MICHIGAN STATE UNIVERSITY

All-Digital Wirelessly Coordinated Phased Array Collaborative Beamforming Using High Accuracy Time Synchronization

2025 IEEE International Symposium on Antennas & Propagation and North American Radio Science Meeting

WE-UC.1A | MIMO, MISO, and Communication Systems

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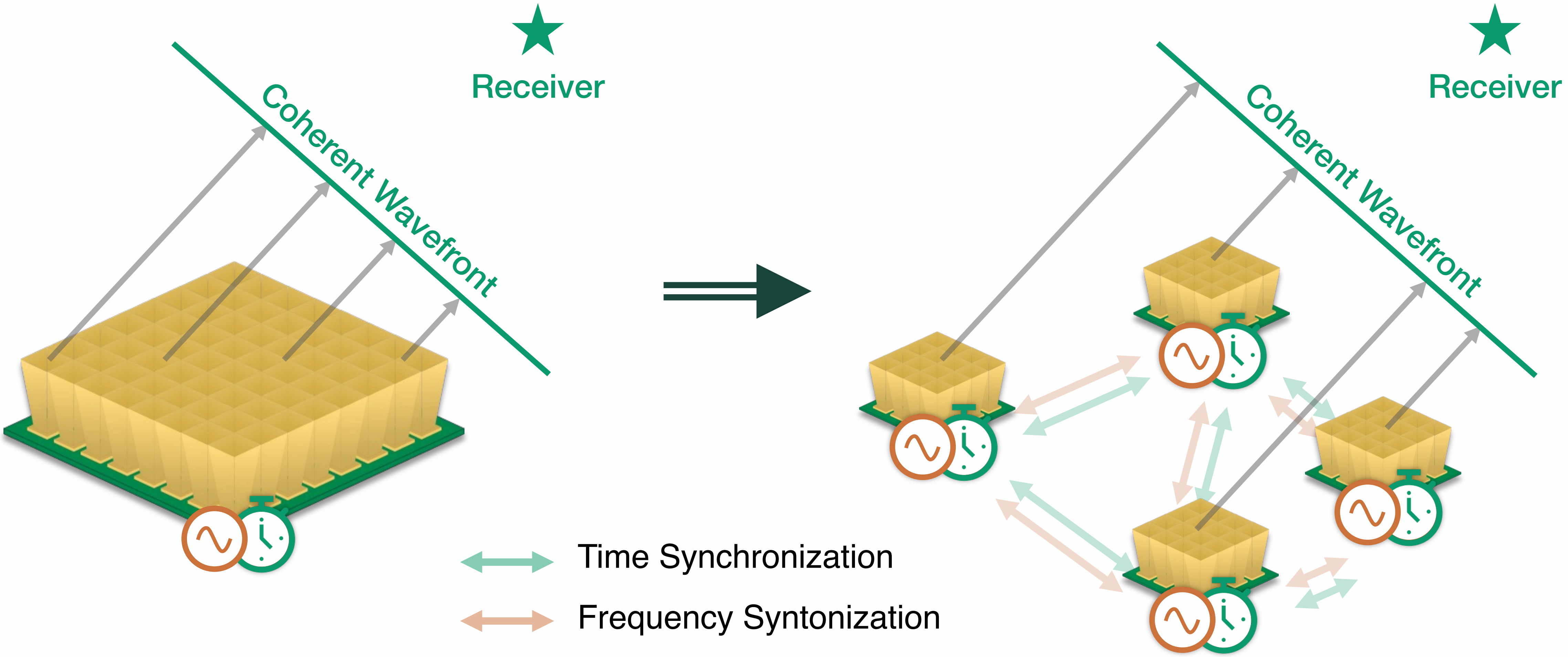
delta
Distributed Electromagnetics Theory and Applications

emrg
Electromagnetics Research Group Michigan State University

Distributed Array Overview

Traditional Antenna Array

Coherent Distributed Array (CDA)



Distributed Array Overview

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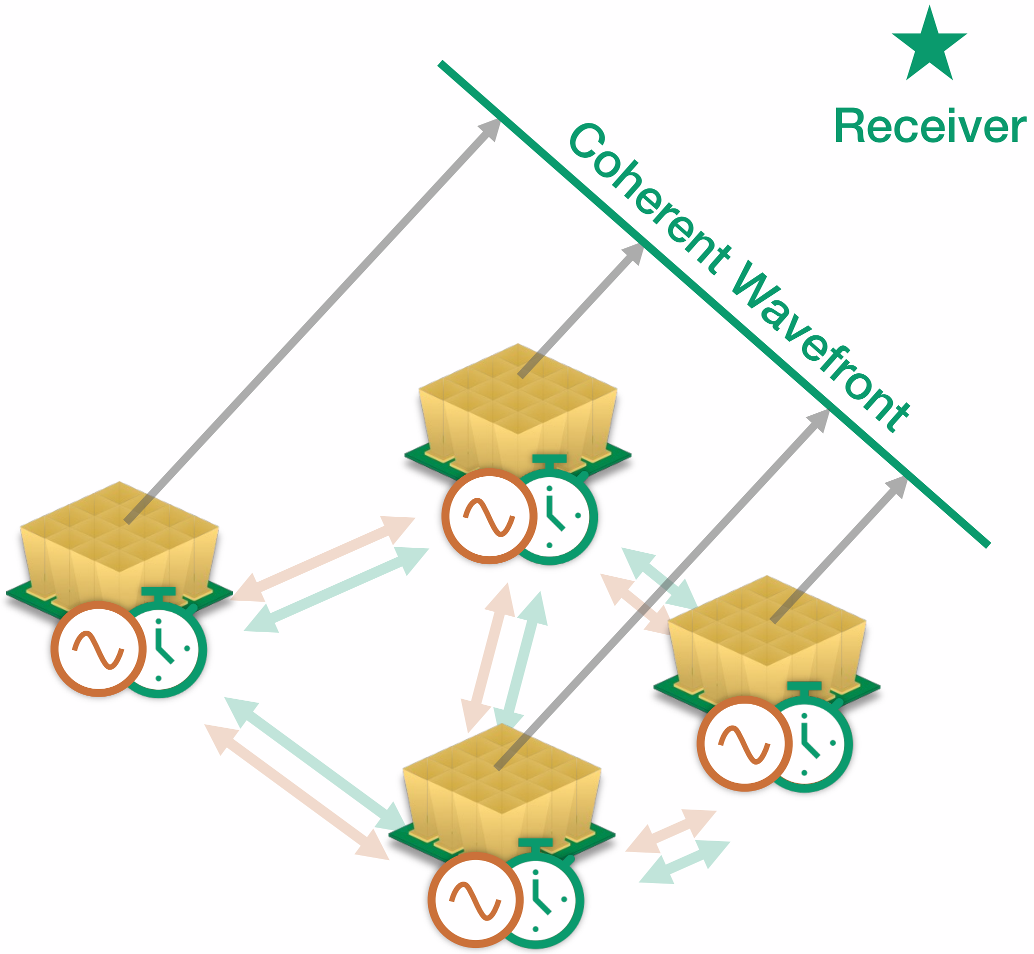
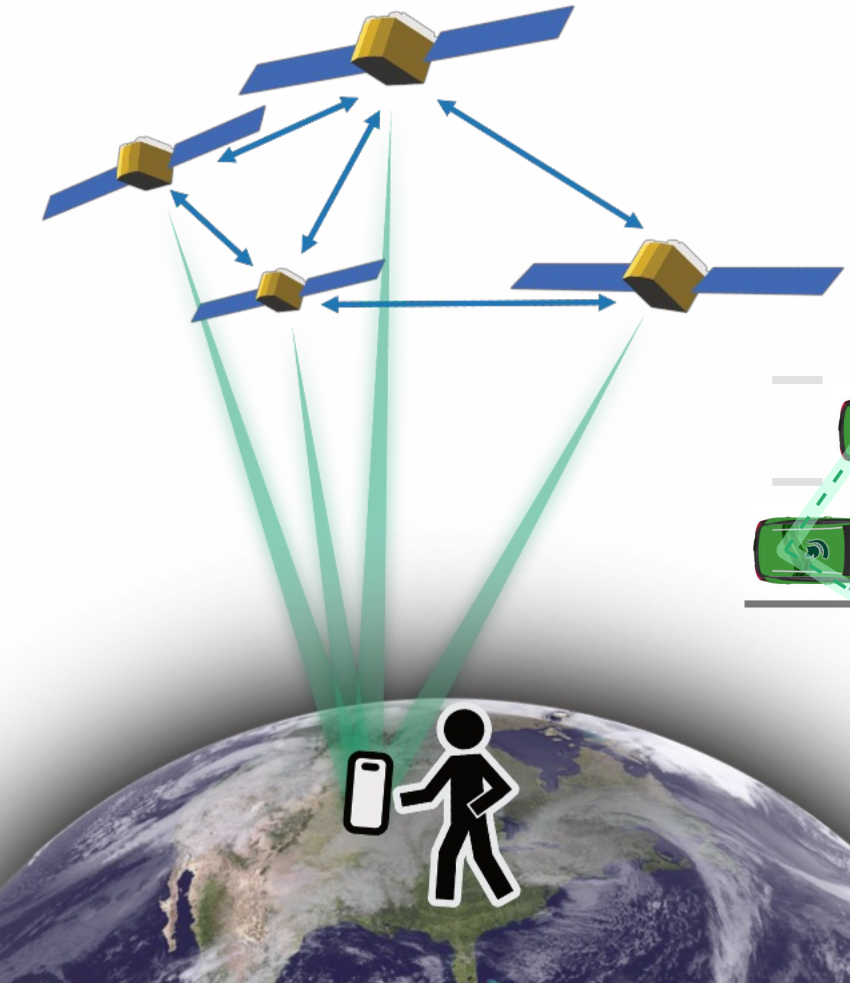


Benefits

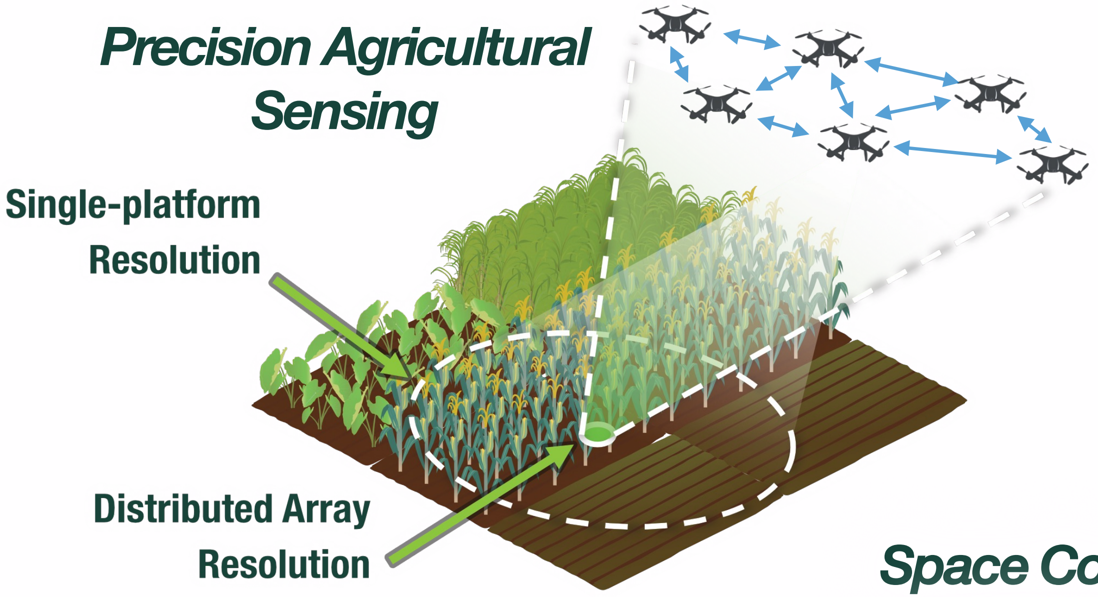
- **Scalability**
  - Reduced deployment cost
  - Larger array sizes possible
  - Increased total gain / throughput
- **Adaptability**
  - Can operate efficiently over larger frequency range
- **Reliability**
  - Decreased thermal management requirements
  - Resilient to antenna / node failure

Applications

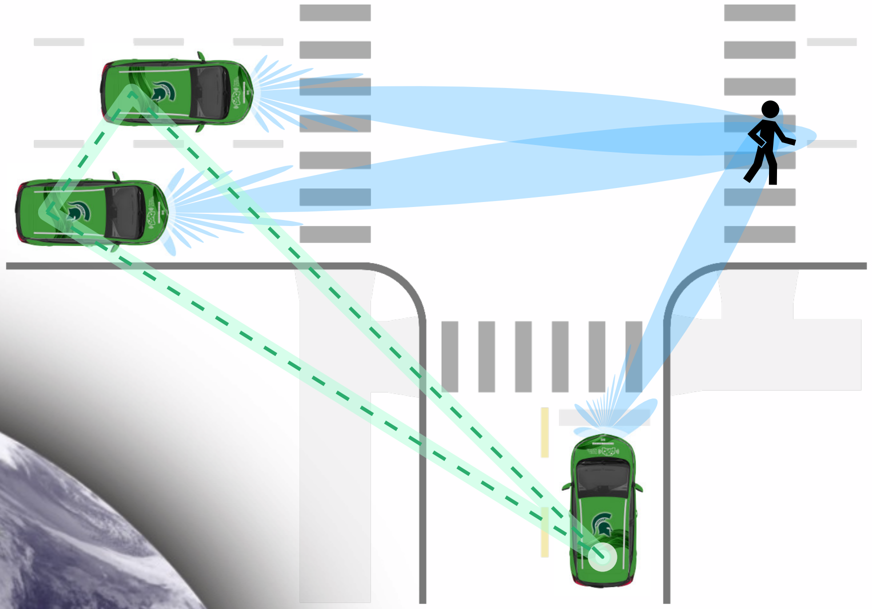
Next Generation 5G/6G Satellite Cellular Networks



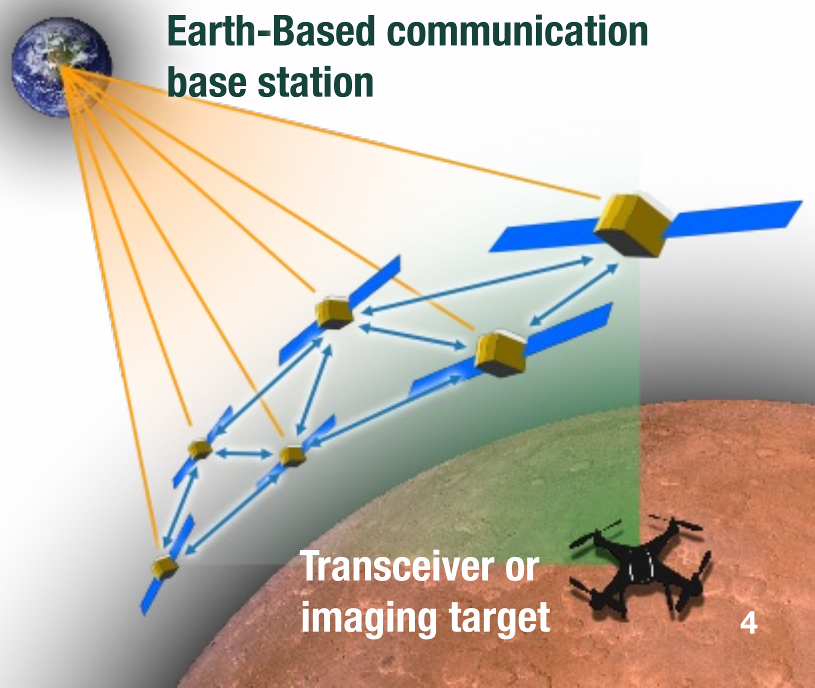
Precision Agricultural Sensing



Distributed V2X Sensing

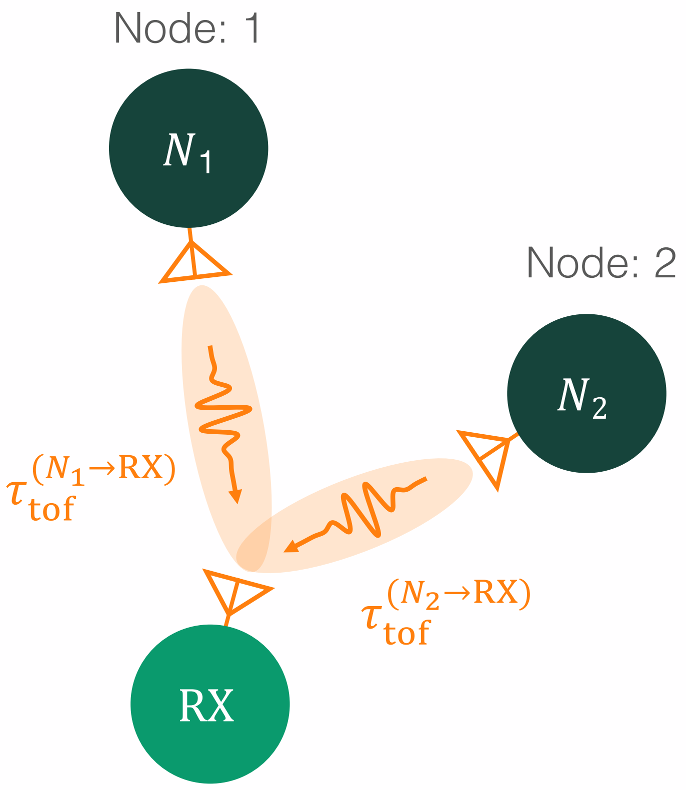


Space Communication and Remote Sensing

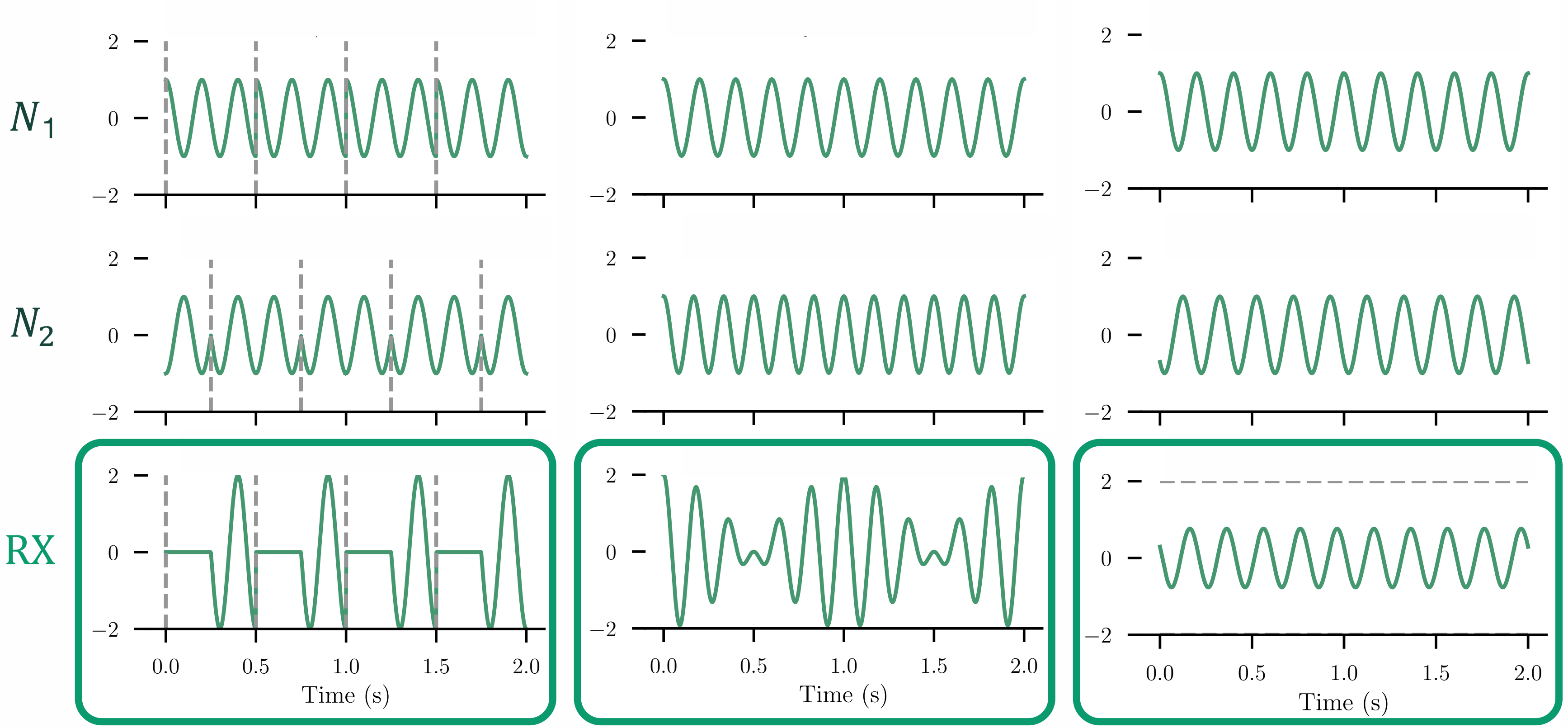


Electrical State Coordination Overview

Two-Node Array



Time Error | Frequency Error | Phase Error

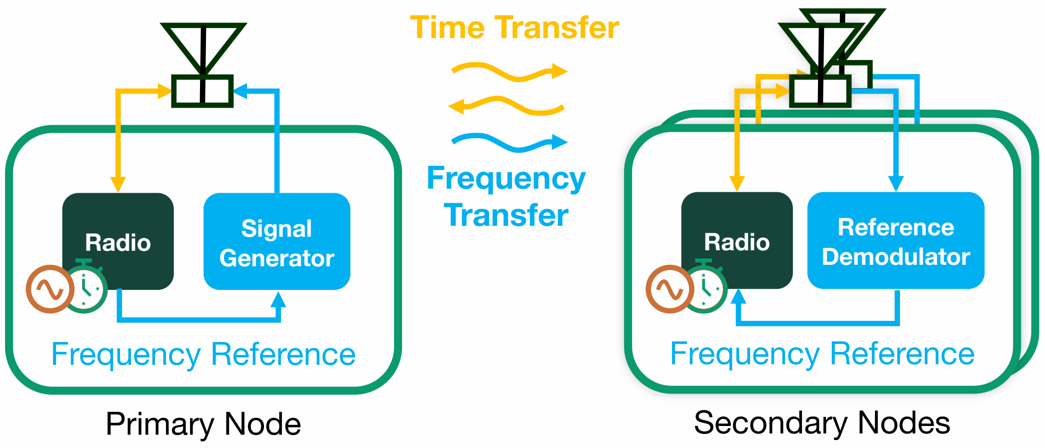


$$s_{\text{RX}}(t) = s^{(1)}(t) + s^{(2)}(t) = \sum_{n=1}^{2} A^{(n)}\Big(\underbrace{t - \delta t^{(n)}}_{\text{Time}} \underbrace{- \tau_{\text{tof}}^{(n \to \text{RX})}}_{\text{Propagation}}\Big) \quad \underbrace{\qquad}_{\text{Frequency}} \quad \underbrace{\qquad}_{\text{Phase}}$$

Motivation for Fully-Digital Coordination

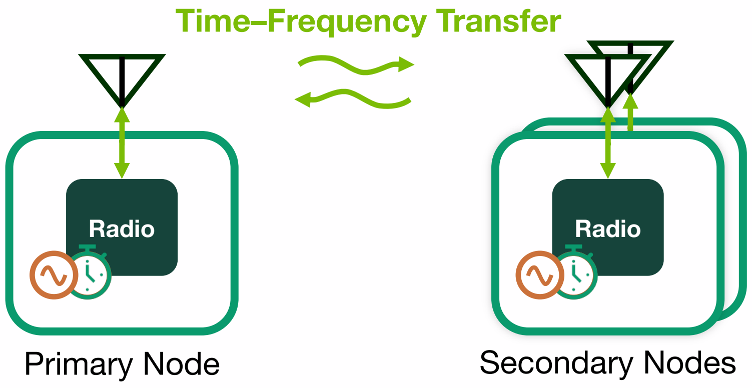
Hybrid Coordination (Prior Work*)

Digital Two-Way Time Transfer + Analog One-way Frequency Transfer



Fully-Digital Coordination

Digital Two-Way Time–Frequency Transfer



* S. R. Mghabghab and J. A. Nanzer, "Open-Loop Distributed Beamforming Using Wireless Frequency Synchronization," in *IEEE T-MTT*, 2021.

Motivation for Fully-Digital Coordination

Hybrid Coordination (Prior Work*)

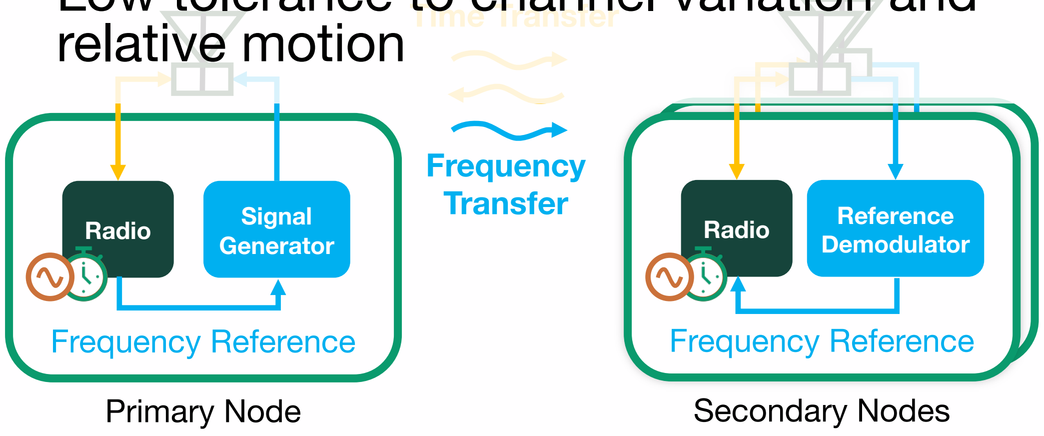
Digital Two-Way Time Transfer + Analog One-way Frequency Transfer

Pros

- Simpler software to implement
- Continuous frequency reference

Cons

- Low tolerance to channel variation and relative motion



Fully-Digital Coordination

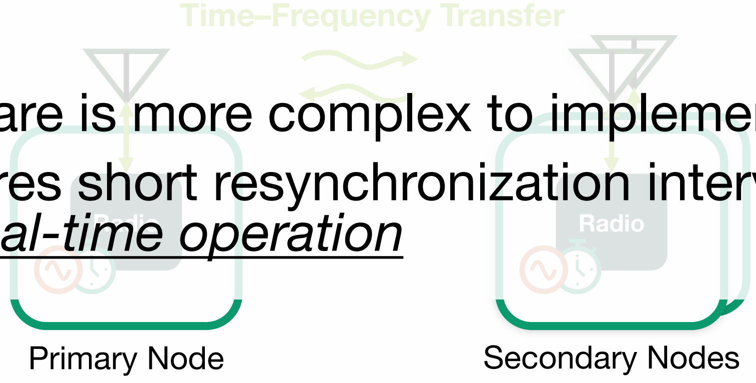
Digital Two-Way Time–Frequency Transfer

Pros

- Resilient to channel variation and motion
- No dedicated hardware required
  - ⇒ *Can be implemented on existing radios*
- Amenable to distributed consensus coordination schemes

Cons

- Software is more complex to implement
- Requires short resynchronization intervals and *real-time operation*



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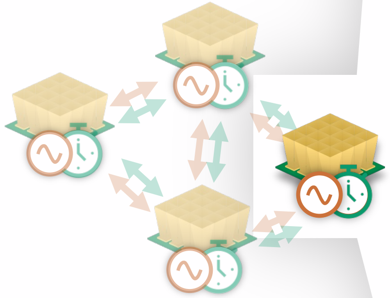
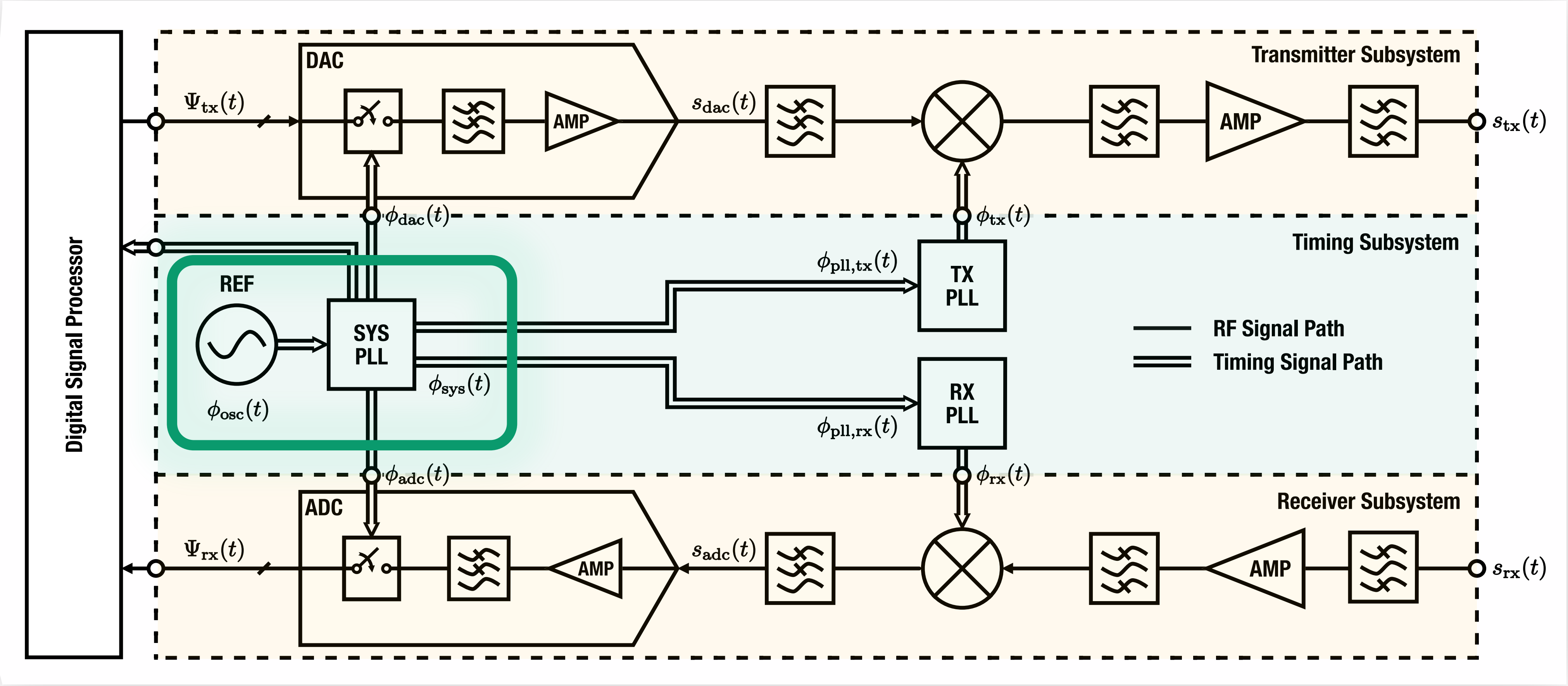
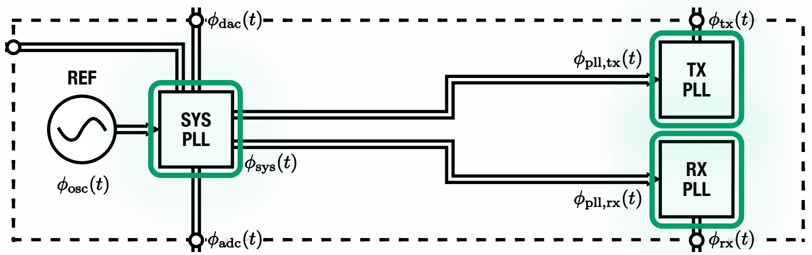
Time/Frequency Error in Software-Defined Radios





System Time Reference



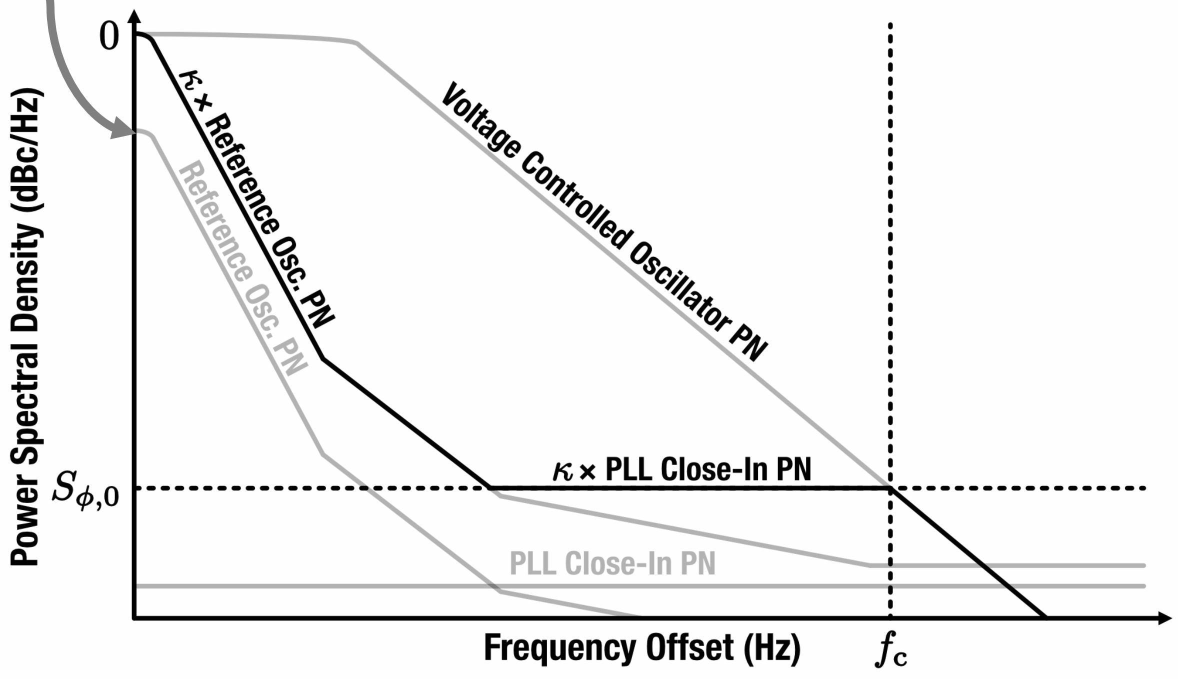
Reference Oscillator Model

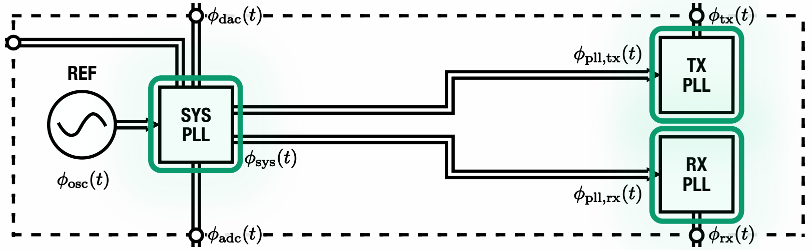
$$\phi_{\text{osc}}(t) = 2\pi f_{0,\text{osc}}\left(1 + \Delta f_{\text{osc}}(t)\right)t + \nu_\phi(t)$$

Deterministic fractional frequency error (initial error, aging, etc.)

Random zero-mean stationary phase noise process

Filtered Output Frequency Spectra





System Time Reference

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$$\phi_{\text{osc}}(t) = 2\pi f_{0,\text{osc}}\big(1 + \Delta f_{\text{osc}}(t)\big)t + \nu_{\phi}(t)$$

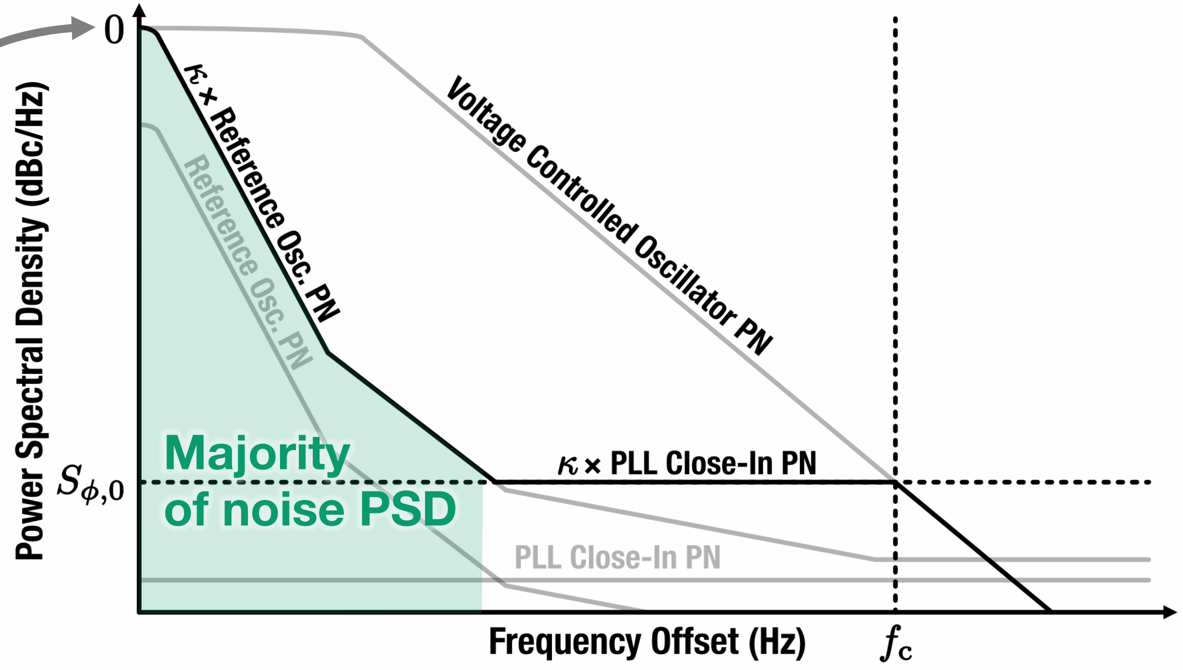
System PLL Model

$$\boxed{\begin{aligned}\phi_{\text{sys}}(t) = \big\langle \kappa_{\text{sys}}\big[\phi_{\text{osc}}(t) + \nu_{\phi,\text{sys,in}}(t)\big]\big\rangle_{\text{lpf}} \\ + \big\langle \nu_{\phi,\text{vco}}(t)\big\rangle_{\text{hpf}} + \phi_{0,\text{sys}}\end{aligned}}$$

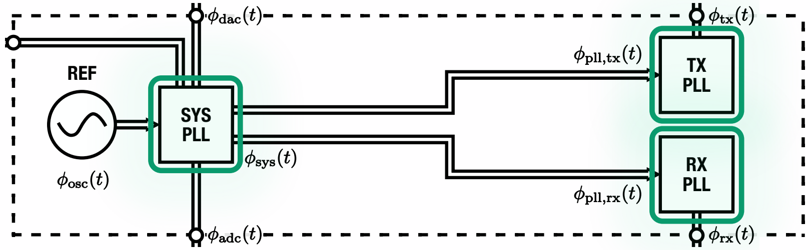
where

κ_{sys}	Feedback scaling coefficient
$\phi_{\text{ref}}(t)$	Reference input phase
$\nu_{\phi,\text{pll,in}}(t)$	Intrinsic phase noise process
$\nu_{\phi,\text{vco}}(t)$	Phase noise from VCO
$\phi_{0,\text{ref}}$	Random initial startup phase

Filtered Output Frequency Spectra



System Time Reference



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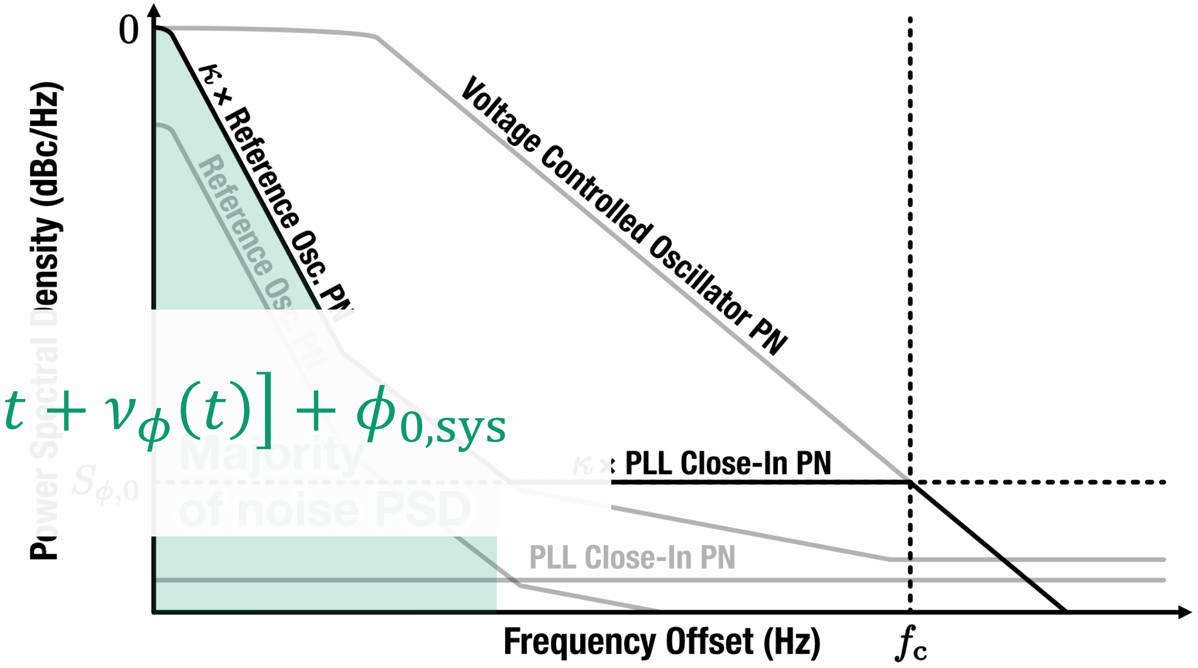
System PLL Approximation

$$\Rightarrow\ \phi_{\text{sys}}(t) \approx \kappa_{\text{sys}}\big[2\pi f_{0,\text{osc}}\big(1 + \Delta f_{\text{osc}}(t)\big)t + \nu_\phi(t)\big] + \phi_{0,\text{sys}}$$

Dominant PSD still due to oscillator drift/noise

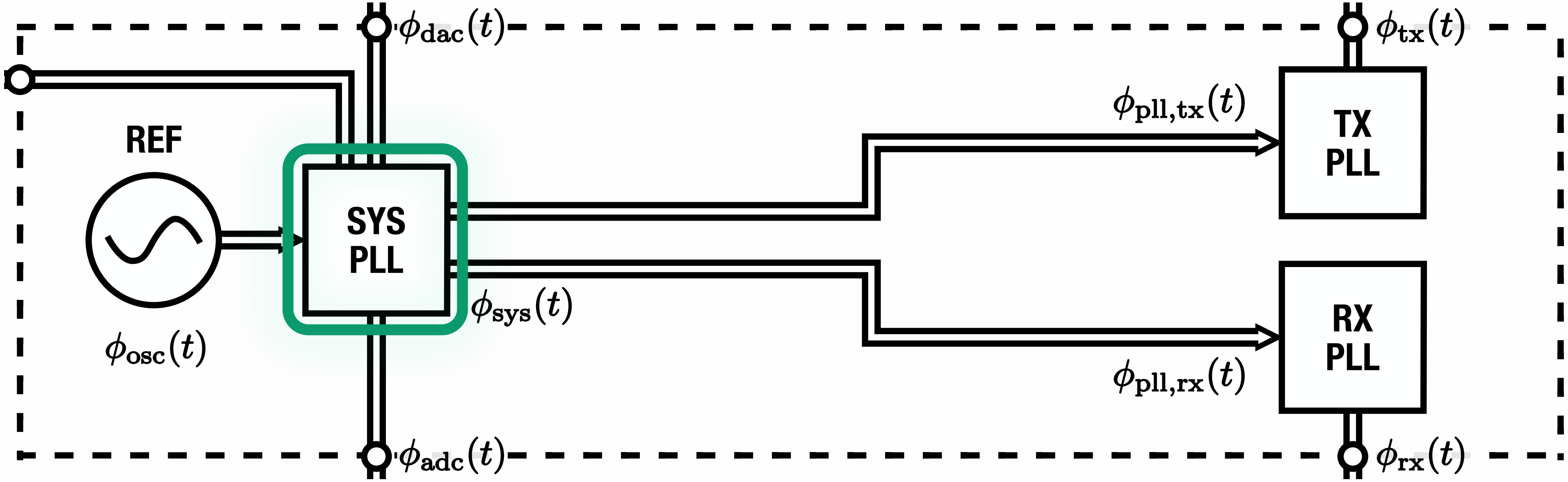
Filtered Output Frequency Spectra



Phase-Locked Loop Synthesizers

Phase can be represented as time by

$$\phi_{\text{sys}}(t) \approx \kappa_{\text{sys}}\left[2\pi f_{0,\text{osc}}\left(1 + \Delta f_{\text{osc}}(t)\right)t + \nu_{\phi}(t)\right] + \phi_{0,\text{sys}} \quad \longrightarrow \quad T_{\text{sys}}(t) = \frac{\phi_{\text{sys}}(t)}{\kappa_{\text{sys}} 2\pi f_{0,\text{osc}}}$$



SYS PLL is the main time/frequency distribution point

Internode Time Error

The system clock phase and time *difference* between two nodes

$$\phi_{\text{sys}}^{(n,m)}(t) = \phi_{\text{sys}}^{(m)}(t) - \phi_{\text{sys}}^{(n)}(t)$$

and

$$\boxed{T_{\text{sys}}^{(n,m)} = \frac{\phi_{\text{sys}}^{(n,m)}(t)}{\kappa_{\text{sys}} 2\pi f_{0,\text{osc}}} \approx \Delta f_{\text{osc}}^{(n,m)}(t)t + T_{0,\text{sys}}^{(n,m)} + \nu_{T,\text{sys}}^{(n,m)}(t)}$$

Time difference <u>results in only the error terms</u>

Goal: Estimate $T_{sys}^{(n,m)}$ to compensate TX waveform

Direct Digital Phase Compensation

Carrier waveform with errors relative to node N_0

$$s_{\mathrm{tx}}^{(n)}(t) \approx \underbrace{\Psi_{\mathrm{tx}}\left(t + T_{\mathrm{sys}}^{(0,n)}(t)\right)}_{\text{Digital baseband waveform with errors}} \exp\underbrace{\left\{j2\pi f_{0,\mathrm{tx}} t + j2\pi f_{0,\mathrm{tx}} T_{\mathrm{sys}}^{(0,n)}(t) + j\phi_{0,\mathrm{tx}}\right\}}_{\text{Carrier phase with errors}}$$

Assume: high-accuracy estimate of $T_{\mathrm{sys}}^{(0,n)}$ is available

Goal: Modify Ψ_{tx} such that errors are compensated

Direct Digital Phase Compensation

Carrier waveform with errors relative to node N_0

$$s_{\text{tx}}^{(n)}(t) \approx \Psi_{\text{tx}}\left(t + T_{\text{sys}}^{(0,n)}(t)\right) \exp\left\{j2\pi f_{0,\text{tx}} t + j2\pi f_{0,\text{tx}} T_{\text{sys}}^{(0,n)}(t) + j\phi_{0,\text{tx}}\right\}$$

Digital compensation waveform:

$$\tilde{\Psi}_{\text{tx}}(t) = \Psi_{\text{tx}}\left(t - \hat{T}_{\text{sys}}^{(0,n)}(t)\right) \exp\left\{-j2\pi f_{0,\text{tx}} \hat{T}_{\text{sys}}^{(0,n)}(t)\right\} \exp\{-j\hat{\phi}_{0,\text{tx}}\}$$

Time-corrected digital baseband waveform

Phase conjugate carrier frequency error and static calibration phases

Direct Digital Phase Compensation

Carrier waveform with errors relative to node N_0

$$s_{\mathrm{tx}}^{(n)}(t) \approx \Psi_{\mathrm{tx}}\left(t + T_{\mathrm{sys}}^{(0,n)}(t)\right) \exp\left\{j2\pi f_{0,\mathrm{tx}} t + j2\pi f_{0,\mathrm{tx}} T_{\mathrm{sys}}^{(0,n)}(t) + j\phi_{0,\mathrm{tx}}\right\}$$

Digital compensation waveform:

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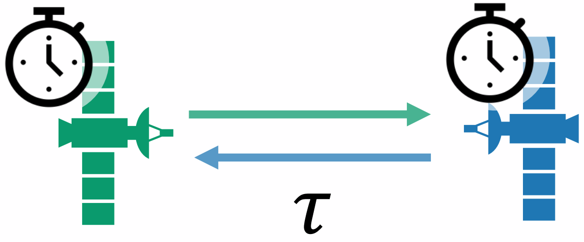
Substitute original waveform $\Psi_{\mathrm{tx}}(t)$ for $\widetilde{\Psi}_{\mathrm{tx}}(t)$

$$\Rightarrow \; s_{\mathrm{tx}}^{(n)}(t) \approx \Psi_{\mathrm{tx}}(t) \exp\{j2\pi f_{0,\mathrm{tx}} t\}$$

Digital Time Coordination Technique



Two-Way Time Synchronization

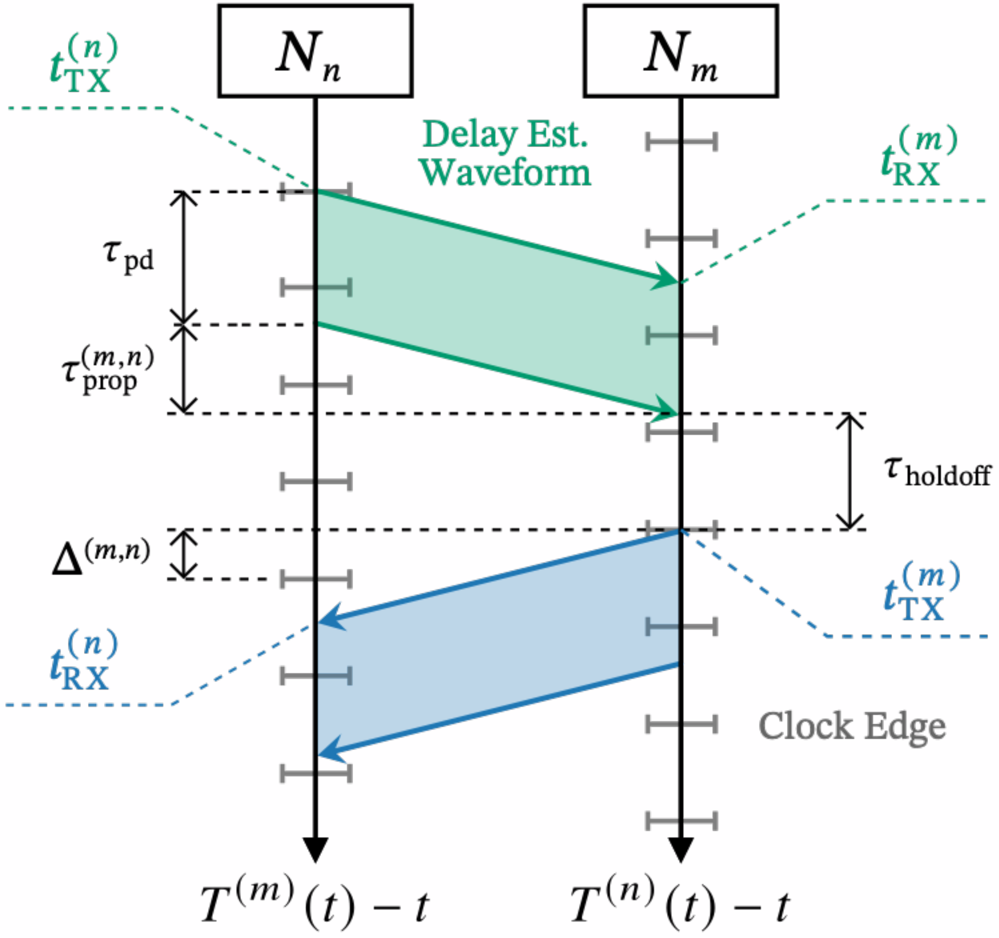
- *Assumption:*
  - Link is reciprocal $\Longrightarrow$ quasi-static during the synchronization epoch

- *Apparent* one-way time of flight (ToF):

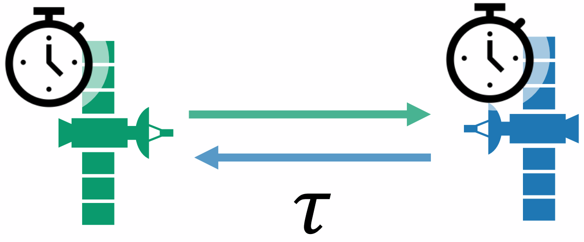
$$\tilde{\tau}^{(n\rightarrow m)}[k] = T_{\mathrm{RX}}^{(m)}\left(t_{\mathrm{RX}}^{(m)}[k]\right) - T_{\mathrm{TX}}^{(n)}\left(t_{\mathrm{TX}}^{(n)}[k]\right)$$

- Internode timing skew:

$$T_{0,\mathrm{sys}}^{(n,m)}[k] = \frac{\tilde{\tau}^{(n\rightarrow m)}[k] - \tilde{\tau}^{(m\rightarrow n)}[k]}{2}$$



Digital Time Coordination Technique



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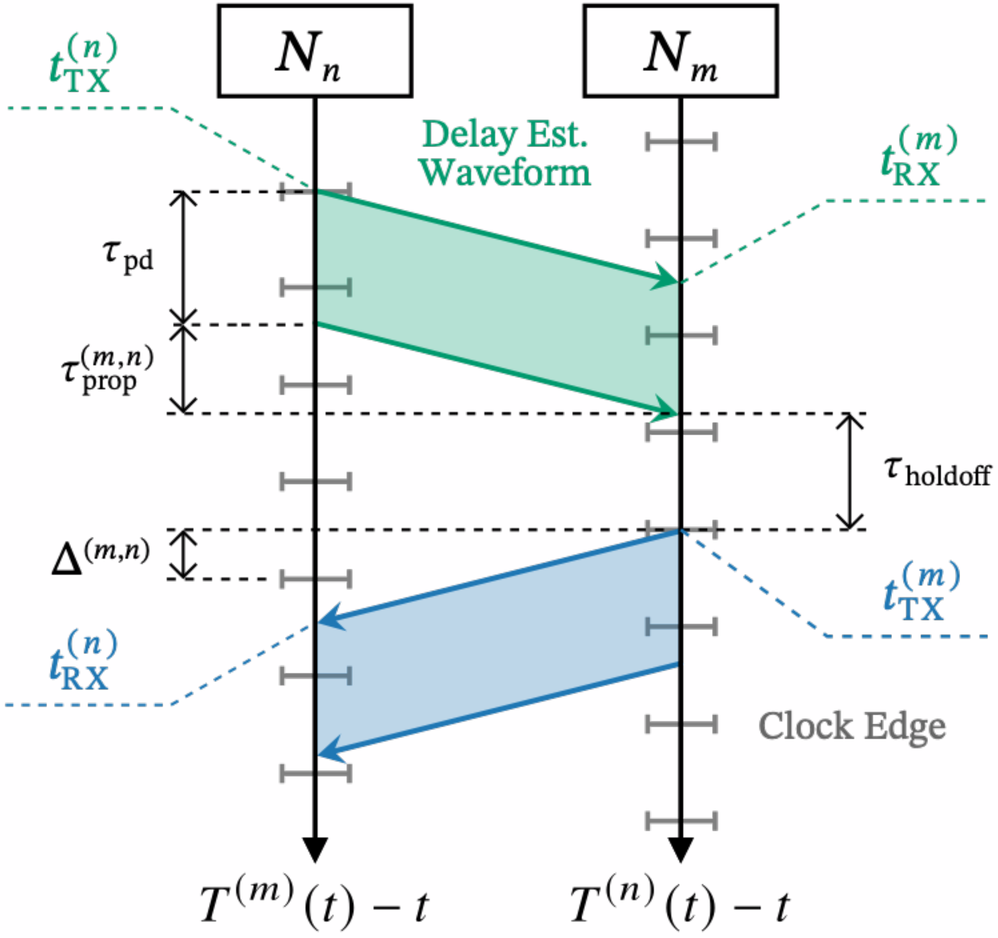
$$\tilde{\tau}^{(n\rightarrow m)}[k] = T_{\mathrm{RX}}^{(m)}\left(t_{\mathrm{RX}}^{(m)}[k]\right) - T_{\mathrm{TX}}^{(n)}\left(t_{\mathrm{TX}}^{(n)}[k]\right)$$

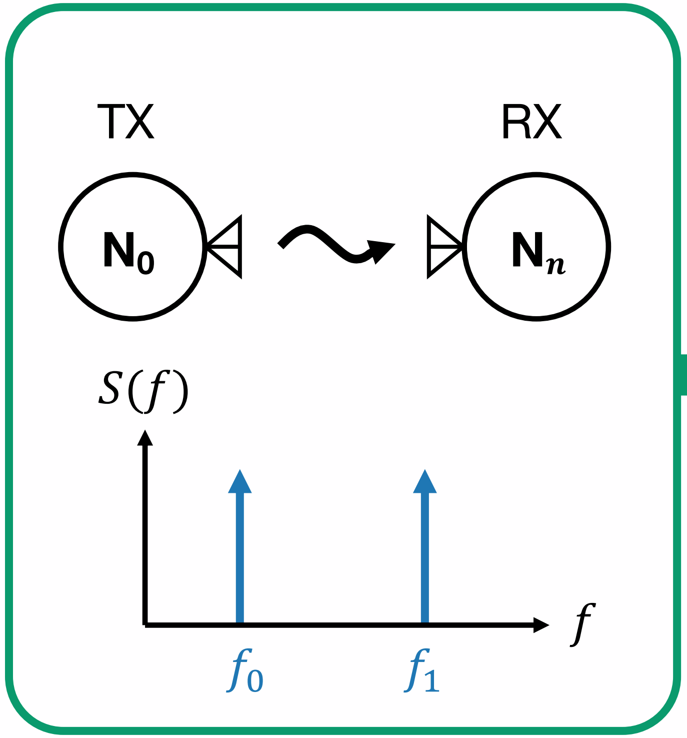
- Internode range:

$$R^{(m,n)}[k] = c \cdot \frac{\tilde{\tau}^{(n\rightarrow m)}[k] + \tilde{\tau}^{(m\rightarrow n)}[k]}{2}$$

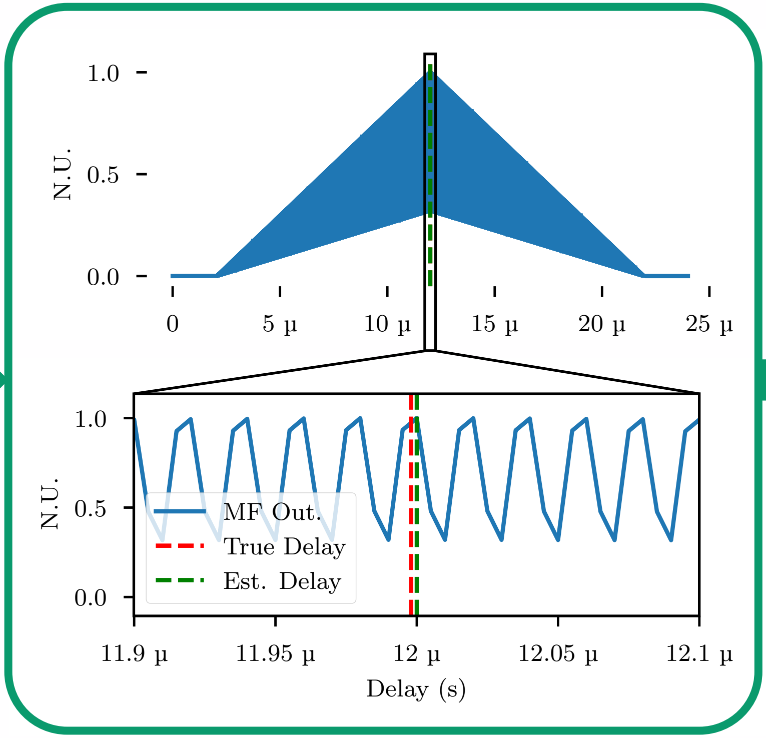


Time of Arrival Estimation Process

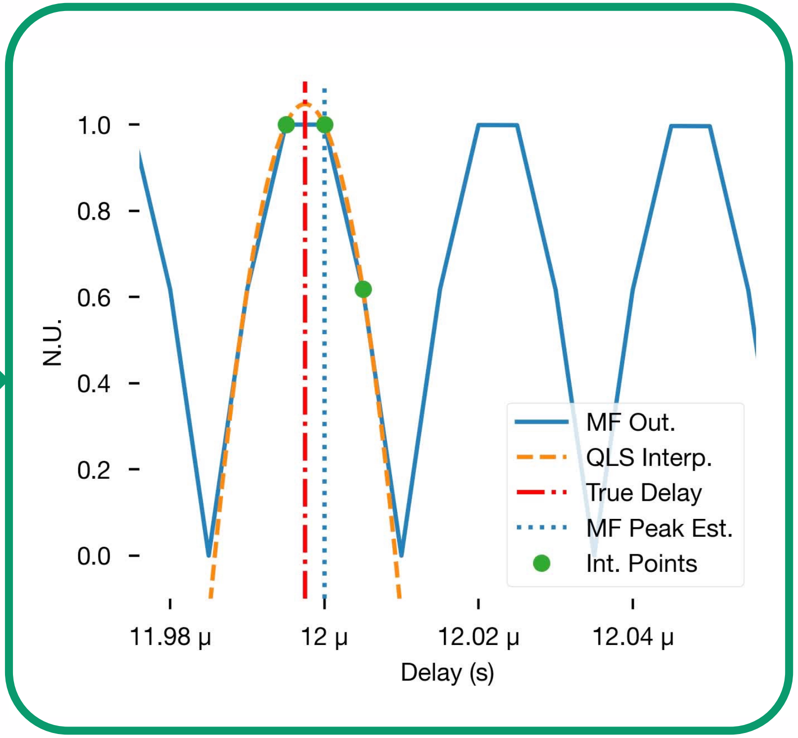
Pulsed Two-Tone Transmission



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.

High-Accuracy Frequency Estimation

Frequency estimate performed by repeated estimates of $T_{\text{sys}}^{(n,m)}$

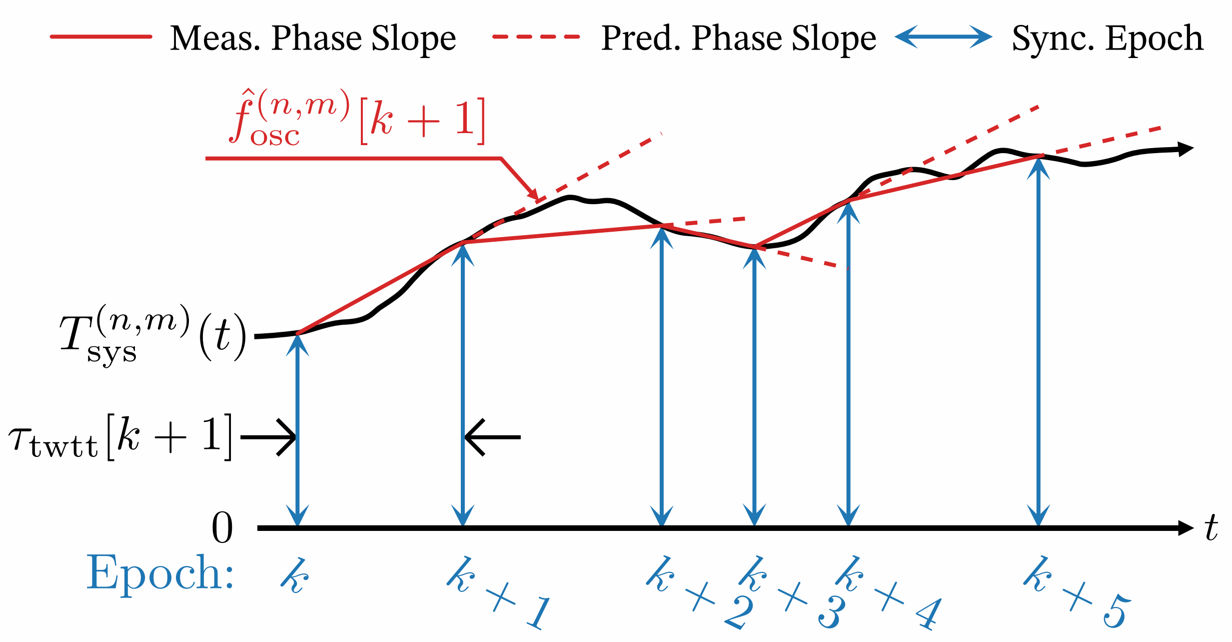
$$\Delta\hat{f}_{\text{osc}}^{(n,m)}[k] = \frac{\hat{T}_{\text{sys}}^{(n,m)}[k] - \hat{T}_{\text{sys}}^{(n,m)}[k-1]}{\tau_{\text{twtt}}[k]}$$

Where time estimate is:

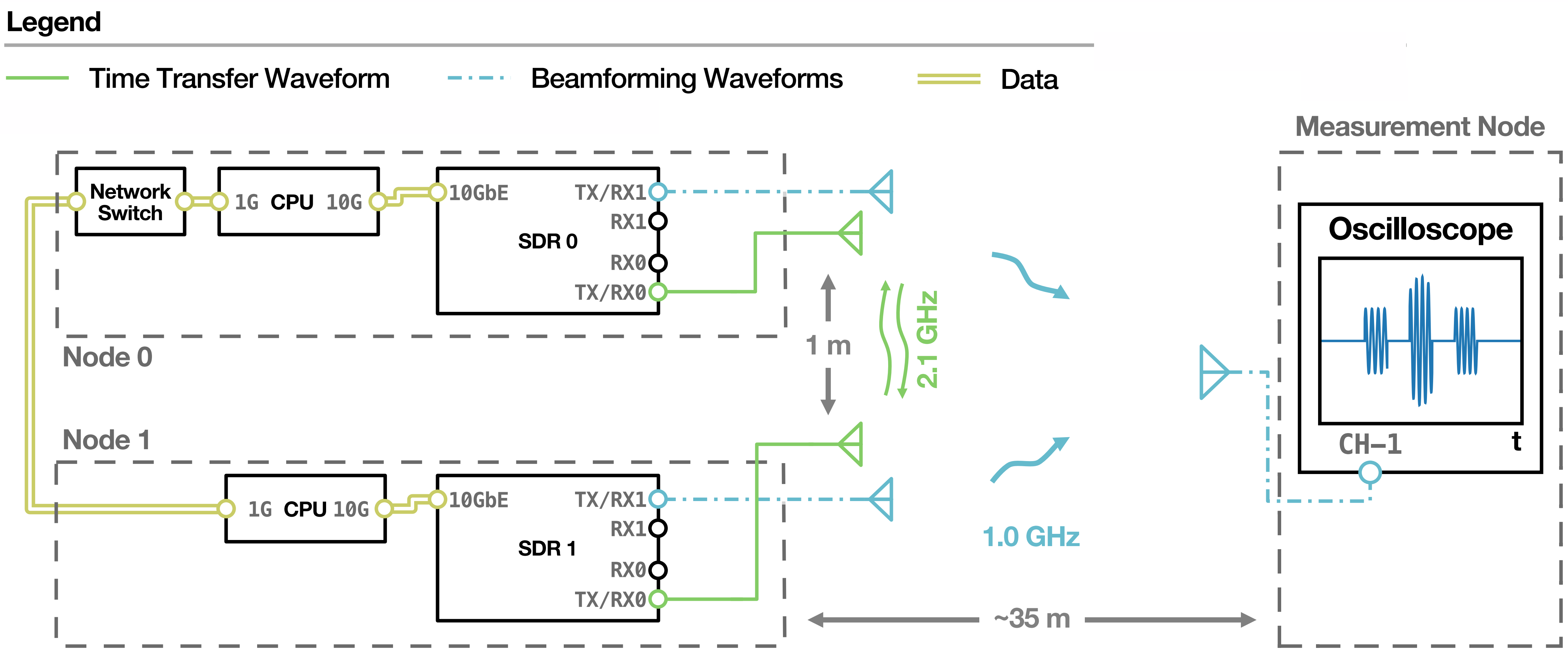
$$\hat{T}_{\text{sys}}^{(0,n)}(t) = \Delta\hat{f}_{\text{osc}}^{(0,n)}(t)t + \hat{T}_{0,\text{sys}}^{(0,n)}$$

Constant component $\hat{T}_{0,\text{sys}}^{(0,n)}$ corrected by initial two-way time transfer

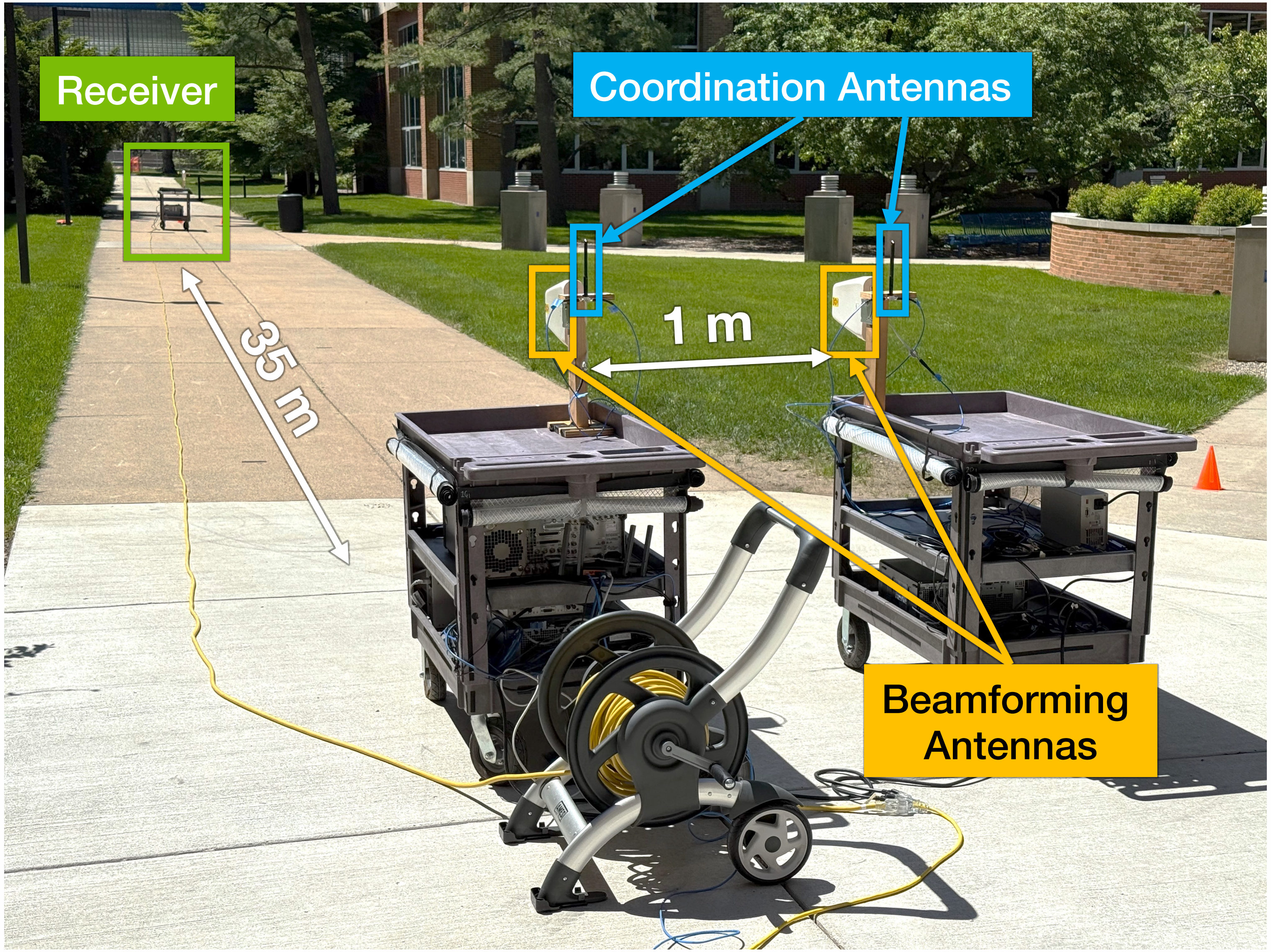
Repeated Estimates of $T_{\text{sys}}^{(n,m)}$



Fully-Digital Coordination System Schematic



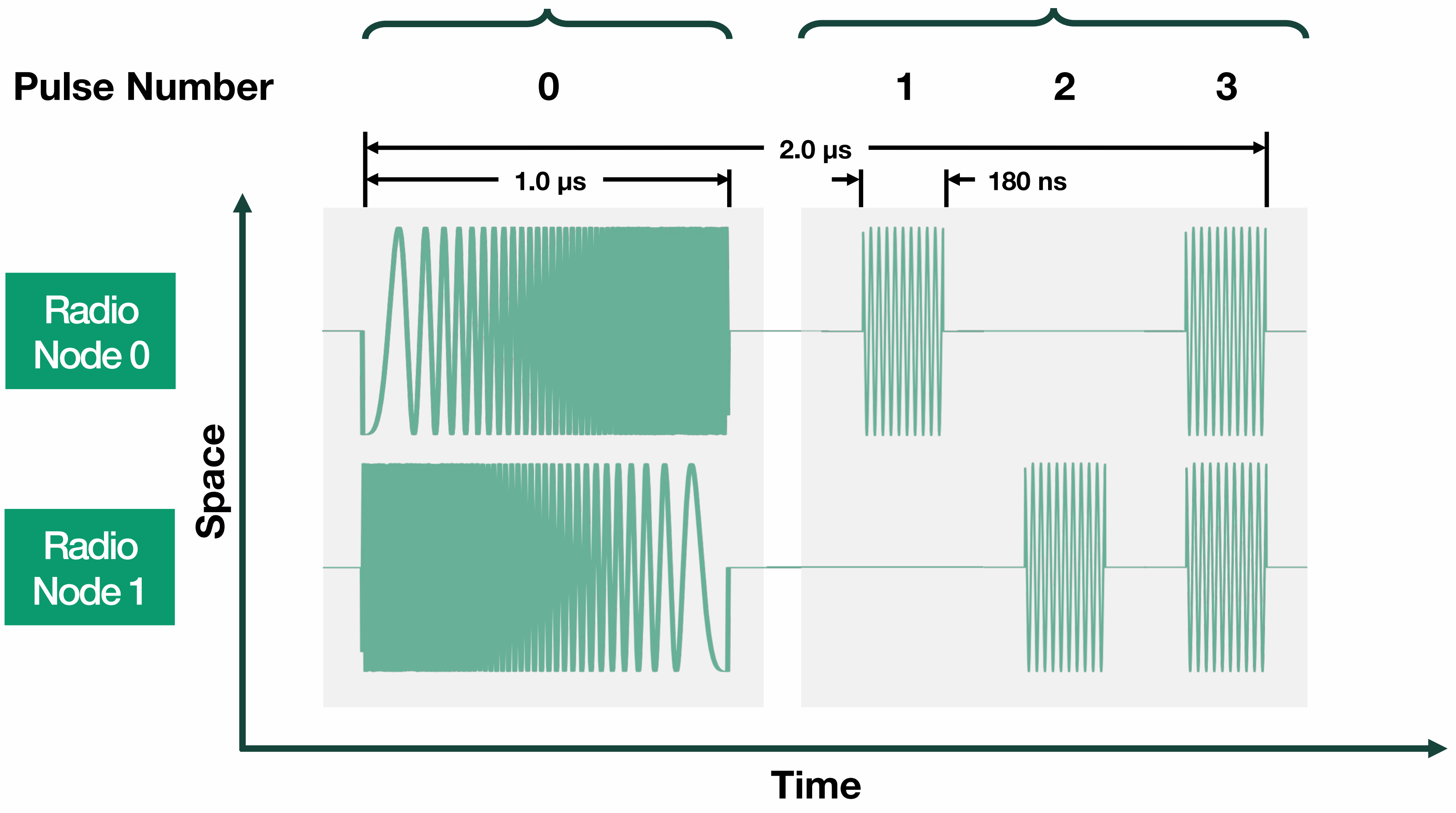
Experimental Setup



Calibration & Performance Evaluation

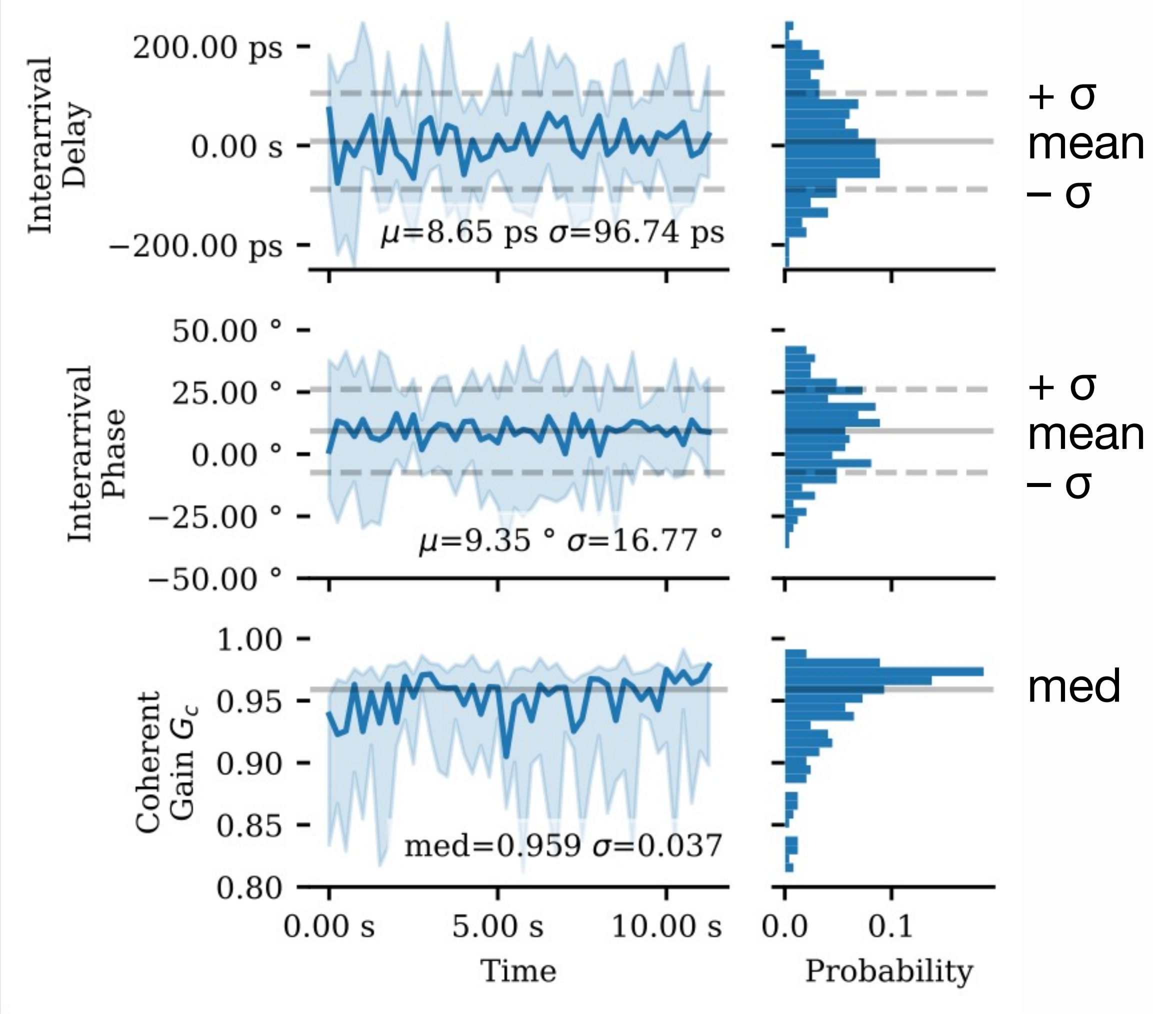
Linear Frequency Modulation (LFM) Pulses
Internode Time Estimation

Continuous Wave (CW) Pulses
Internode Phase / Coherent Gain Estimation



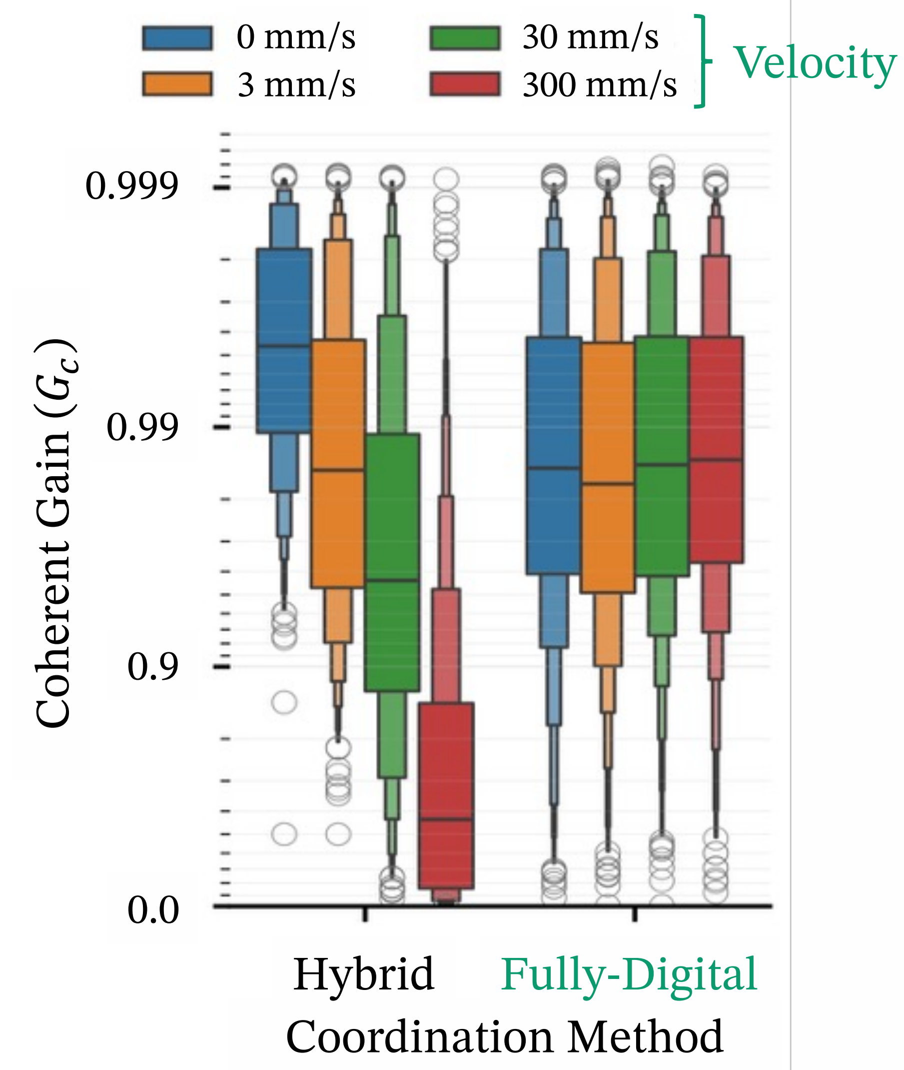
Collaborative Beamforming Measurements

Static Outdoor Fully-Digital Beamforming



Shaded region ⟹ min/max

Dynamic In-Lab Beamforming Comparison



Experiment Summary

- Presented new fully-digital high-accuracy time–frequency coordination technique for SDRs, independent of external time/frequency references
- Benchmarked new approach against hybrid coordination technique
- Achieved G_c = ~0.96 over 35 m range at 1.0 GHz

Technique	Beamforming Coherent Gain	Phase Std.	Time Std.	Theoretical Throughput*
Hybrid (Baseline)	~0.97	10.36°	82.66 ps	~1.2 Gbps
Fully-Digital	**~0.96**	**16.77°**	**96.74 ps**	**~1.0 Gbps**

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

* P. Chatterjee and J. A. Nanzer, "Effects of time alignment errors in coherent distributed radar," in 2018 IEEE Radar Conference (RadarConf18), pp. 0727–0731, 2018.

Questions?

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