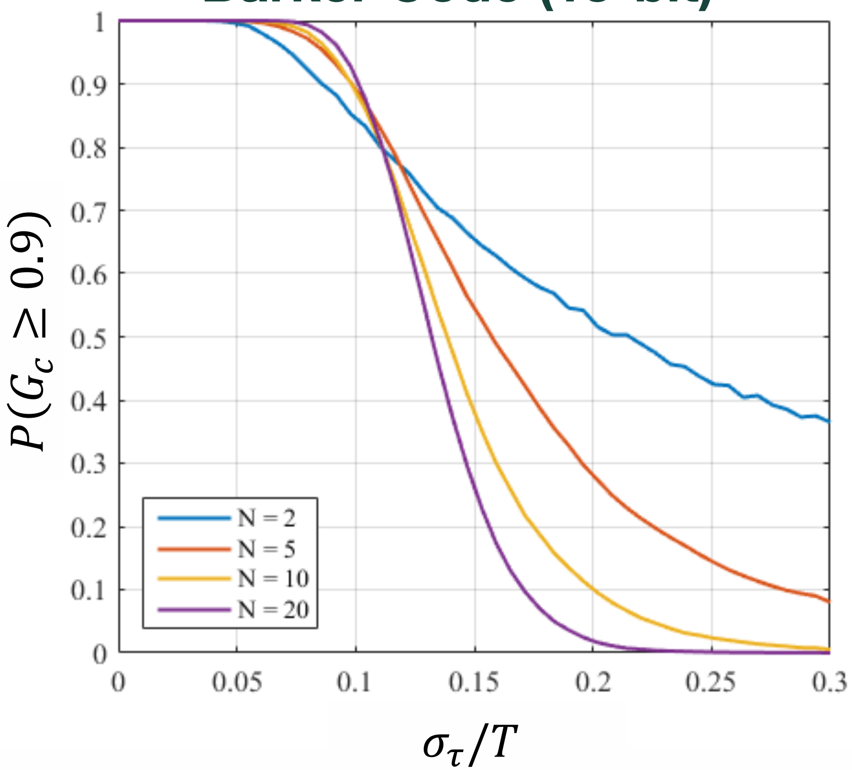
$$P(G_c \geq X)$$

where

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

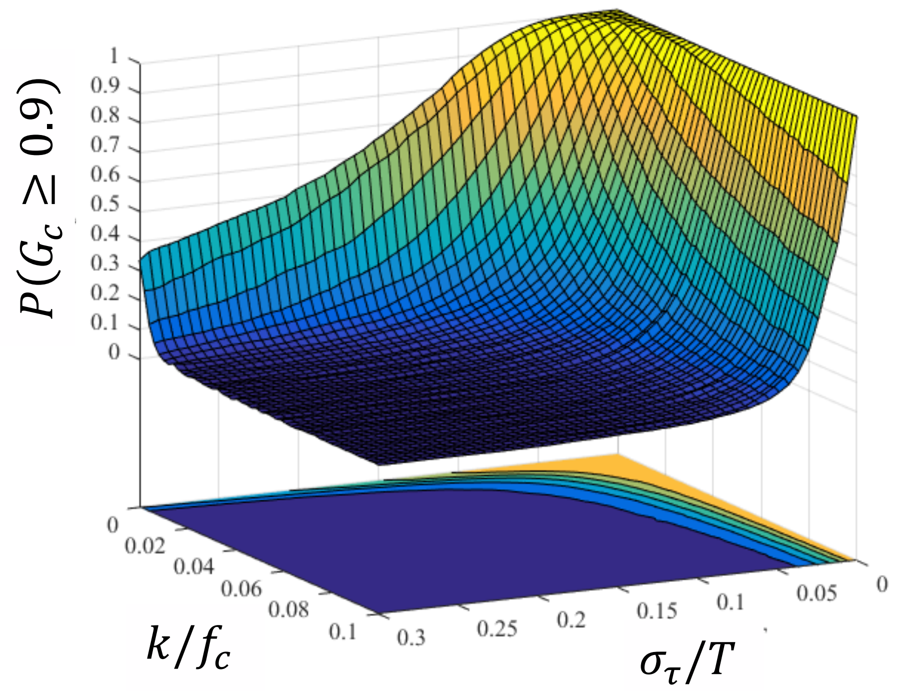
- s_r: received signal
- s_i: ideal signal

Barker Code (13-bit)



Timing error <10% pulse duration

Linear Frequency Modulated



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] P. Chatterjee and J. A. Nanzer, "Effects of time alignment errors in coherent distributed radar," in Proc. IEEE Radar Conf. (RadarConf), Apr. 2018, pp. 0727–0731.

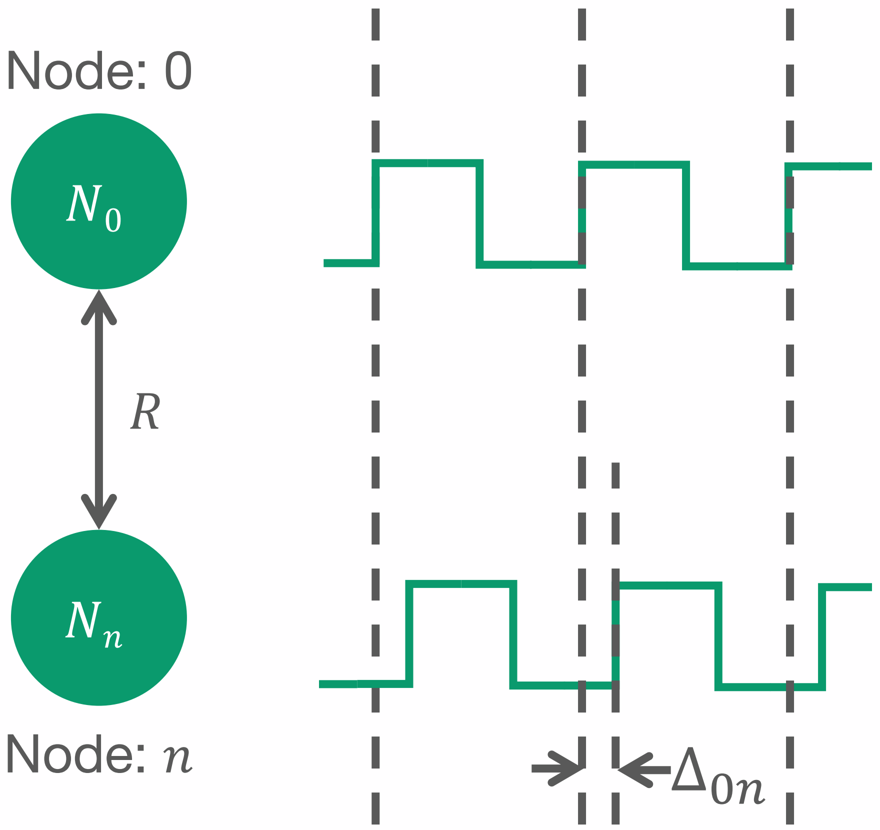
System Time Model

- Local time at node n:

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

  - α_n: time rate of change
  - t : true time
  - $\delta_n(t)$: time-varying offset from global true time
  - $\nu_n(t)$: other zero-mean noise sources
  - $\Delta_{0n}(t) = T_0(t) - T_n(t)$
- Goal:
  - Estimate and compensate for Δ_{0n}

Relative Clock Alignment



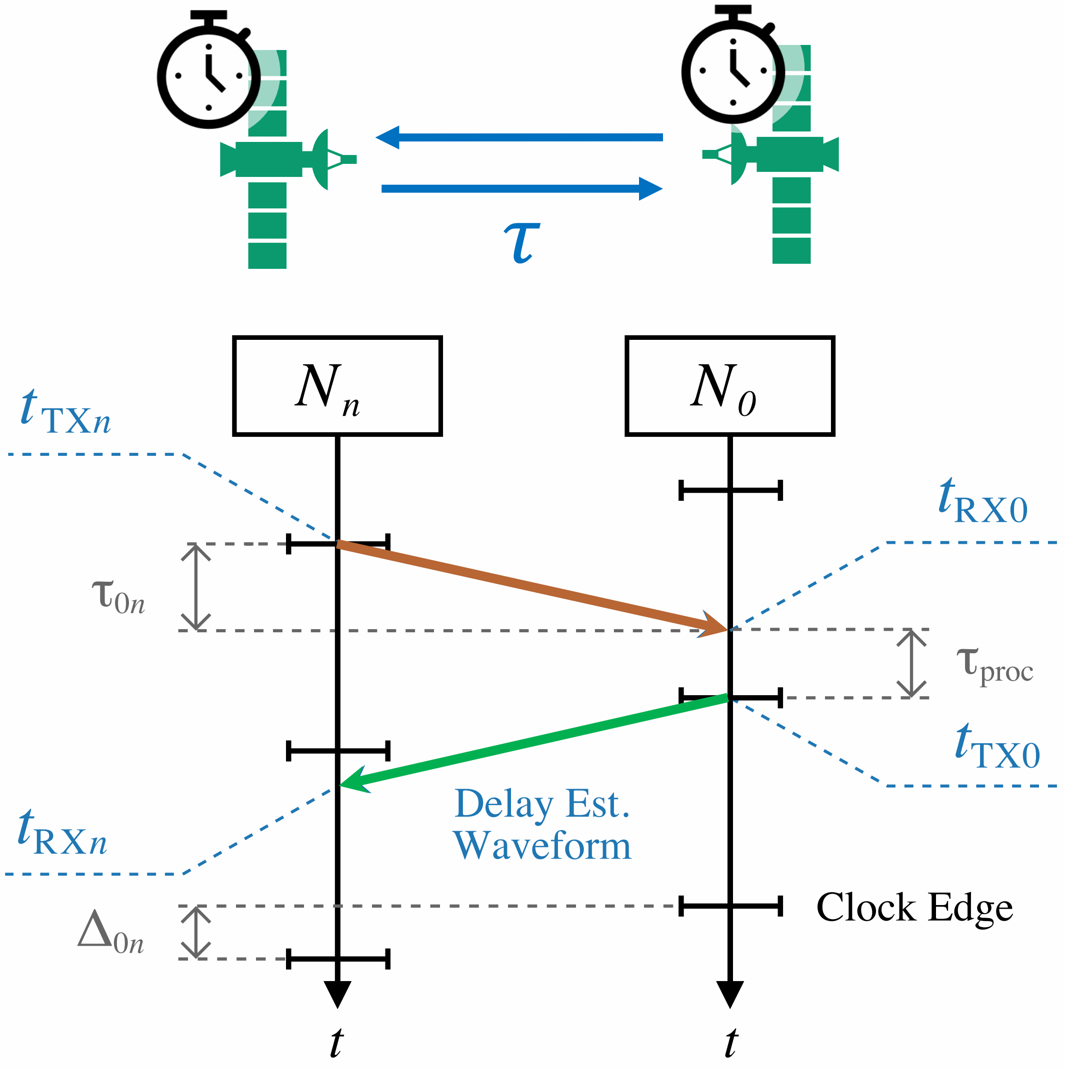
Time Synchronization Overview

Two-Way Time Synchronization

- *Assumptions:*
  - Link is reciprocal ⟹ quasi-static during the synchronization epoch
- Timing skew estimate:

$$\Delta_{0n} = \frac{(T_{\mathrm{RX}0} - T_{\mathrm{TX}n}) - (T_{\mathrm{RX}n} - T_{\mathrm{TX}0})}{2}$$

For compactness of notation: $T_m(t_{\mathrm{TX}n}) = T_{\mathrm{TX}n}$

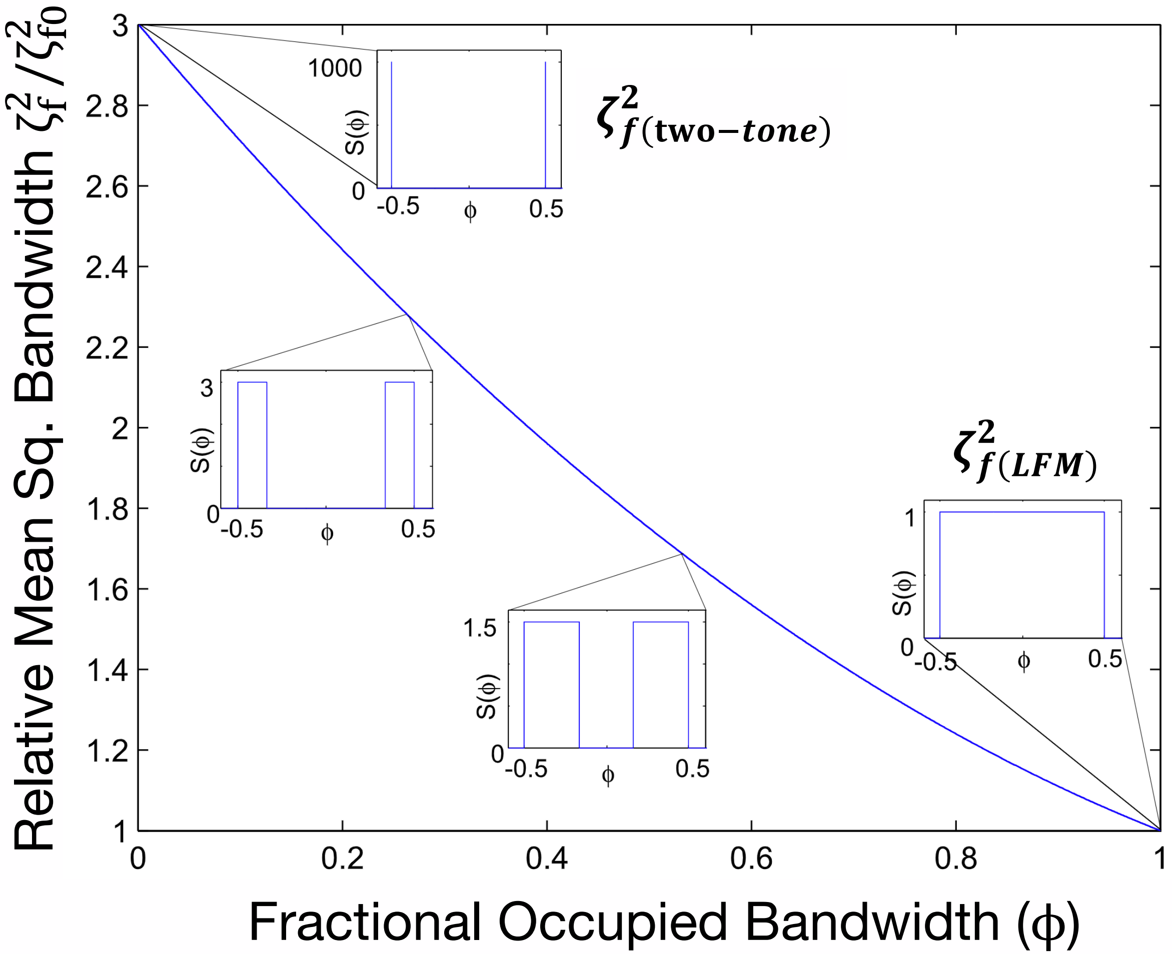


High Accuracy Delay Estimation

- 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
  - $\frac{E_s}{N_0}$: post-processed SNR



[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.

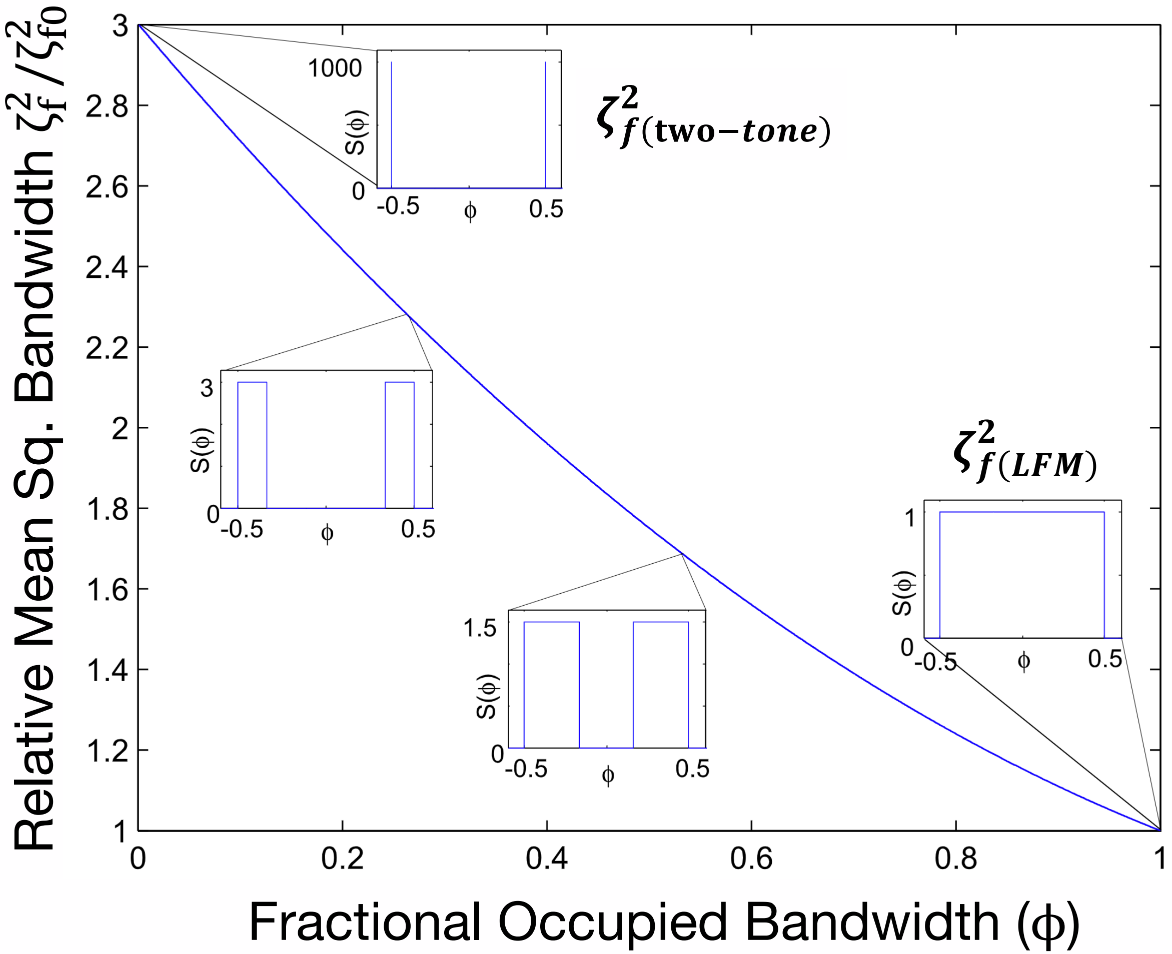
High Accuracy Delay Estimation

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

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

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

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



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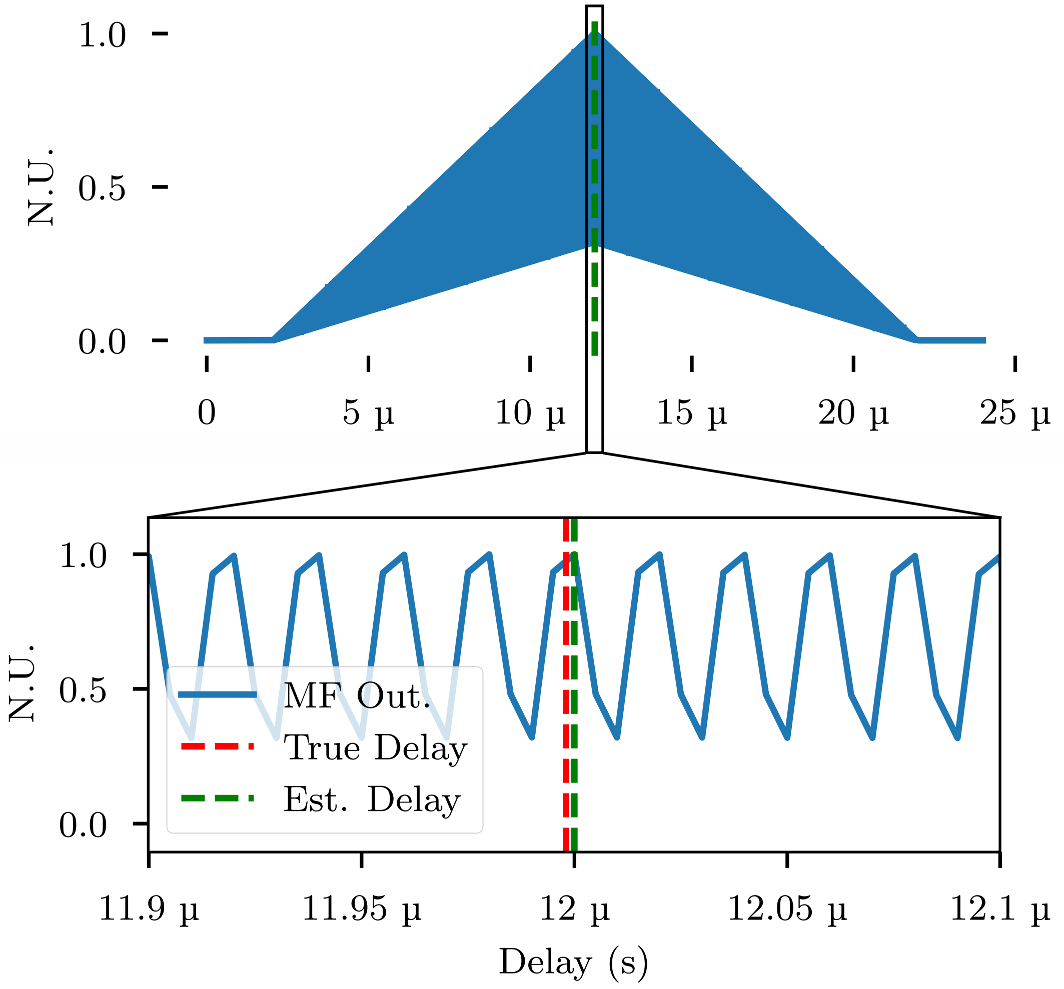
Delay Estimation

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

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

- High SNR typically required to disambiguate correct peak

- Many other waveforms exist which balance accuracy and ambiguity



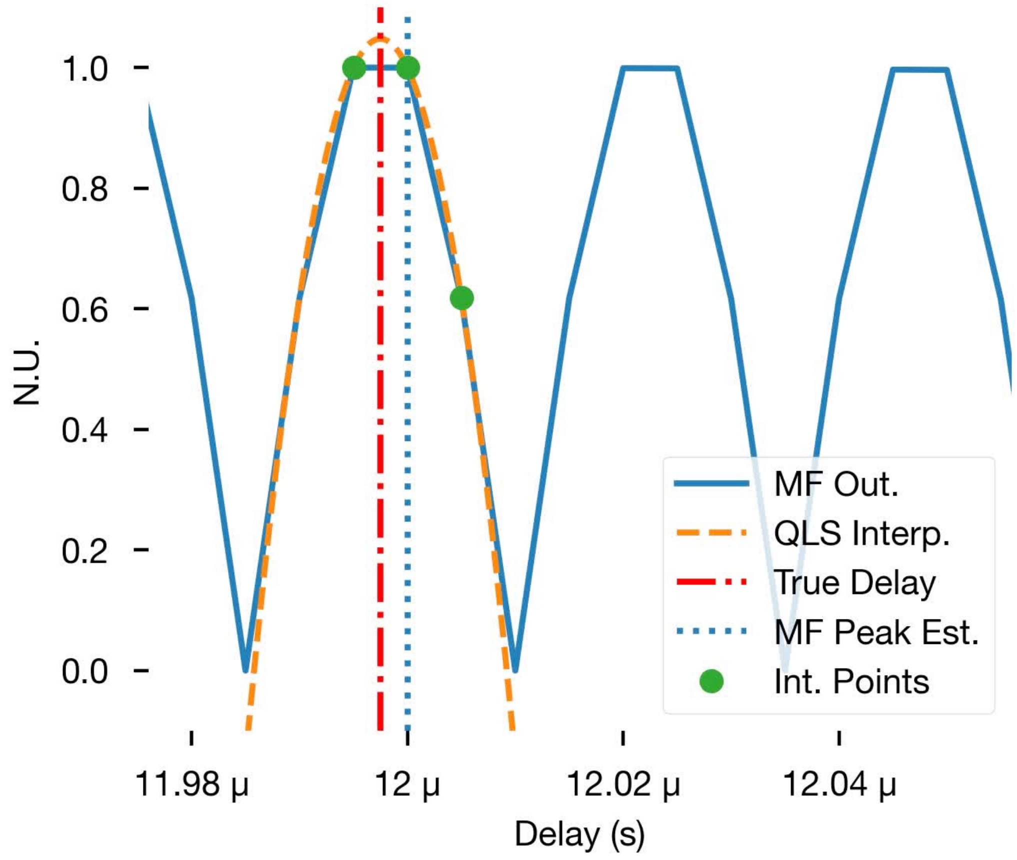
Delay Estimation Refinement

- MF causes estimator bias due to time discretization limited by sample rate
- Refinement of MF obtained using Quadratic Least Squares (QLS) fitting to find true delay based on three sample points

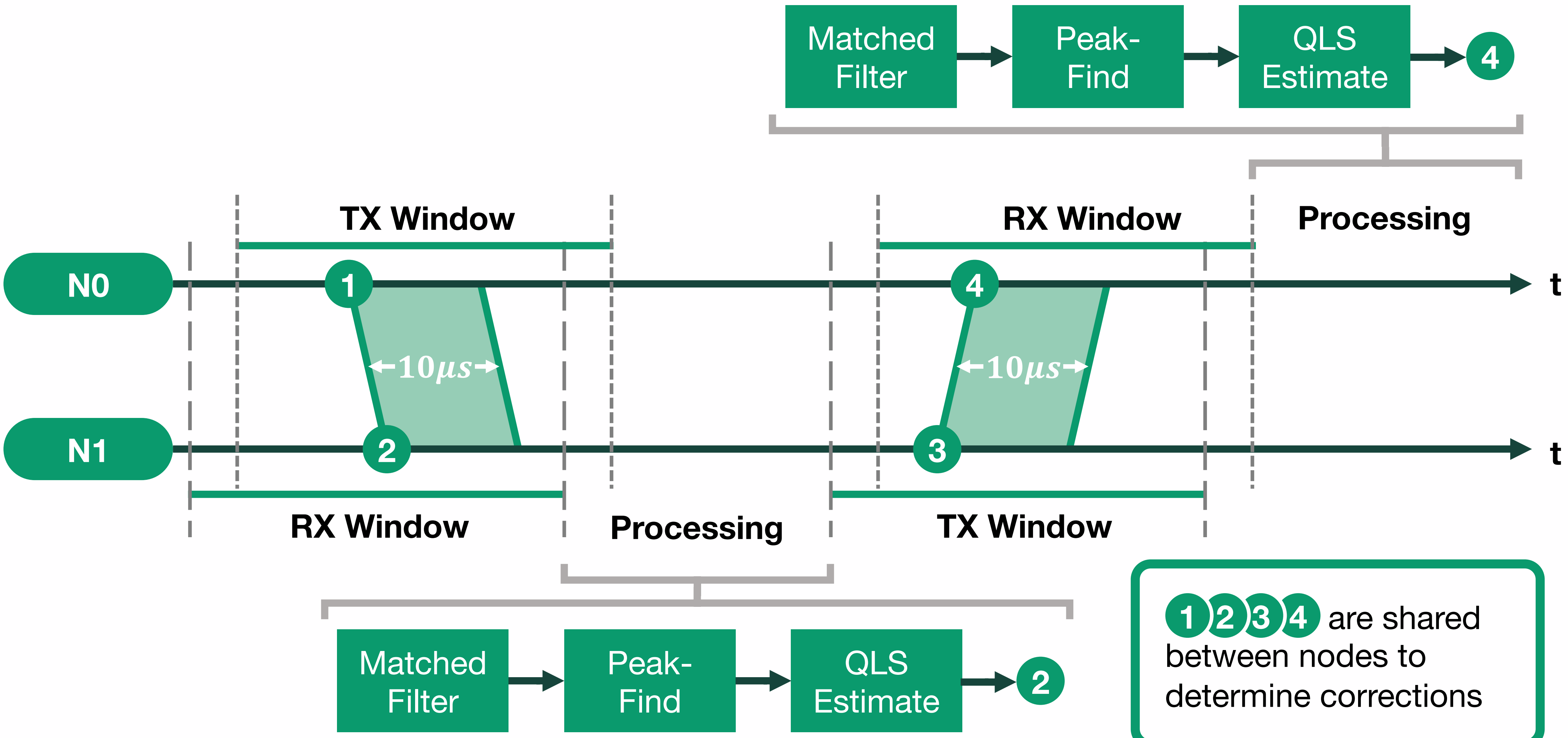
$$\hat{\tau} = \frac{T_s}{2} \frac{s_{\mathrm{MF}}[n_{\max} - 1] - s_{\mathrm{MF}}[n_{\max} + 1]}{s_{\mathrm{MF}}[n_{\max} - 1] - 2s_{\mathrm{MF}}[n_{\max}] + s_{\mathrm{MF}}[n_{\max} + 1]}$$

where

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

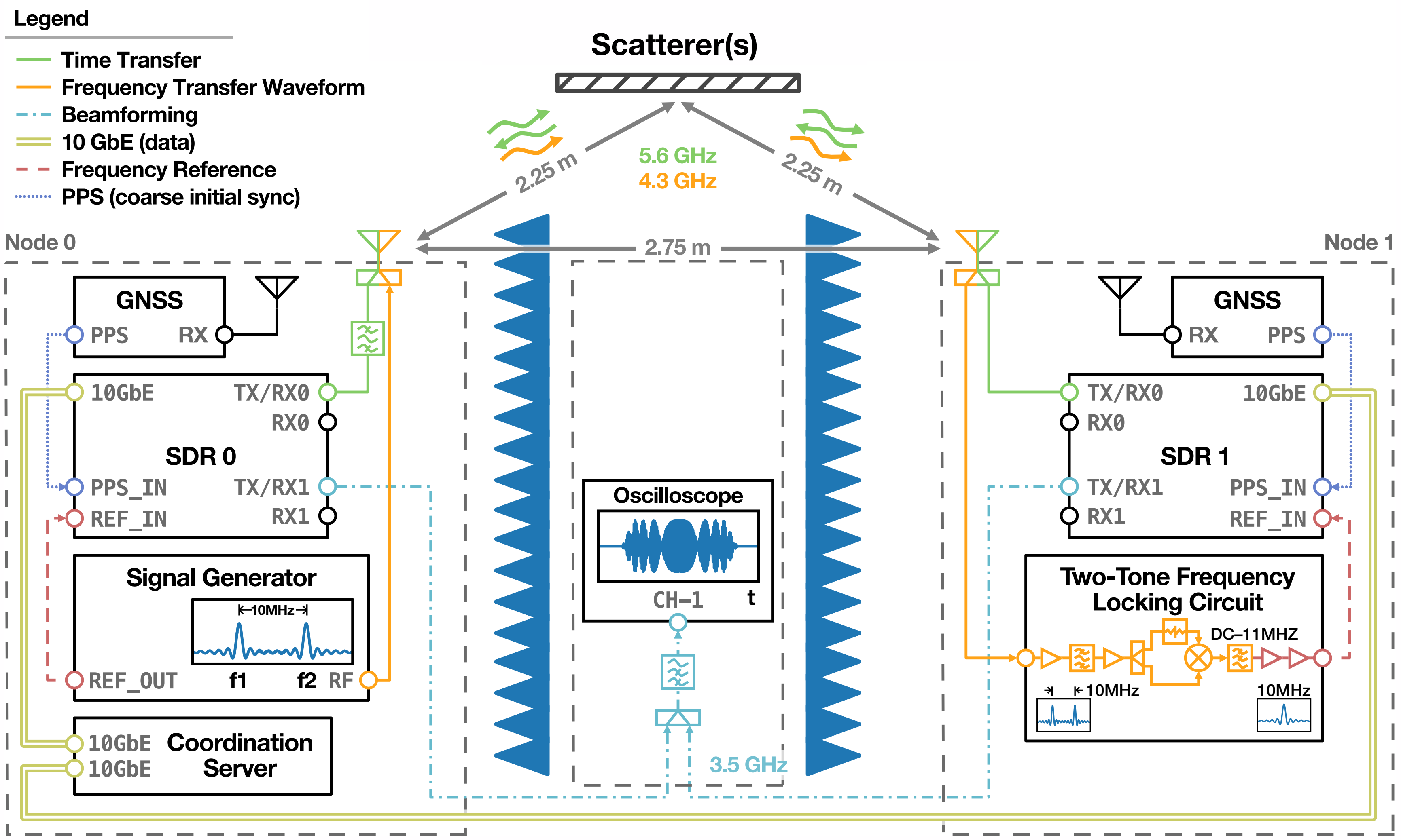


Time Estimation Process



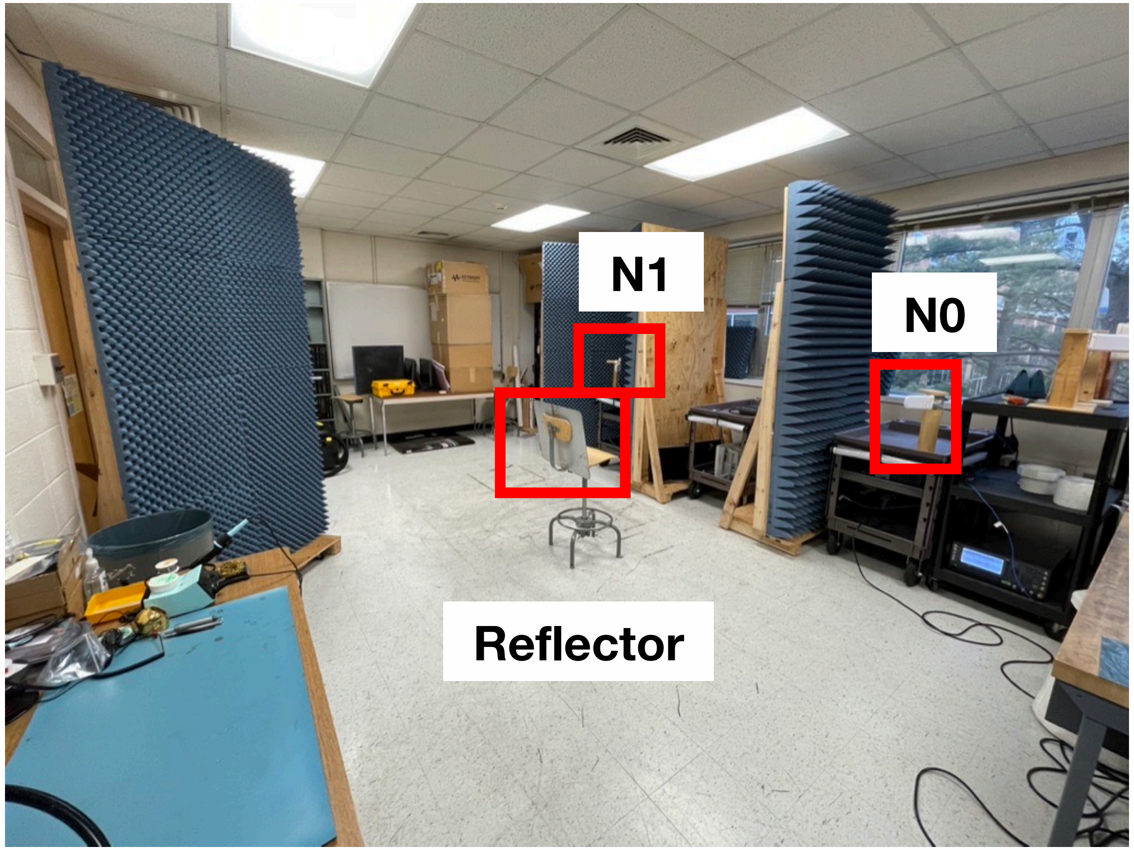
1 2 3 4 are shared between nodes to determine corrections

System Configuration

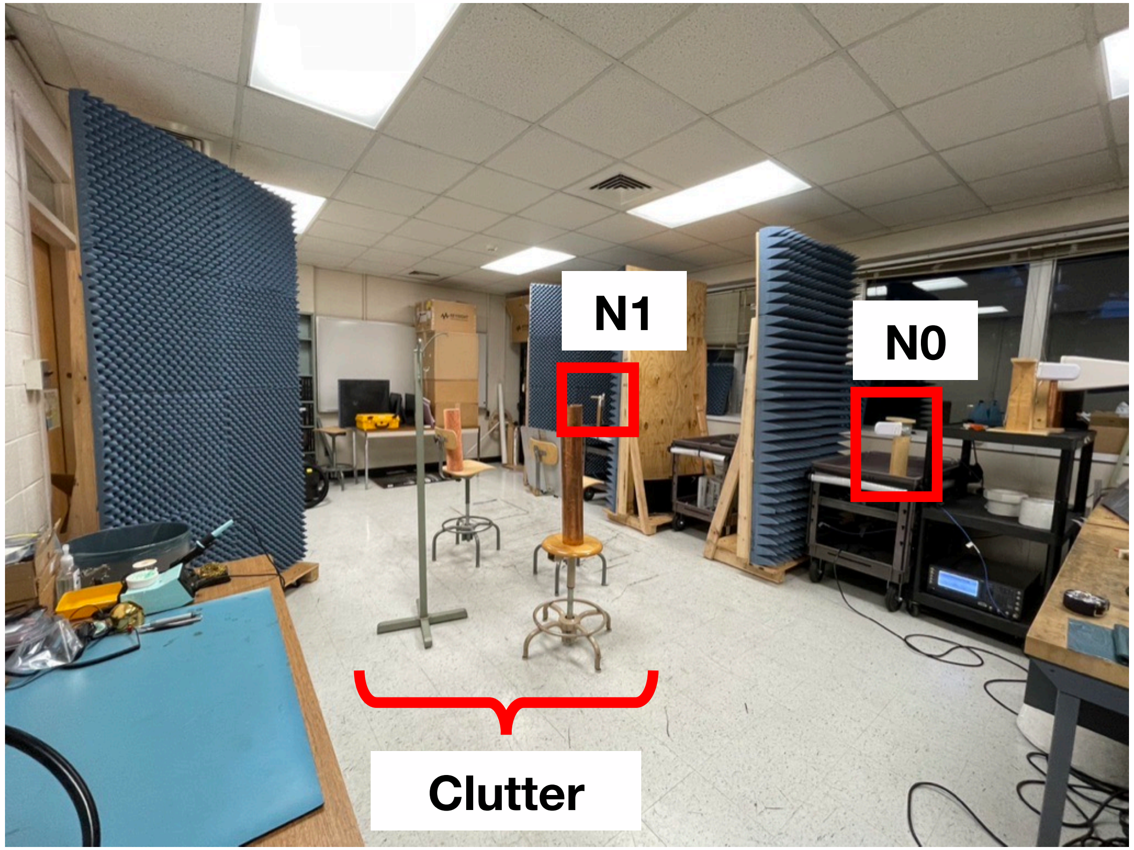


System Configuration

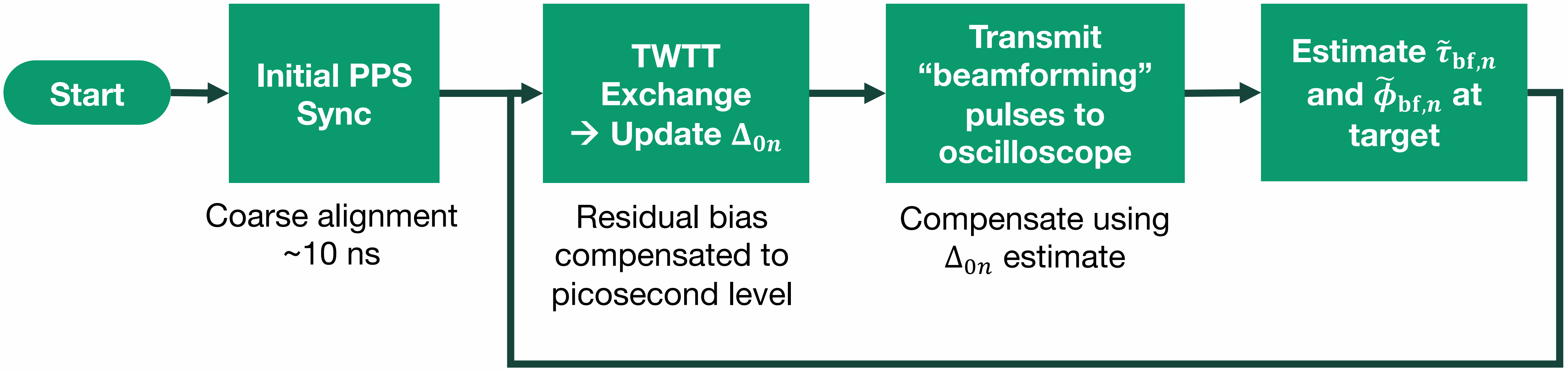
Single Scatterer // "No Clutter"



Multiple Scatterers // "With Clutter"



System State Flow

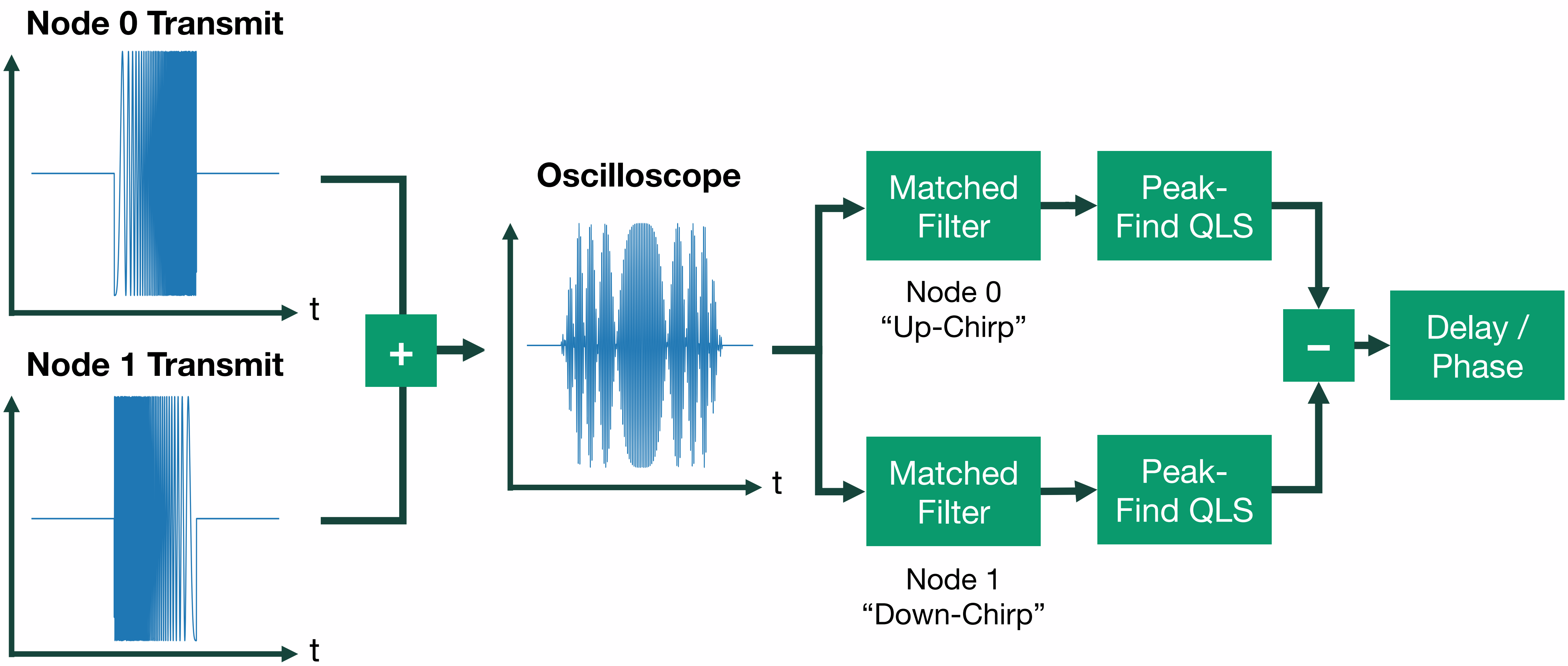


Where

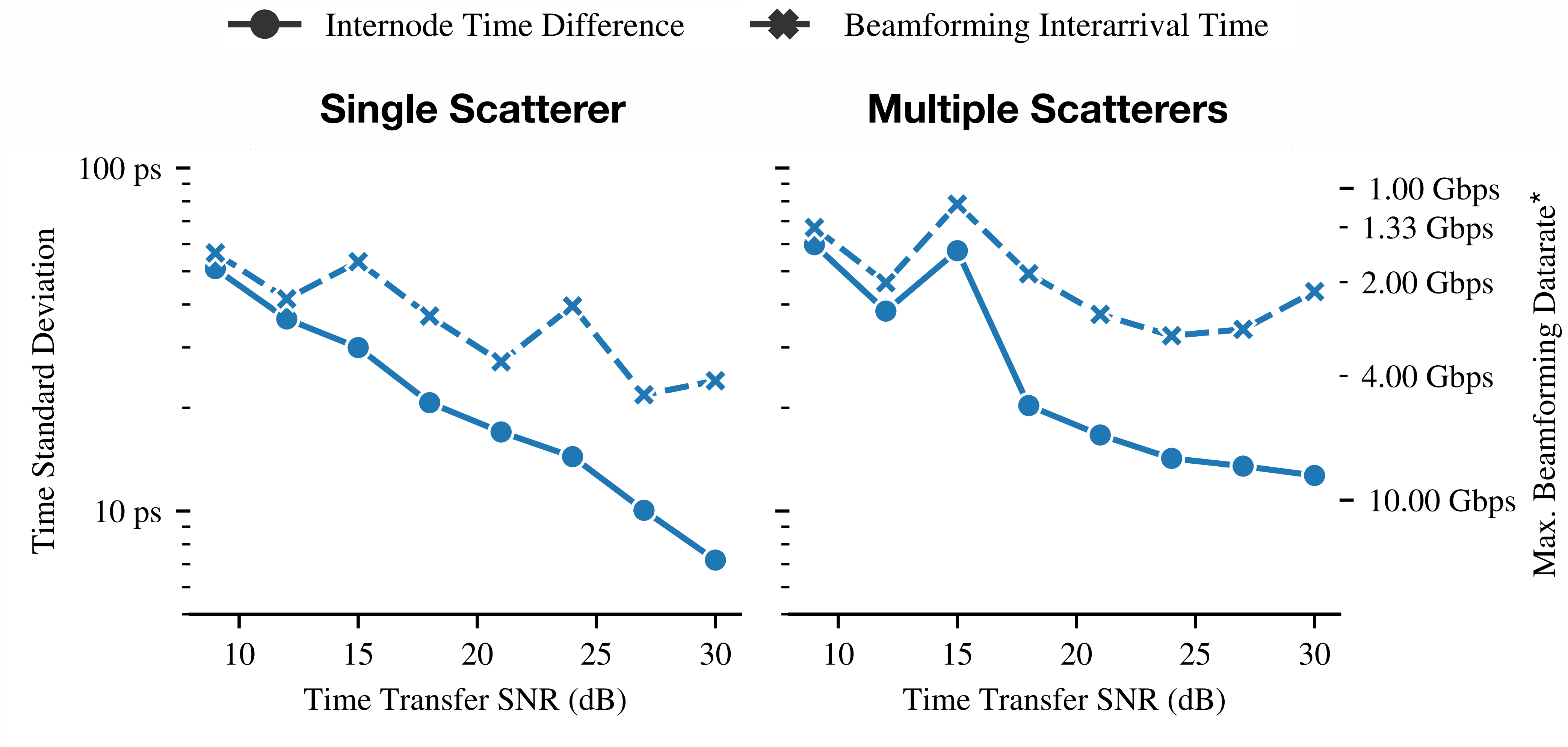
$\tilde{\tau}_{bf,n}$ → estimated beamforming time of arrival of pulse transmitted by node n

$\tilde{\phi}_{bf,n}$ → estimated beamforming phase of pulse transmitted by node n

System Performance Evaluation

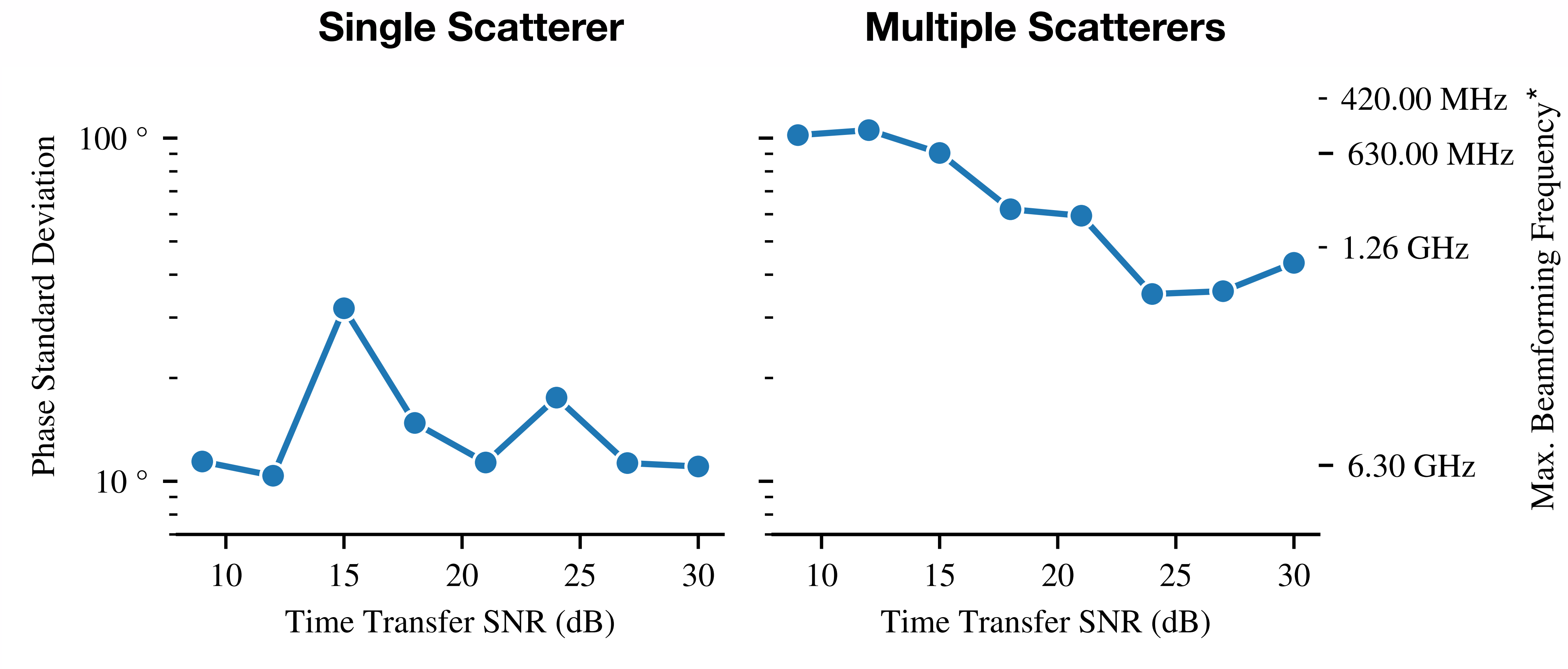


System and Inter-Pulse Arrival Time Differences



* Maximum theoretical BPSK throughput; $\Pr(\boldsymbol{G_c} \geq \mathbf{0.9}) > \mathbf{0.9}$

Inter-Pulse Arrival Phase Differences



* Maximum theoretical carrier frequency; $\Pr(\boldsymbol{G_c} \geq \mathbf{0.9}) > \mathbf{0.9}$

Conclusion

- Discussed our technique for high accuracy wireless time-frequency synchronization for distributed antenna arrays
- Demonstrated time and frequency synchronization performance in multiple wireless non-line-of-sight scenarios

Scenario	System Error	Beamforming Error			
	Time (ps)	Time (ps)	Max BPSK* (Gbps)	Phase (°)	Max Freq.† (GHz)
Single Scatterer	**7.19**	**21.81**	**4.59**	**11.04**	**5.71**
Multiple Scatterer	**12.69**	**32.44**	**3.08**	**43.30**	**1.45**

* Maximum theoretical BPSK throughput; $\Pr(\boldsymbol{G_c} \geq \mathbf{0.9}) > \mathbf{0.9}$

† Maximum theoretical carrier frequency; $\Pr(\boldsymbol{G_c} \geq \mathbf{0.9}) > \mathbf{0.9}$

Questions?

Thank you to our project sponsors and collaborators:

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National Science Foundation

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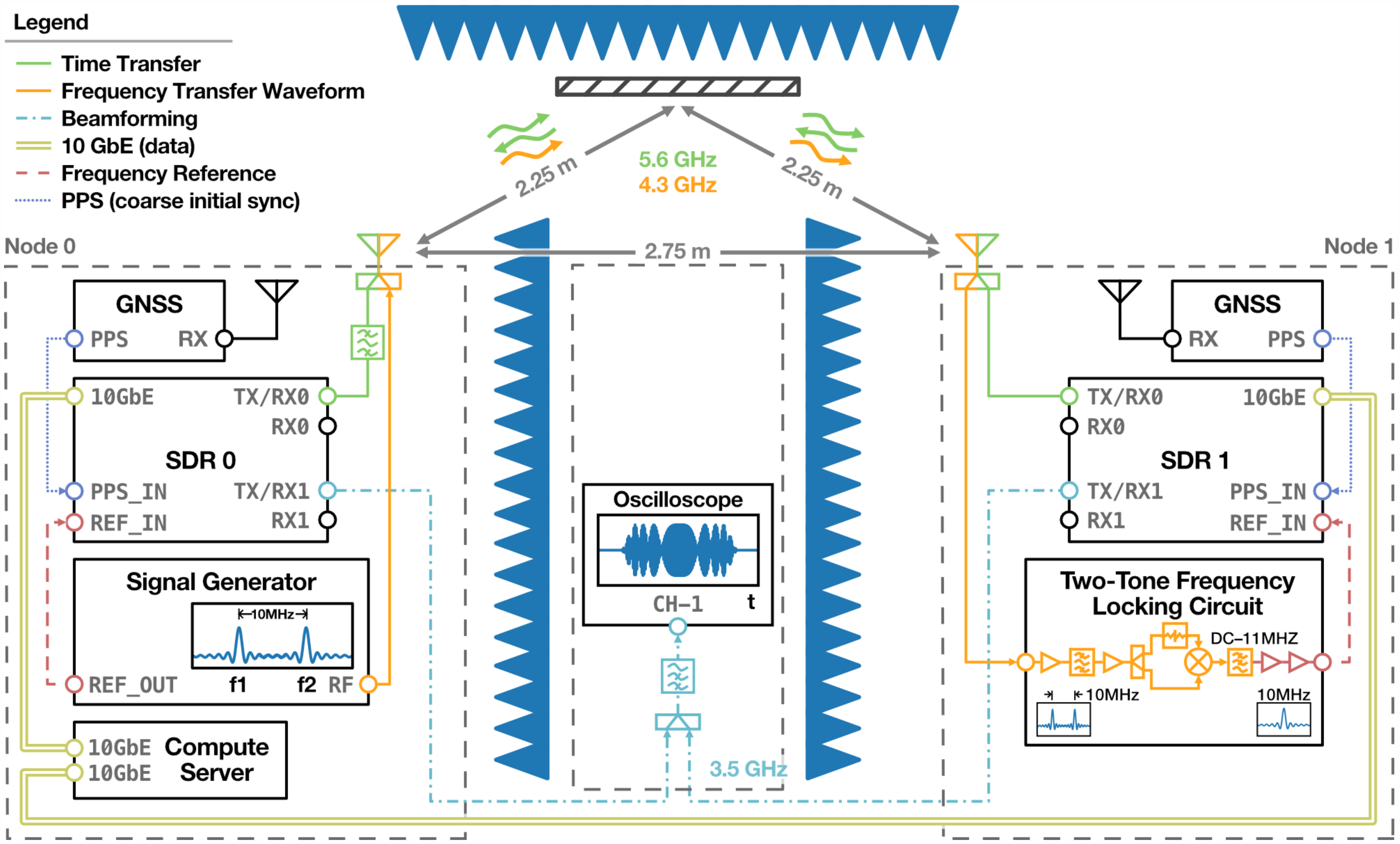
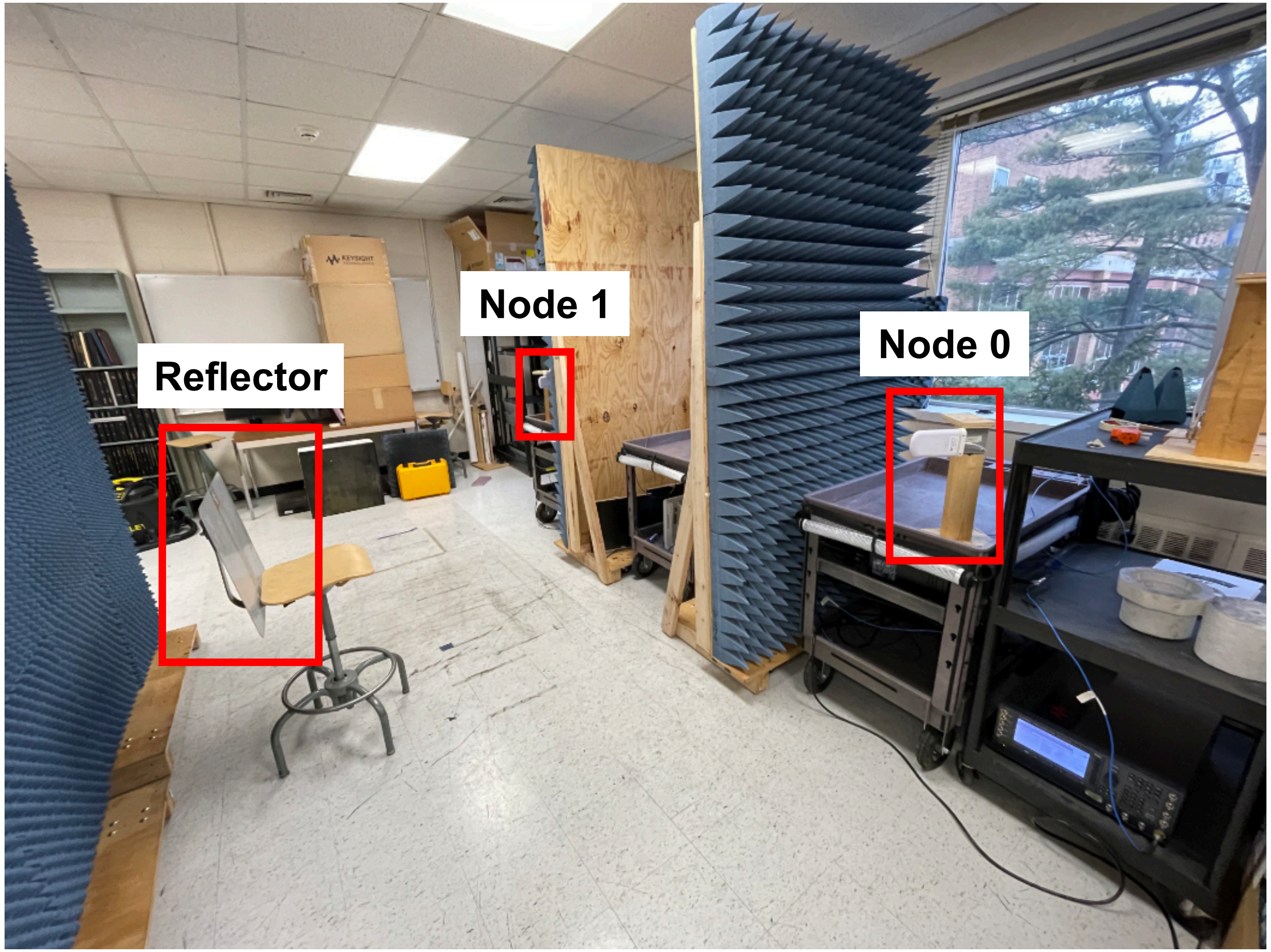
Backup Slides

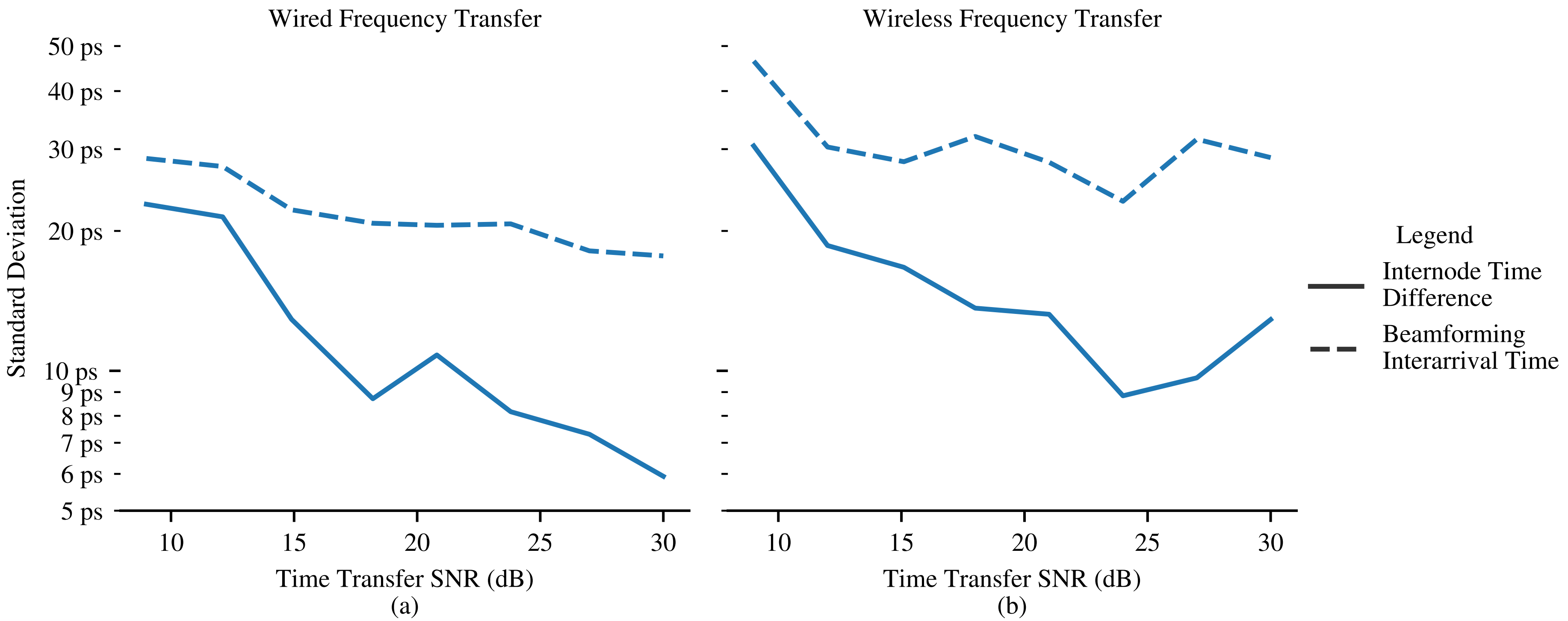
System Configuration



System Configuration



System Time and Inter-Pulse Arrival Differences



Note:

Each SNR taken with ~40 data points over ~1 minute

More points would likely smooth out the curves

Wired frequency transfer (wireless time transfer):

- System time accuracy: 5.93 ps
- Cabled beamforming accuracy: 17.67 ps
  - Max. data rate: 5.6 Gb/s
- Cabled beamforming phase accuracy: 0.67° @ 3.5 GHz
  - Max. beamforming frequency: 125 GHz

Fully wireless time-frequency transfer:

- System time accuracy: 8.84 ps
- Cabled beamforming accuracy: 23.17 ps
  - Max. data rate: **4.3 Gb/s**
- Cabled beamforming phase accuracy: 10° @ 3.5 GHz
  - Max. beamforming frequency: **8.4 GHz**