Student Paper Finalist

We2D-3

Fully Wireless Coherent Distributed Phased Array System for Networked Radar Applications

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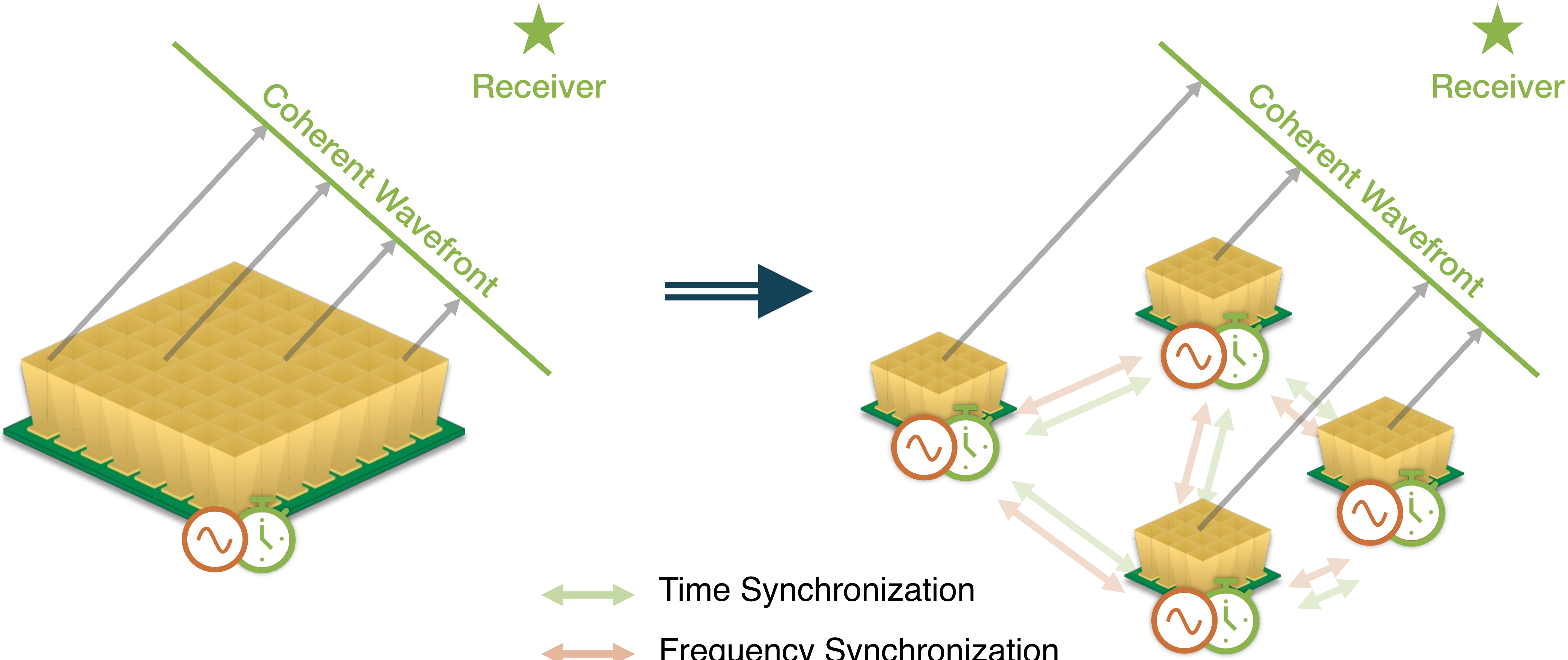
Motivation

Traditional Phased Array

Distributed Phased Array

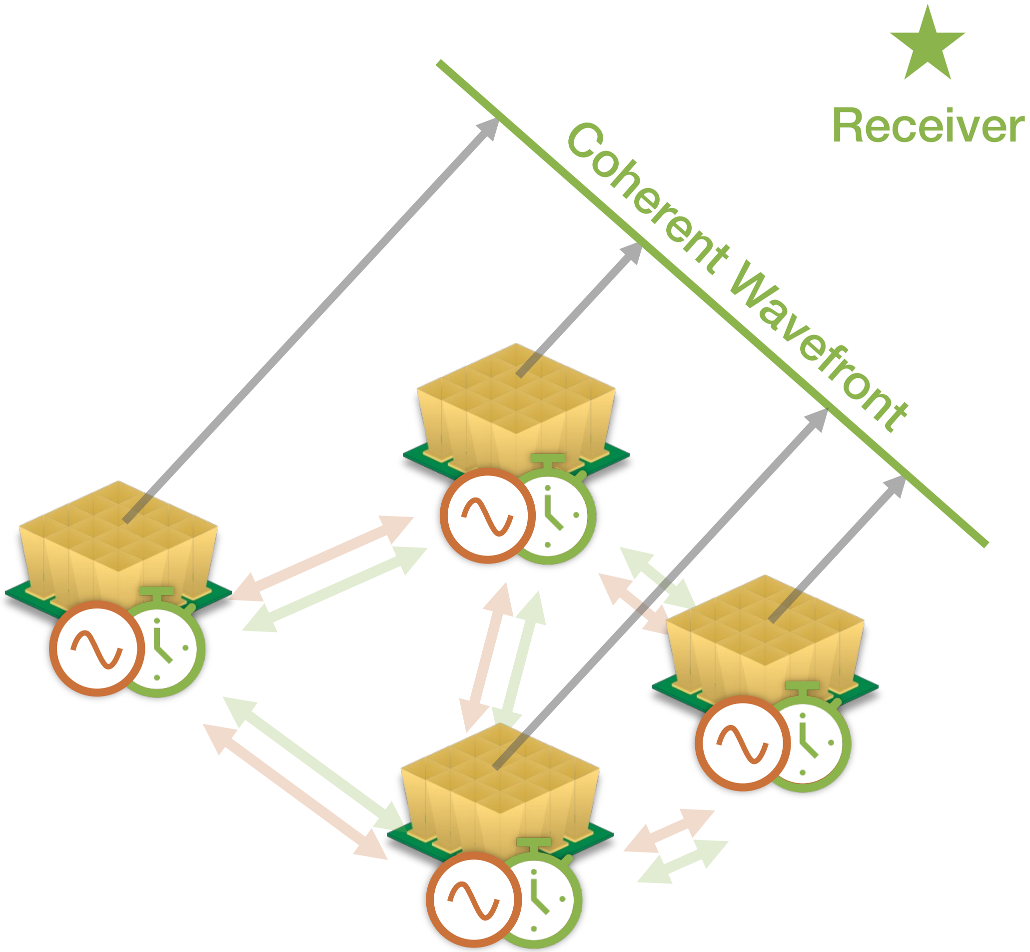


🟩 Time Synchronization

🟧 Frequency Synchronization

Motivation

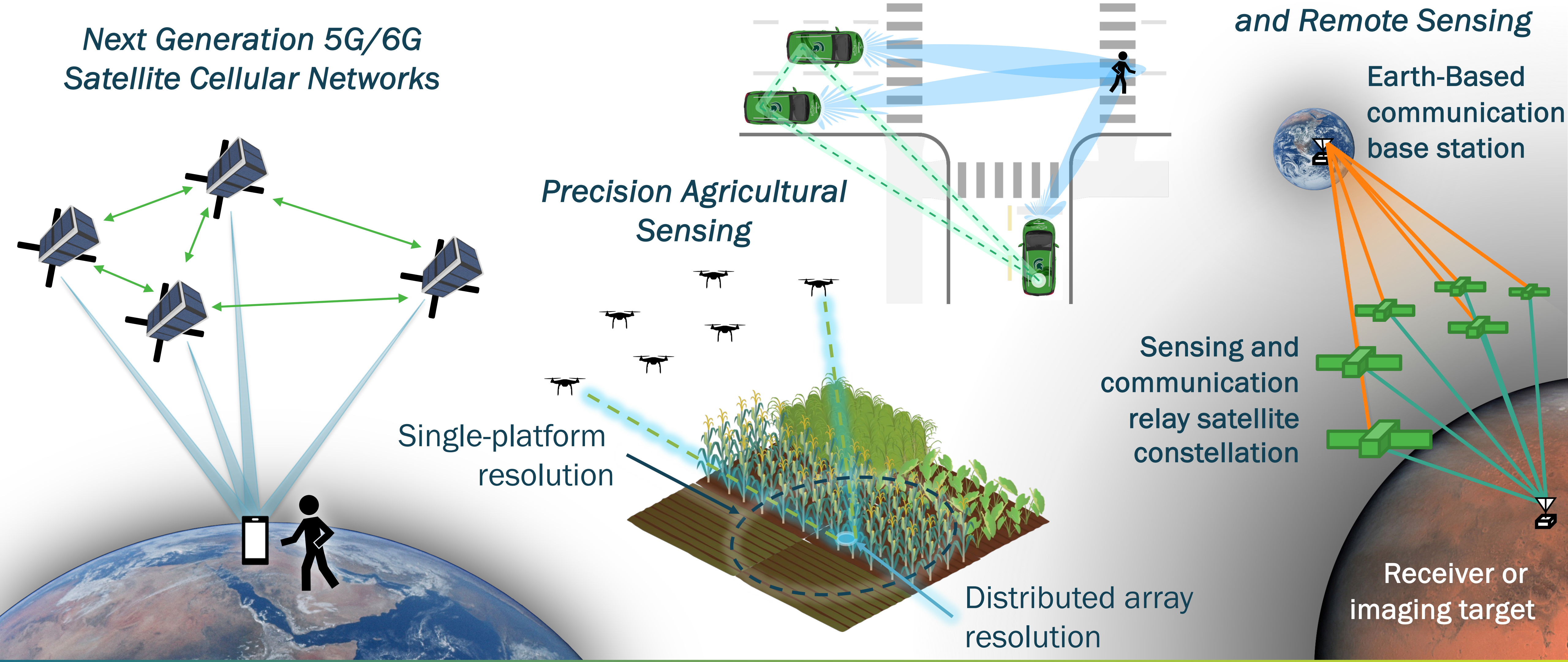
Distributed Phased Array



Benefits

- Many small nodes make up array
  - Reduced deployment cost
  - Decreased thermal management requirements
  - Resilient to antenna / node failure
- Larger array sizes possible
  - Increased total gain / throughput
- Can operate over much larger frequency range

Applications



Next Generation 5G/6G Satellite Cellular Networks

Distributed V2X Sensing

Precision Agricultural Sensing

Single-platform resolution

Distributed array resolution

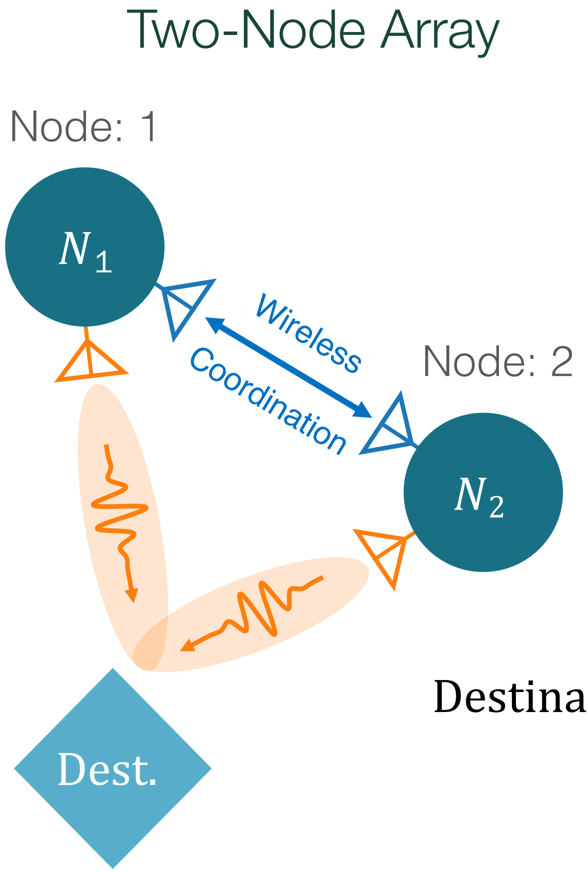
Space Communication and Remote Sensing

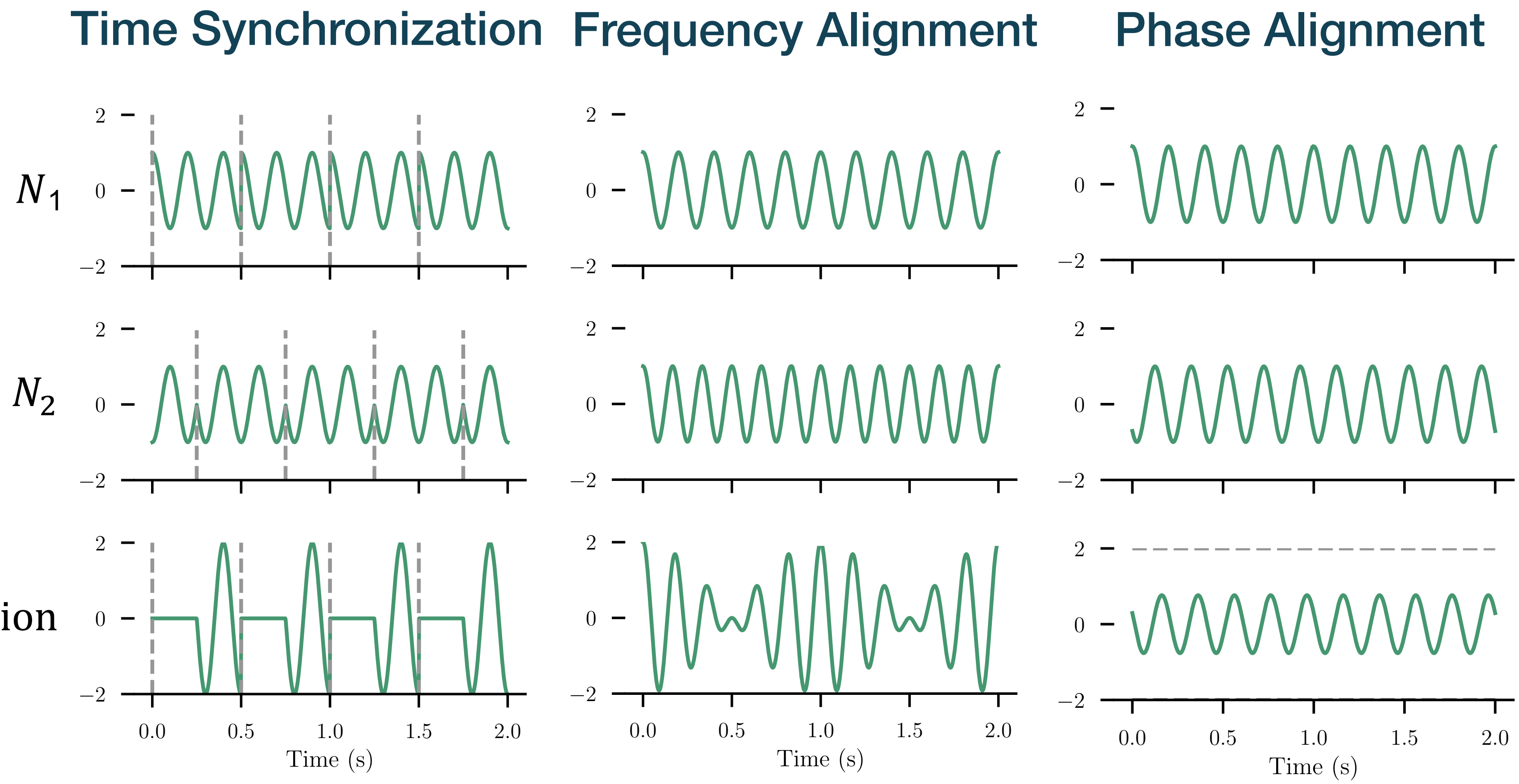
Earth-Based communication base station

Sensing and communication relay satellite constellation

Receiver or imaging target

Coherent Distributed Array Synchronization





$$s_{\text{dest}}(t) = s^{(1)}(t) + s^{(2)}(t) = \sum_{n=1}^{2} A^{(n)} \underbrace{\left(t - \delta_t^{(n)}\right)}_{\text{Time}} \exp\left\{ j \left[\underbrace{2\pi \left(f + \delta_f^{(n)}\right) t}_{\text{Frequency}} + \underbrace{\phi^{(n)}}_{\text{Phase}} \right] \right\}$$

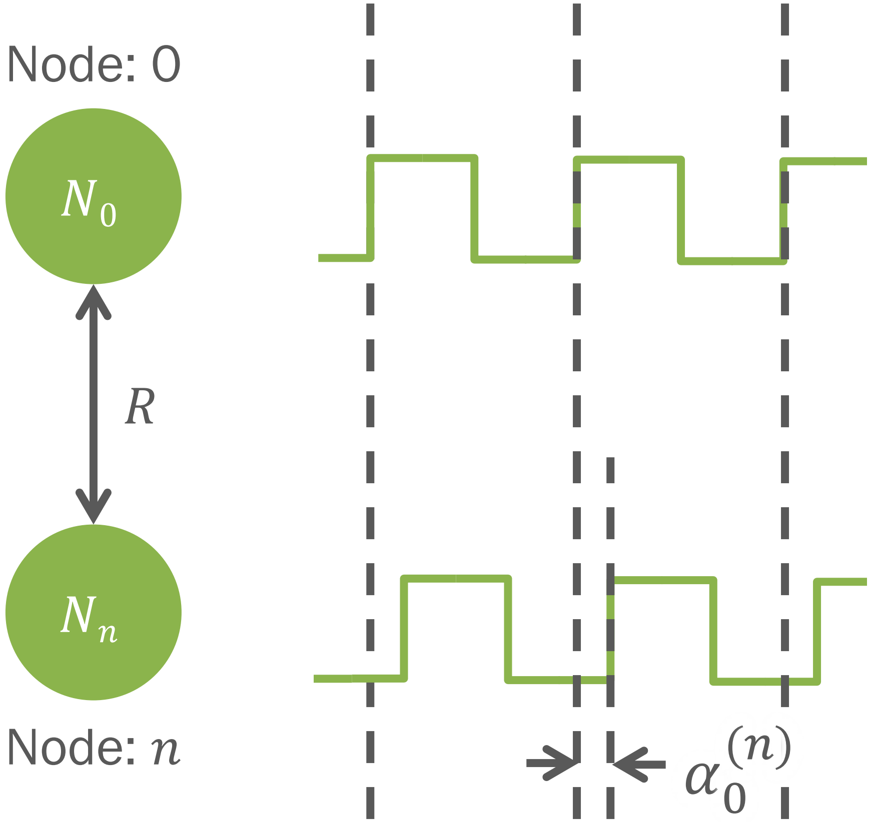
System Time Model (Polynomial)

- Local time at node n:

$$T^{(n)}(t) = \sum_{k=0}^{K} \alpha_k^{(n)} t^k + \nu^{(n)}\ (t)$$

  - K: time model polynomial order
  - $\alpha_k^{(n)}$: kth clock drift coefficient at nth node
  - t : global true time
  - $\nu_n(t)$: other zero-mean noise sources
- Goal:
  - Identify $\alpha_k\ \forall\ n$

Relative Clock Alignment



System Time Model (Linear)

- Assumption:
  - Over short observation intervals time τ, higher order terms are negligible

$$\alpha_k \approx 0 \ \forall \ k > 1$$

- Simplifies local time at node n:

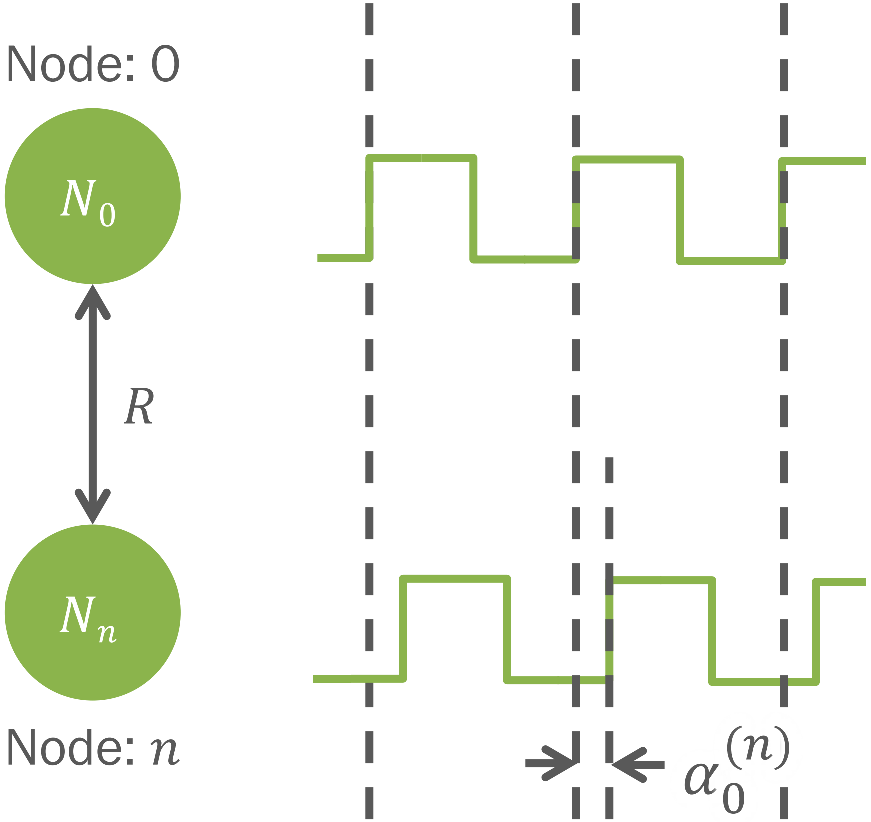
$$T^{(n)}(t) = \alpha_1^{(n)} t + \alpha_0^{(n)} + \nu^{(n)}\ (t)$$

where:

- $\alpha_0^{(n)}$: time bias
- $\alpha_1^{(n)}$: relative frequency scale

In practice, α_k will be time-varying

Relative Clock Alignment



Time Synchronization Technique

Two-Way Time Synchronization

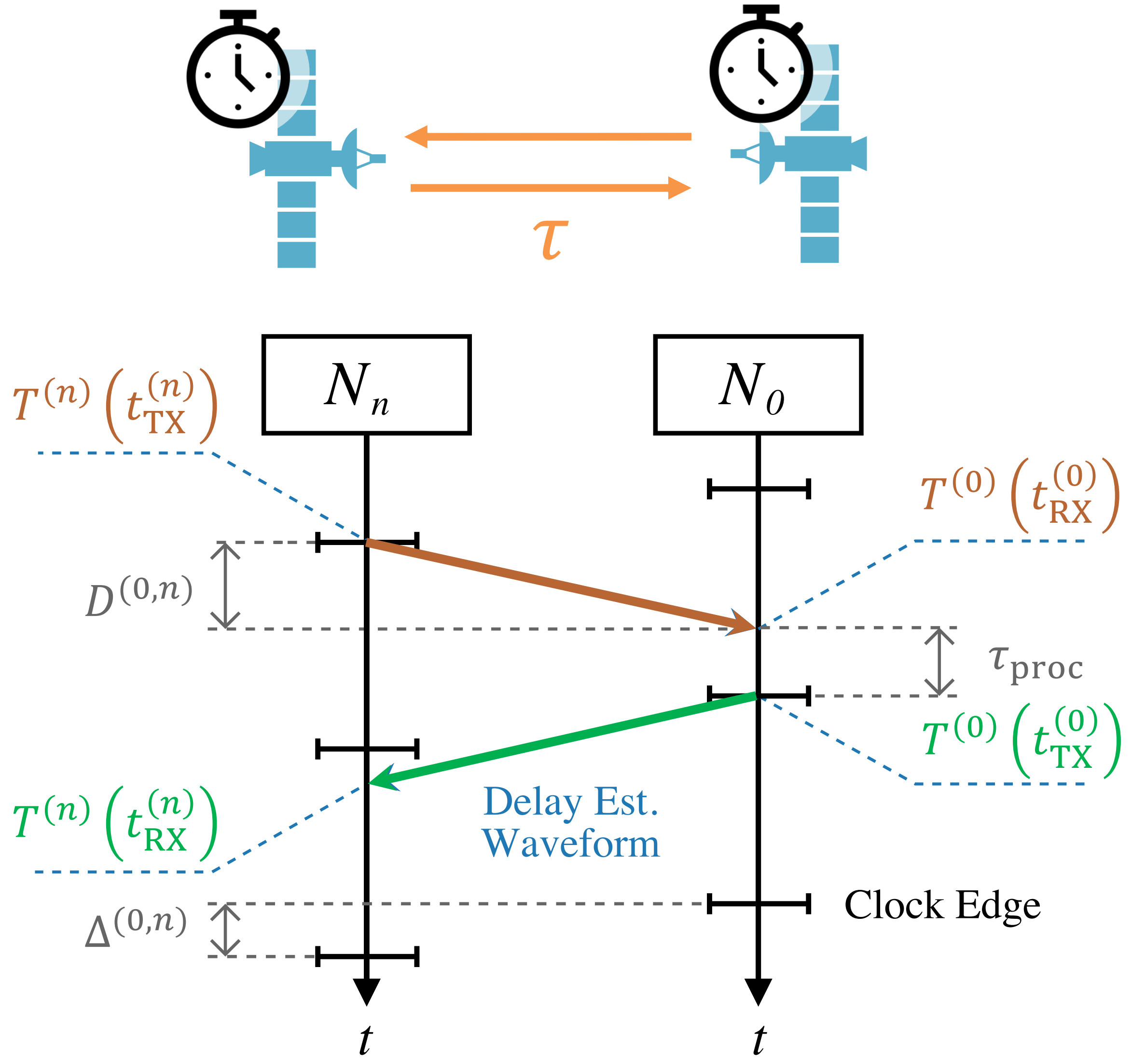
- *Assumption:*
  - Link is reciprocal $\Longrightarrow$ quasi-static during the synchronization epoch

- Timing skew estimate:

$$\Delta^{(0,n)} = \frac{\left(T^{(0)}\left(t_{\mathrm{RX}}^{(0)}\right) - T^{(n)}\left(t_{\mathrm{TX}}^{(n)}\right)\right) - \left(T^{(n)}\left(t_{\mathrm{RX}}^{(n)}\right) - T^{(0)}\left(t_{\mathrm{TX}}^{(0)}\right)\right)}{2}$$

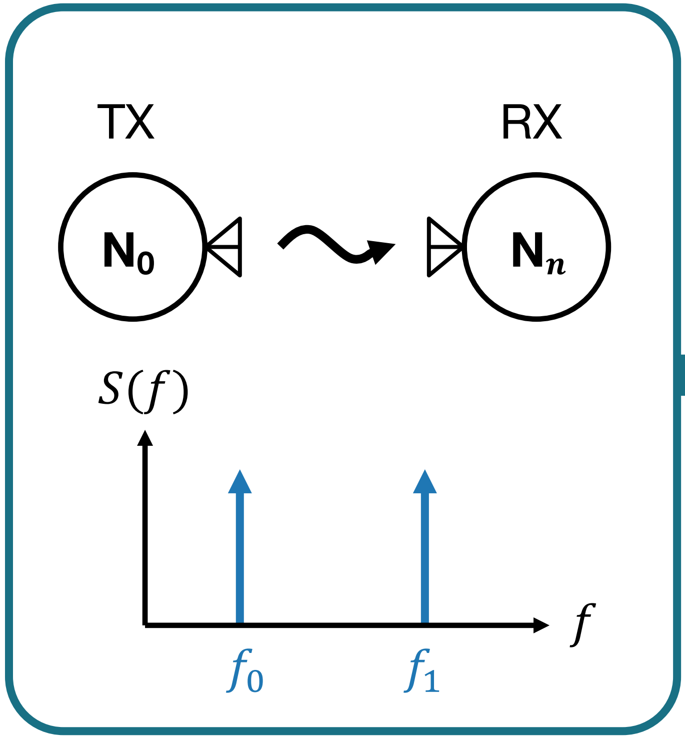
- Inter-node range estimate:

$$D^{(0,n)} = c \cdot \frac{\left(T^{(0)}\left(t_{\mathrm{RX}}^{(0)}\right) - T^{(n)}\left(t_{\mathrm{TX}}^{(n)}\right)\right) + \left(T^{(n)}\left(t_{\mathrm{RX}}^{(n)}\right) - T^{(0)}\left(t_{\mathrm{TX}}^{(0)}\right)\right)}{2}$$

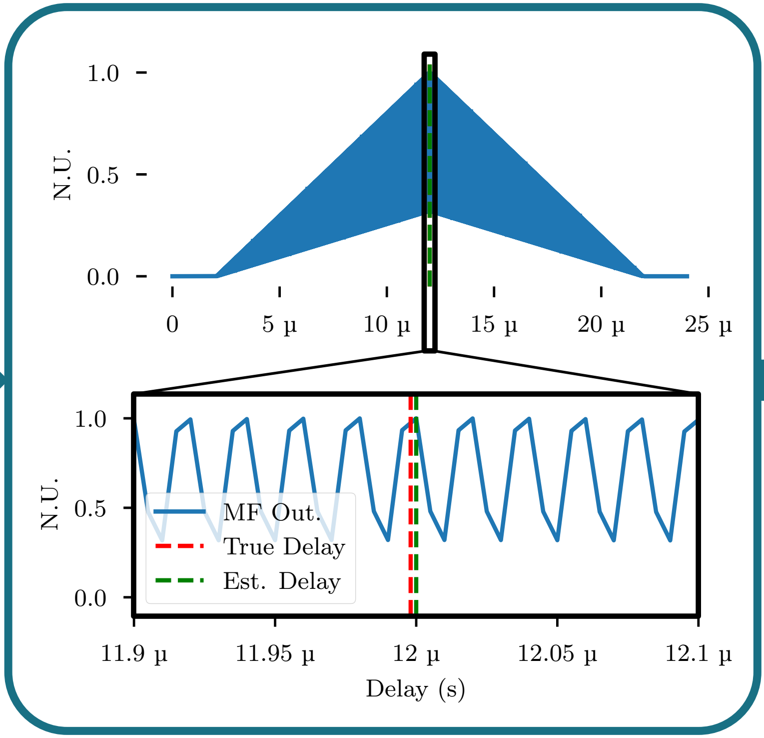


One-Way Delay Estimation — $T_{\mathrm{RX}}^{(n)}(t)$

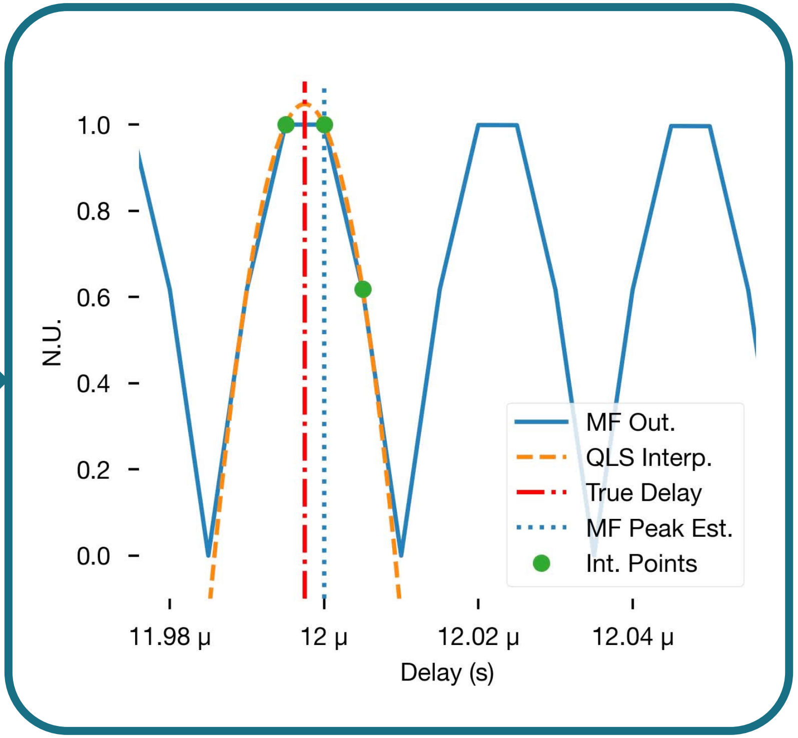
Pulsed Two-Tone Transmission



Matched Filter



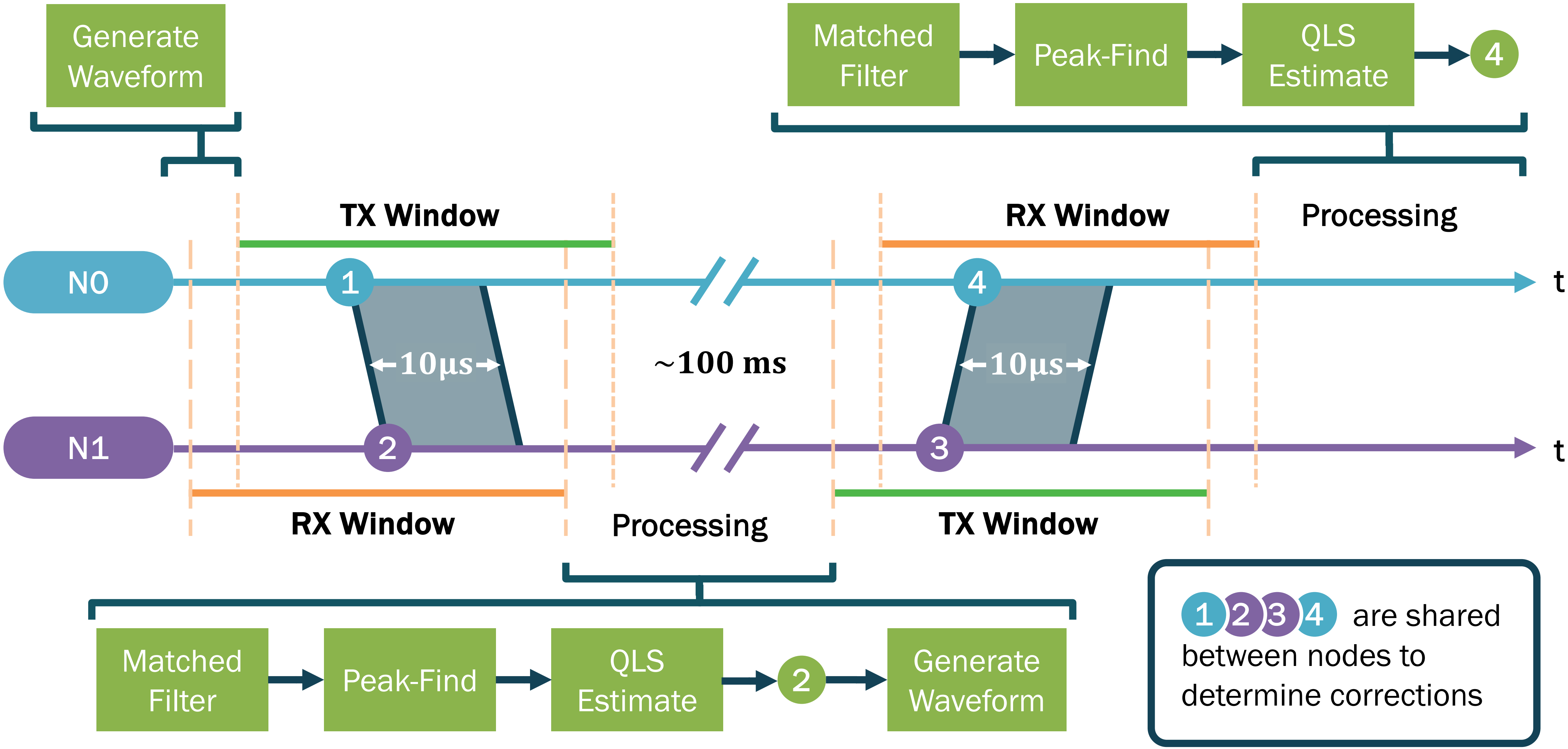
Quadratic Least Squares Peak Refinement



The same process is repeated in the reverse direction from $\mathbf{N}_n$ to $\mathbf{N}_0$

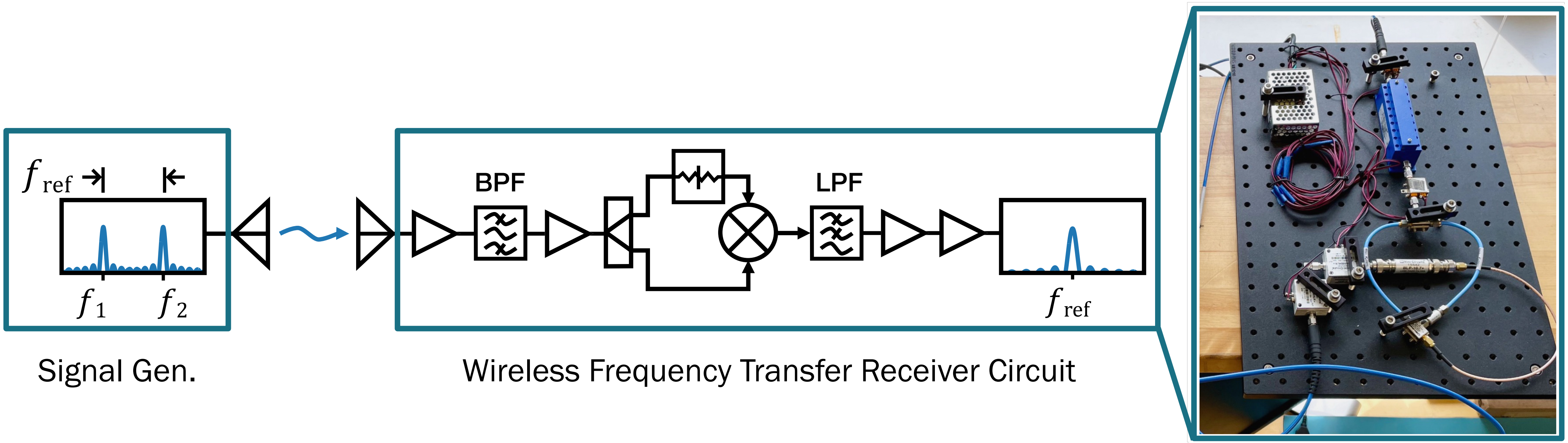
J. M. Merlo, S. R. Mghabghab and J. A. Nanzer, "Wireless Picosecond Time Synchronization for Distributed Antenna Arrays," in IEEE Transactions on Microwave Theory and Techniques, vol. 71, no. 4, pp. 1720-1731, April 2023, doi: 10.1109/TMTT.2022.3227878.

Time Offset Estimation Process



1 2 3 4 are shared between nodes to determine corrections

Wireless Frequency Syntonization



- Two-tone transmitter with carrier spacing f_{ref}
- Self-mixing receiver: Mixes received signal with itself, low-pass filters frequencies above f_{ref}
- Fundamental frequency f_{ref} received at output used to discipline local oscillators on the radio nodes (tracks $\alpha_1^{(n)}$)

S. R. Mghabghab and J. A. Nanzer, "Open-Loop Distributed Beamforming Using Wireless Frequency Synchronization," in IEEE Transactions on Microwave Theory and Techniques, vol. 69, no. 1, pp. 896-905, Jan. 2021, doi: 10.1109/TMTT.2020.3022385.

Carrier Model

- The carrier at any node

$$\Phi^{(n)}(t) = \exp\{j2\pi f_c \underbrace{T^{(n)}(t)}_{\alpha_1^{(n)}(t)t + \alpha_0^{(n)}(t) + \nu^{(n)}(t)}\} \exp\left(j\phi^{(n)}\right)$$

- To compensate, we must:
  - Calibrate the static phase rotations $\left(\phi_{\mathrm{TX}}^{(n)},\ \phi_{\mathrm{RX}}^{(n)}\right) \rightarrow \left(\phi_{\mathrm{TX,cal}}^{(n)},\ \phi_{\mathrm{RX,cal}}^{(n)}\right)$
  - Estimate and correct for $\alpha^{(n)}$ using wireless time and frequency transfer techniques

Transmit Signal

Linear Frequency Modulation (LFM)

LFM bandwidth

Steering angle phase

$$s_{\mathrm{TX}}^{(n)}(t) = \underbrace{\Phi^{(n)}(t)}_{\text{Carrier}}\;\underbrace{\Pi\left(\frac{T_{\mathrm{LFM}}^{(n)}(t)}{\tau_{\mathrm{LFM}}}\right)}_{\text{Amplitude Modulation}}\;\underbrace{\exp\left\{j\pi\left(\frac{\beta_{\mathrm{LFM}}}{\tau_{\mathrm{LFM}}}\right)\left(T_{\mathrm{LFM}}^{(n)}(t)\right)^{2}\right\}}_{\text{Frequency Modulation}}\;\underbrace{\exp\left\{-j\left(\phi_{\mathrm{TX,cal}}^{(n)} + \phi_{\mathrm{bf}}^{(n)}\right)\right\}}_{\text{Phase Compensation}}$$

Pulse duration

Phase calibration

Local LFM Time

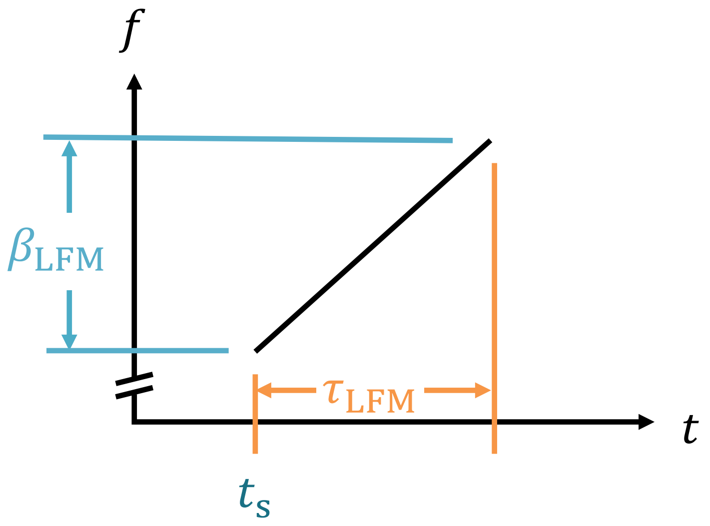
$$T_{\mathrm{LFM}}^{(n)}(t) = T^{(n)}(t) - \Delta^{(n,0)}(t) - t_{\mathrm{s}}^{(n)} + \tau_{\mathrm{bf}}^{(n)}$$

Pulse start time

Beamsteering

$$\tau_{\mathrm{bf}}^{(n)} = \frac{D^{(n)}}{c}\sin\theta_{\mathrm{bf}}$$

$$\phi_{\mathrm{bf}}^{(n)} = 2\pi f_{\mathrm{c}}\tau_{\mathrm{bf}}^{(n)}$$



Receive Signal

- Received signal at each element (after compensation):

Transmitters Scatterers

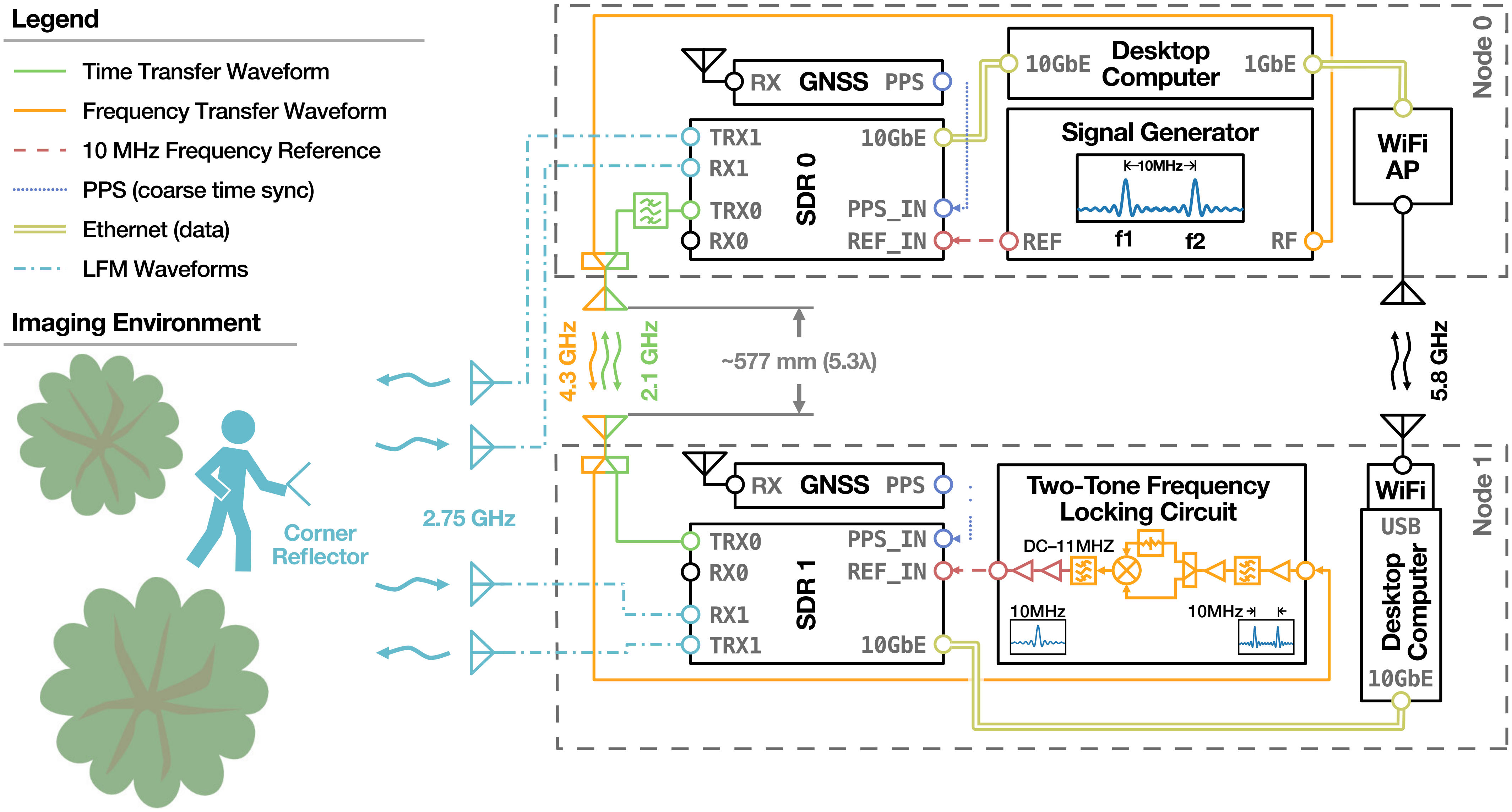
$$s_{\mathrm{RX}}^{(n)}(t) = \underbrace{\sum_{m=0}^{M}\sum_{l=0}^{L} A^{(l)}\, s_{\mathrm{TX}}^{(m)}\left(t-\tau_{\mathrm{d}}^{(m,l,n)}\right)}_{\text{sum of time-delayed scatters}} \underbrace{\exp\left\{j\left(\phi_{\mathrm{RX}}^{(n)}-\phi_{\mathrm{RX,cal}}^{(n)}-\phi_{\mathrm{bf}}^{(n)}\right)\right\}}_{\text{phase}}$$

  - $A^{(l)}$: complex scattering coefficient of lth scatterer
  - $\tau_{\mathrm{d}}^{(m,l,n)}$: time delay of waveform transmitted from node m, reflecting off scatterer l, and received at node n

Receivers

- Downrange matched filter: $s_{\mathrm{mf}}(t) = \mathcal{F}^{-1}\left\{\mathcal{F}\left[\sum_{n=0}^{N} s_{\mathrm{RX}}^{(n)}(t)\right] S_{\mathrm{TX}}^{*}\right\}$

System Schematic

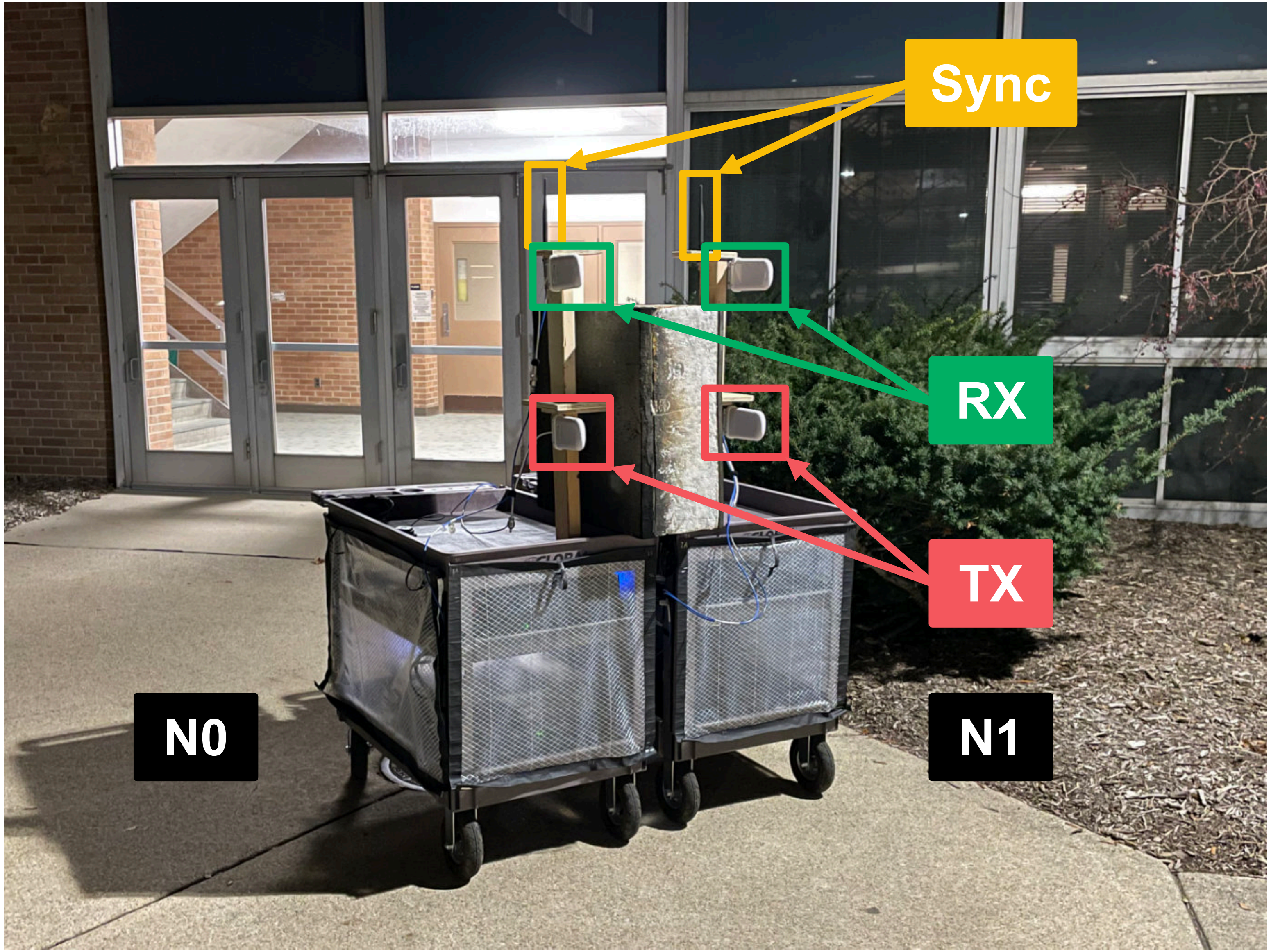


Legend

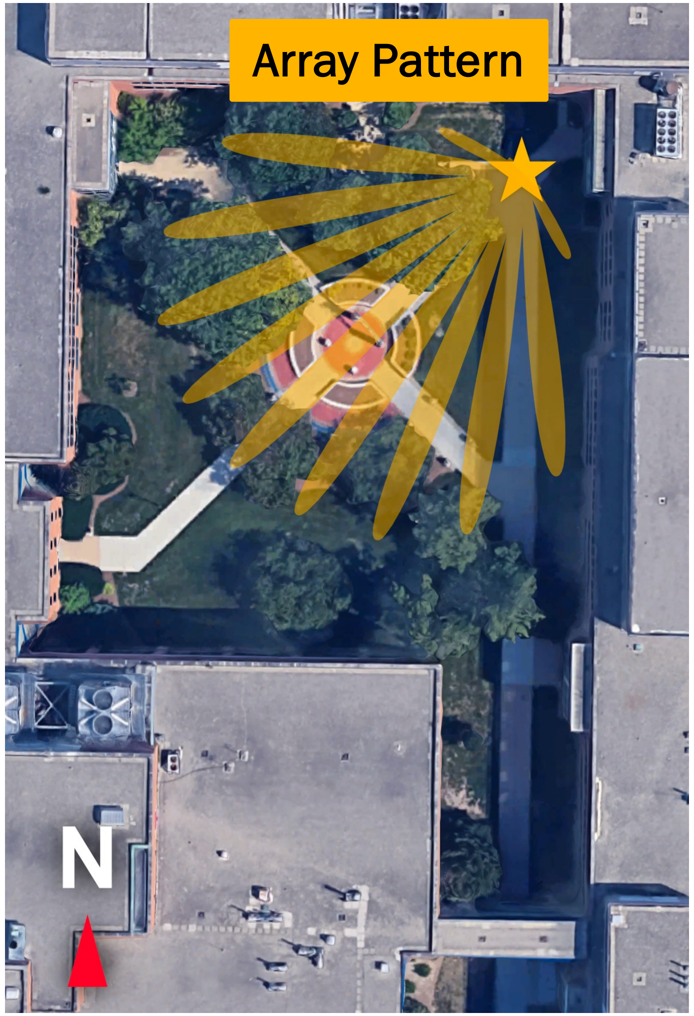
- — Time Transfer Waveform
- — Frequency Transfer Waveform
- - - - 10 MHz Frequency Reference
- ······ PPS (coarse time sync)
- ═ Ethernet (data)
- -·- LFM Waveforms

Imaging Environment

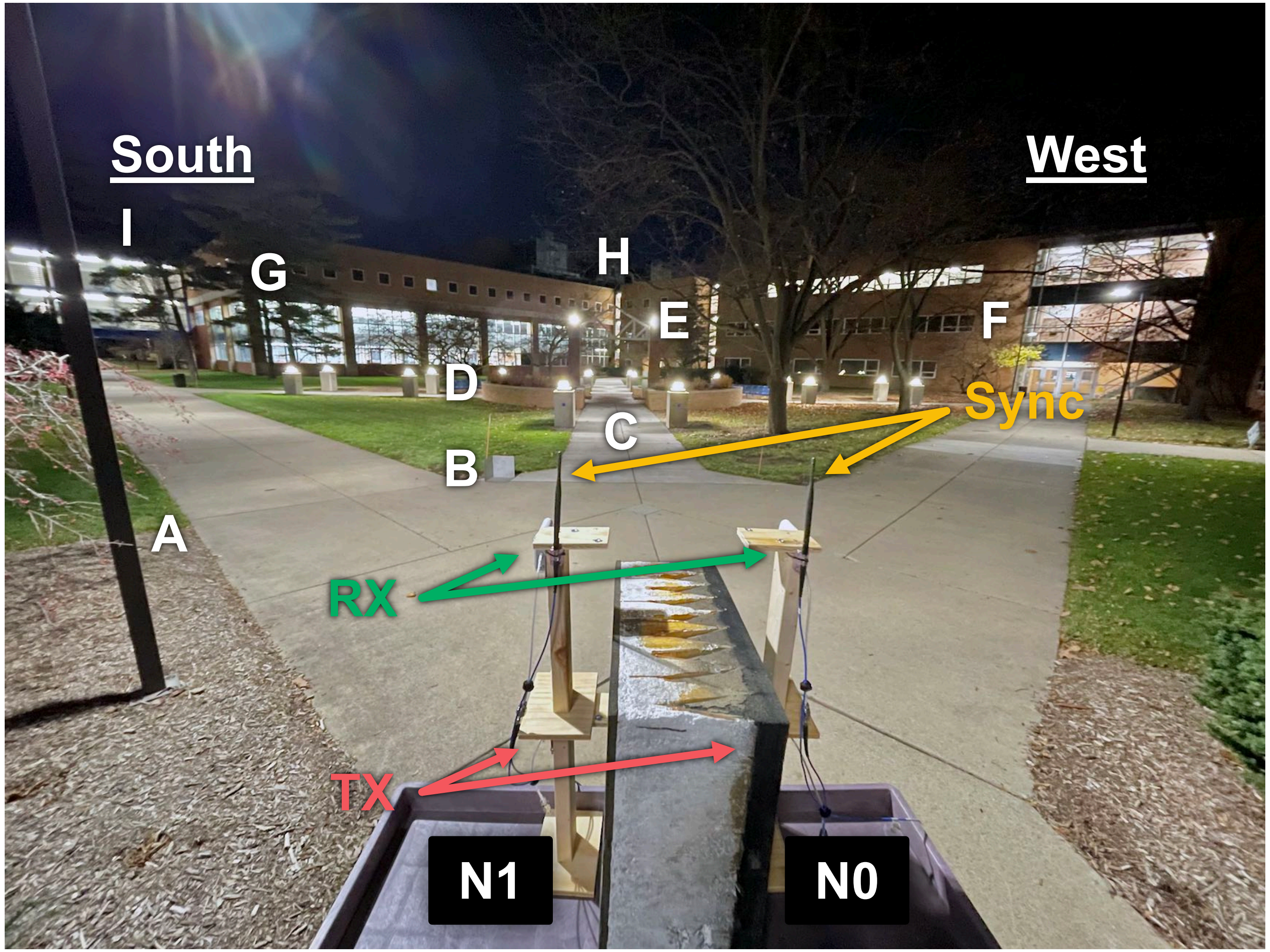
Experimental Setup



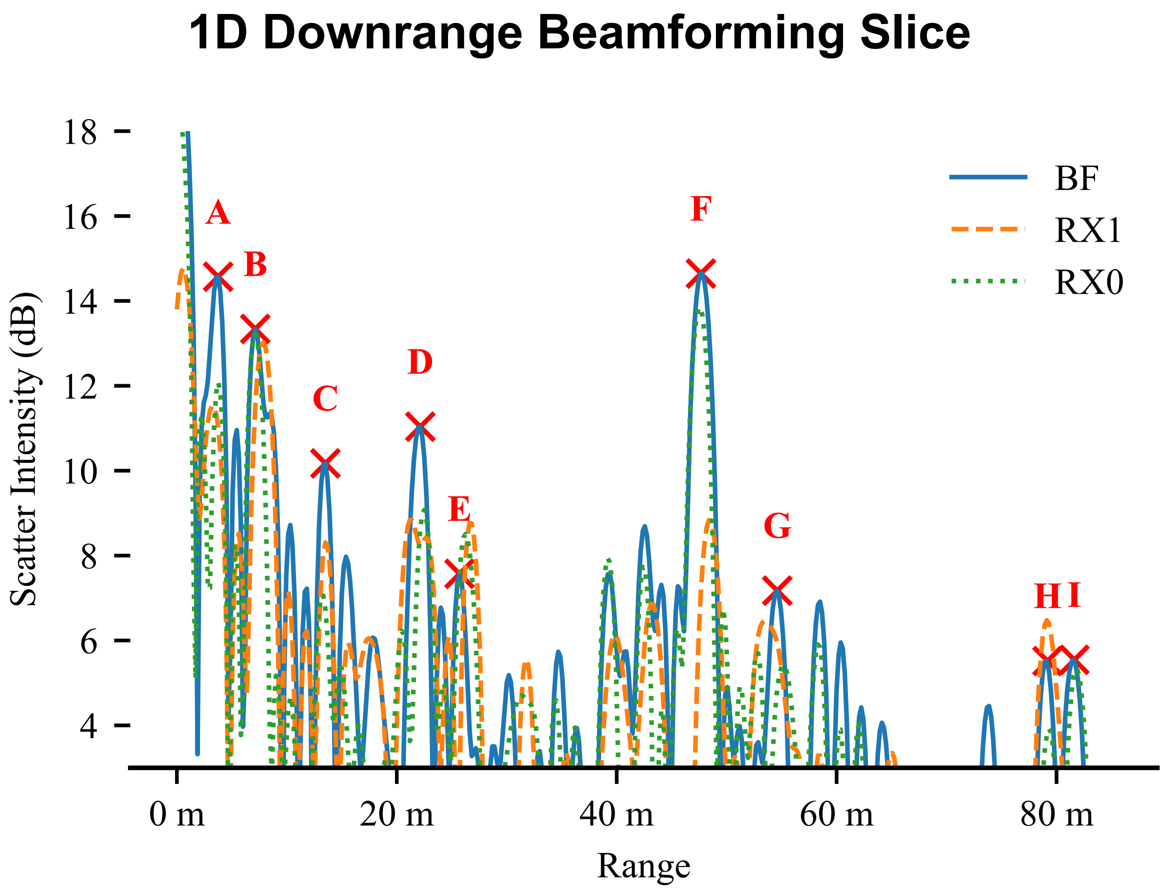
Experimental Setup



Imagery ©2023 Google, map data ©2023



Static Measurement Results

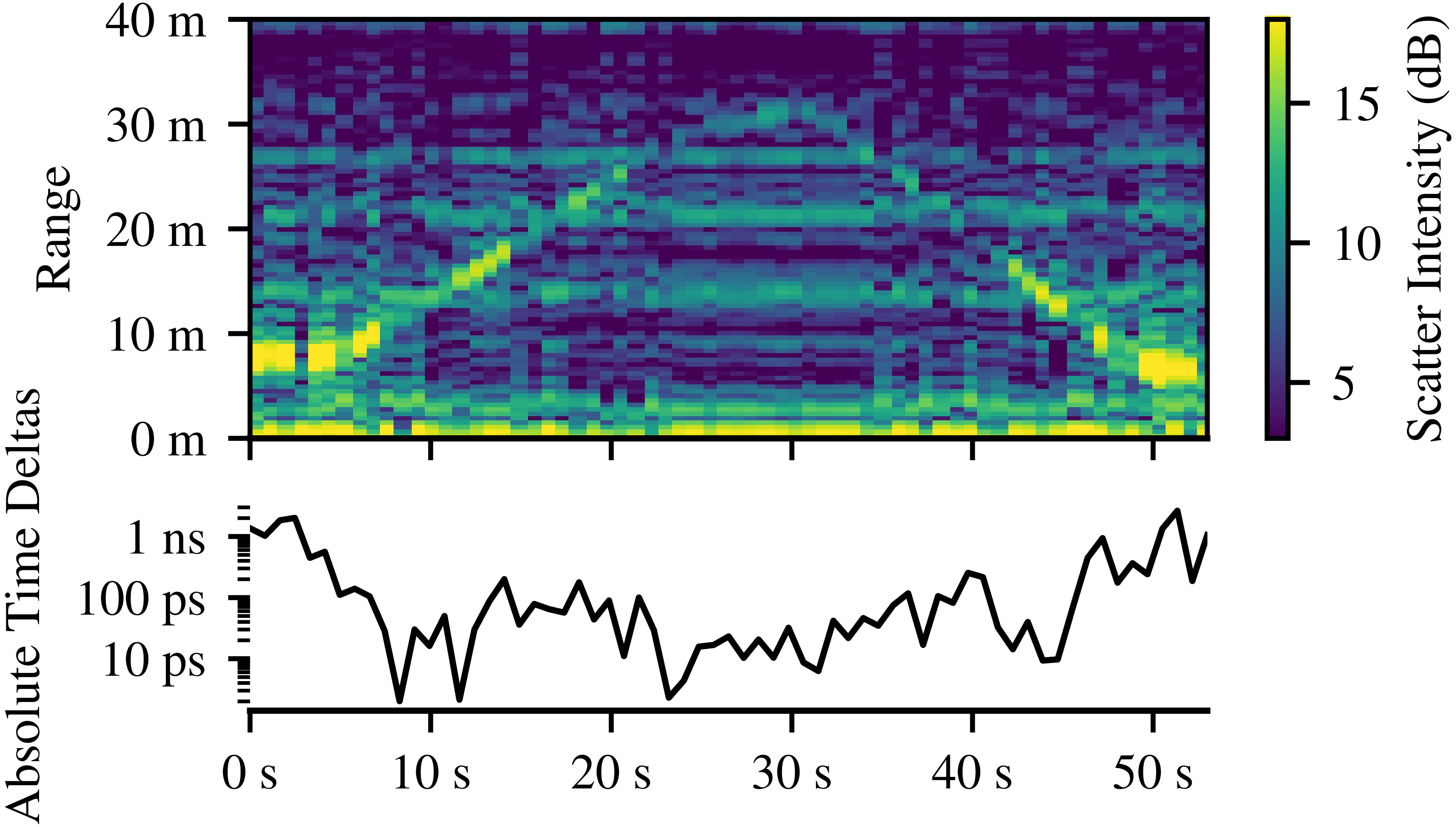

1D Downrange Beamforming Slice

Label	RX0	RX1	BF	Realized Gain	
	dB	dB	dB	dB	%-ideal
A	12.082	11.508	**14.570**	2.765	94.5
B	13.221	12.240	**13.340**	0.581	57.2
C	7.057	8.307	**10.172**	2.445	87.8
D	8.993	8.508	**11.037**	2.279	84.5
E	**8.119**	5.232	7.572	0.660	58.2
F	13.840	7.769	**14.645**	2.857	96.5
G	5.121	6.246	**7.174**	1.454	69.9
H	3.916	**6.478**	5.516	0.133	51.6
I	5.323	1.121	**5.544**	1.832	76.2

Boldface values denote the highest received power after matched filtering

Dynamic Measurement Results

- Pedestrian walking with corner reflector
  - Started ~7 m away, walked to ~30 m then returned
- Absolute time corrections shown below
  - Indicates high level of timing accuracy once pedestrian >~15 m away



Conclusion

- Discussed a High accuracy time-frequency-phase coordinated coherent distributed phased array
- Demonstrated a 2×2 distributed coherent radar array in static and dynamic environments
- Static measurement performance summary:

Statistic	**Realized Receive Gain**	
	dB	**%–ideal**
Maximum	**2.86**	**96.5**
Median	**2.12**	**81.5**

Questions

Thank you to our project sponsors and collaborators:

Lawrence Livermore National Laboratory

Office of Naval Research Science & Technology

National Science Foundation

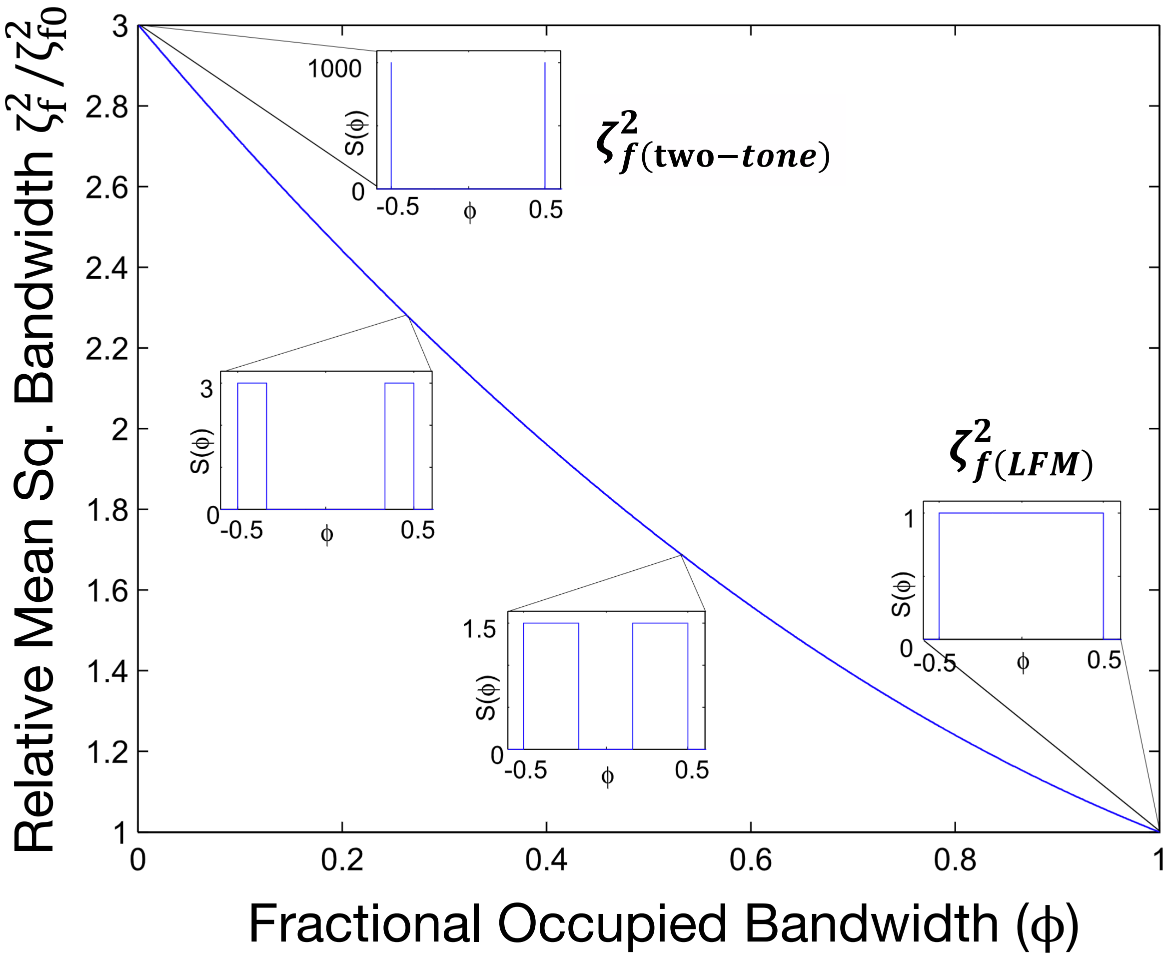
Backup Slides

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



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.

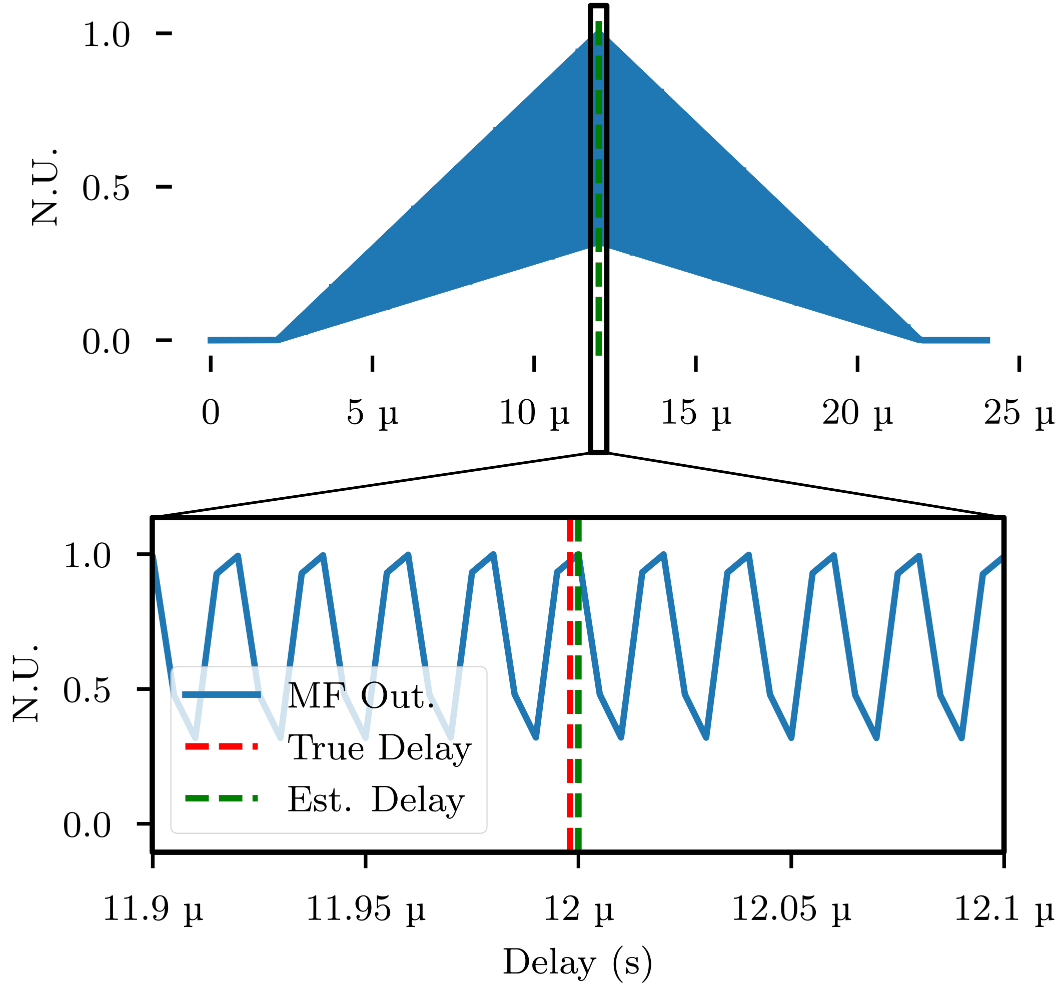
High Accuracy Delay Estimation

- 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



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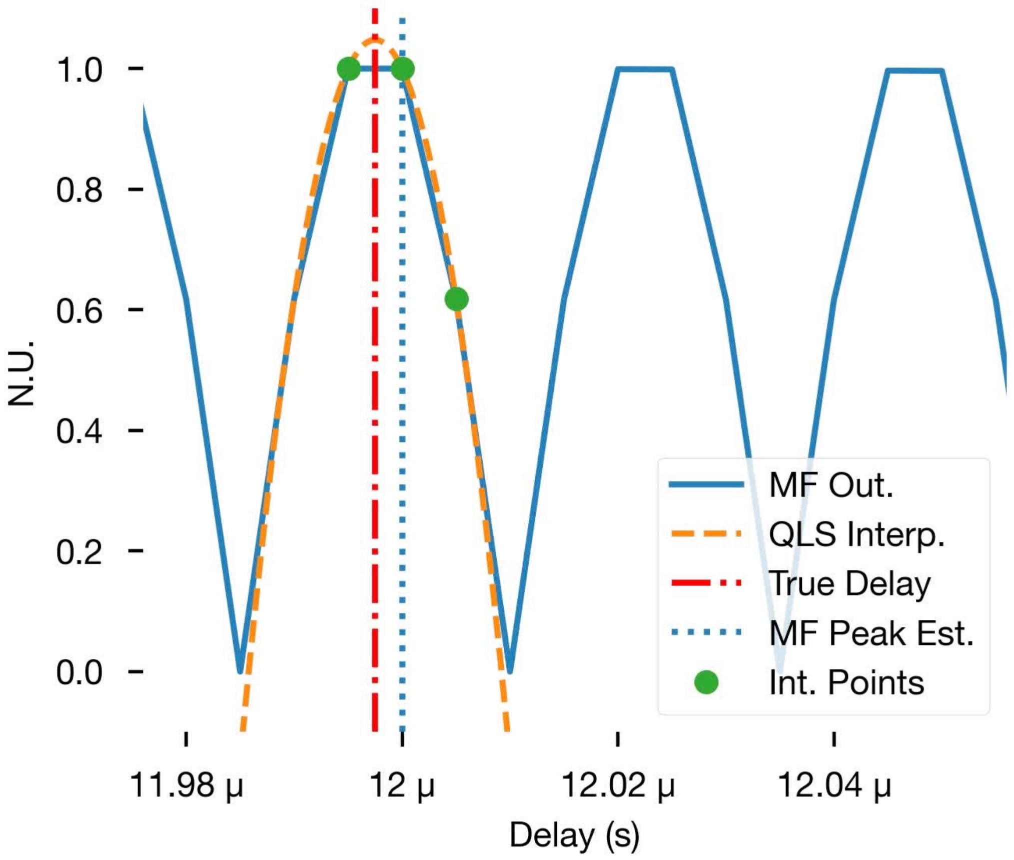
Delay Estimation Refinement

- MF is biased due to time discretization limited by sample rate
- Refinement obtained using Quadratic Least Squares (QLS) fitting to find true delay from 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

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



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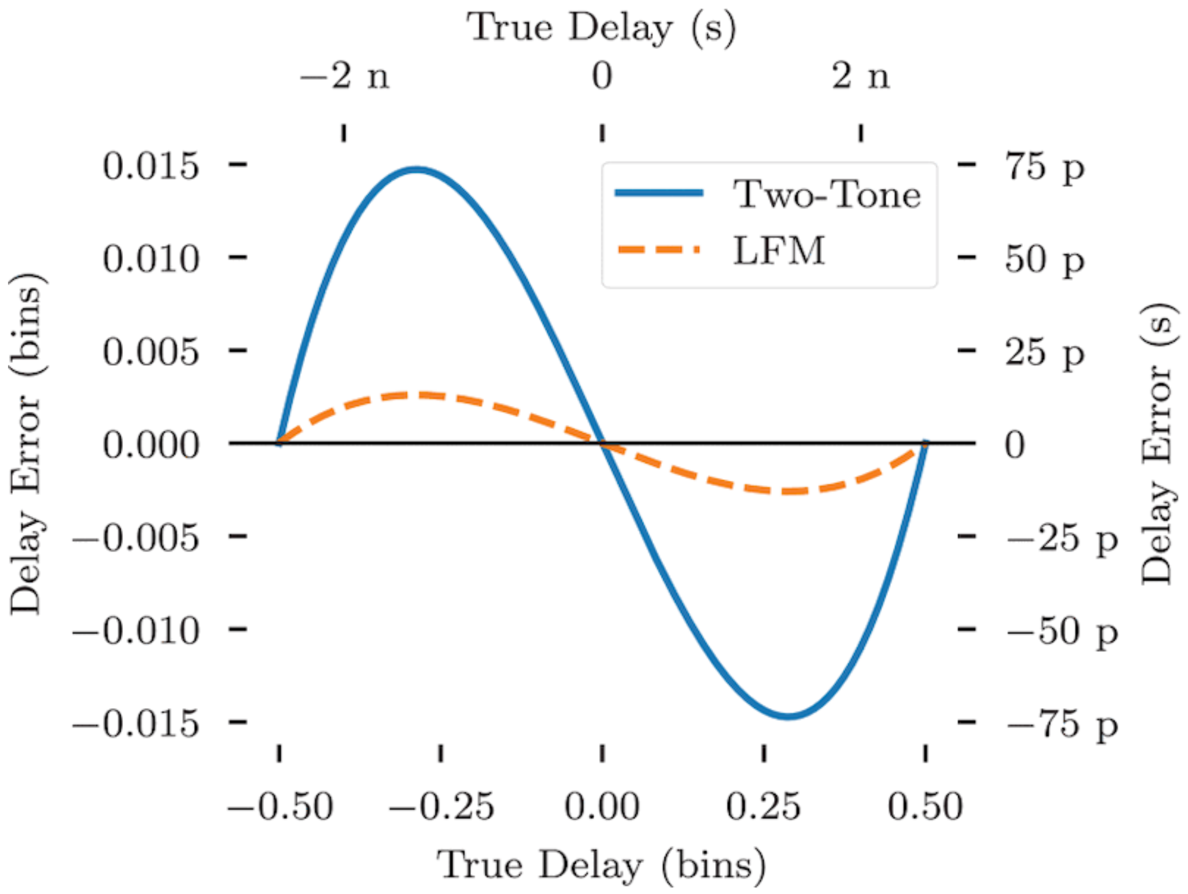
Delay Estimation Refinement

- 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 corrected via lookup table based on where estimate falls within a bin

Predicted Bias for Two-Tone & LFM



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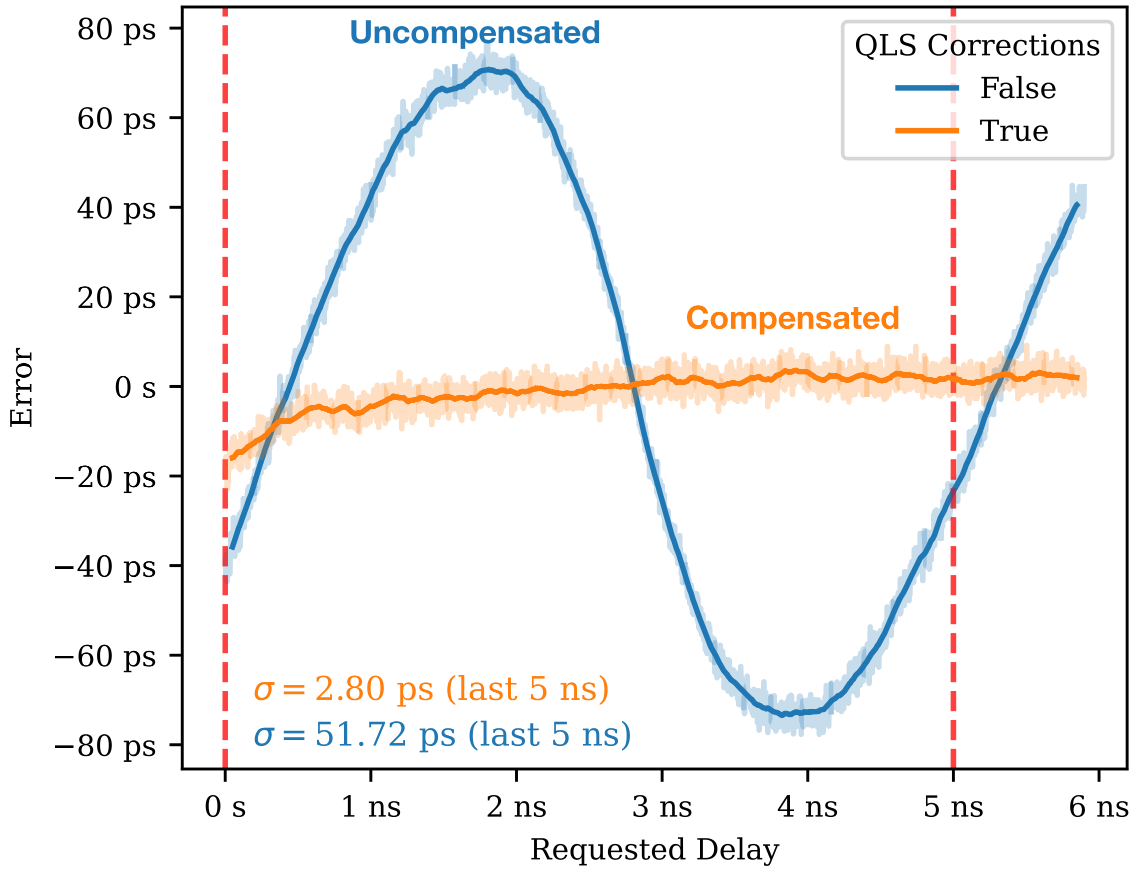
Measured Bias for Two-Tone

(before and after applying corrections)



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