Wireless Time and Phase Alignment for Wideband Beamforming in Distributed Phased Arrays

2023 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting

TU-A1.1A.9 | Advances in Phased Array Antennas

LLNL-PRES-851645

Jason M. Merlo and Jeffrey A. Nanzer

Michigan State University, East Lansing, MI, USA

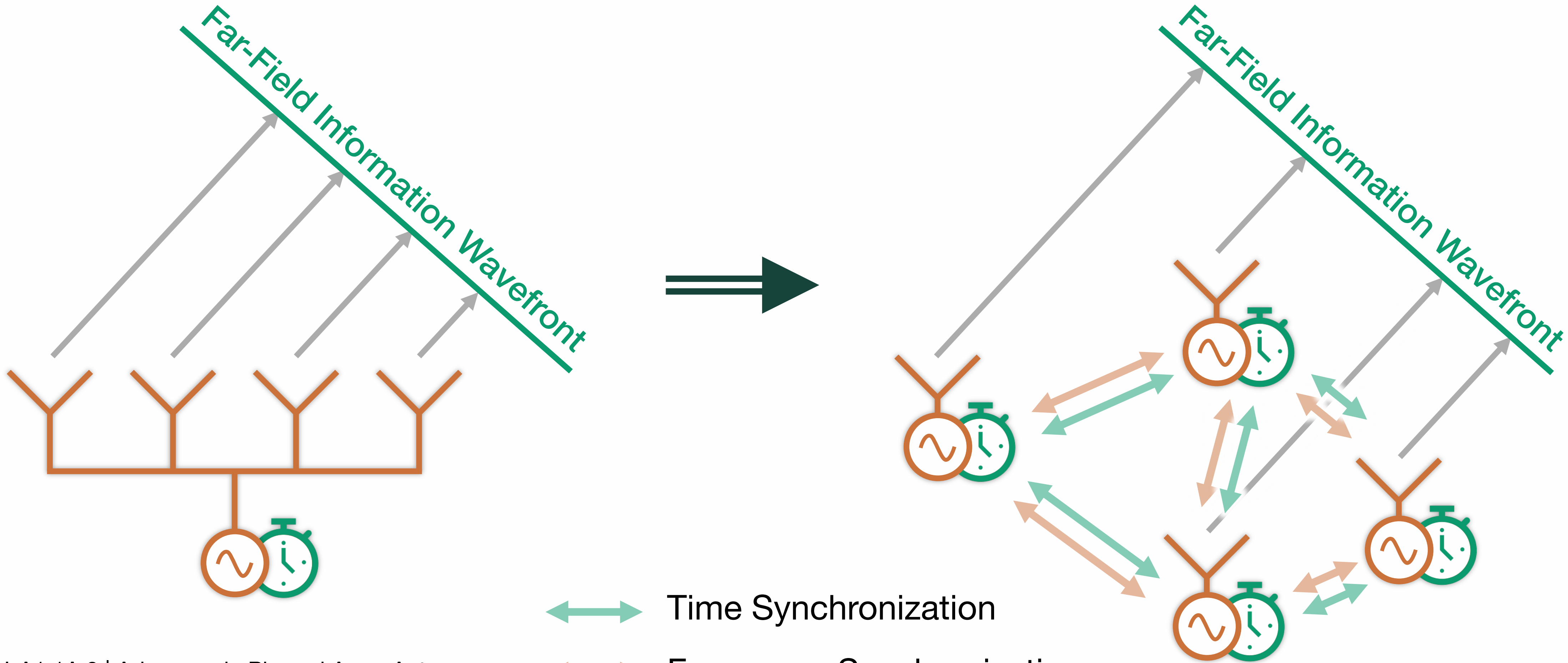
Outline

1. Overview & Applications
2. Array Coordination
3. Distributed Phased Array Beamsteering
4. Experimental Results

Distributed Phased Array Overview

Traditional Phased Array

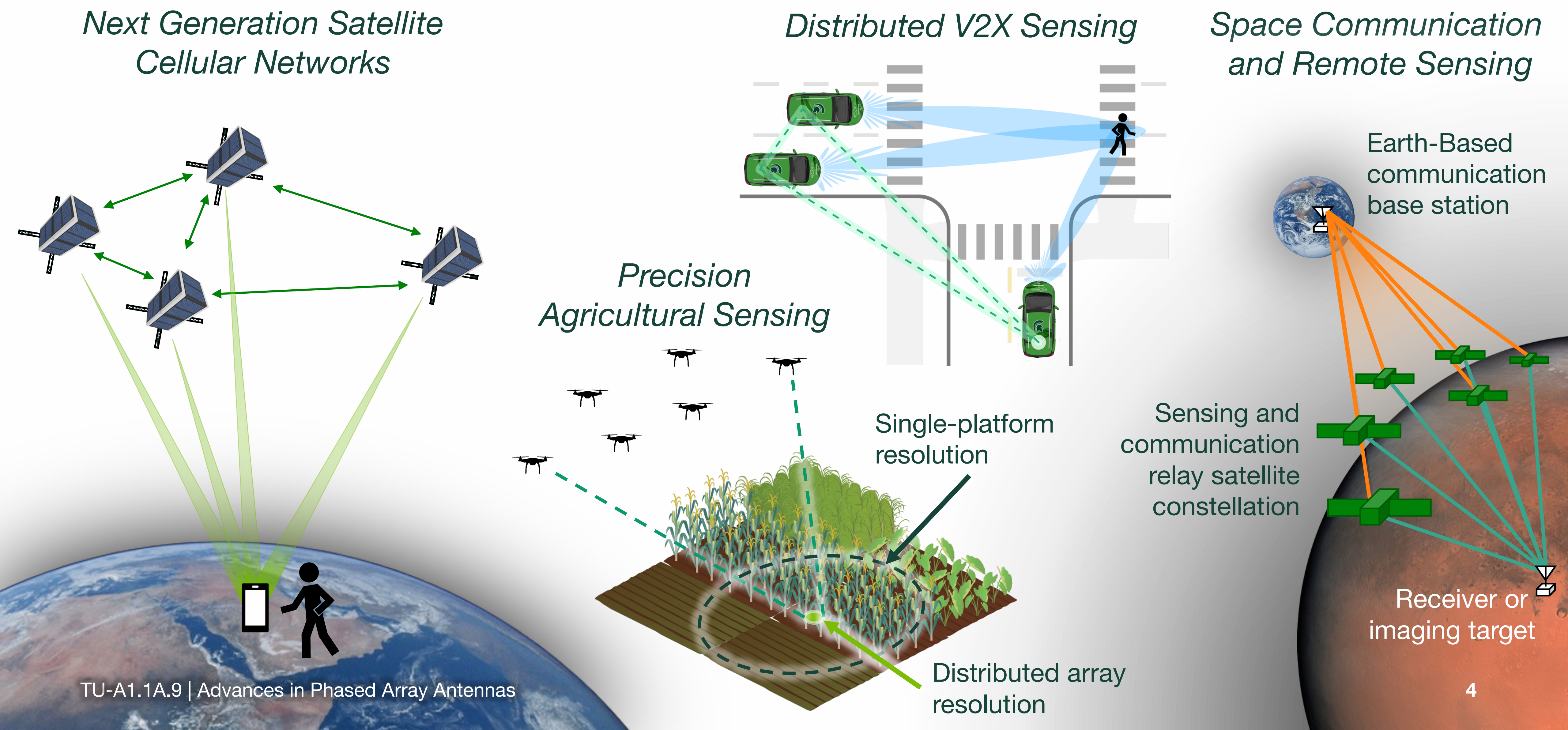
Distributed Phased Array



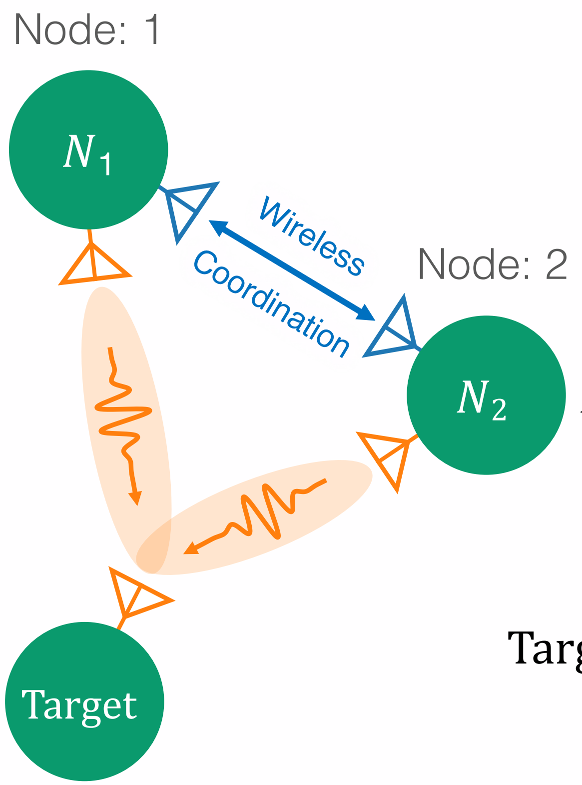
Time Synchronization

Frequency Synchronization

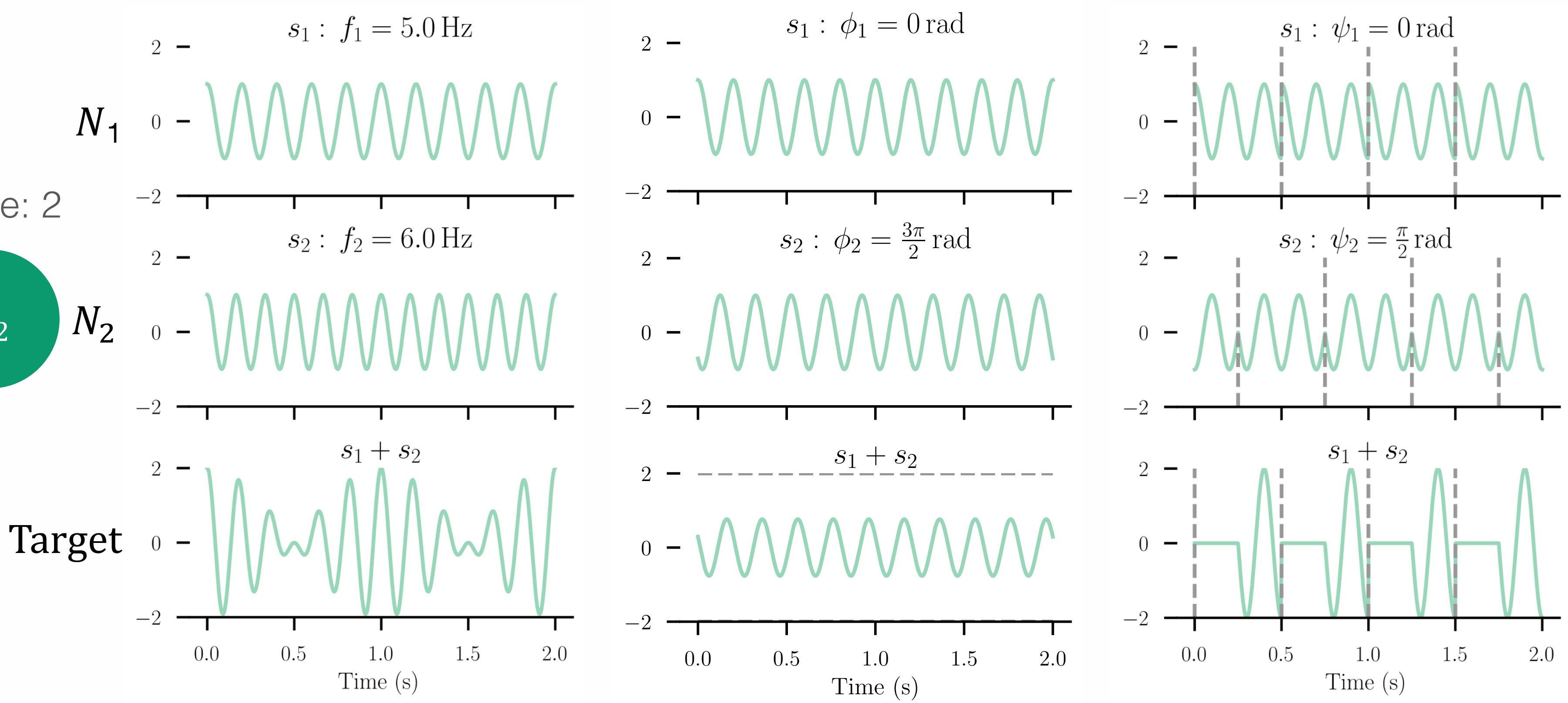
Distributed Phased Array Applications



Distributed Phased Array Synchronization



Frequency Syntonization | **Phase Alignment** | **Time Synchronization**



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

Distributed Phased Array Performance

Probability of coherent gain:

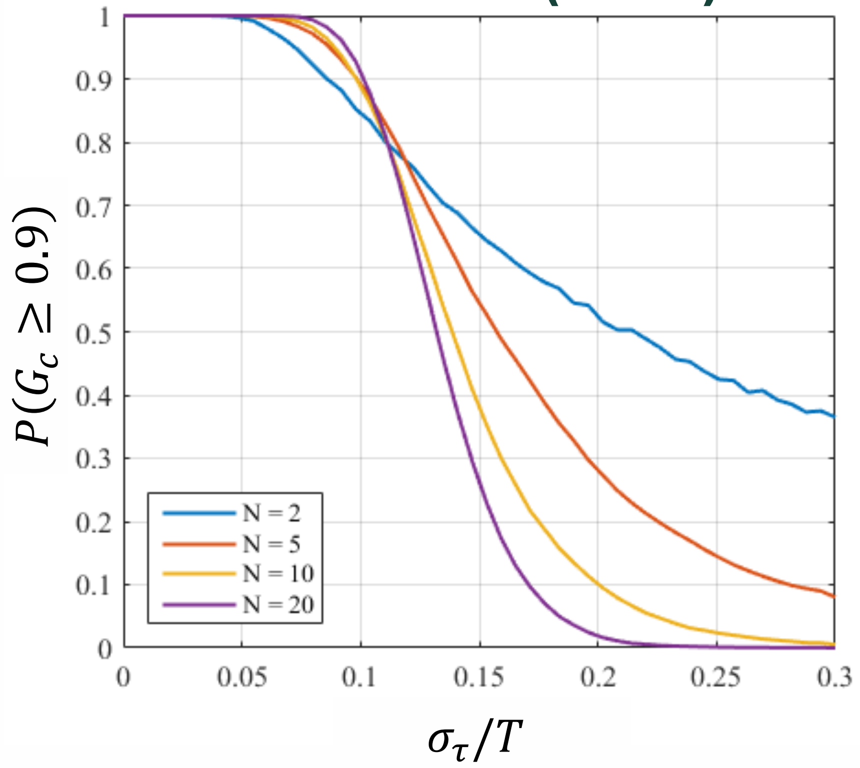
$$P(G_c \geq X)$$

where

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

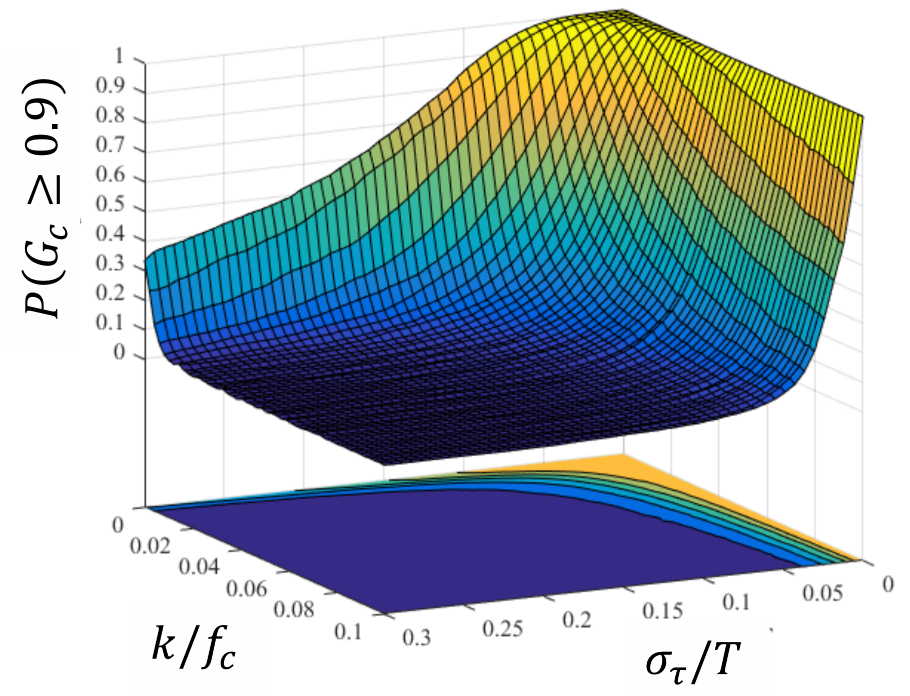
- s_r: received signal
- s_i: ideal signal

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.

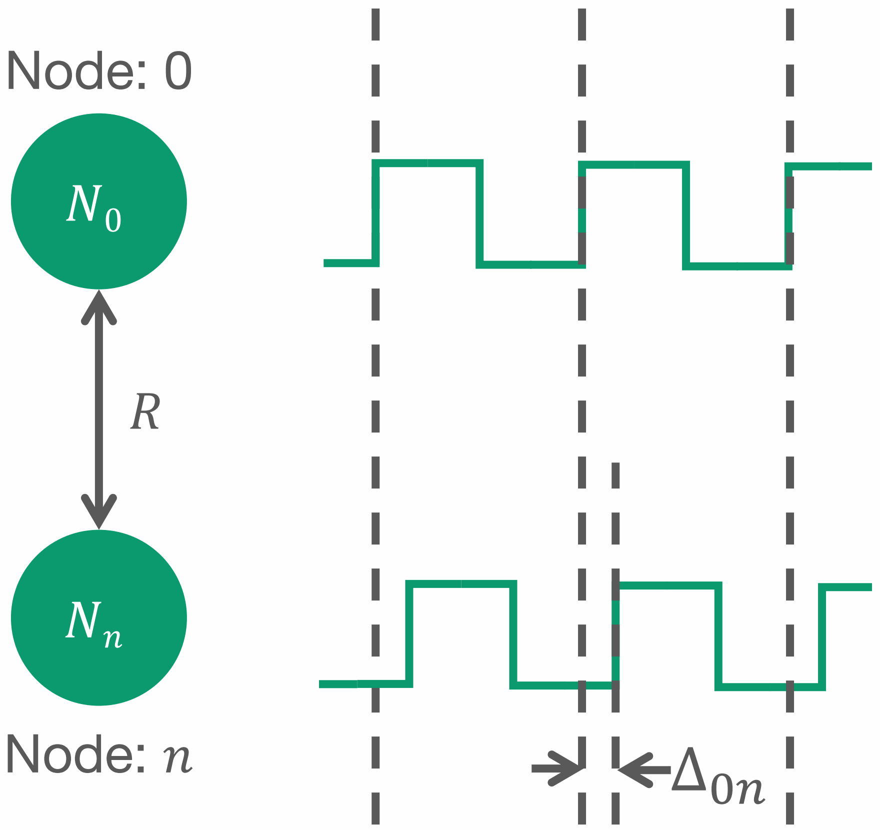
System Time Model

- Local time at node n:

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

  - 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



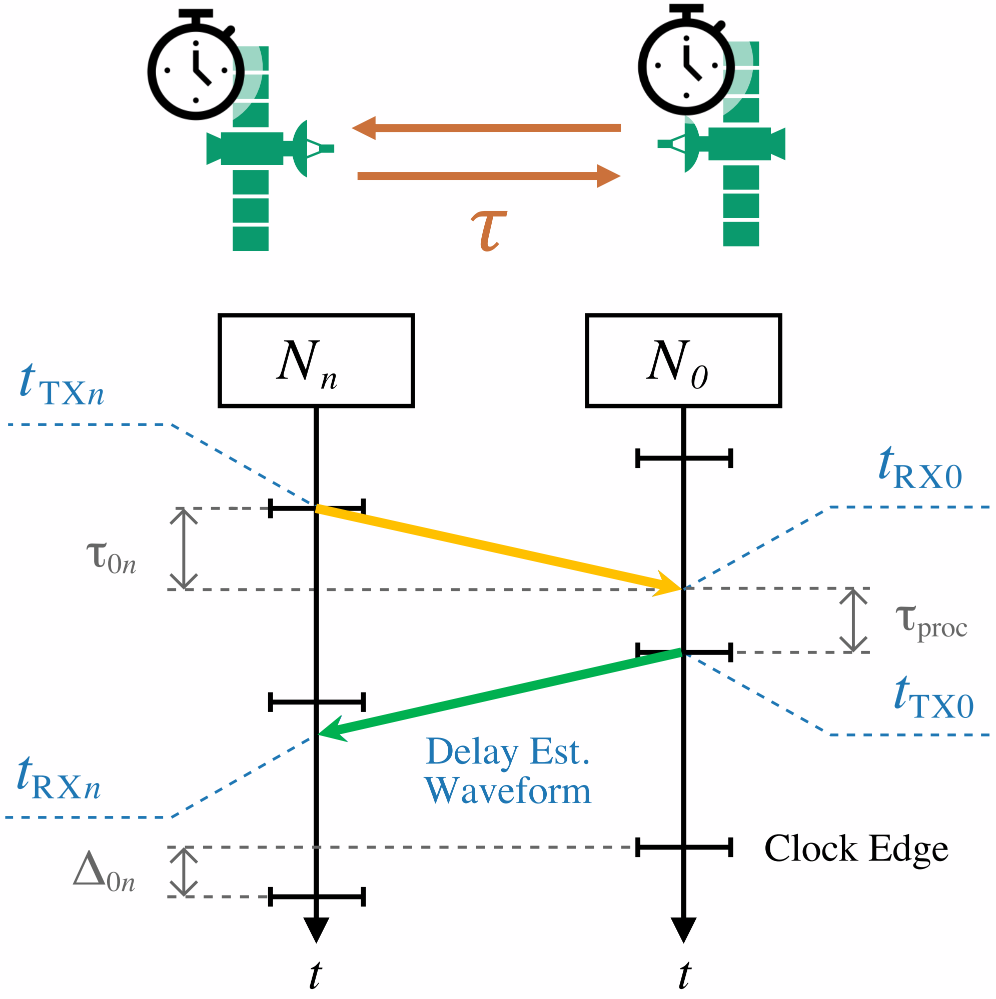
Time Synchronization Technique

Two-Way Time Synchronization

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

$$\Delta_{0n} = \frac{(T_{\mathrm{RX0}} - T_{\mathrm{TX}n}) - (T_{\mathrm{RX}n} - T_{\mathrm{TX0}})}{2}$$

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



High Accuracy Delay Estimation

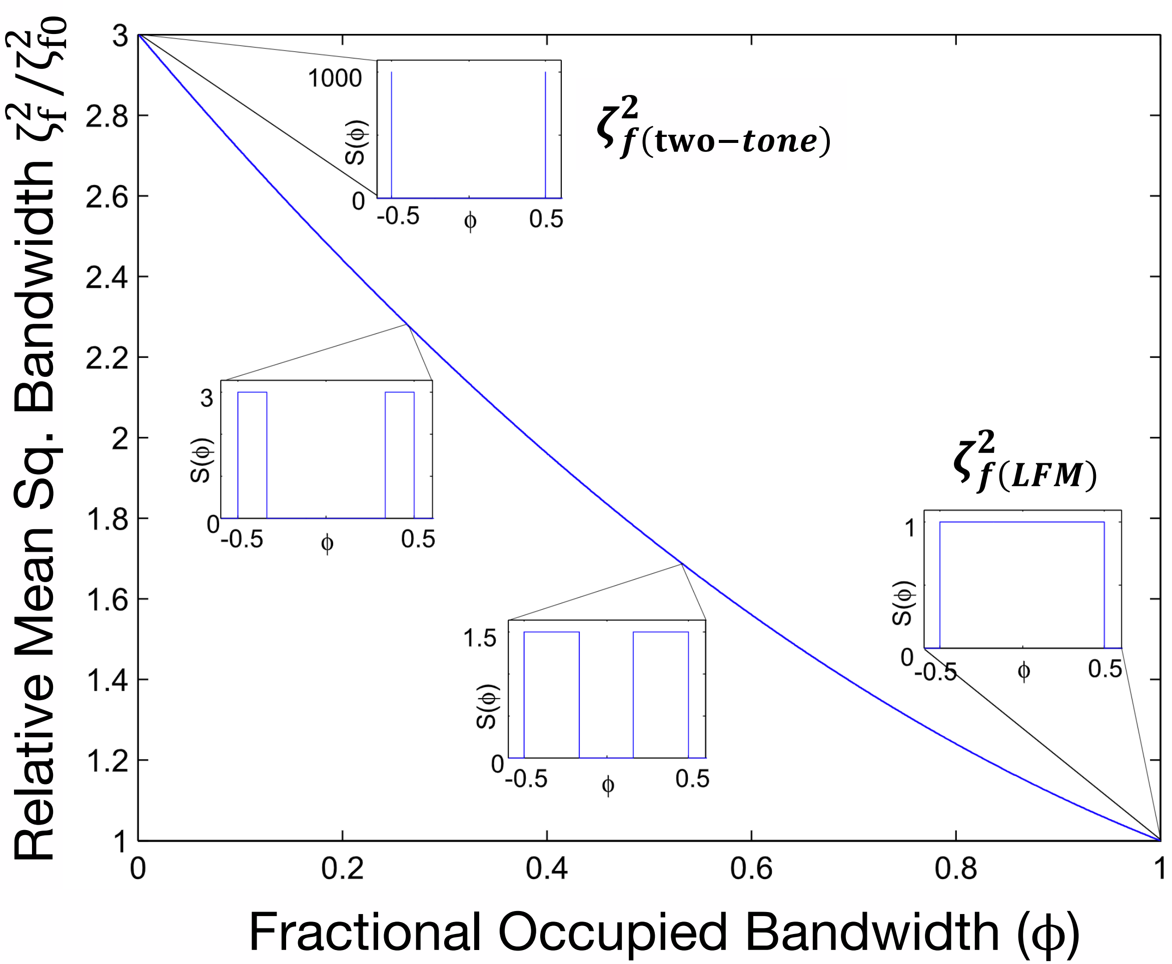
- The delay accuracy lower bound (CRLB) for time is given by

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

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

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

  - 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.

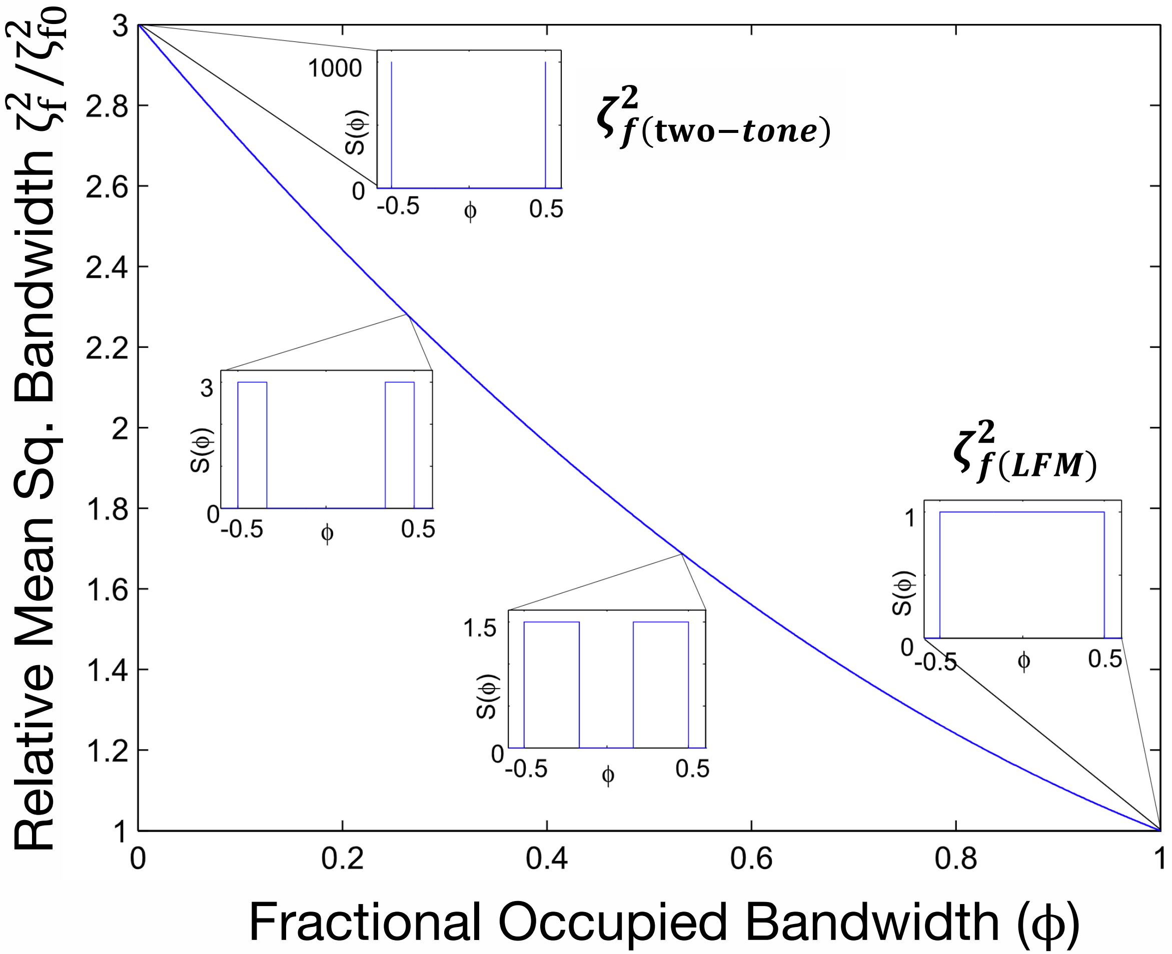
High Accuracy Delay Estimation

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

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

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

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



[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.

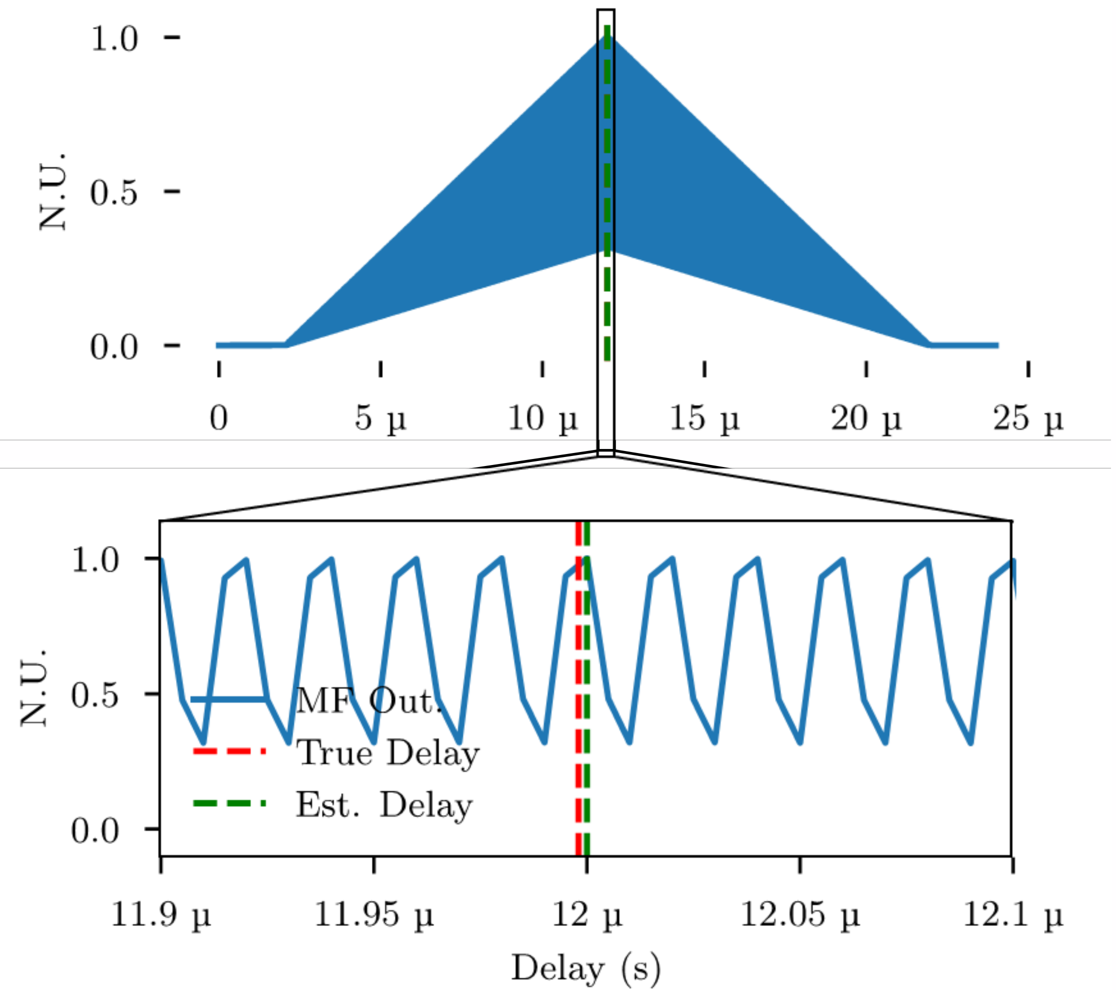
Delay Estimation

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

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

- Two-tone matched filter waveform is highly ambiguous

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



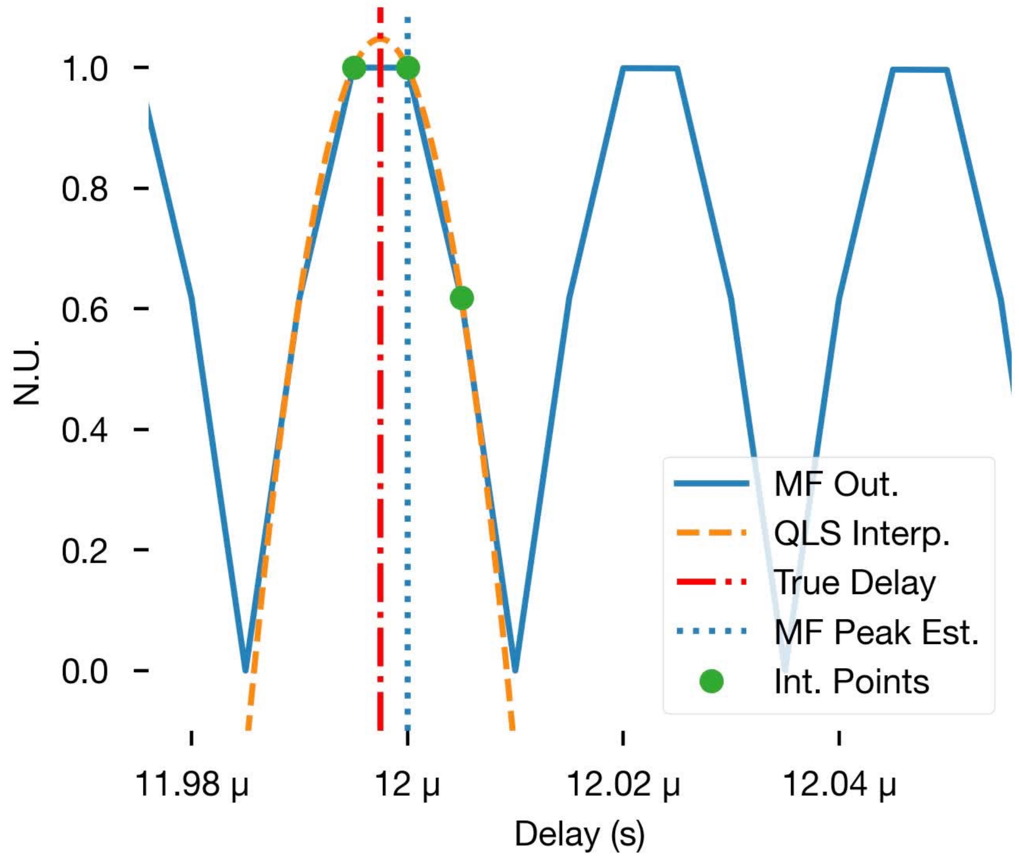
Delay Estimation Refinement

- 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

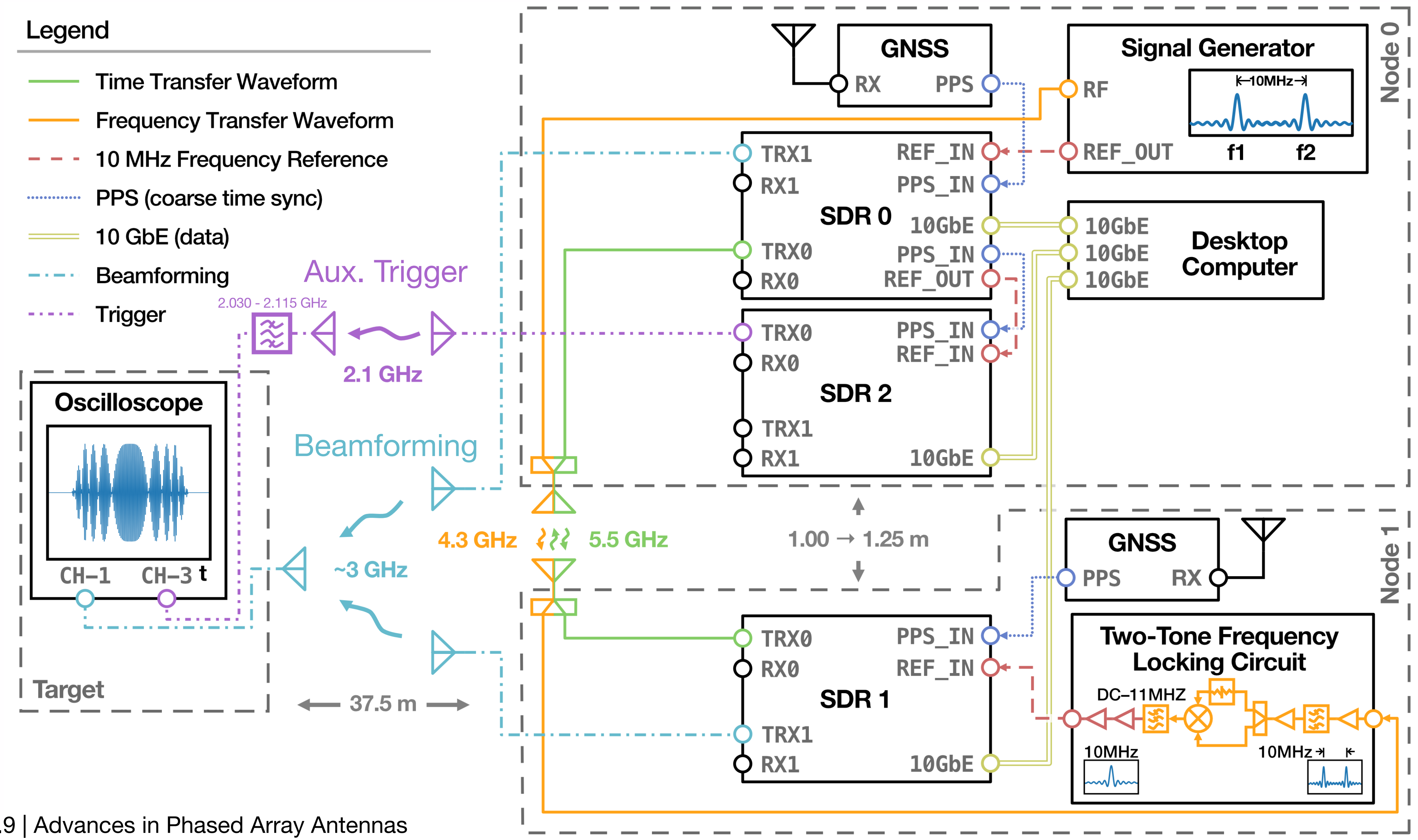
$$\hat{\tau} = \frac{T_s}{2} \frac{s_{\mathrm{MF}}[n_{\max} - 1] - s_{\mathrm{MF}}[n_{\max} + 1]}{s_{\mathrm{MF}}[n_{\max} - 1] - 2s_{\mathrm{MF}}[n_{\max}] + s_{\mathrm{MF}}[n_{\max} + 1]}$$

where

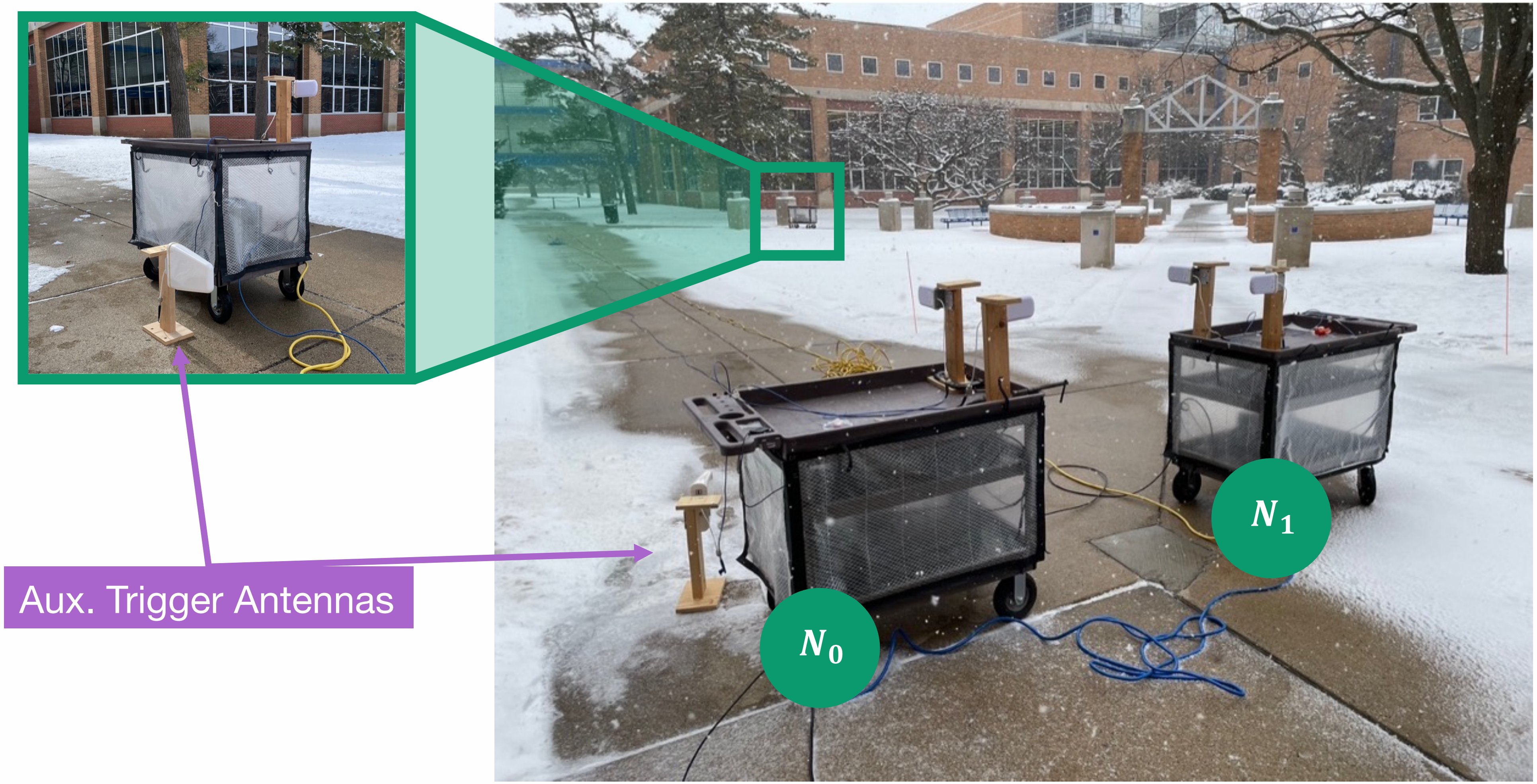
$$n_{\max} = \underset{n}{\operatorname{argmax}}\{s_{\mathrm{MF}}[n]\}$$



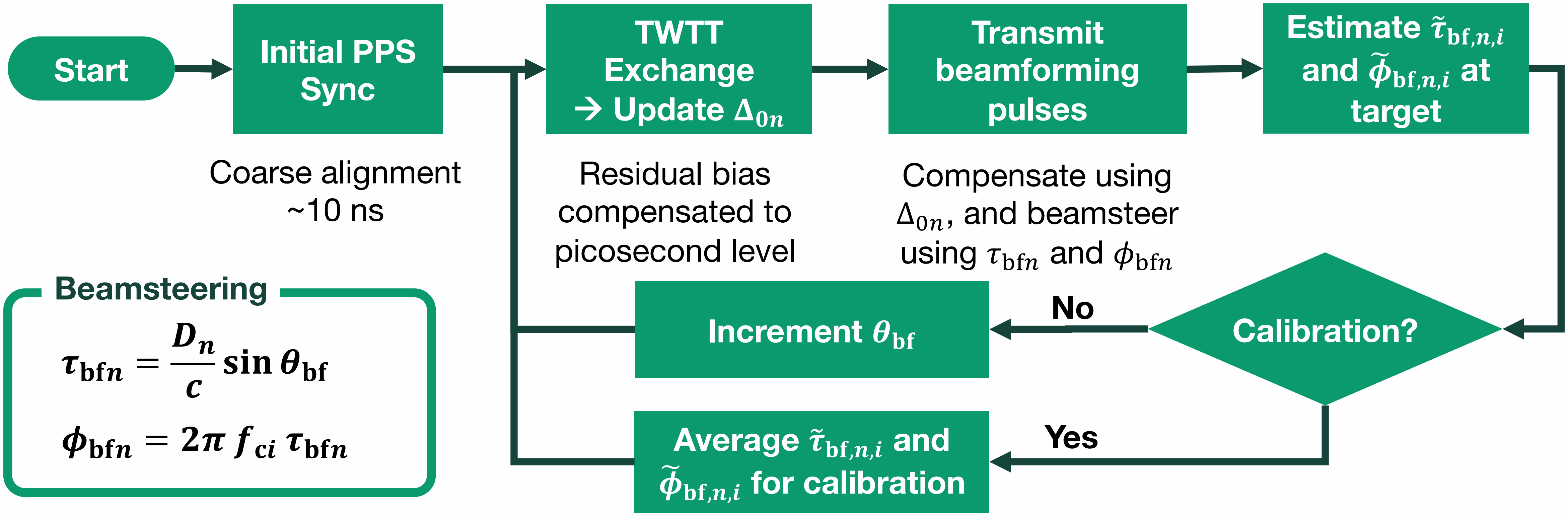
System Configuration



System Configuration



System State Flow



Beamsteering

$$\tau_{\mathrm{bf}n} = \frac{D_n}{c} \sin\theta_{\mathrm{bf}}$$

$$\phi_{\mathrm{bf}n} = 2\pi f_{ci}\, \tau_{\mathrm{bf}n}$$

Transmitted Waveform

$$s_n(t) = \sum_{i=0}^{I} \exp\left[j\pi(2f_{ci}\tau + k\tau^2) + j\phi_{\mathrm{bf}n}\right]$$

Subscripts

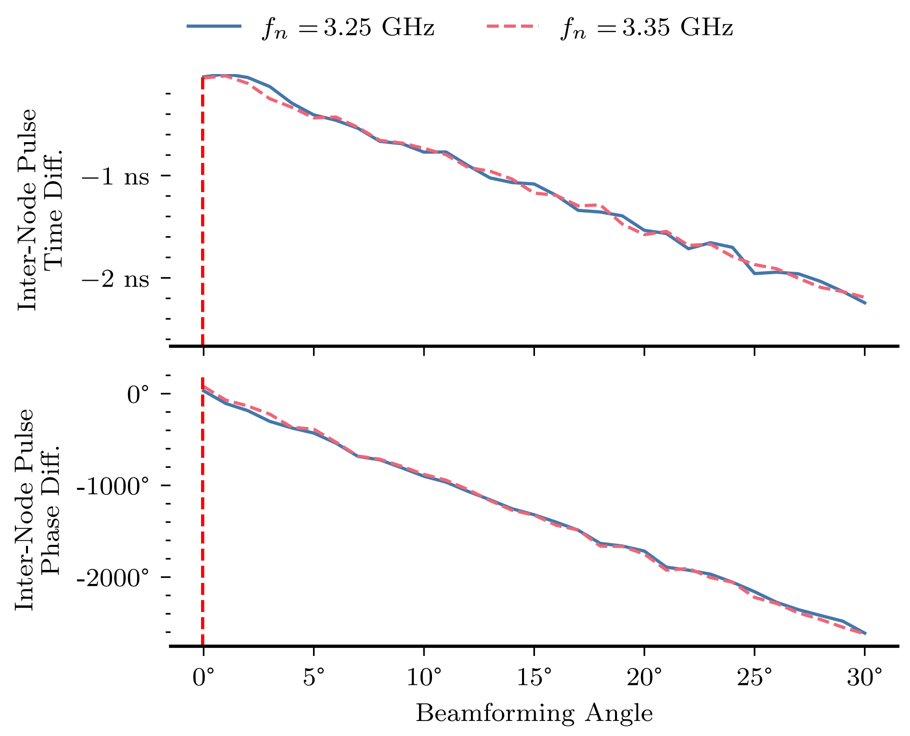
n: Node Index

i: Frequency Step Index

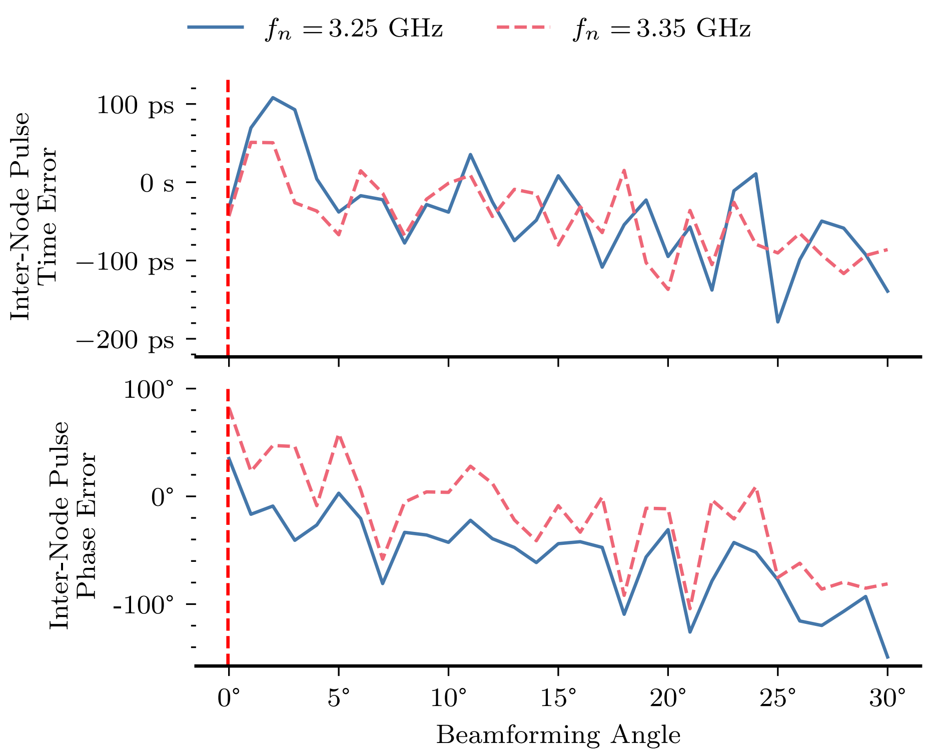
Beamforming Measurements

Target Location ~**0°**; Internode Range **~1.25m**

Direct Measurements



Beamforming Error



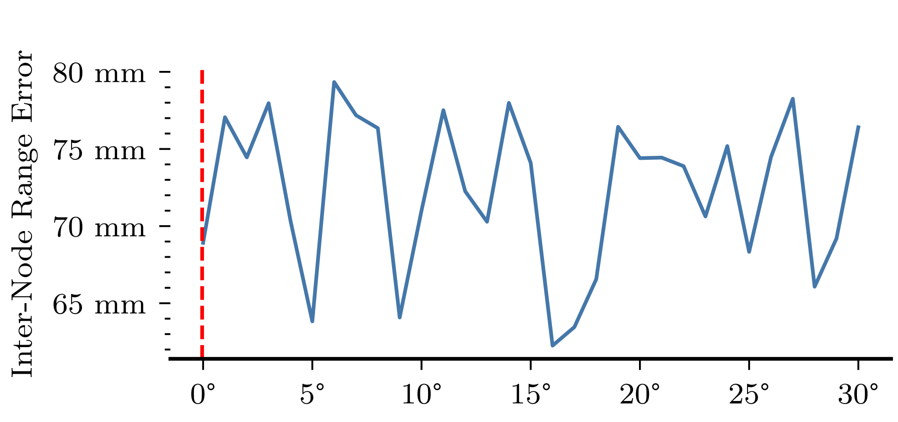
----- Target Location Angle

Total Error (All Freq. & Angle) : μ_τ = **–42.28 ps** , σ_τ = **55.59 ps** and μ_ϕ = **–37.09°**, σ_ϕ = **47.96°**

Beamforming Measurements

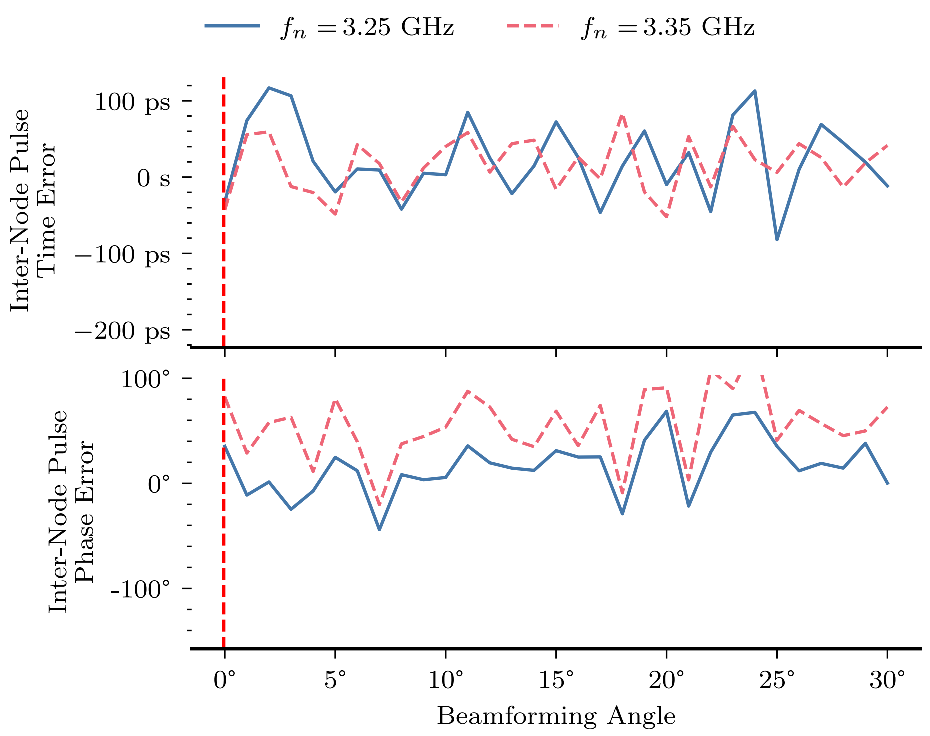
Target Location ~0°; Internode Range ~1.25m

Internode Ranging Bias ($D_n - \widetilde{D}_n$)



Range Compensated Beamforming Error

(Mean ranging bias removed)



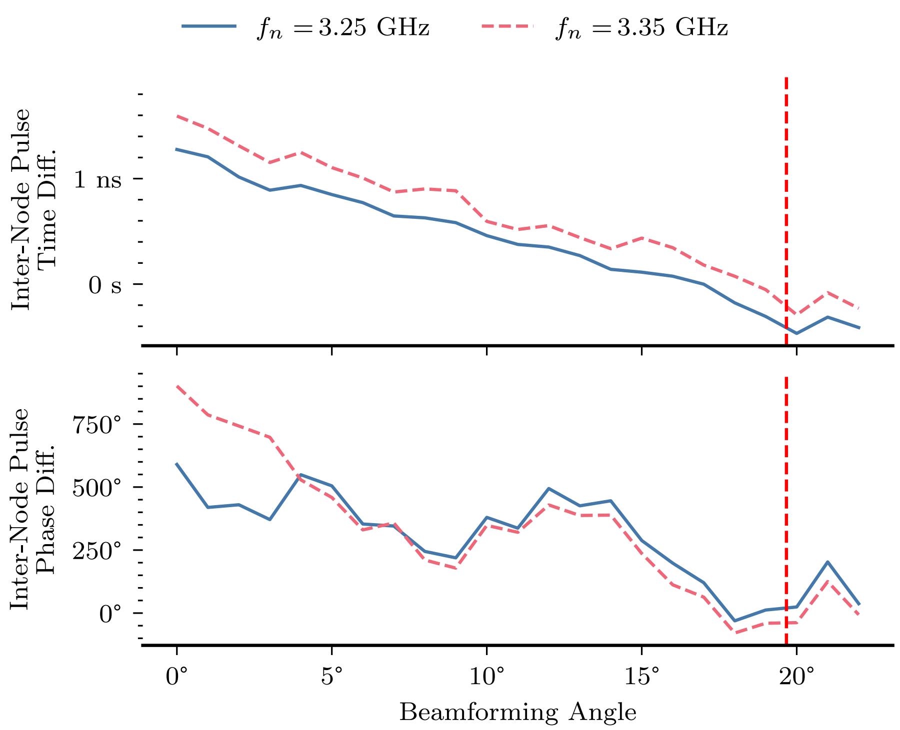
----- Target Location Angle

Total Range-Compensated Error: μ_τ = **19.42 ps** , σ_τ = **43.26 ps** and μ_ϕ = **36.22°**, σ_ϕ = **35.76°**

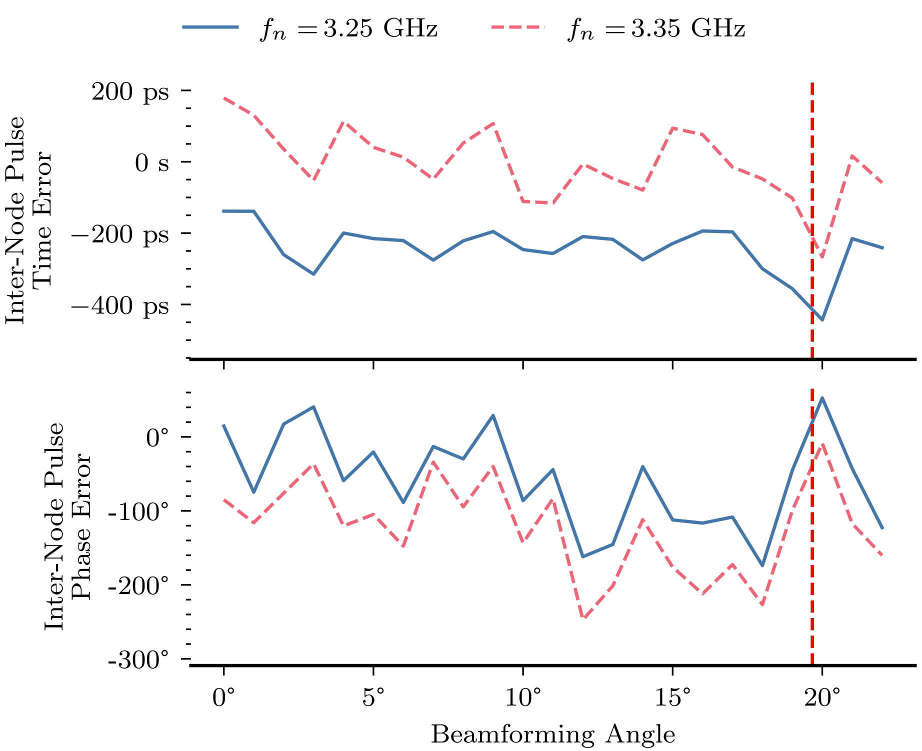
Beamforming Measurements

Target Location **~20°**; Internode Range **~1.25m**

Direct Measurements



Beamforming Error



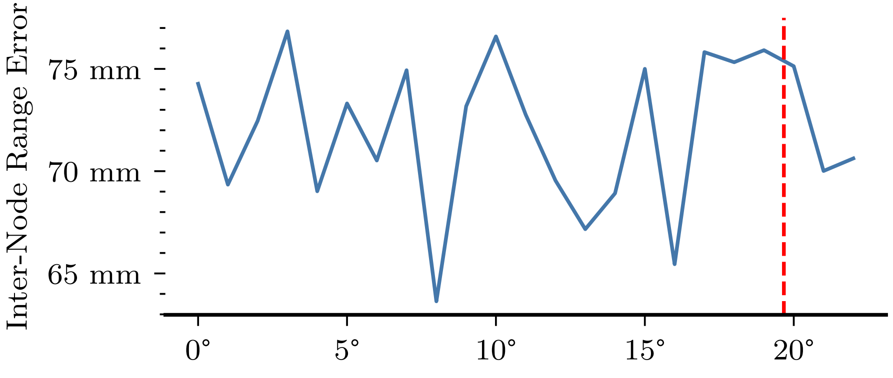
----- Target Location Angle

Total Error (All Freq. & Angle) : μ_τ = **–122.97 ps** , σ_τ = **145.17 ps** and μ_ϕ = **–90.09°**, σ_ϕ = **70.85°**

Beamforming Measurements

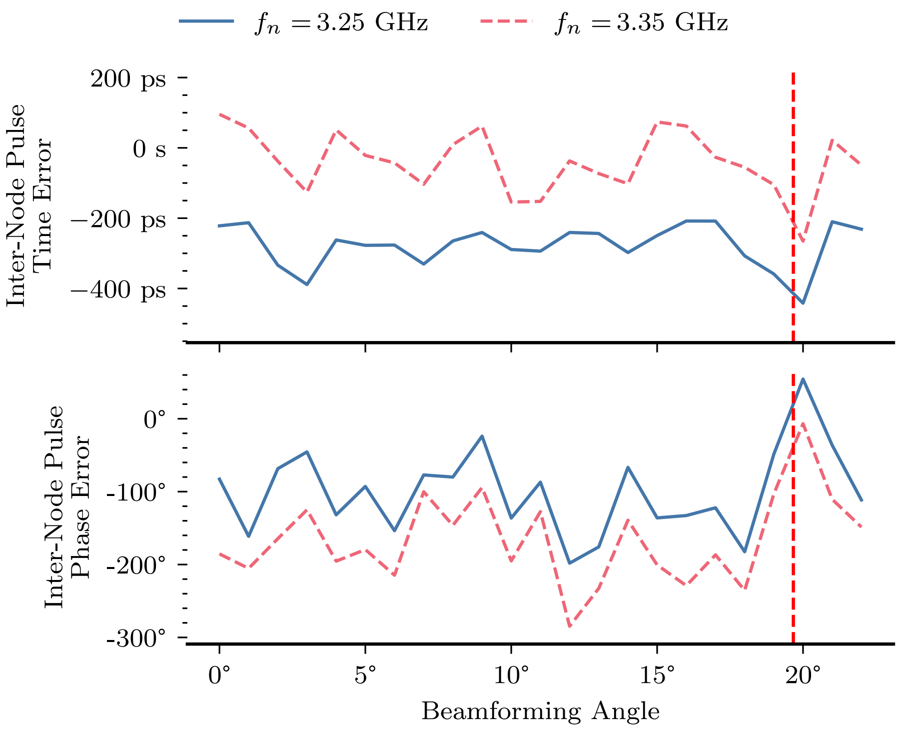
Target Location ~**20°**; Internode Range **~1.25m**

Internode Ranging Bias ($D_n - \widetilde{D}_n$)



Range Compensated Beamforming Error

(Mean ranging bias removed)



----- Target Location Angle

Total Range-Compensated Error: μ_τ = **–158.88 ps** , σ_τ = **140.36 ps** and μ_ϕ = **–132.76°**, σ_ϕ = **67.29°**

Conclusion

- Discussed high accuracy time-frequency-phase synchronization technique using pulsed two-tone time/range estimation and continuous two-tone frequency transfer
- Demonstrated fully-wireless time-frequency-phase synchronized distributed array beamformer

Steering Angle	Absolute Error			Range Compensated Error		
	Time (ps)	Phase (°)	Max BPSK*	Time (ps)	Phase (°)	Max BPSK*
0°	55.6	48.0	1.8 Gbps	43.3	35.8	2.3 Gbps
20°	145.2	70.8	688 Mbps	140.4	67.3	712 Mbps

* Maximum theoretical BPSK throughput; $G_c \geq 0.9$

Questions?

Thank you to our project sponsors and collaborators:

Lawrence Livermore National Laboratory

Office of Naval Research Science & Technology

National Science Foundation

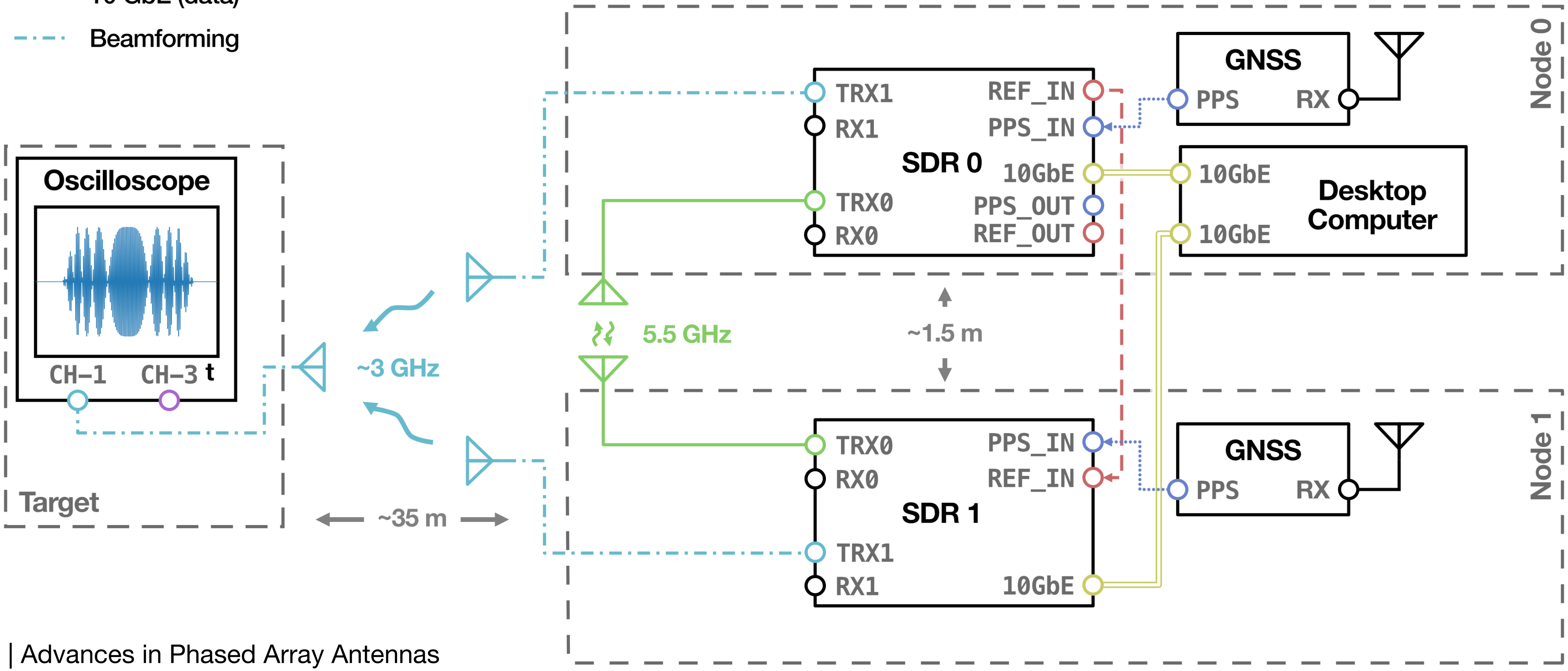
This work was supported under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DEAC52-07NA27344, by the LLNL-LDRD Program under Project No. 22-ER-035, by the Office of Naval Research under grant #N00014-20-1-2389, and by the National Science Foundation under Grant #1751655.

Backup Slides

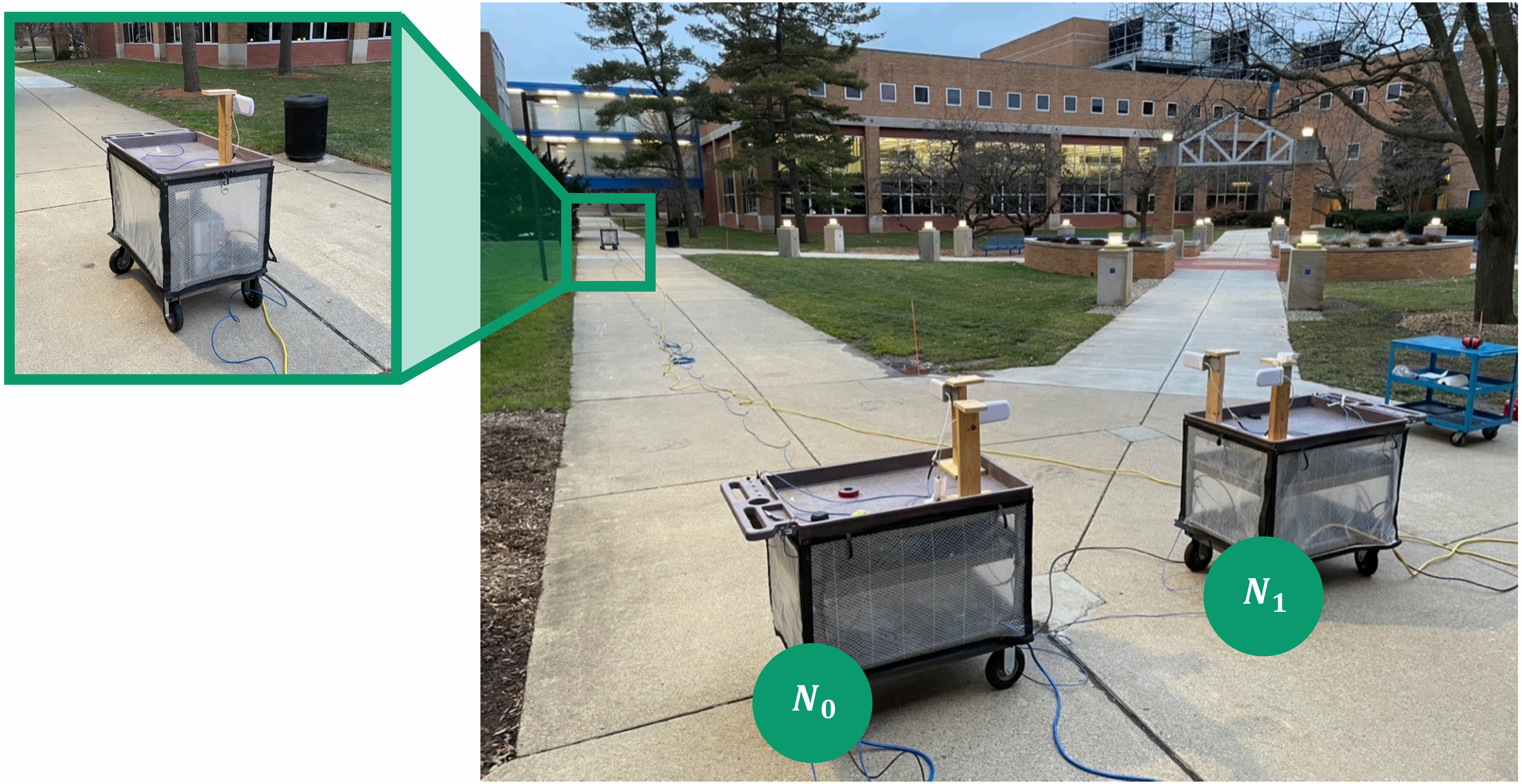
System Configuration 1

Legend

- Time Transfer Waveform
- Frequency Transfer Waveform
- 10 MHz Frequency Reference
- PPS (coarse time sync)
- 10 GbE (data)
- Beamforming



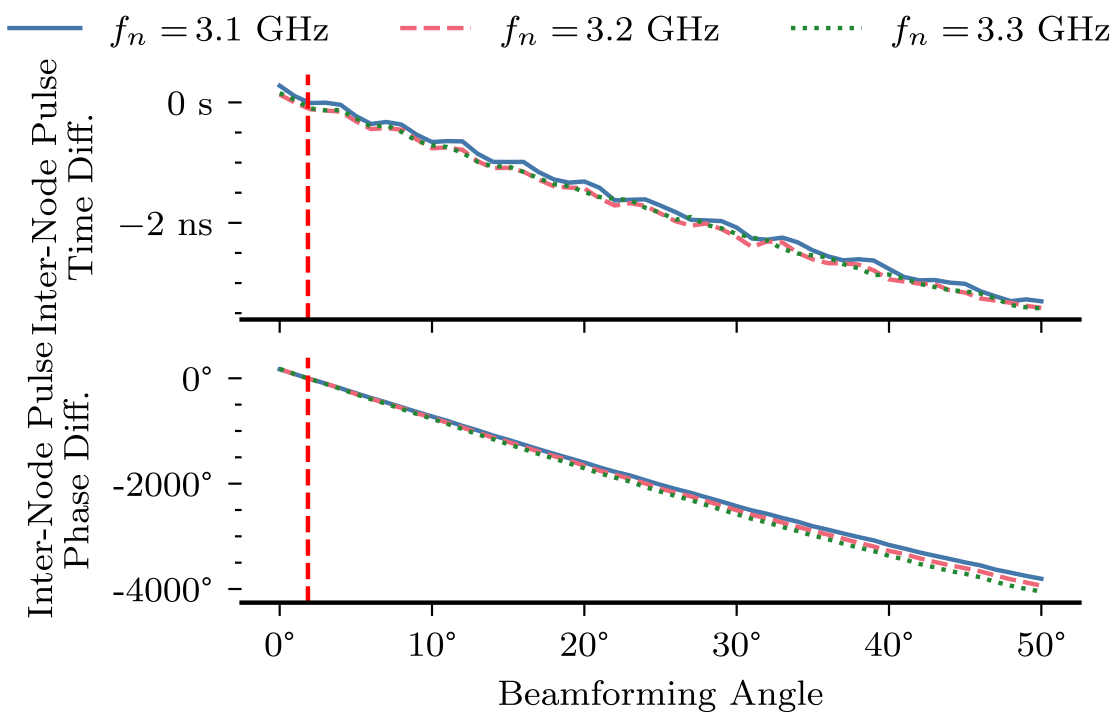
System Configuration 1



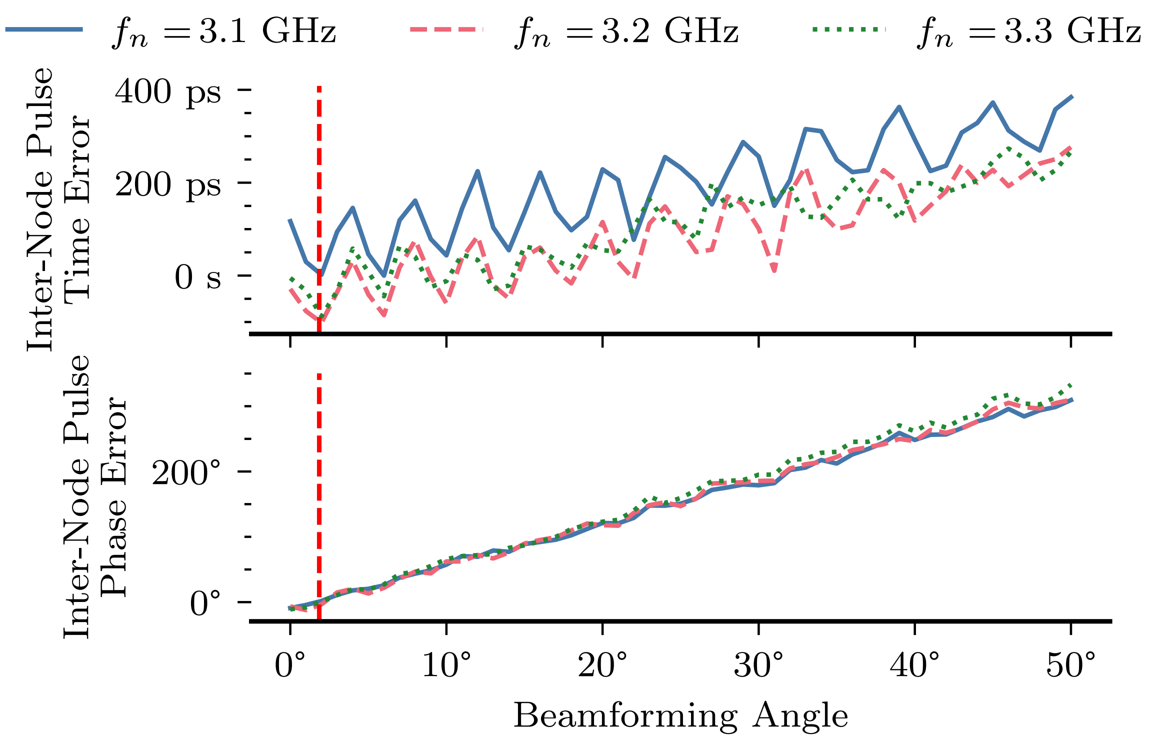
Beamforming Measurements (1)

Target Location **~0°**; Internode Range **~1.5m**

Direct Measurements



Beamforming Error



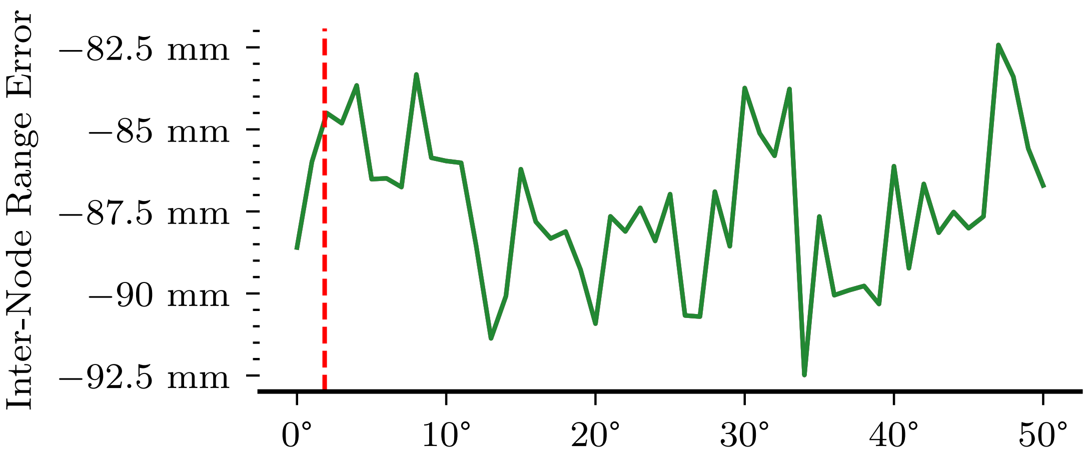
----- Target Location Angle

Total Error (All Freq. & Angle) : μ_τ = **131.44 ps** , σ_τ = **109.29 ps** and μ_ϕ = **155.96°**, σ_ϕ = **98.00°**

Beamforming Measurements (1)

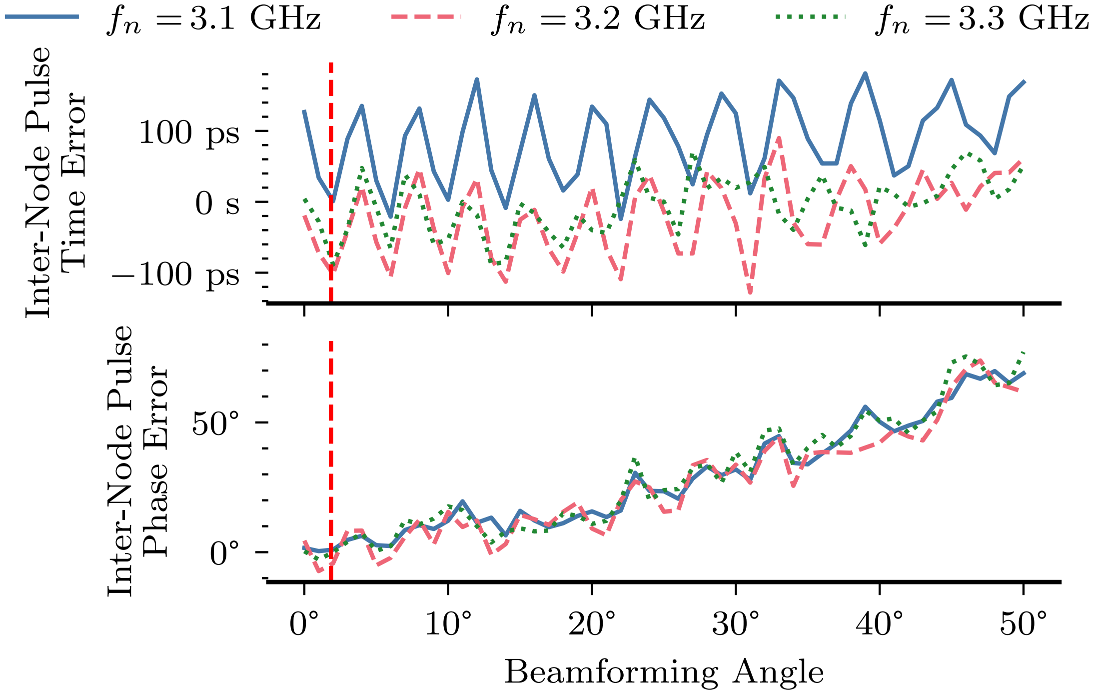
Target Location **~0°**; Internode Range **~1.5m**

Internode Ranging Bias ($D_n - \widetilde{D}_n$)



----- Target Location Angle

Range Compensated Beamforming Error
(Mean ranging bias removed)



Total Range-Compensated Error: $\boldsymbol{\mu_\tau}$ = **20.47 ps** , $\boldsymbol{\sigma_\tau}$ = **69.33 ps** and $\boldsymbol{\mu_\phi}$ = **28.11°**, $\boldsymbol{\sigma_\phi}$ = **21.69°**

Experimental Configurations

Configuration 1

Synchronization Parameter	Method
Time	Wireless
Phase / Range	Wireless
Frequency	Wired

Objectives

- Demonstrate **baseline performance** of time—phase synchronization strategy with frequency hopping

Configuration 2

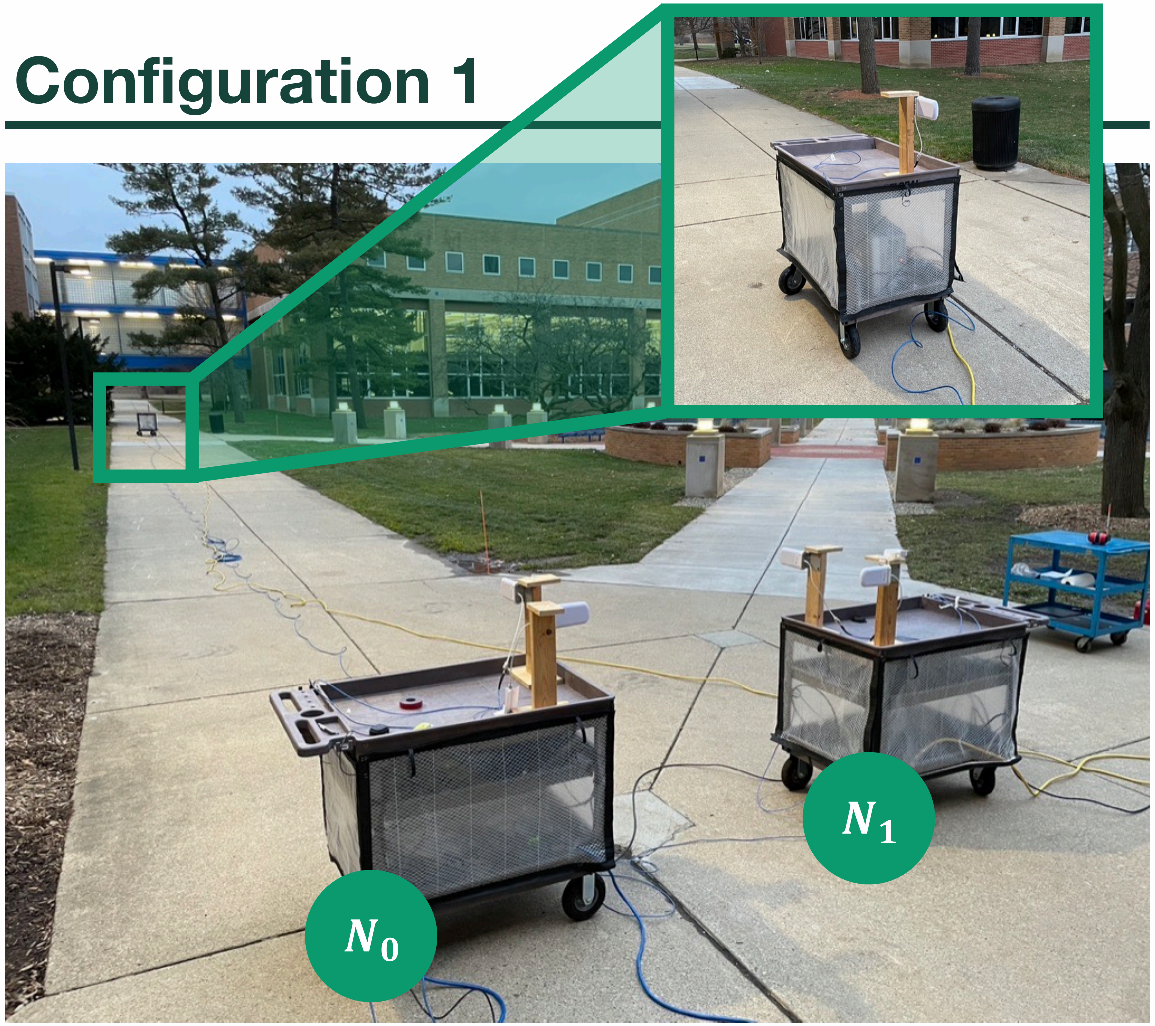
Synchronization Parameter	Method
Time	Wireless
Phase / Range	Wireless
Frequency	Wireless

Objectives

- Demonstrate **fully wireless phased array beamforming** performance with frequency hopping
- Demonstrate beamforming with **varying internode distance**

Experimental Setup

Configuration 1



Configuration 2