Array 2024
Boston Massachusetts

Michigan State University

Fully Wireless Collaborative Beamforming Using A Three-Element Coherent Distributed Phased Array

2024 IEEE International Symposium on Phased Array Systems & Technology

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delta
Distributed Electromagnetics Theory and Applications

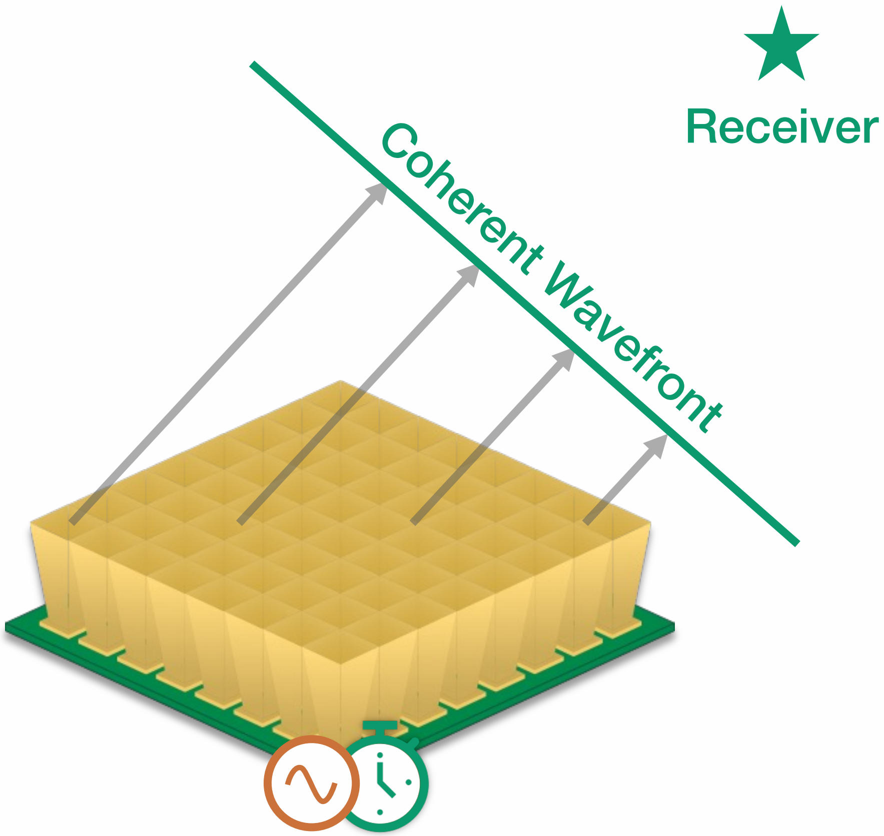
emrg
Electromagnetics Research Group
Michigan State University

Outline

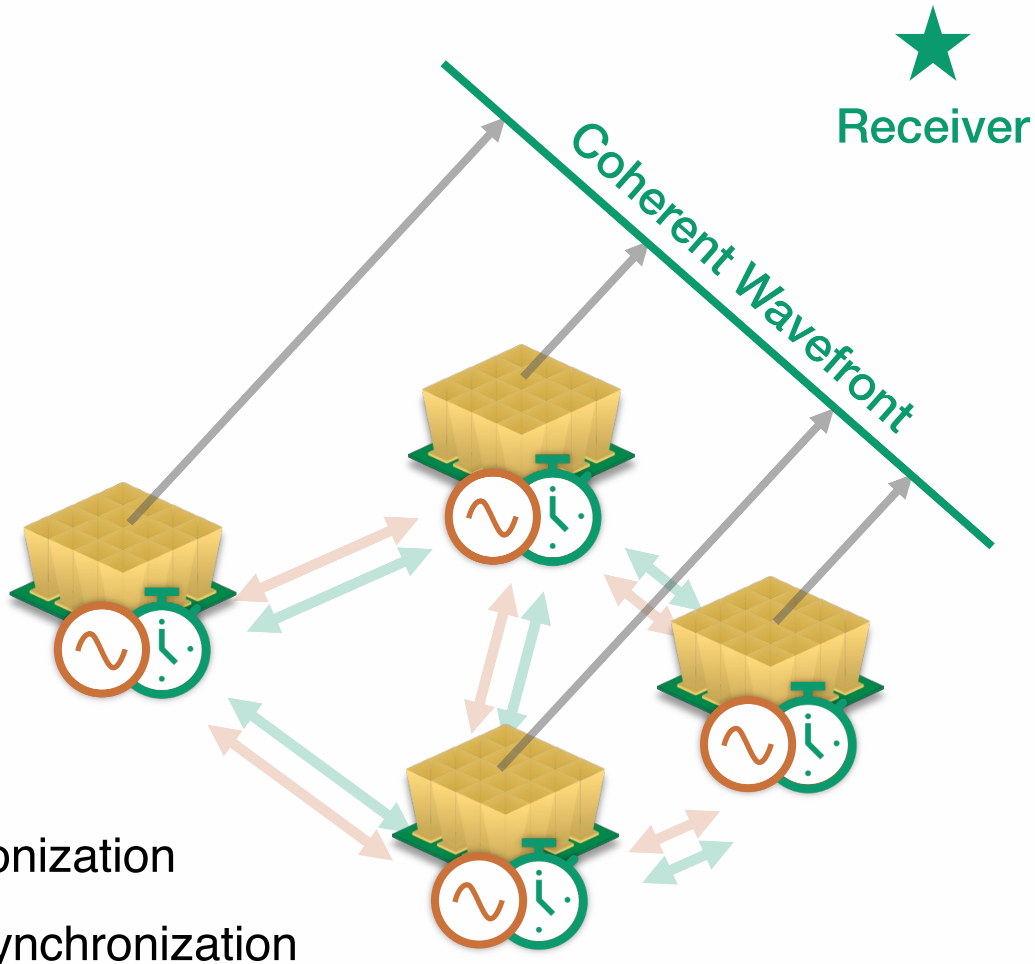
1. Motivation and Applications
2. System Model
3. Electrical State Estimation
4. Electrical State Alignment
5. Experimental Evaluation

Motivation

Traditional Phased Array



Distributed Phased Array

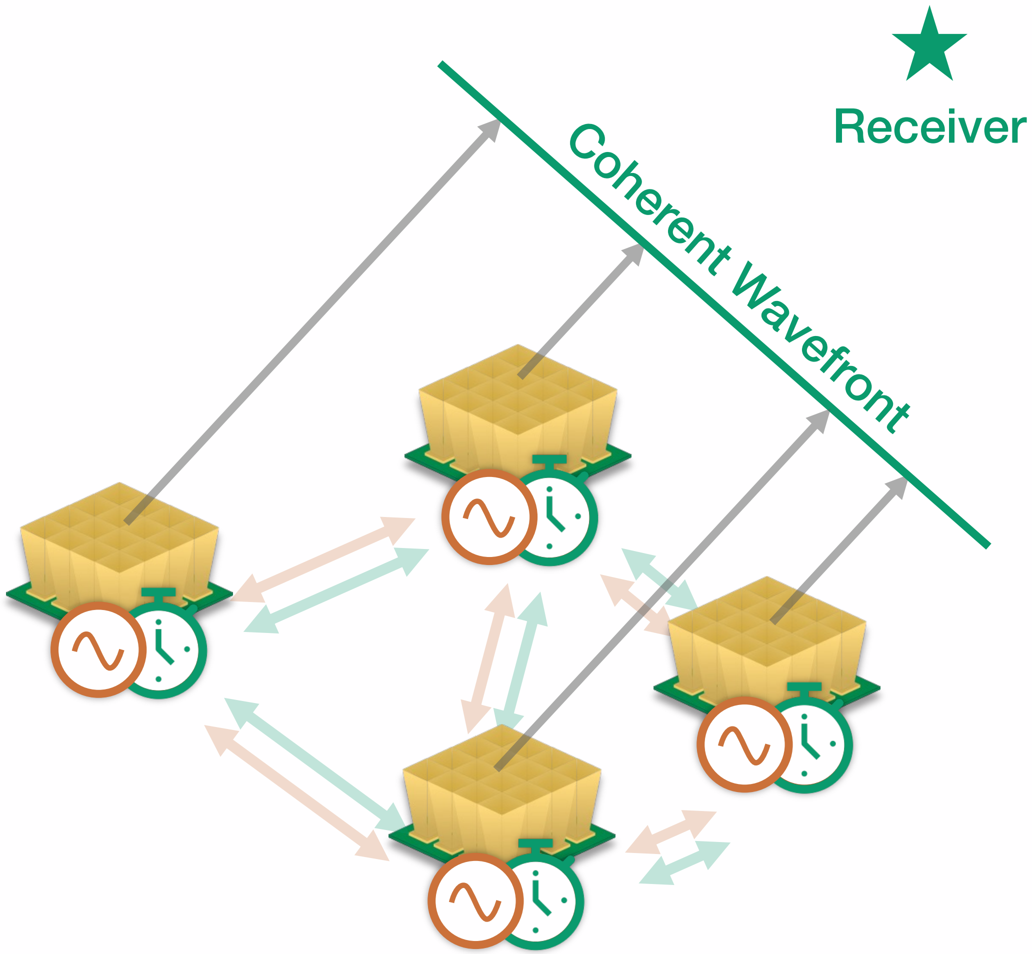


Time Synchronization

Frequency Synchronization

Motivation

Distributed Phased Array

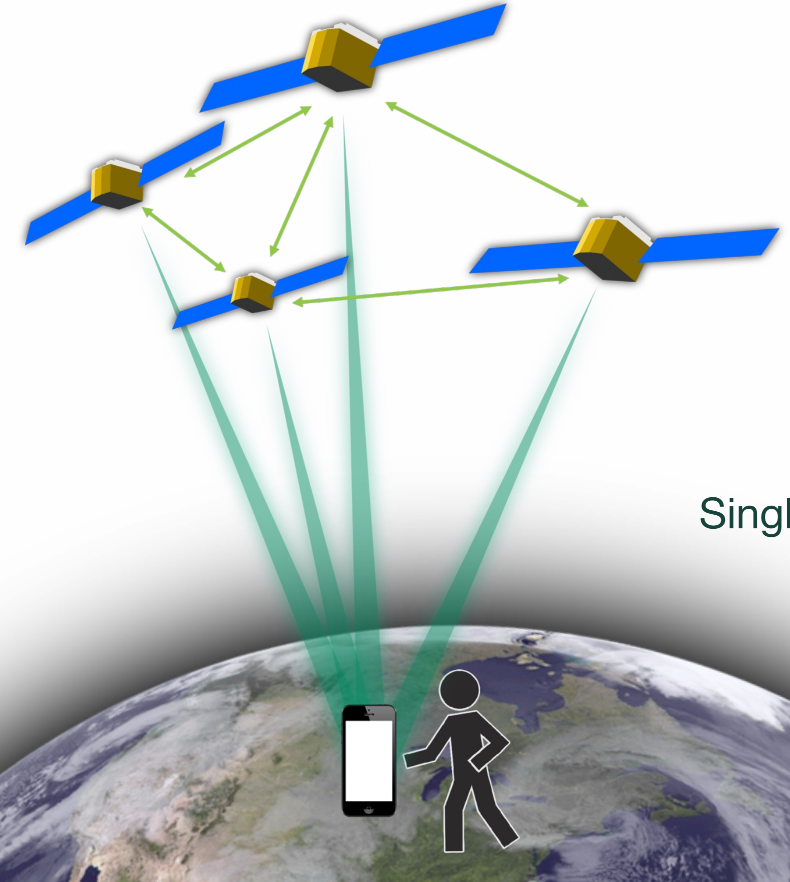


Benefits

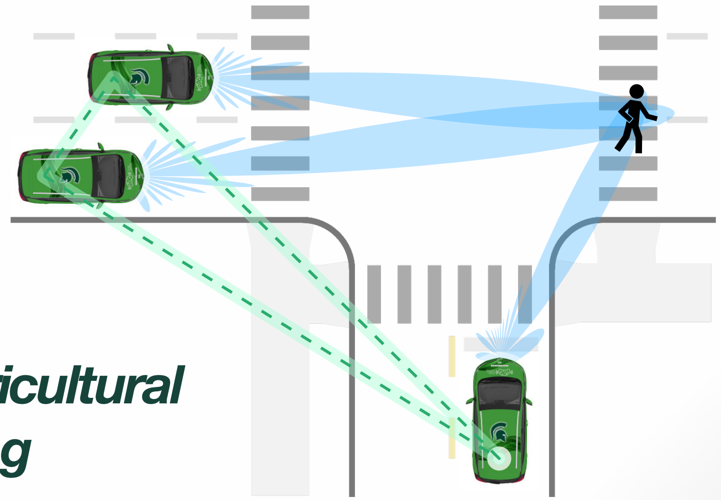
- Many small nodes make up array
  - Reduced deployment cost
  - Decreased thermal management requirements
  - Resilient to antenna / node failure
- Larger array sizes possible
  - Increased total gain / throughput
- Can operate efficiently over larger frequency range

Applications

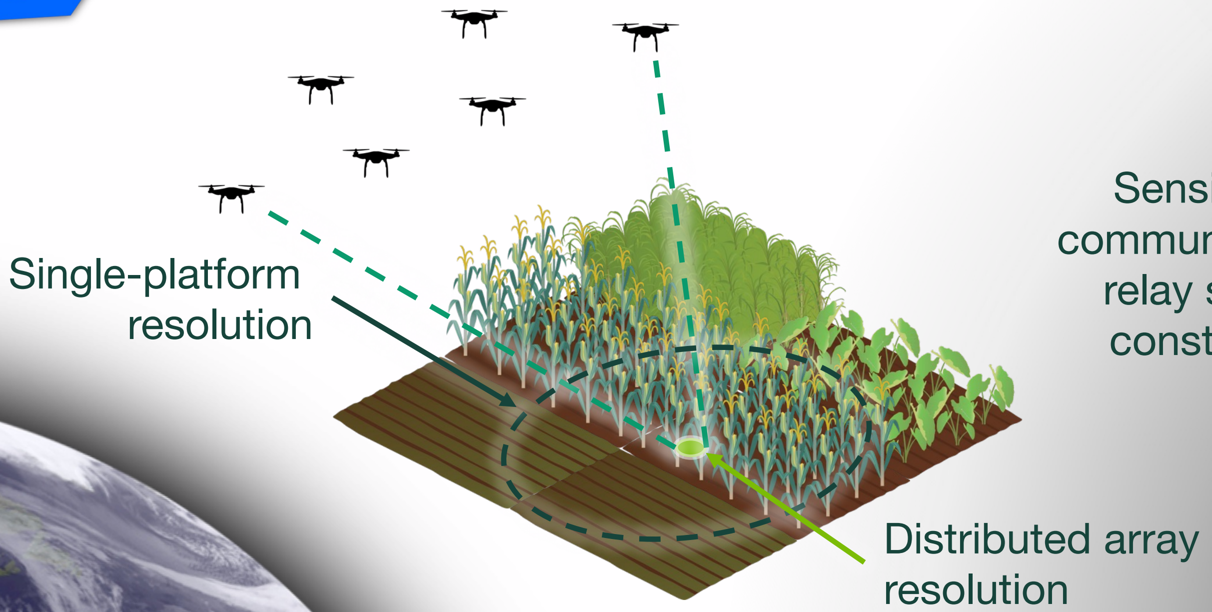
Next Generation 5G/6G Satellite Cellular Networks



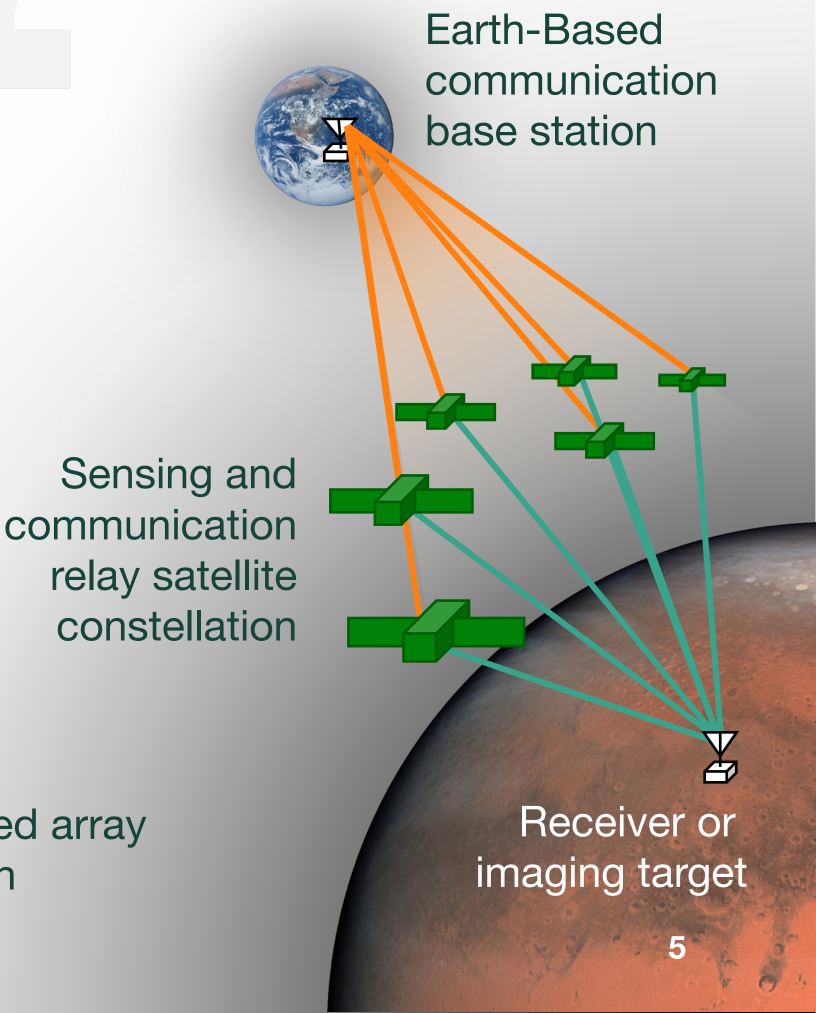
Distributed V2X Sensing



Precision Agricultural Sensing

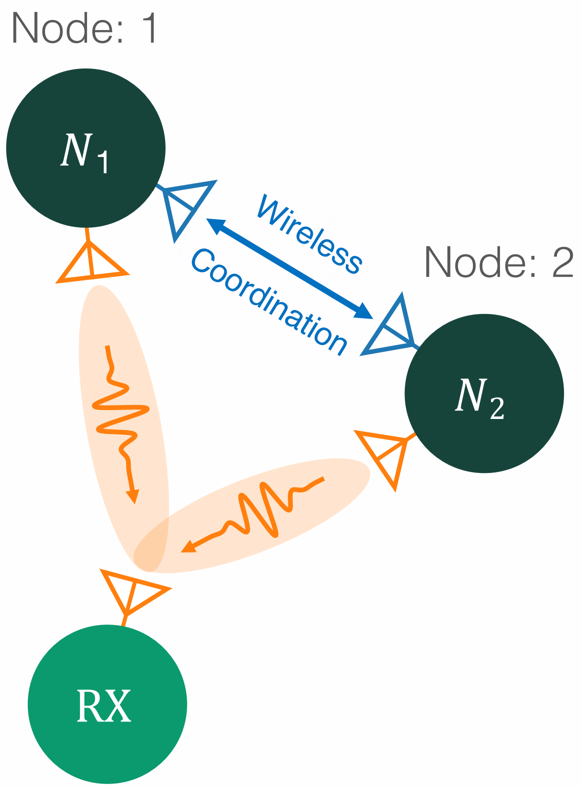


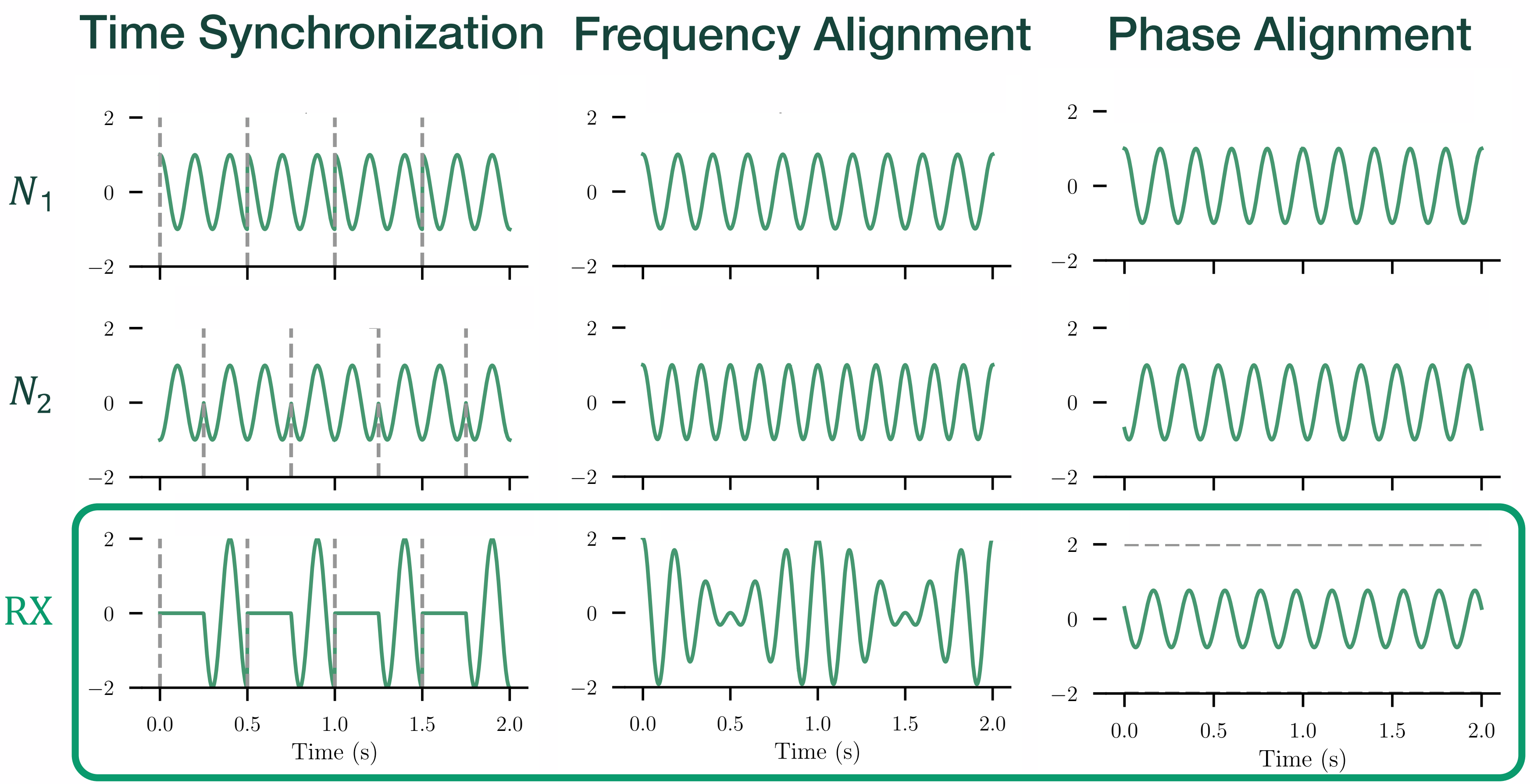
Space Communication and Remote Sensing



Impacts of Coordination Errors

Two-Node Array



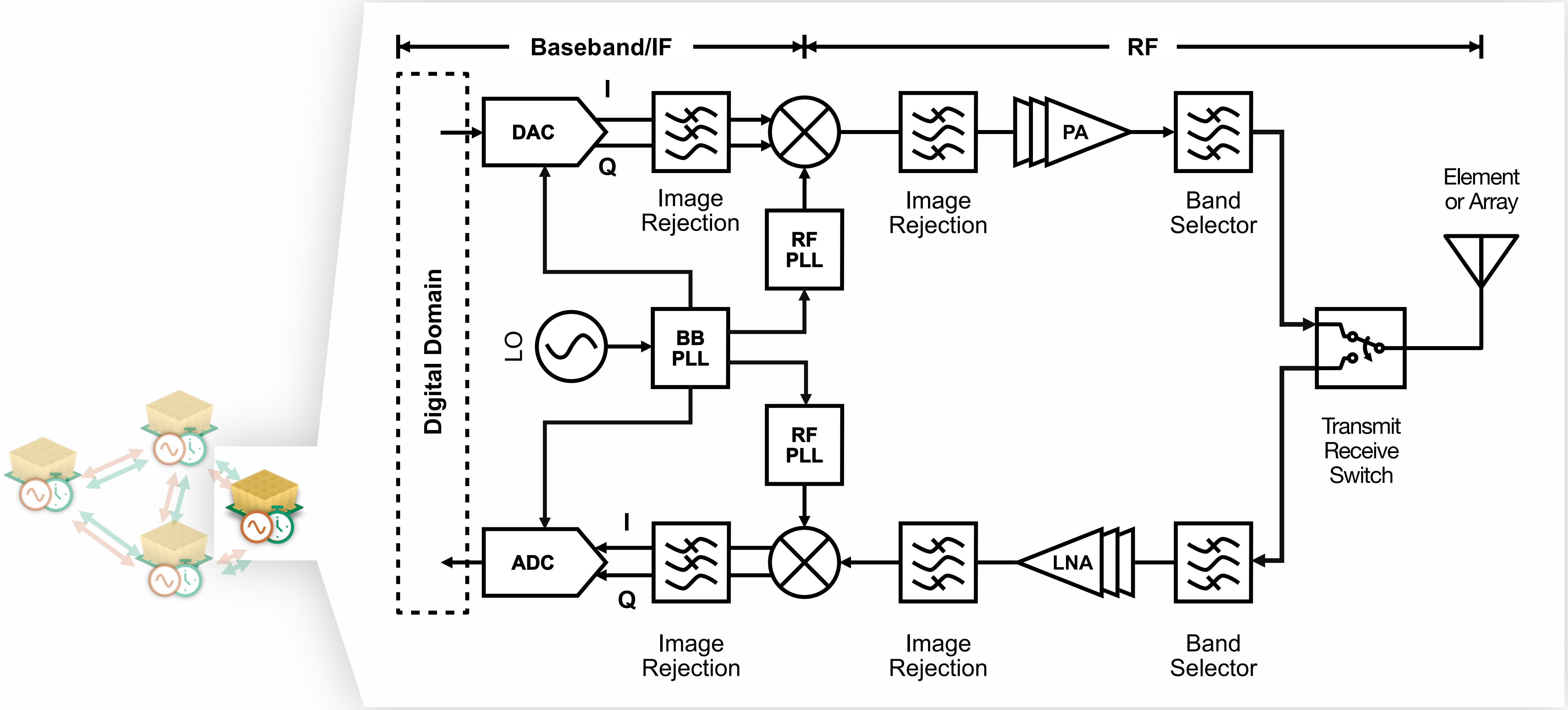


$$s_{\mathrm{RX}}(t) = s^{(1)}(t) + s^{(2)}(t) = \sum_{n=1}^{2} A^{(n)}\underbrace{\left(t-\delta_t^{(n)}\right)}_{\text{Time}}\exp\left\{j\left[\underbrace{2\pi\left(f+\delta_f^{(n)}\right)t}_{\text{Frequency}}+\underbrace{\phi^{(n)}+\delta_\phi^{(n)}}_{\text{Phase}}\right]\right\}$$

System Model

System Model

Simplified Direct Conversion Software Defined Radio Front End



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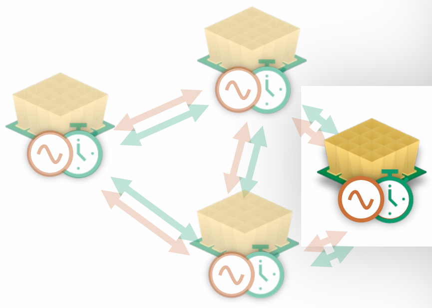

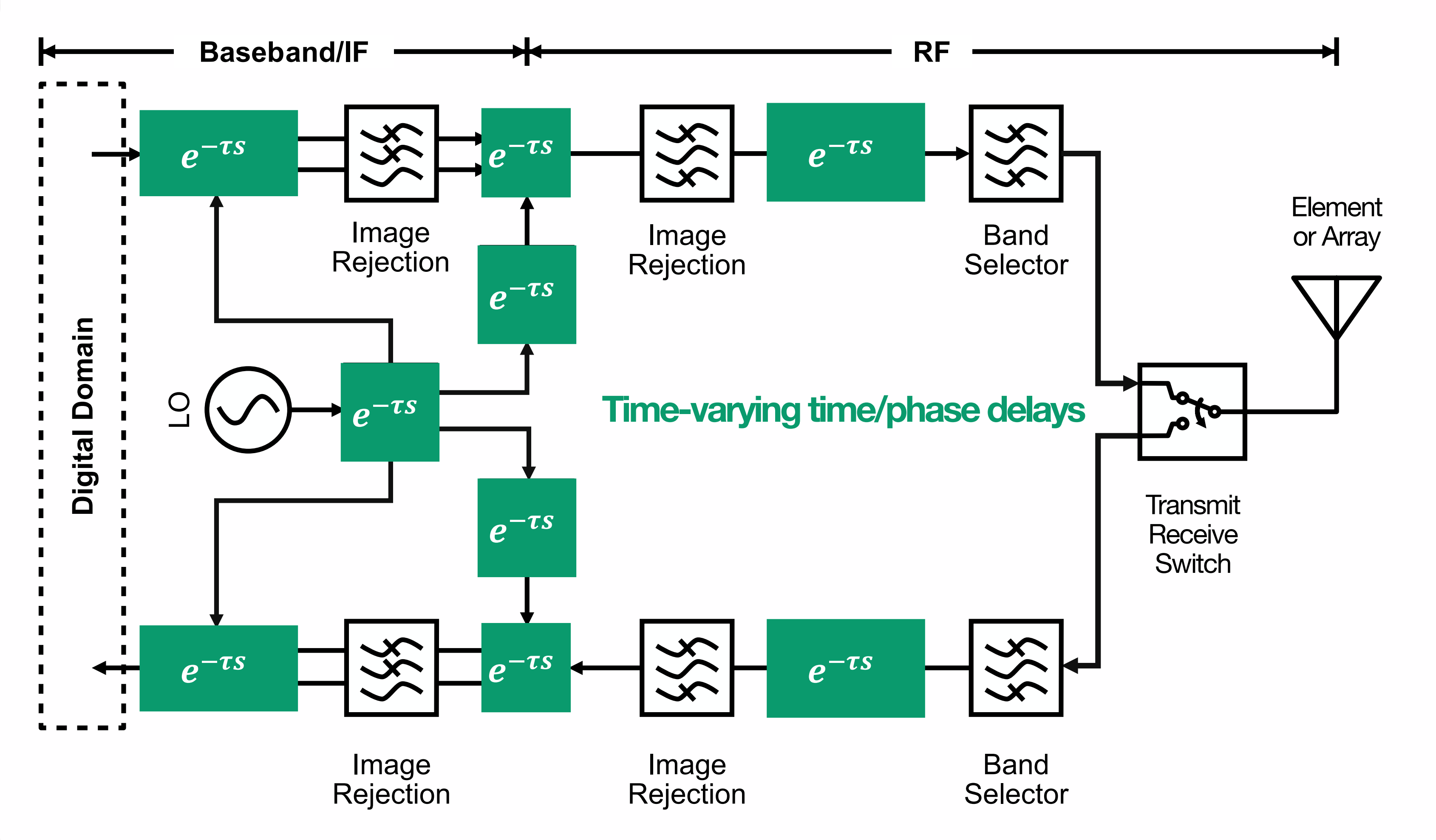

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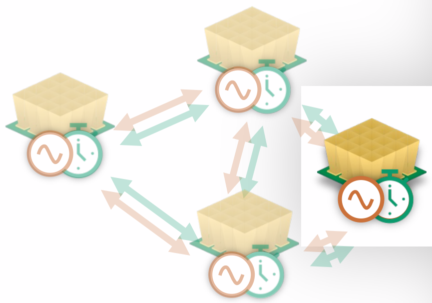
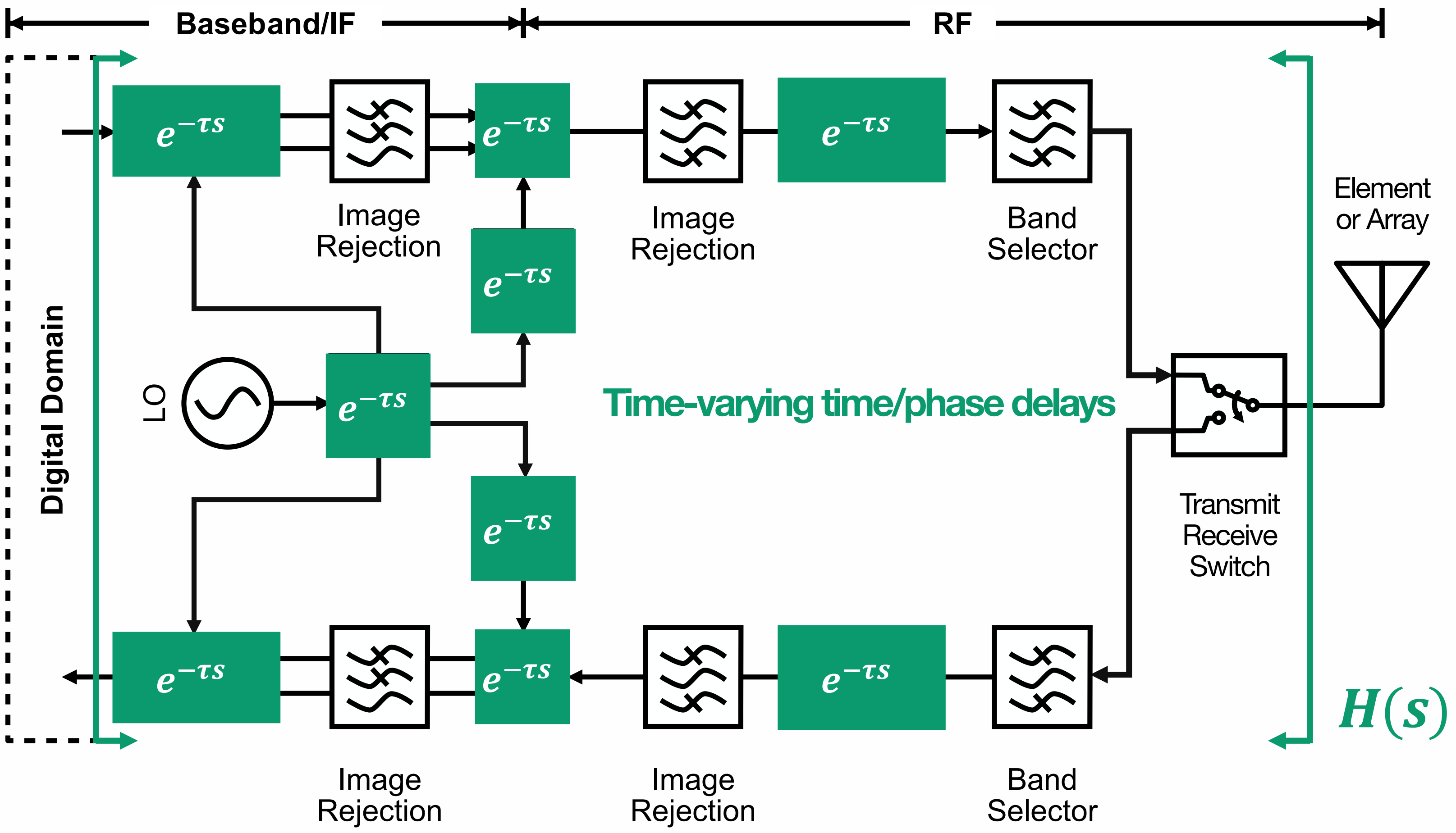




System Time Model

- Assumption:

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

$$\alpha_p \approx 0 \; \forall \, k > 1$$

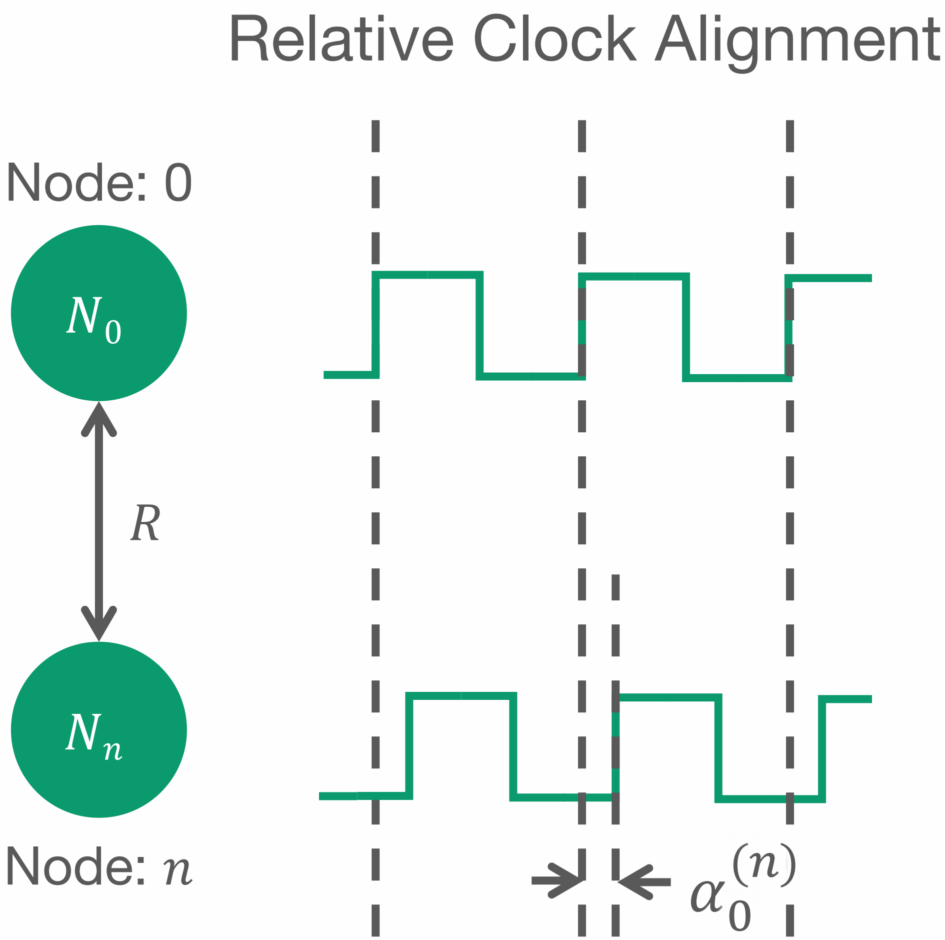
- Simplifies observed time at node n:

$$T_{\mathrm{T/R}}^{(n)}(t) = \alpha_{1,\mathrm{T/R}}^{(n)} t + \alpha_{0,\mathrm{T/R}}^{(n)} + \nu_{\mathrm{T/R}}^{(n)}(t)$$

where:

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

In practice, α_p will be time-varying



Carrier Model

The carrier at node n observed in the true time reference is

$$s_{\mathrm{c,T/R}}^{(n)}(t) = \exp\left\{j\,2\pi \cdot f_{\mathrm{RF,T/R}} \cdot \underbrace{T_{\mathrm{T/R}}^{(n)}(t)}_{\alpha_{1,\mathrm{T/R}}^{(n)} t + \alpha_{0,\mathrm{T/R}}^{(n)} + \nu_{\mathrm{T/R}}^{(n)}(t)} + j\,\phi_{0,\mathrm{T/R}}^{(n)}\right\}$$

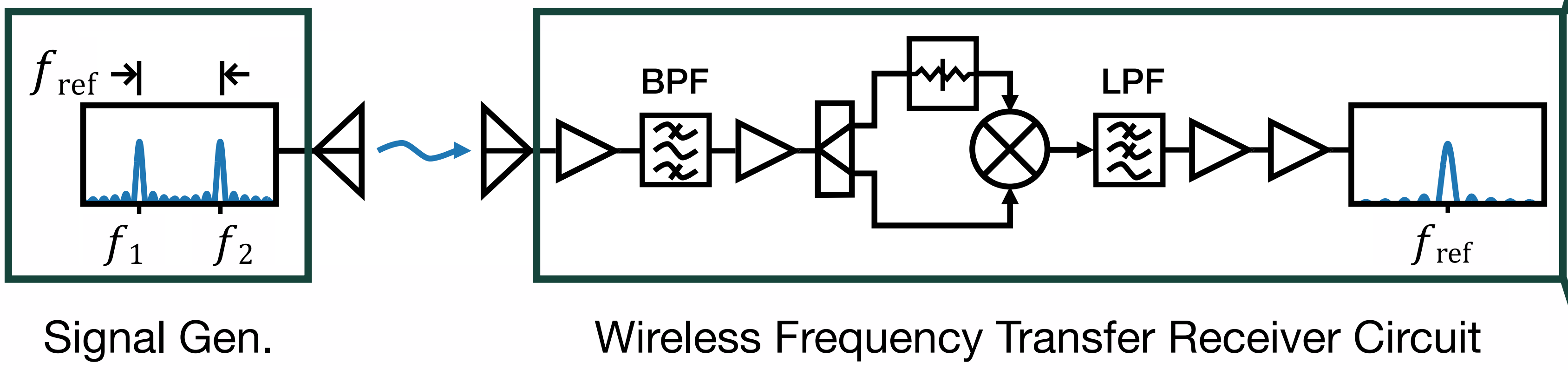
Compensation steps:

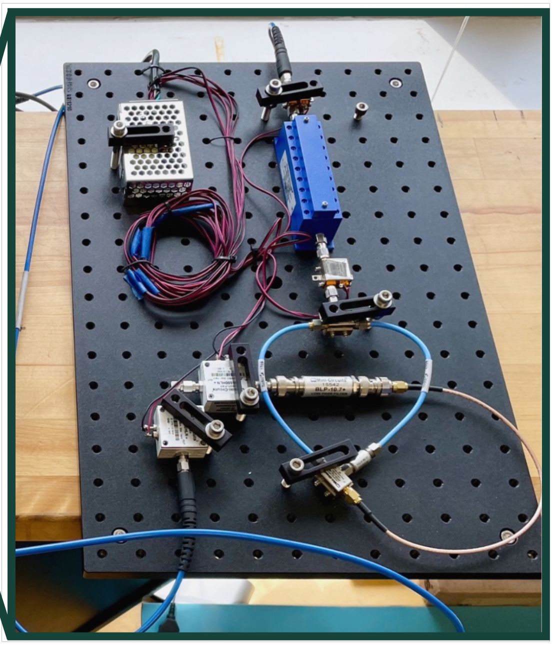
1. Estimate and correct for $\alpha_{p,\mathrm{T/R}}^{(n)}$
2. Calibrate the static delay and phase rotations $\left(\phi_{0,\mathrm{T}}^{(n)},\ \phi_{0,\mathrm{R}}^{(n)}\right) \rightarrow \left(\phi_{\mathrm{T,cal}}^{(n)},\ \phi_{\mathrm{R,cal}}^{(n)}\right)$

Electrical State Alignment

Analog Frequency Syntonization

Compensating for $\alpha_1^{(n)}$





- 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.

Digital Time Compensation

Compensating for $\alpha_0^{(n)}$

With frequencies syntonized, the carrier is now

$$s_{\mathrm{c,T/R}}^{(n)}(t) = \exp\left\{j2\pi \cdot f_{\mathrm{RF,T/R}} \cdot \left(t + \alpha_{0,\mathrm{T/R}}^{(n)} + \nu_{\mathrm{T/R}}^{(n)}(t)\right) + j\phi_{0,\mathrm{T/R}}^{(n)}\right\}$$

The digital baseband waveform is used to compensate for carrier phase offset

Baseband Waveform Sampling Correction

Carrier Phase Compensation

$$s_{\mathrm{b}}^{(n)}[i] = s_{\mathrm{m}}\left(t_s[i] + \alpha_{0,\mathrm{T/R}}^{(n)}[k]\right)\exp\left\{-j\left(2\pi \cdot f_{\mathrm{RF,T/R}}\,\alpha_{0,\mathrm{T/R}}^{(n)} + \phi_{0,\mathrm{T/R}}^{(n)}\right)\right\}$$

Modulated waveform function

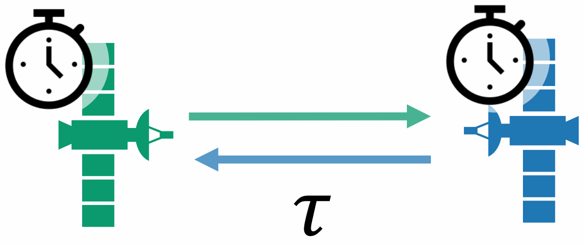
Sampling time at sample index i

kth digital time offset estimate

Static phase compensation

Time Offset Estimation

Time Coordination Technique



Two-Way Time Synchronization

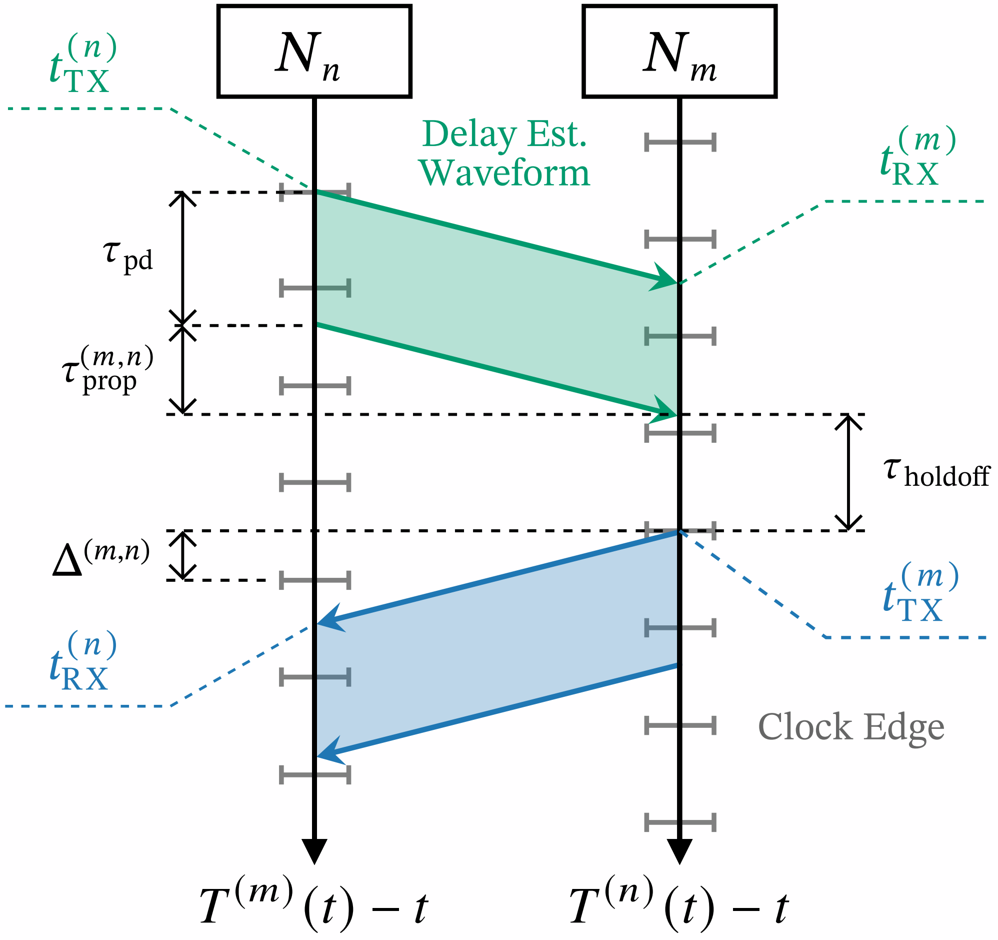
- *Assumption:*
  - Link is <u>reciprocal</u> $\Longrightarrow$ <u>quasi-static</u> during the synchronization epoch

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

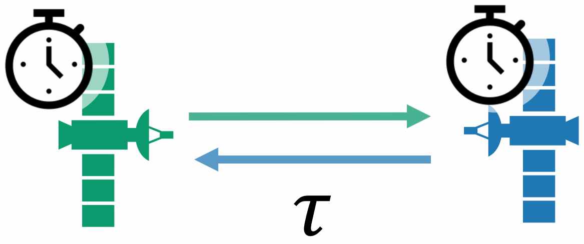
$$\tilde{\tau}^{(n\rightarrow m)}[k] = T_{\mathrm{RX}}^{(m)}\left(t_{\mathrm{RX}}^{(m)}[k]\right) - T_{\mathrm{TX}}^{(n)}\left(t_{\mathrm{TX}}^{(n)}[k]\right)$$

- Internode timing skew:

$$\alpha_0^{(m,n)}[k] = \frac{\tilde{\tau}^{(n\rightarrow m)}[k] - \tilde{\tau}^{(m\rightarrow n)}[k]}{2}$$



Time Coordination Technique



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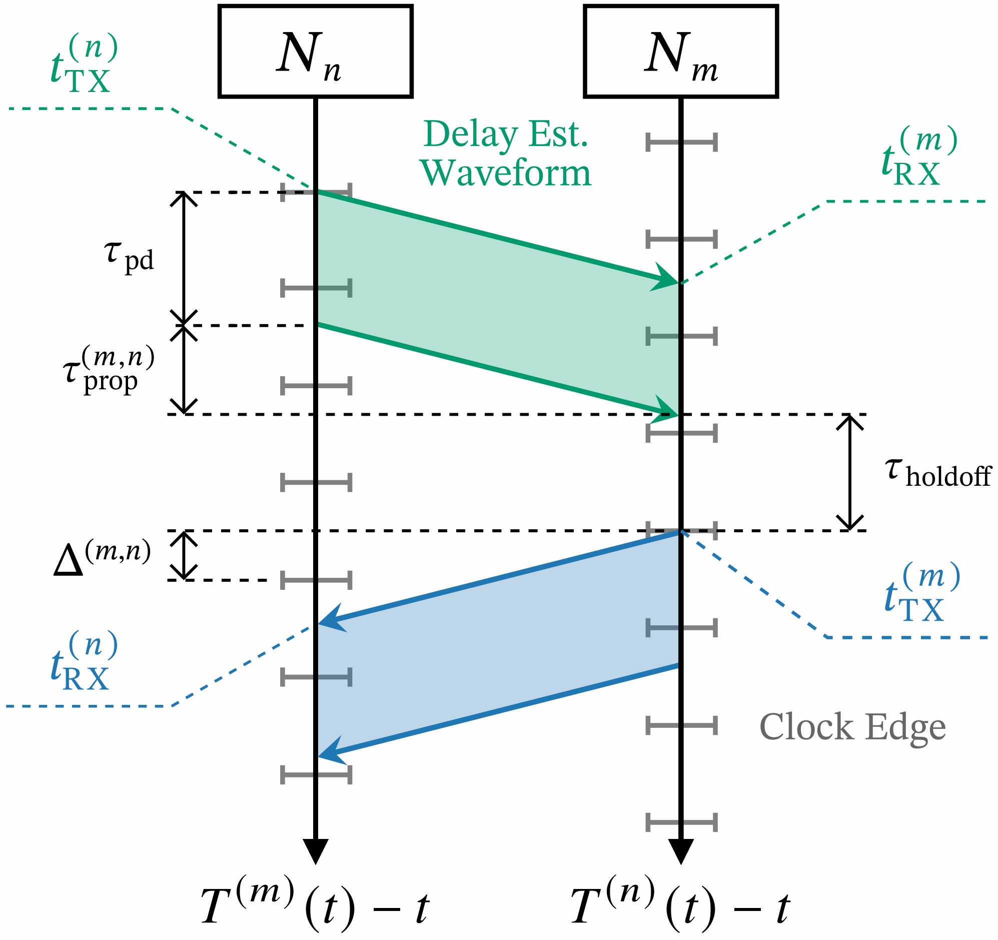
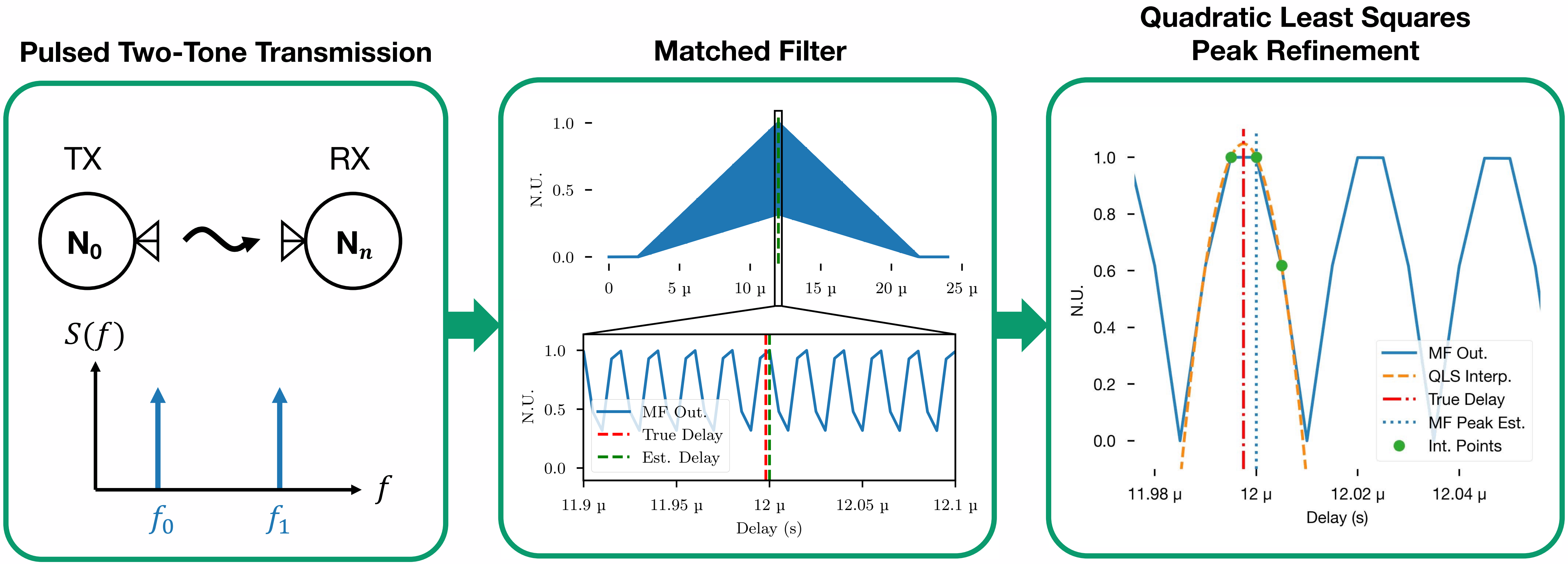
$$\tilde{\tau}^{(n\to m)}[k] = T^{(m)}_{\mathrm{RX}}\left(t^{(m)}_{\mathrm{RX}}[k]\right) - T^{(n)}_{\mathrm{TX}}\left(t^{(n)}_{\mathrm{TX}}[k]\right)$$

- Internode range:

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



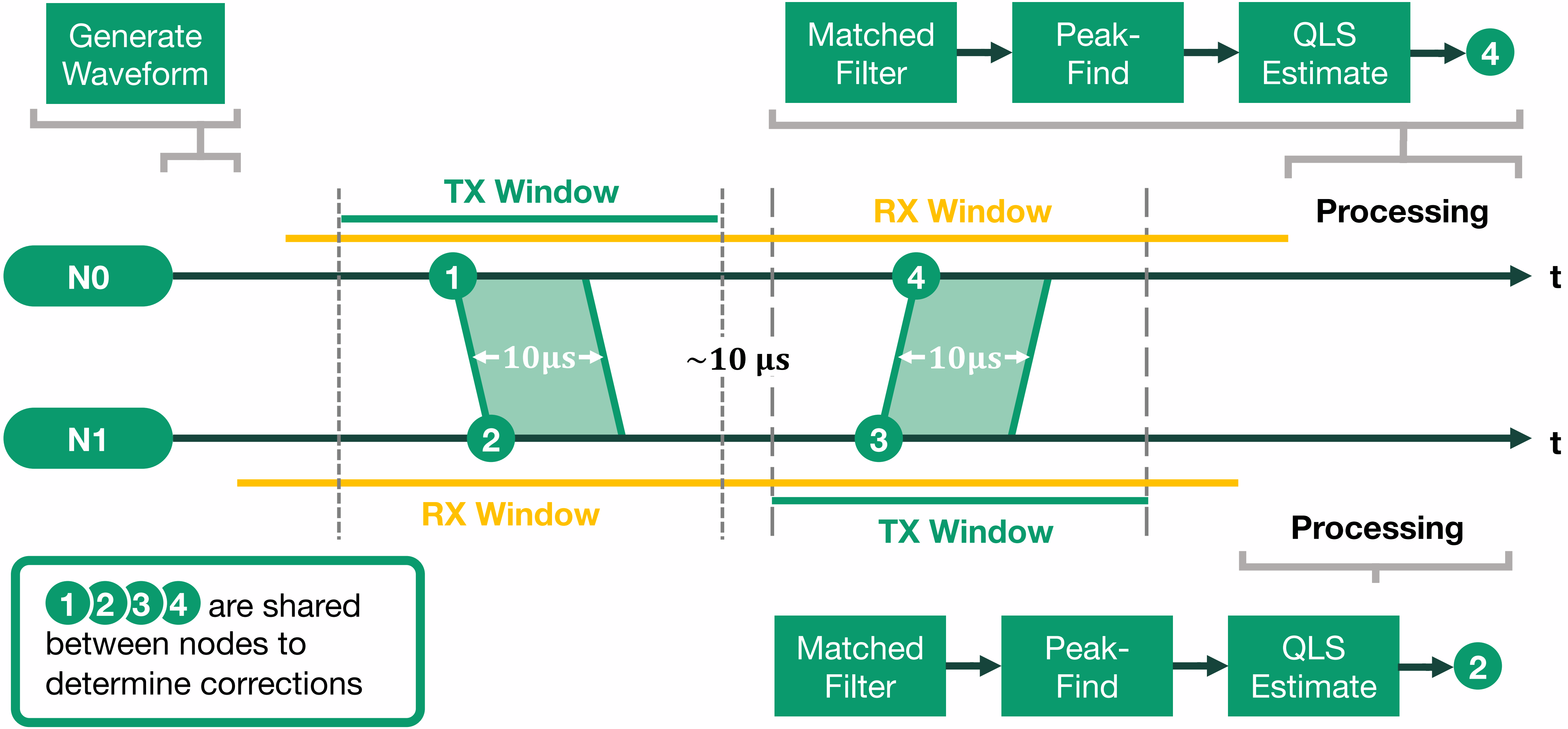
Time of Arrival Estimation | $\bar{T}_{\mathrm{RX}}^{(n)}\left(t_{RX}^{(n)}\right)$



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

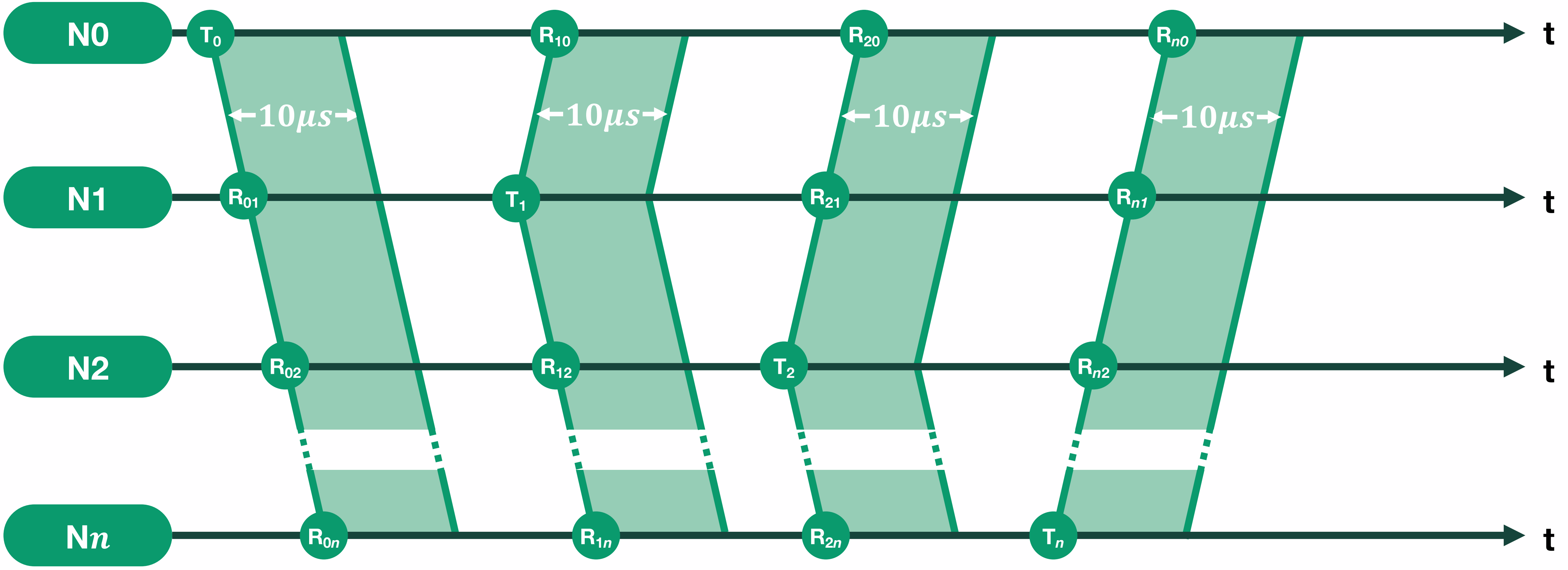
J. M. Merlo, S. R. Mghabghab and J. A. Nanzer, "Wireless Picosecond Time Synchronization for Distributed Antenna Arrays," in IEEE Transactions on Microwave Theory and Techniques, vol. 71, no. 4, pp. 1720-1731, April 2023, doi: 10.1109/TMTT.2022.3227878.

Time Offset Estimation Process



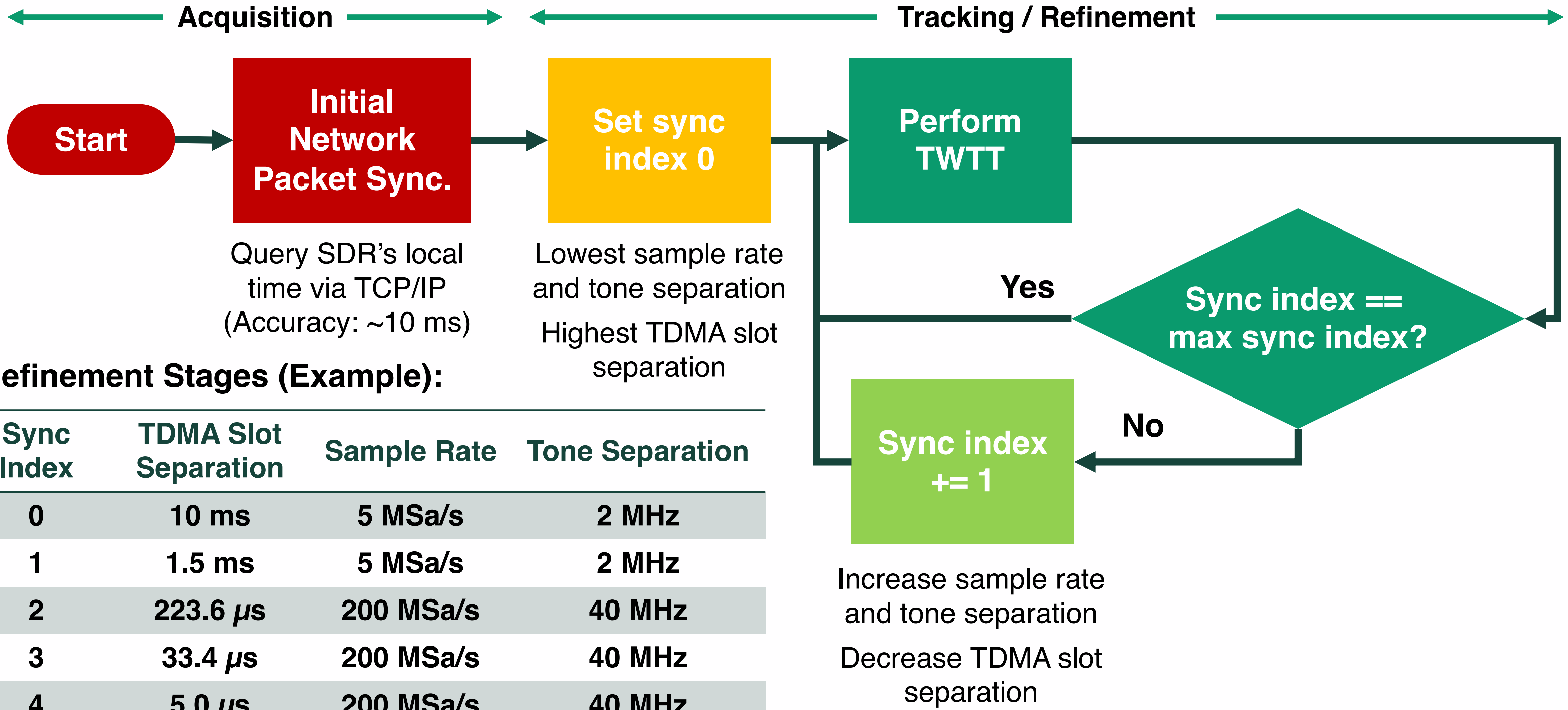
1 2 3 4 are shared between nodes to determine corrections

Time Estimation Implementation Scaling



Timestamps T_i and R_{ij} are shared between nodes to determine corrections

Time Synchronization Refinement



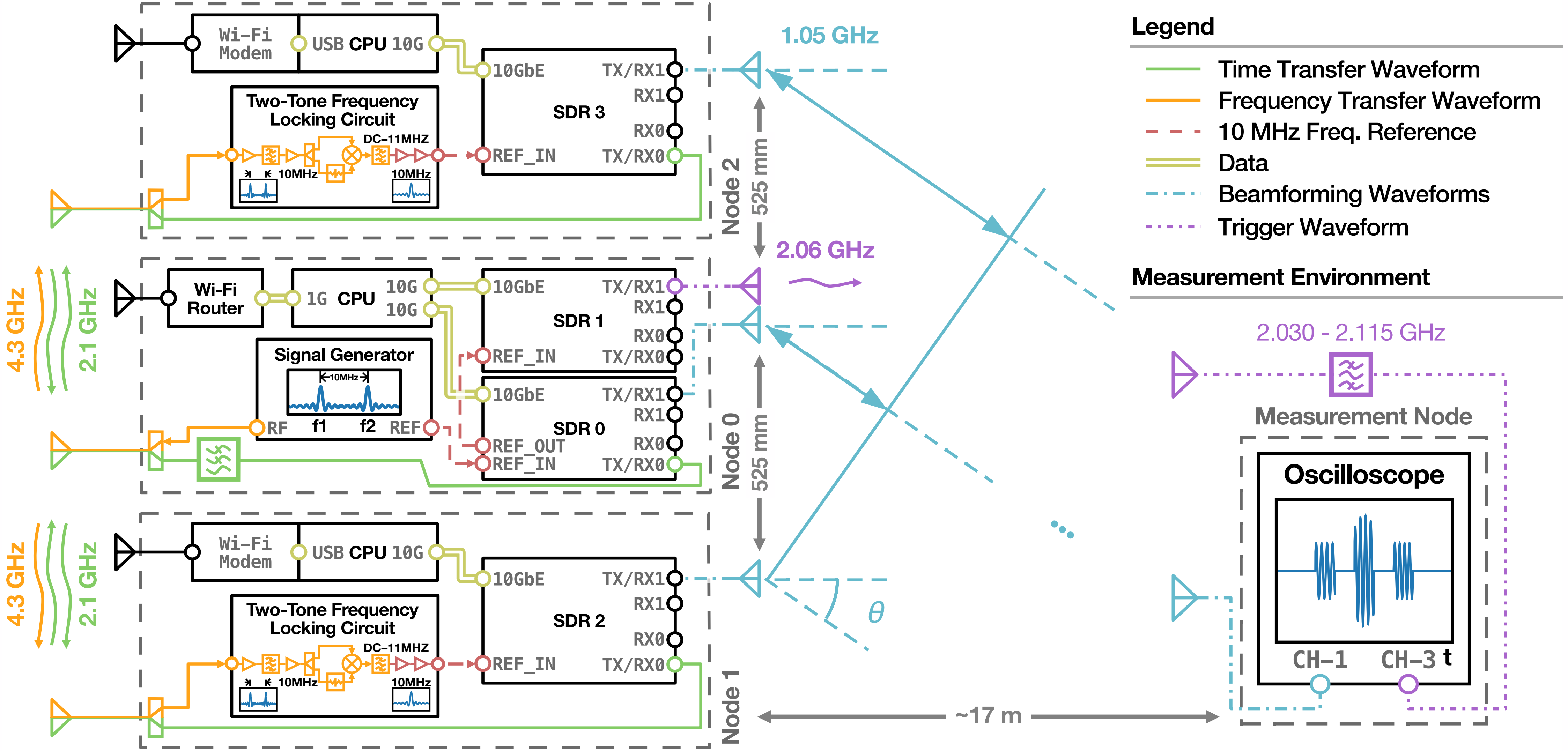
Refinement Stages (Example):

Sync Index	TDMA Slot Separation	Sample Rate	Tone Separation
0	10 ms	5 MSa/s	2 MHz
1	1.5 ms	5 MSa/s	2 MHz
2	223.6 μs	200 MSa/s	40 MHz
3	33.4 μs	200 MSa/s	40 MHz
4	5.0 μs	200 MSa/s	40 MHz

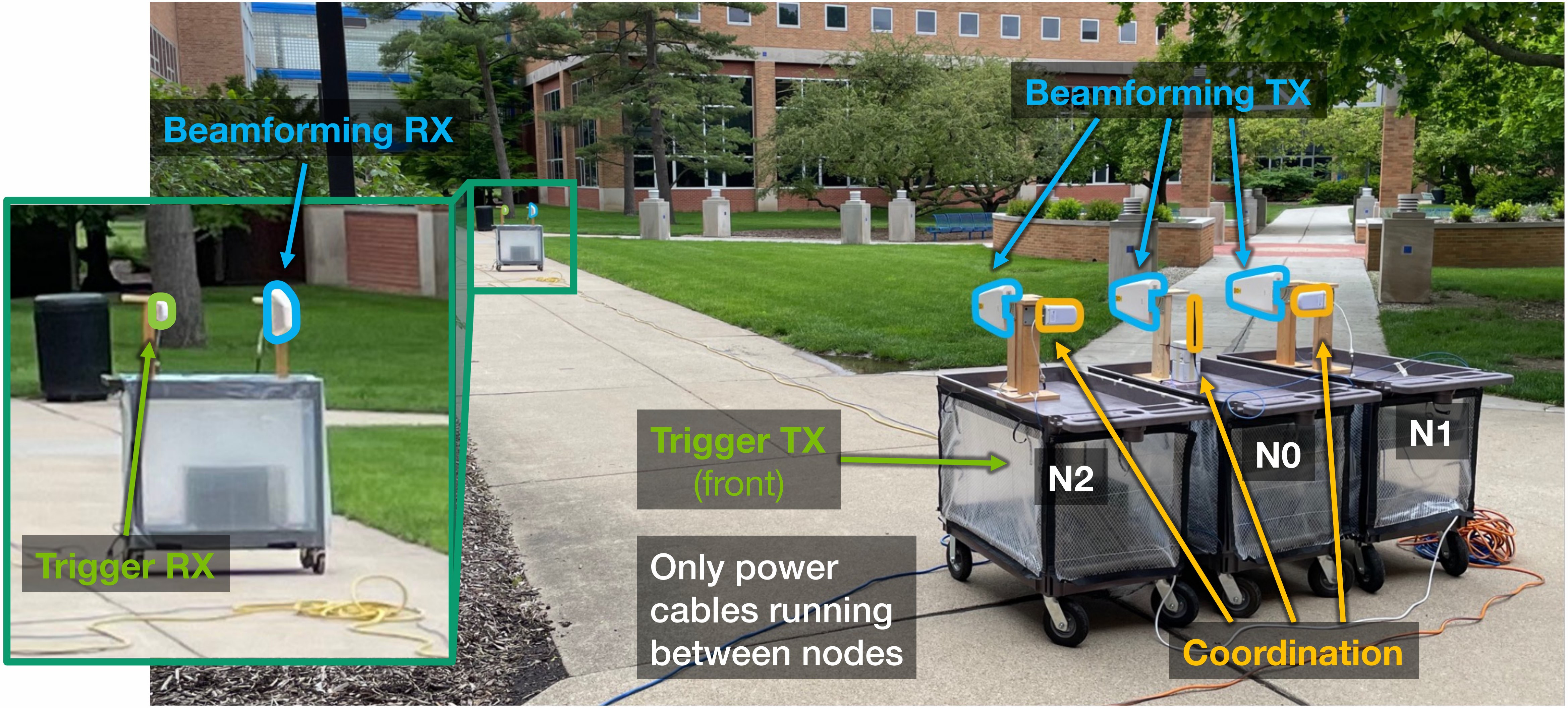
Experimental Evaluation

Three Element Beamformer

Full System Schematic

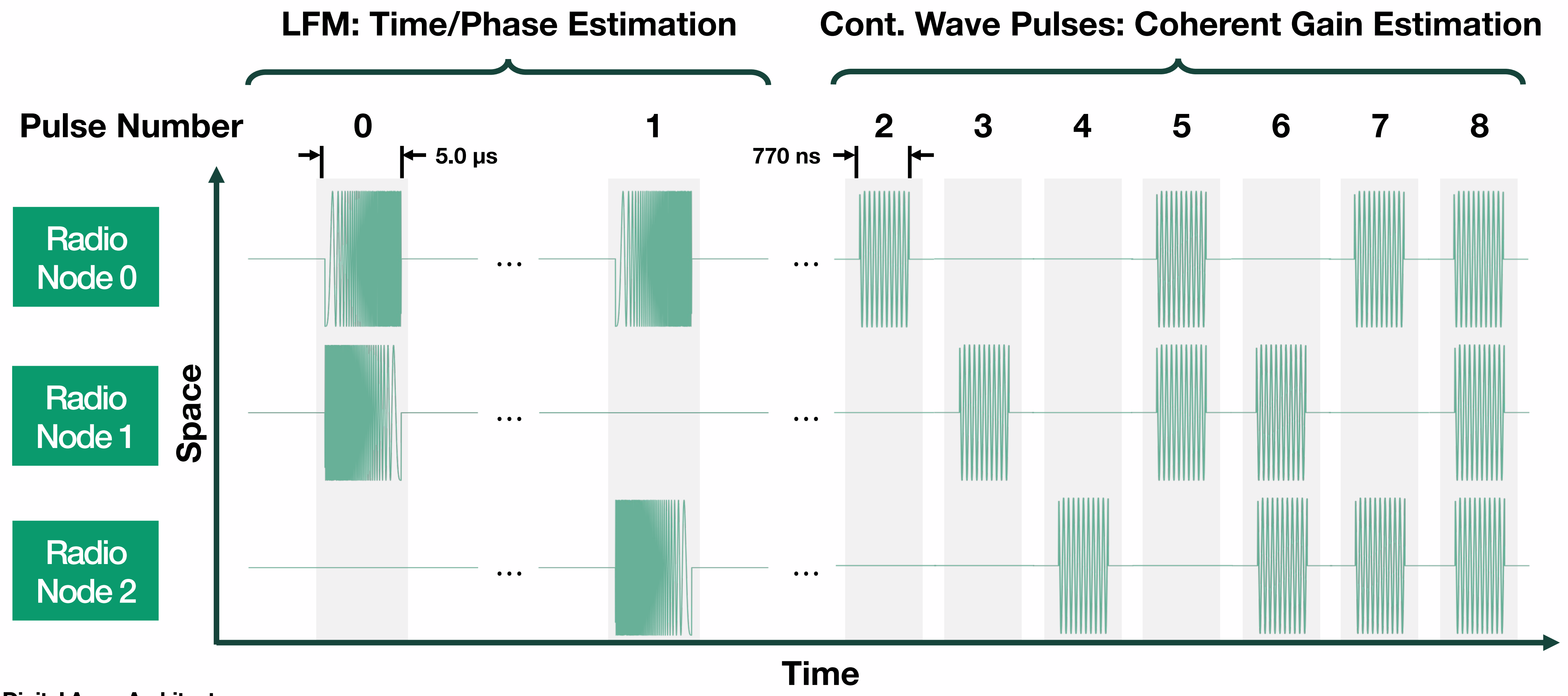


Experimental Setup



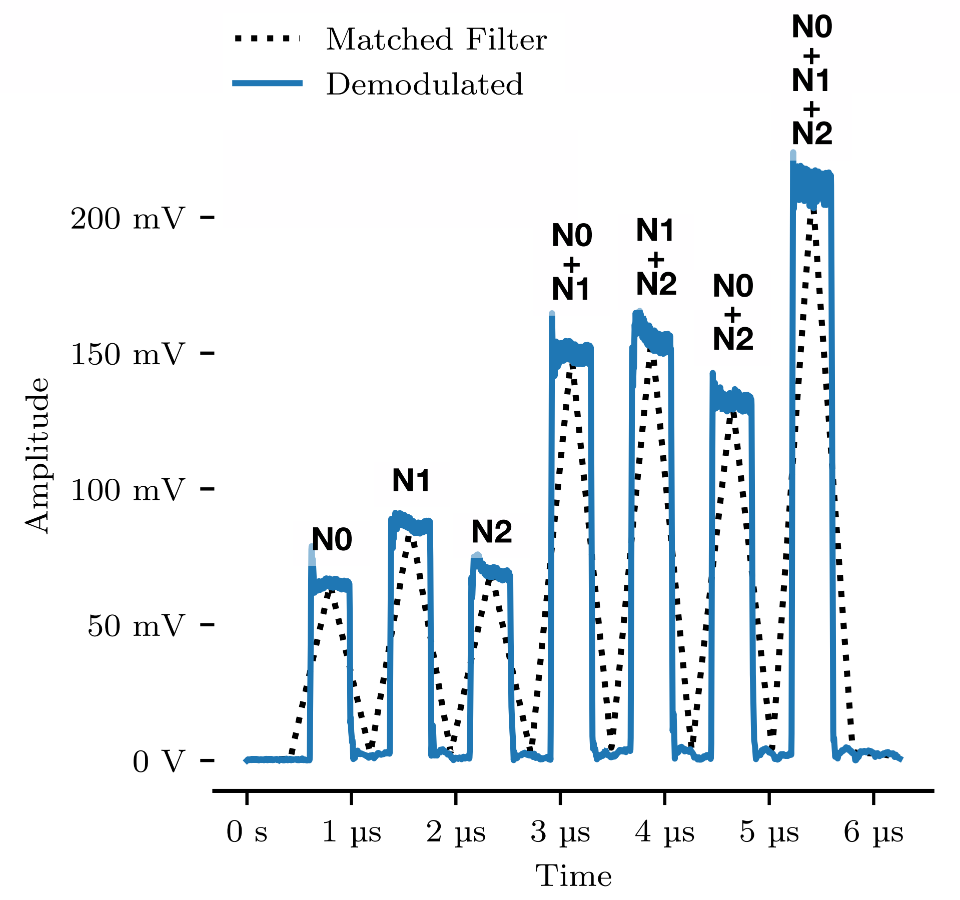
Calibration and Evaluation Waveforms

- Each node transmitted orthogonal LFMs followed by continuous wave pulse train

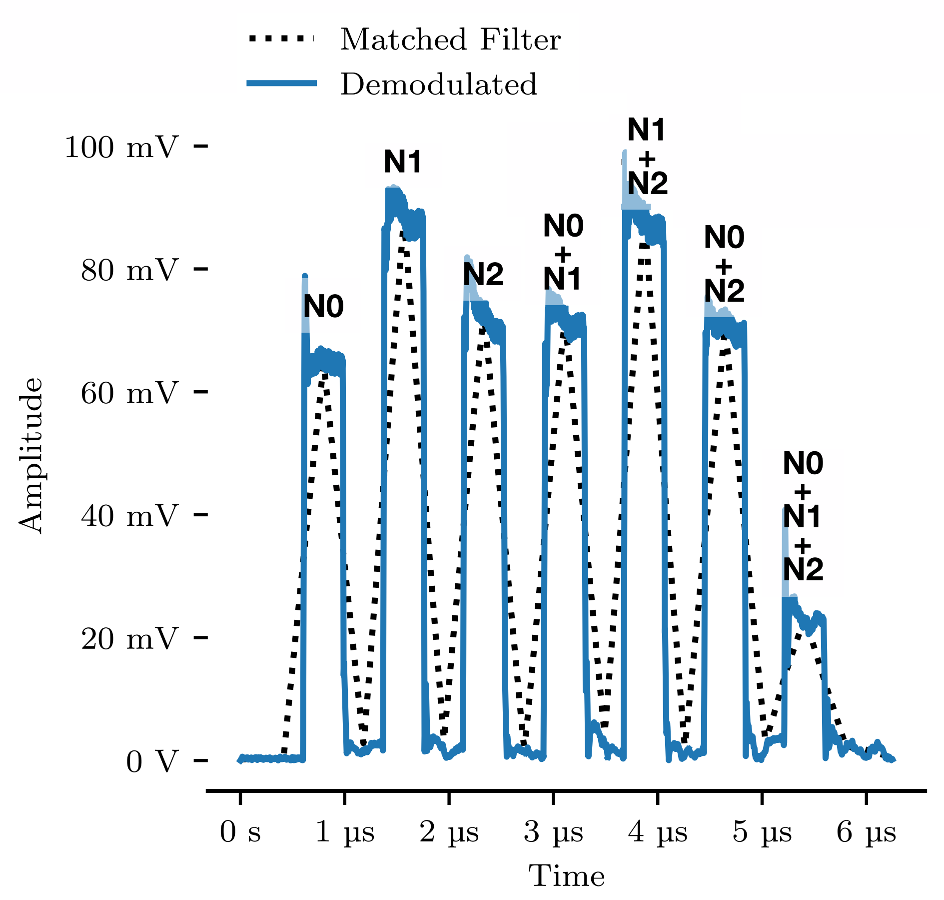


Coherent Gain Measurement Results

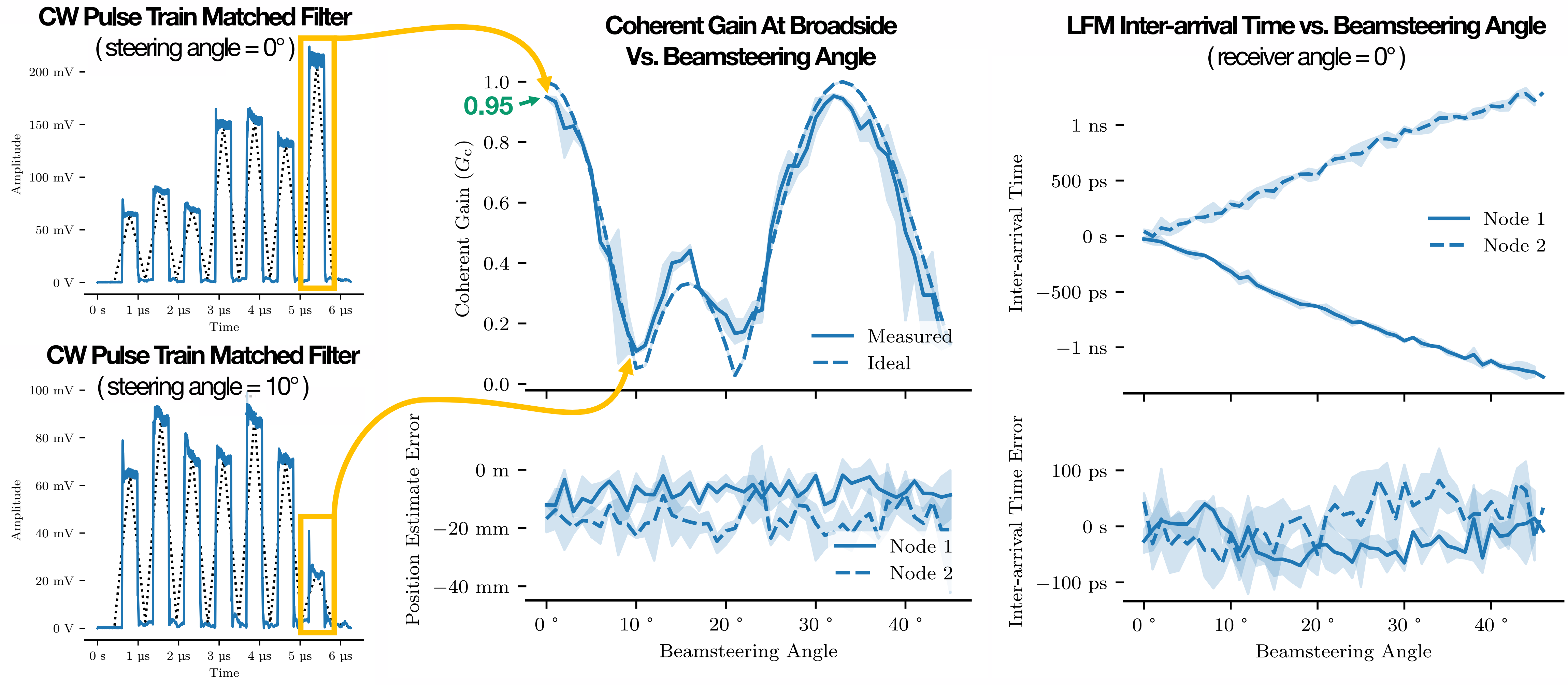
CW Pulse Train Matched Filter
(steering angle = 0°, receiver angle = 0°)



CW Pulse Train Matched Filter
(steering angle = 10°, receiver angle = 0°)



Beamsteering Results



Experiment Summary

- Demonstrated fully-wireless three-element distributed phased array beamsteering
- Independent of external time or frequency reference
- Achieved $G_c = 0.95$ over 17 m range at 1.05 GHz

Beamforming Coherent Gain	Beamforming Absolute Gain	Beamforming Std.	Theoretical Throughput*
0.95	9.32 dB	< 60.00 ps	~1.6 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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Thank you to our project sponsor:

This work was supported by the Office of Naval Research under grant #N00014-20-1-2389.

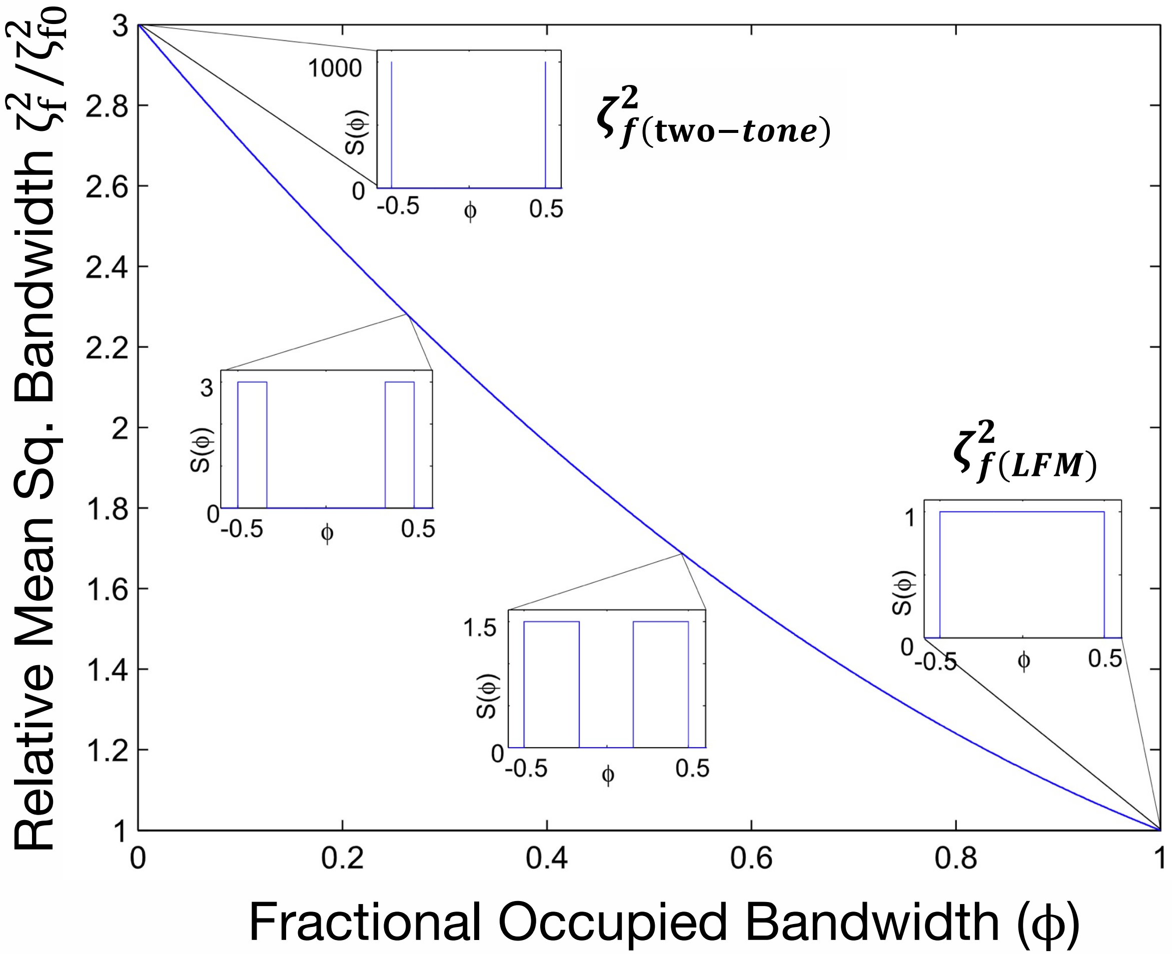
Backup Slides

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.

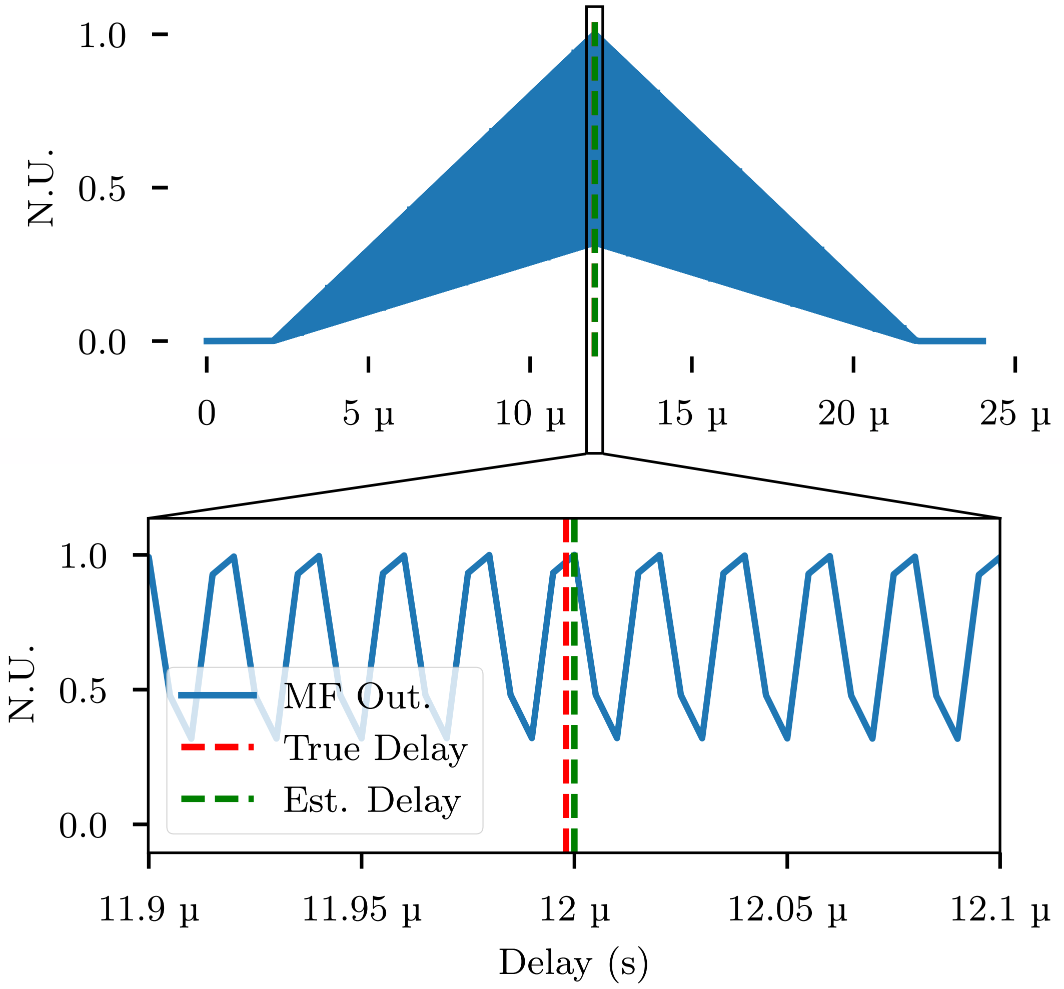
Delay Estimation

- 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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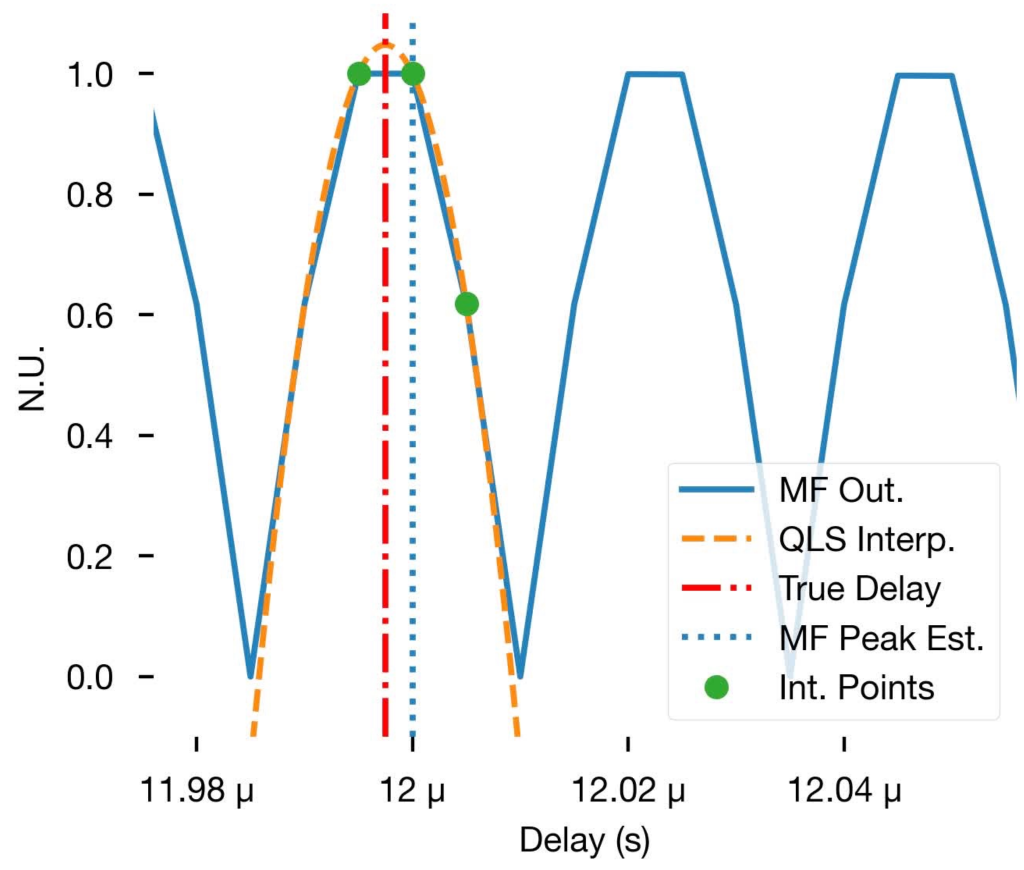
Delay Estimation Refinement

- MF 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

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



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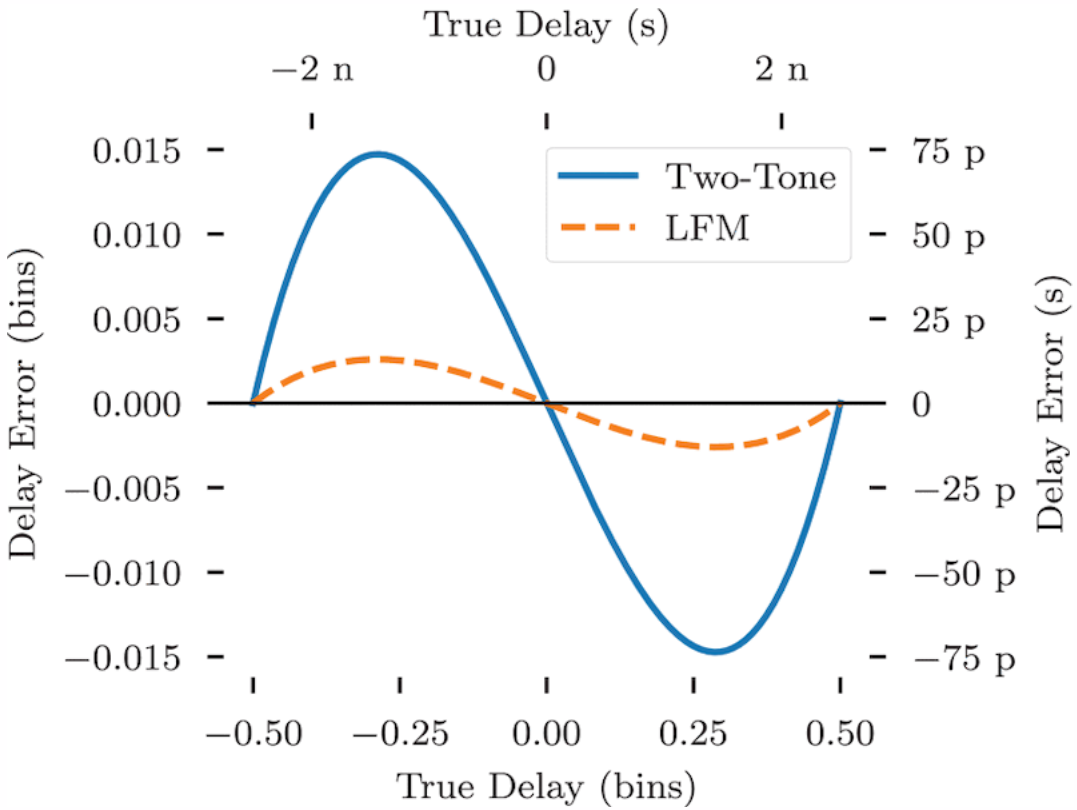
Delay Estimation Refinement

- 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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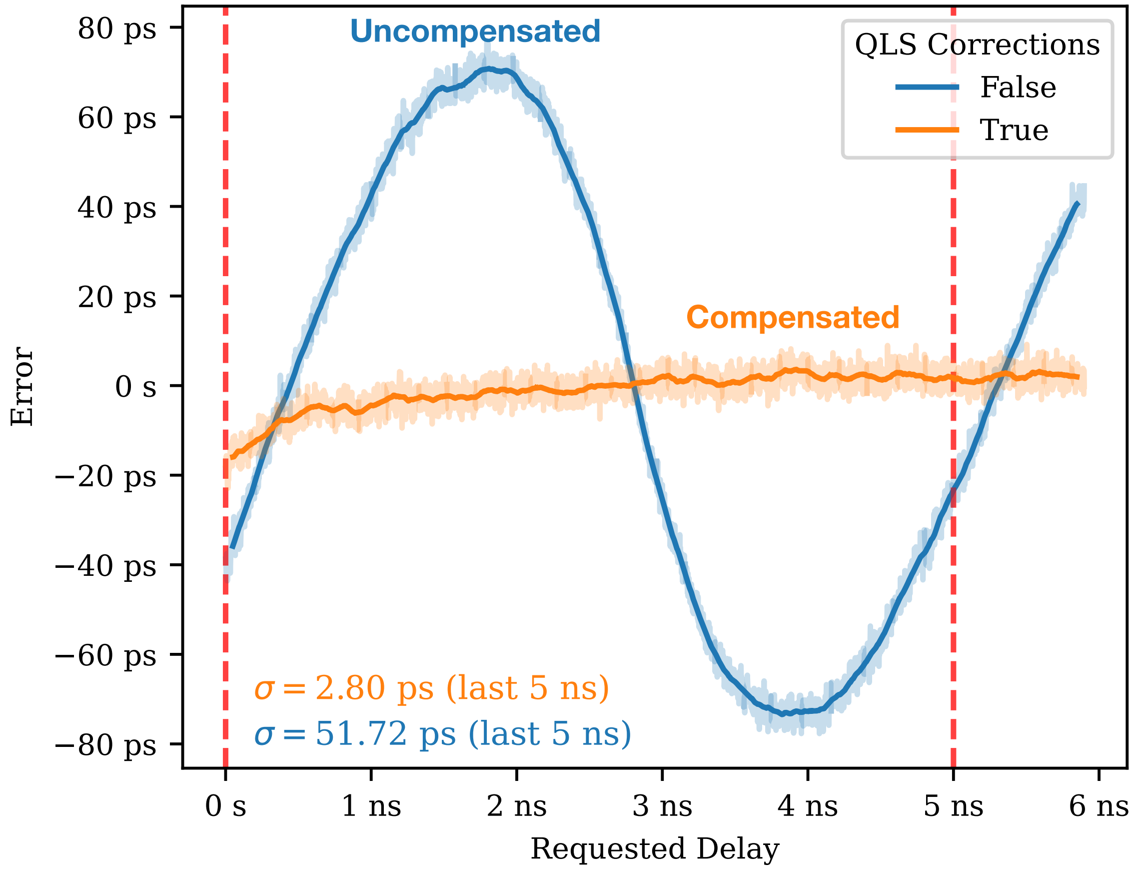
Measured Bias for Two-Tone
(before and after applying corrections)



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