MICHIGAN STATE UNIVERSITY

Distributed Phased Arrays:

Coordinating Wireless Systems at the Wavelength Level and Their Application to Communications and Sensing

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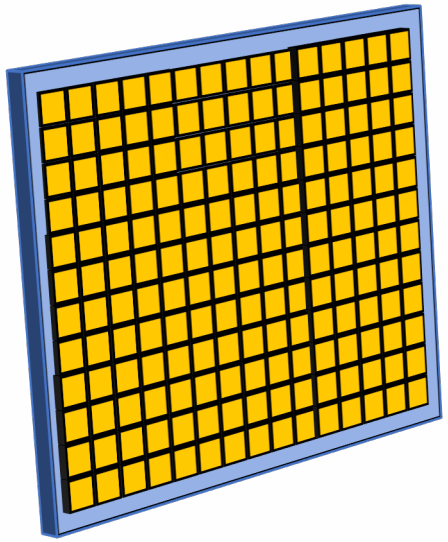
delta
Distributed Electromagnetics Theory and Applications

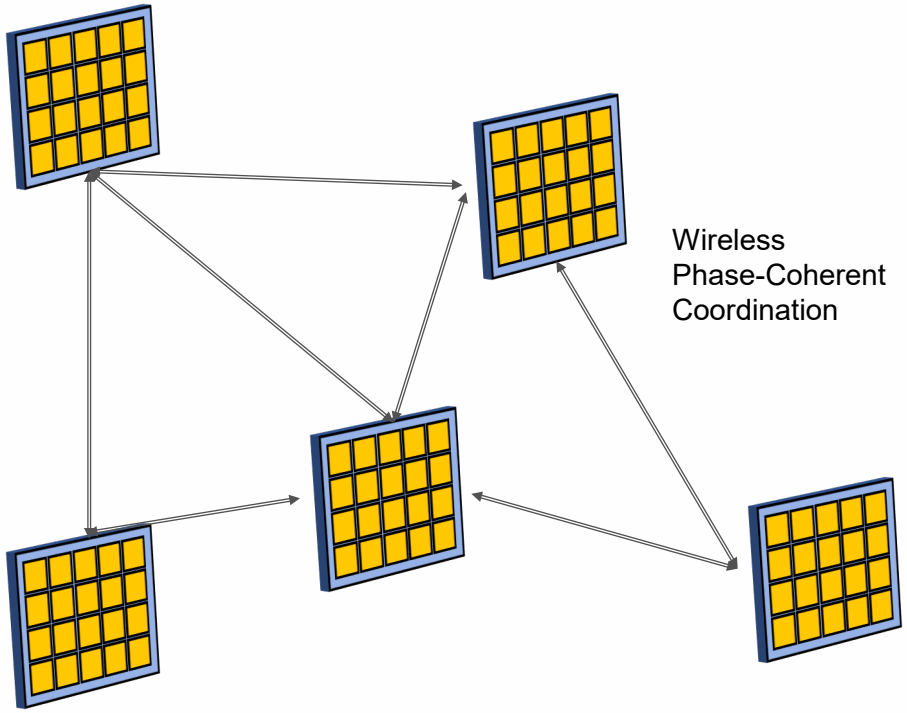
emrg
Electromagnetics Research Group
Michigan State University

Distributed Phased Arrays

Traditional Single-Platform Phased Array



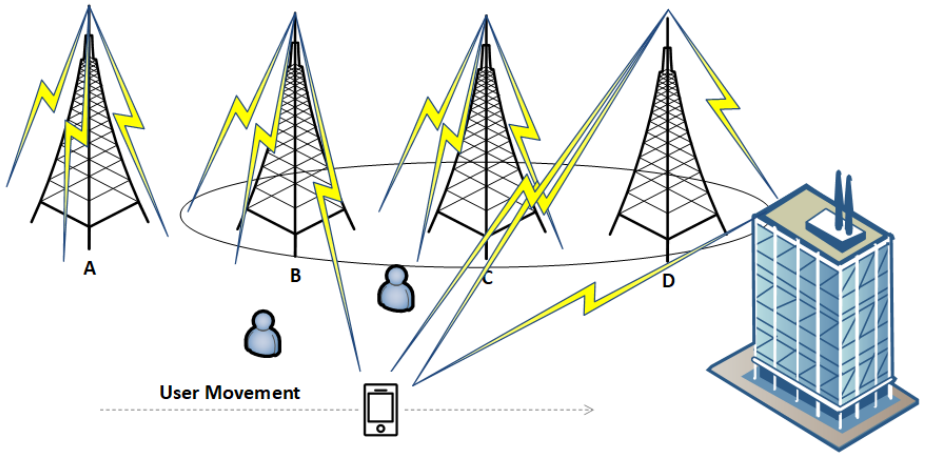
Distributed Array



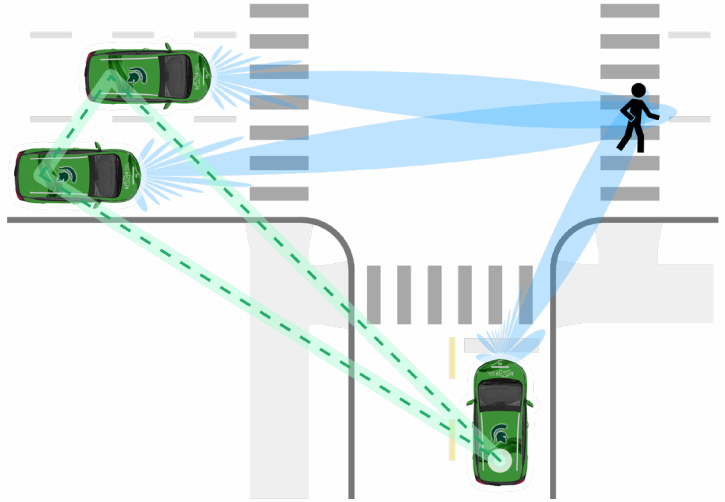
Applications

Develop technologies supporting coordination of the spatioelectrical states of networked wireless systems

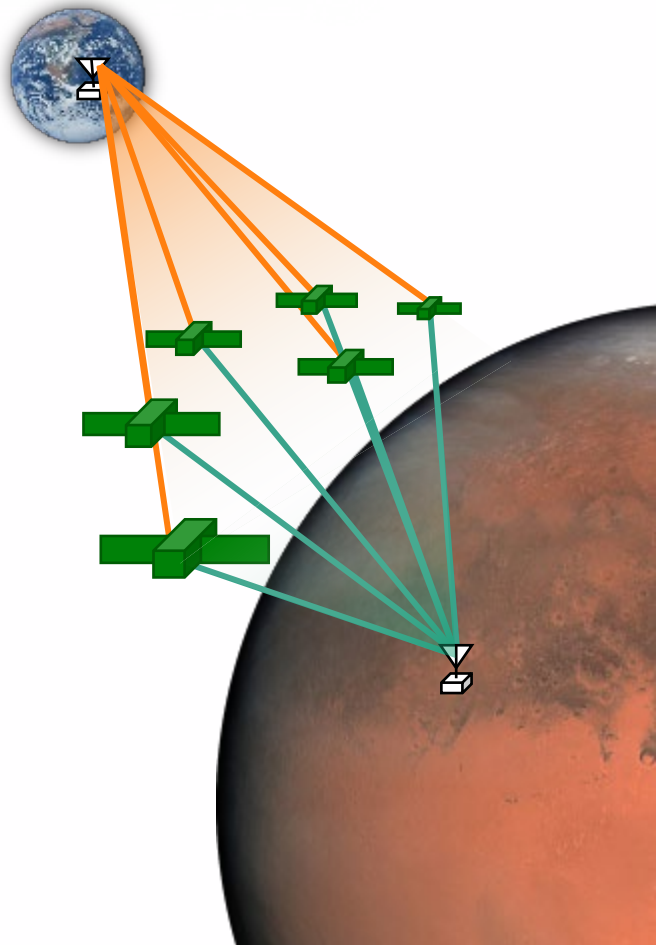
5G/6G Communication



V2X Sensing and Communication

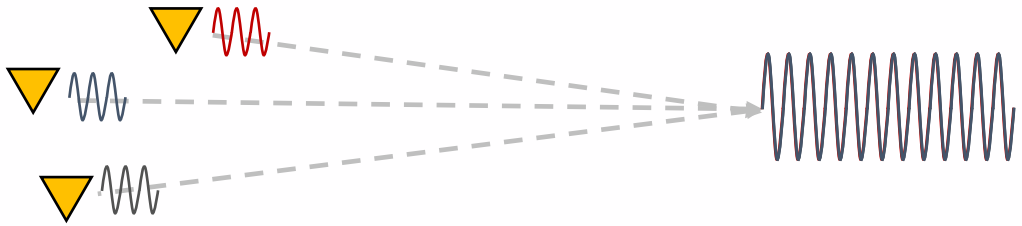


Space Communication and Remote Sensing



Coordination

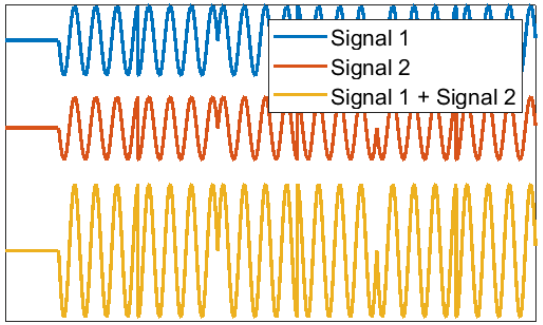
Alignment of the electrical states of the array nodes



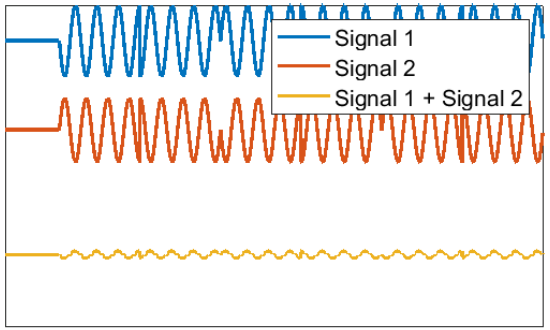
$$\mathbf{J} = \hat{\mathbf{z}} e^{-j\omega t} \sum_n I_n \delta l_n \delta(x - dx_n)\delta(y - dy_n)\delta(z - dz_n)$$

$$\mathbf{E} = \hat{\boldsymbol{\theta}} jk\eta \sin\theta \frac{e^{-jkr}}{4\pi r} \sum_{n=1}^{N} I_n \delta l_n e^{-j\omega t} e^{j\frac{2\pi}{\lambda} d_n \cos\theta_n}$$

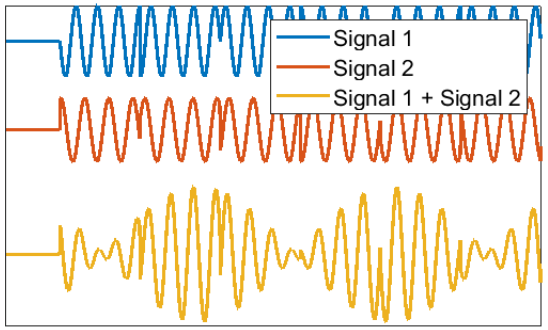
$$s_r(t) = \sum_{n=1}^{N} h_n \alpha_n \left(t - \delta t_n\right) e^{j[2\pi(f+\delta f_n)(t-\delta t_n)+\phi_n]}$$



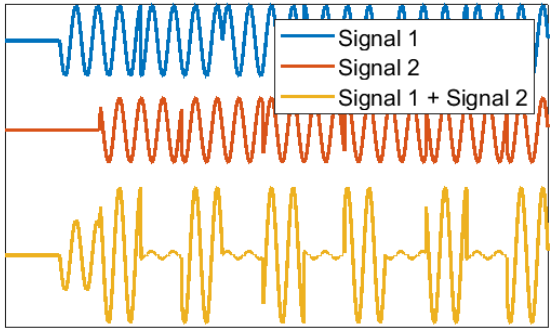
Ideal summation



w/o phase coherence



w/o frequency syntonization



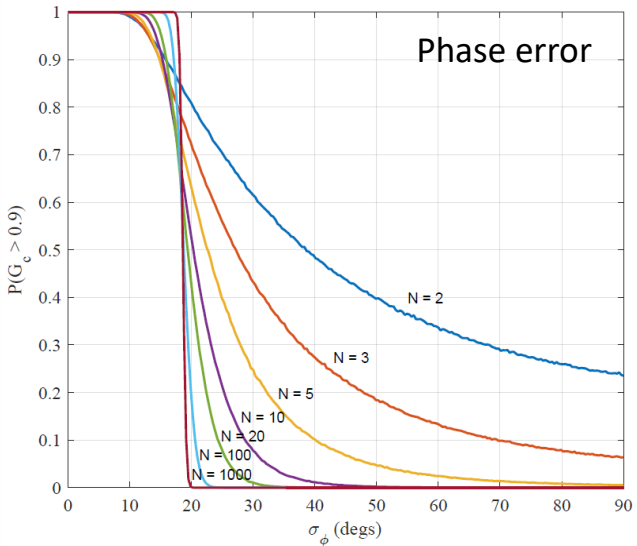
w/o time synchronization

Error Tolerance

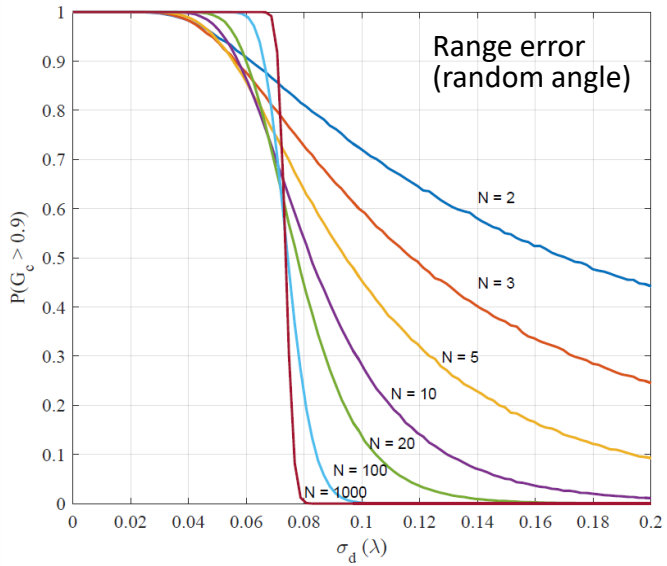
Beamforming signal relative to ideal

$$s_i(t) = C \sum e^{j\left(2\pi f t + \frac{2\pi}{\lambda} d_n \cos\theta_n\right)}$$

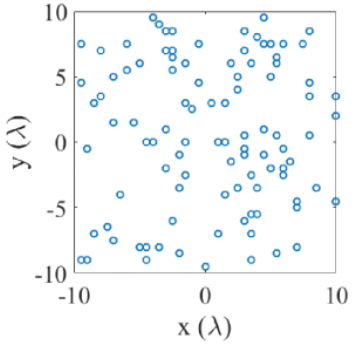
$$G_c = \frac{|s_r s_r^*|}{|s_i s_i^*|}$$

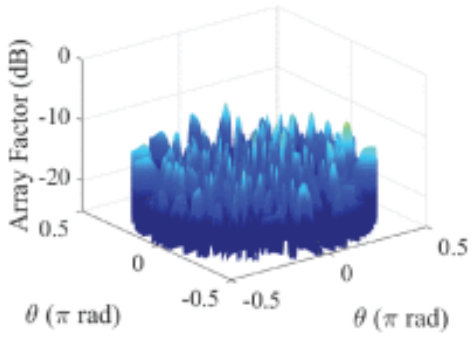


Phase errors <18° for 90% coherent gain

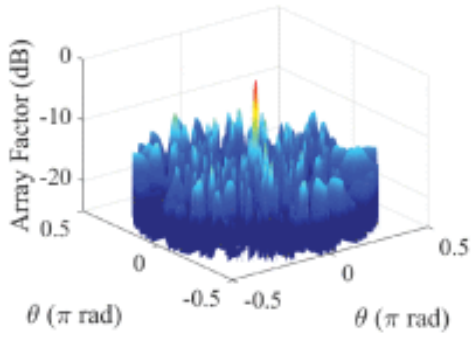


Internode range errors <λ/15 for 90% coherent gain

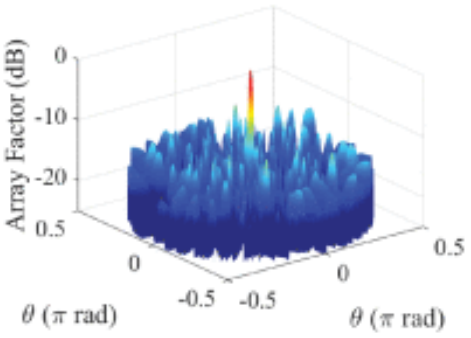




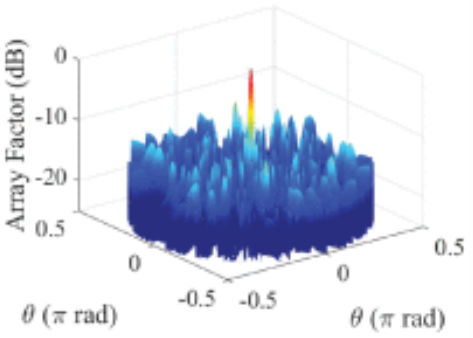
Phase error: 180°



Phase error: 90°



Phase error: 36°

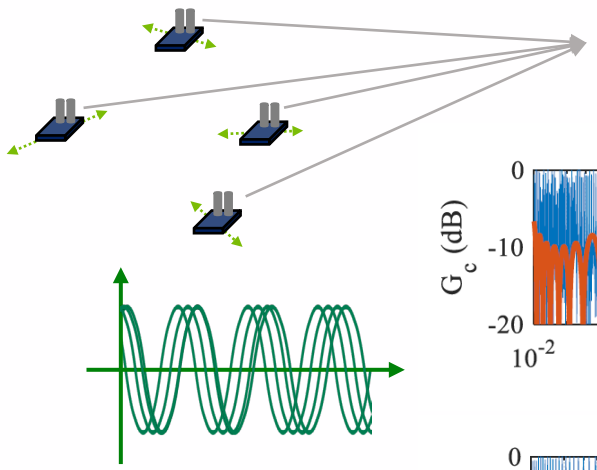


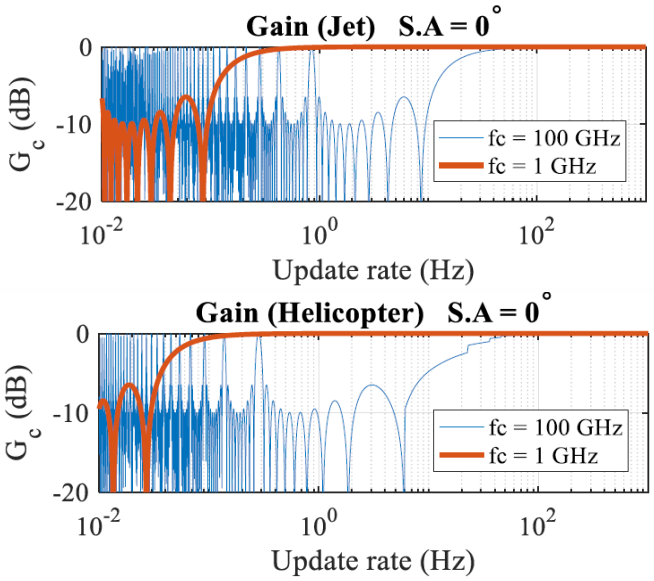
Phase error: 18°

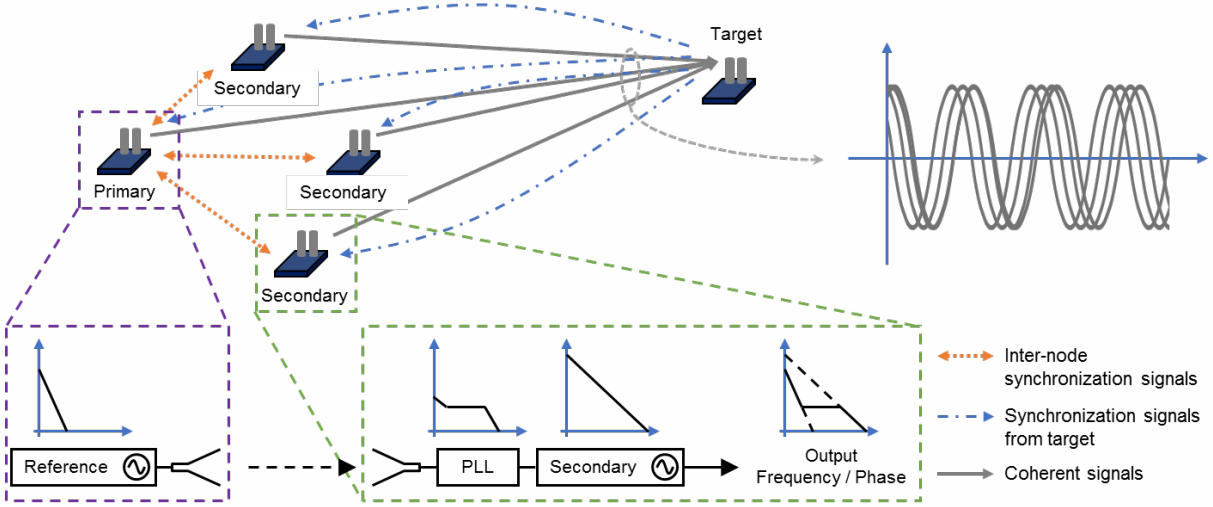
IEEE TMTT 65 (5) 2017
IEEE Radar Conference, 2018

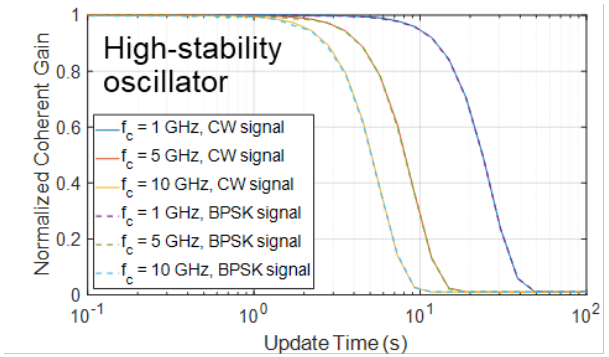
System Impacts on Phase Errors

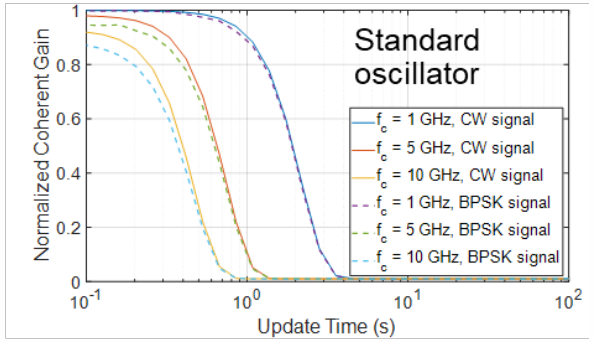
- Multiple system aspects impact beamforming performance
  - E.g.: phase noise, vibration, Doppler, system phases
- Some can be calibrated or minimized (system phase delays, Doppler)







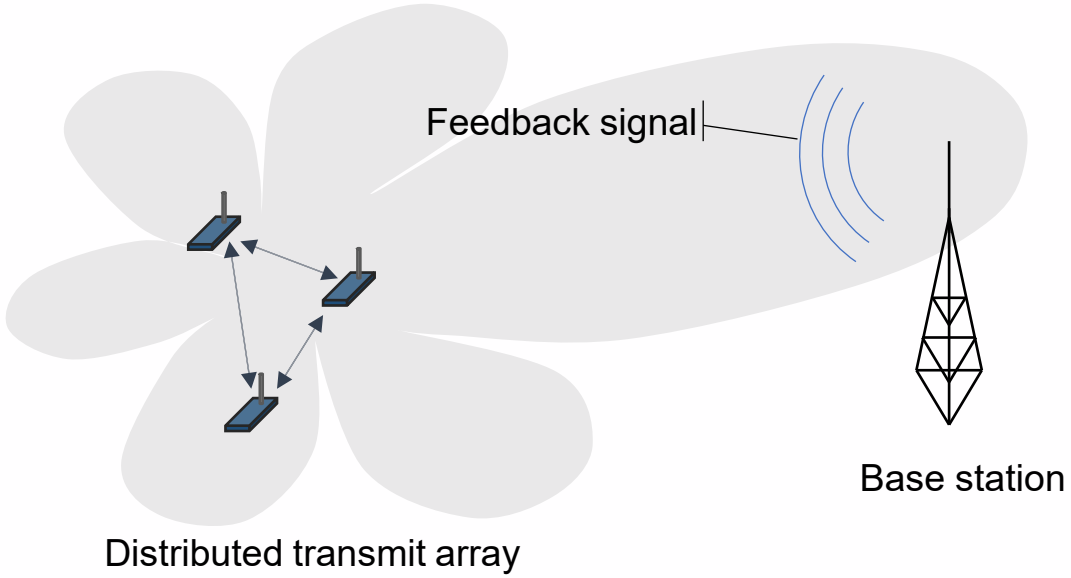




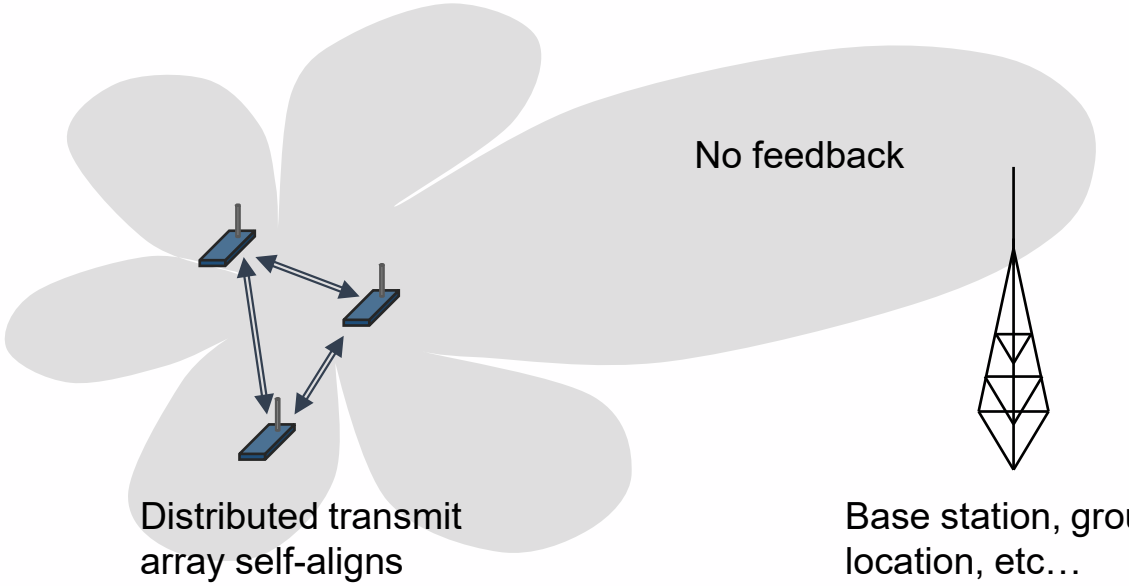
USNC-URSI 2017
IEEE Access 9 2021

Coordination Approaches

Closed-Loop



Open-Loop



IEEE Trans. Info. Theory 56 (1) 2010

IEEE TMTT 65 (5) 2017
IEEE TMTT 69 (11) 2021

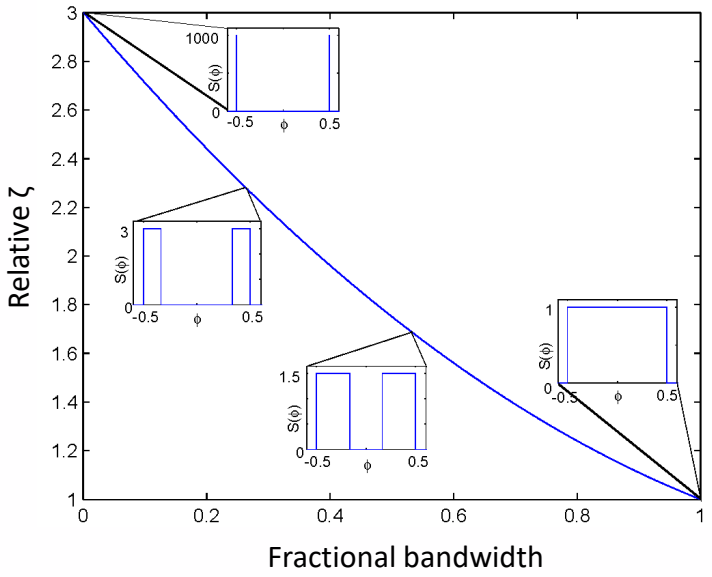
Optimal Range Estimation

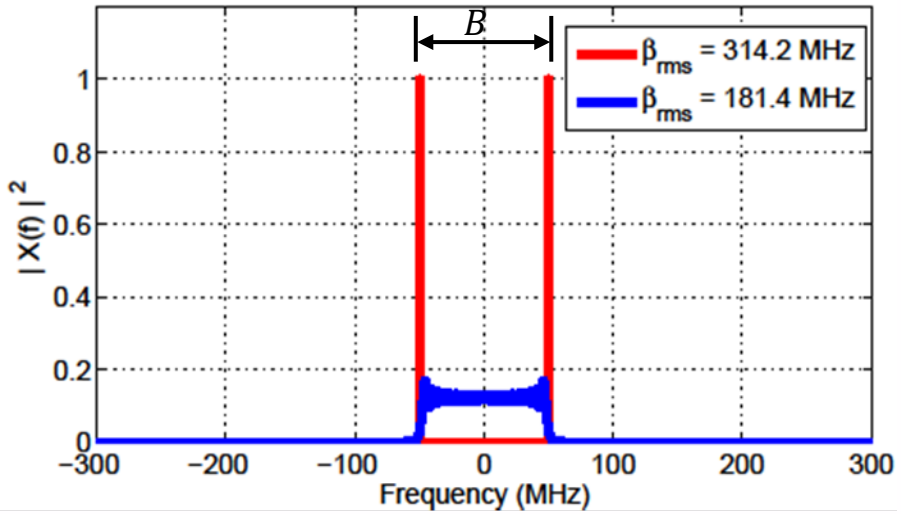
Estimation accuracy

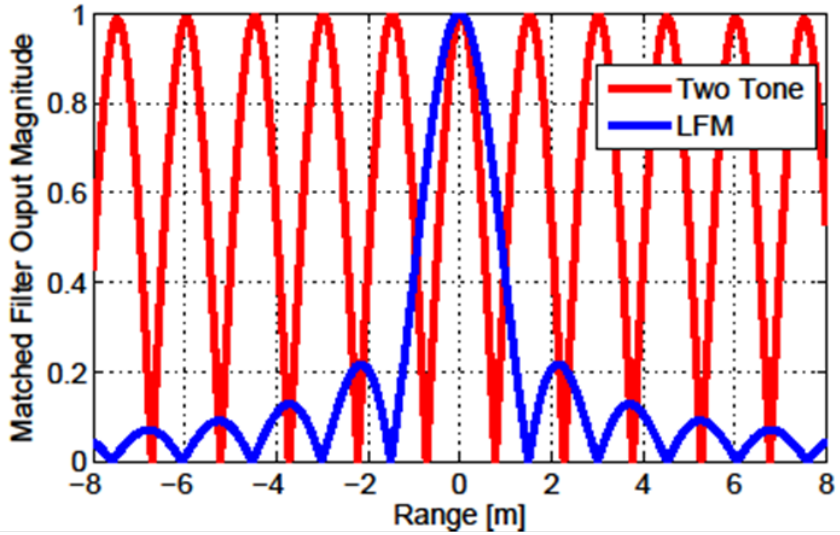
$$\mathrm{var}(\hat{\tau} - \tau) \geq \frac{N_o}{2|\alpha|^2 \zeta_f^2}$$

Mean-square bandwidth

$$\zeta_f^2 = \int (2\pi f)^2 |G(f)|^2 \, df$$

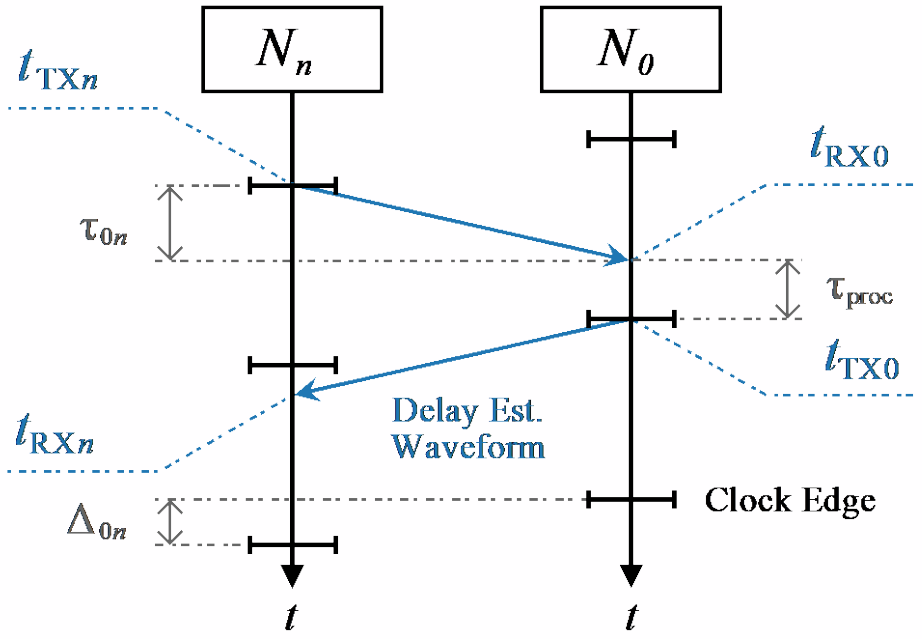




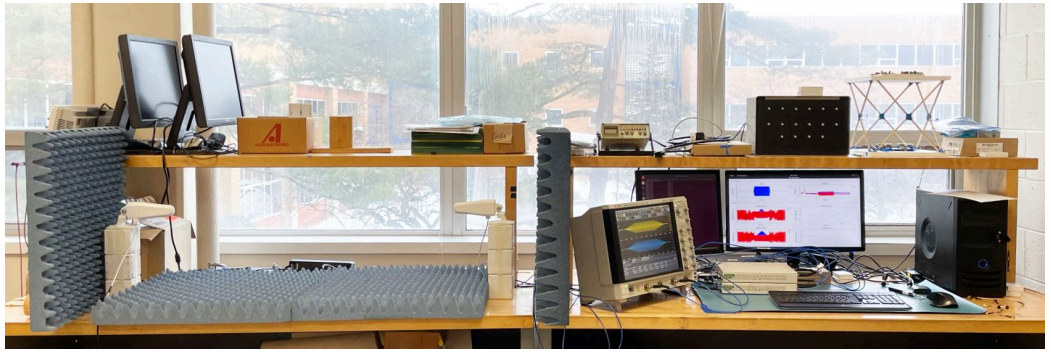


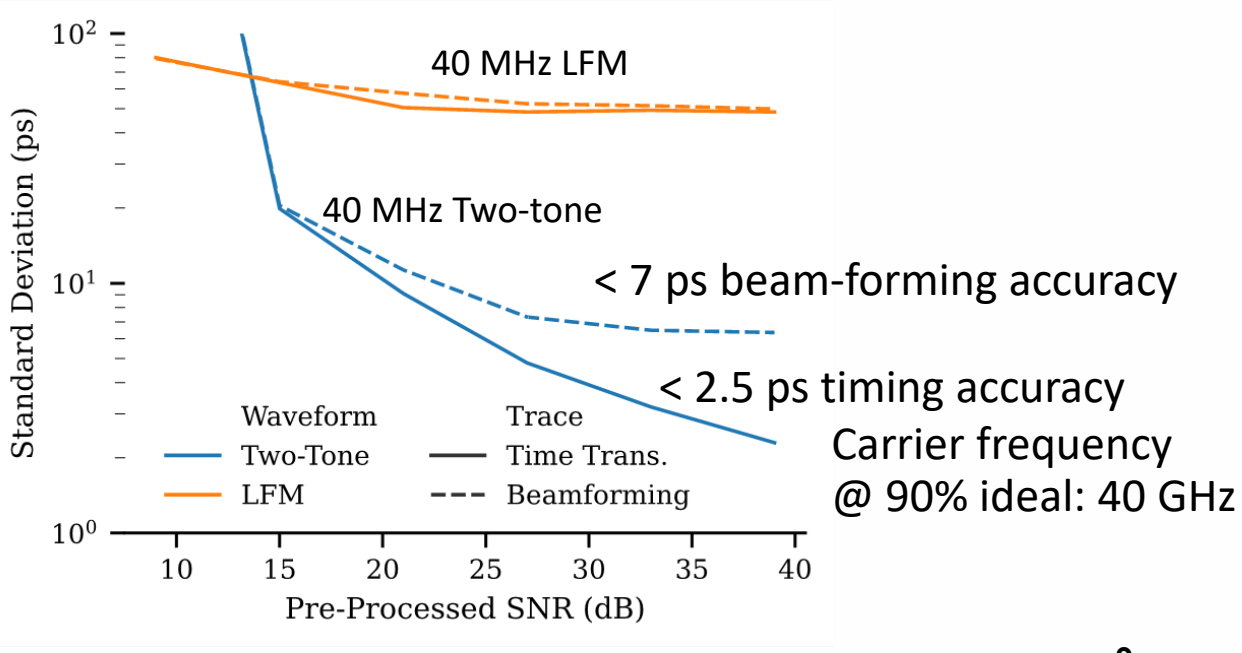
Time Synchronization

Accurate delay estimation supports picosecond-level wireless time synchronization



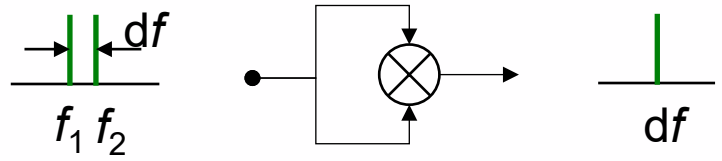
$$\Delta_{0n} = \frac{(t_{RX0} - t_{TXn}) - (t_{RXn} - t_{TX0})}{2}$$

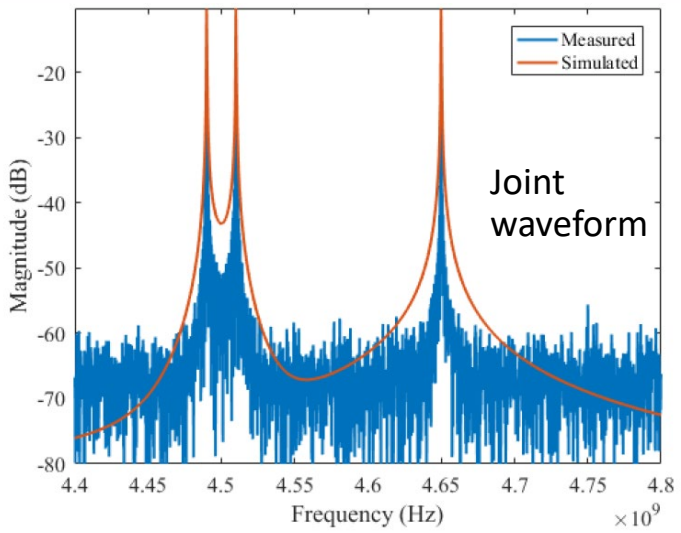


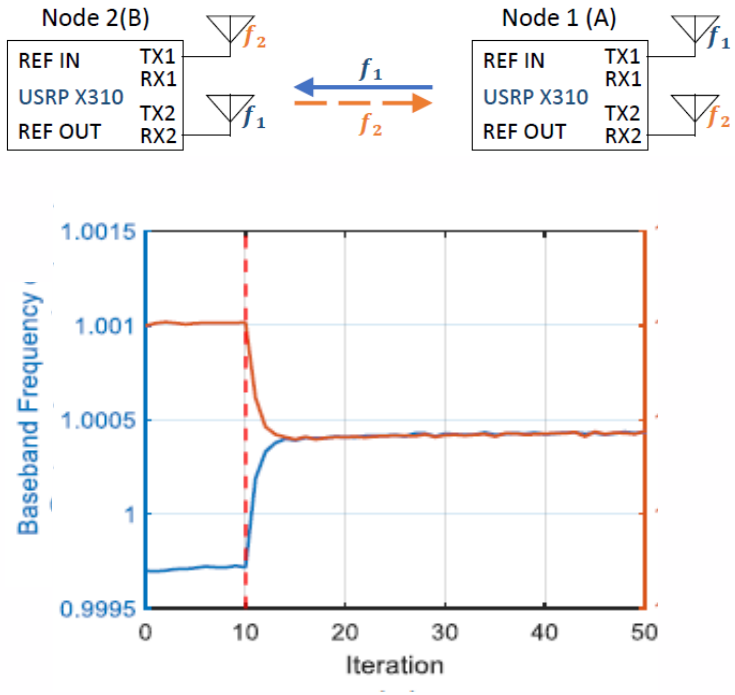


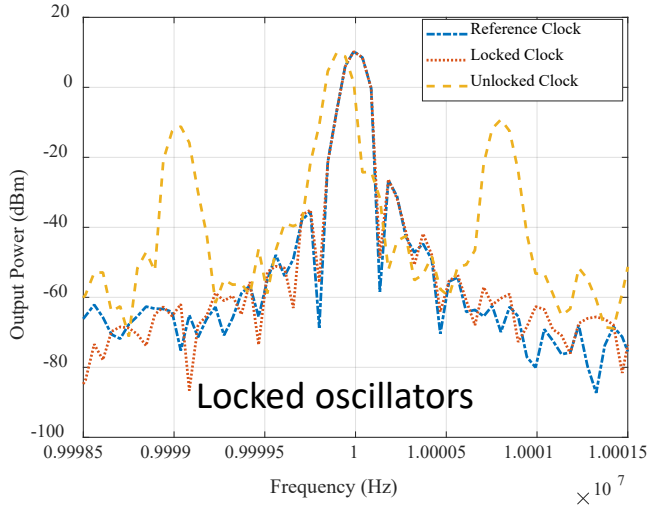
Frequency Syntonization

Spectrally sparse waveforms support additional coordination functions, including frequency transfer



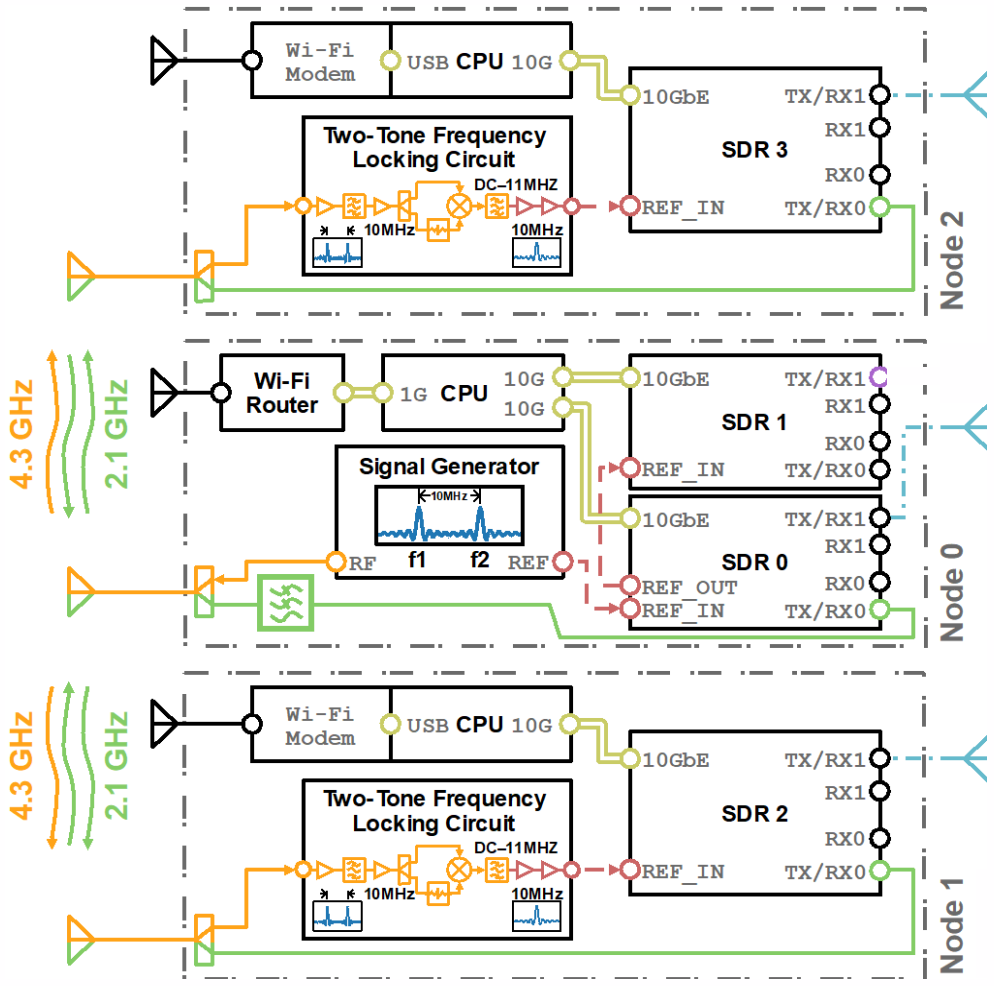


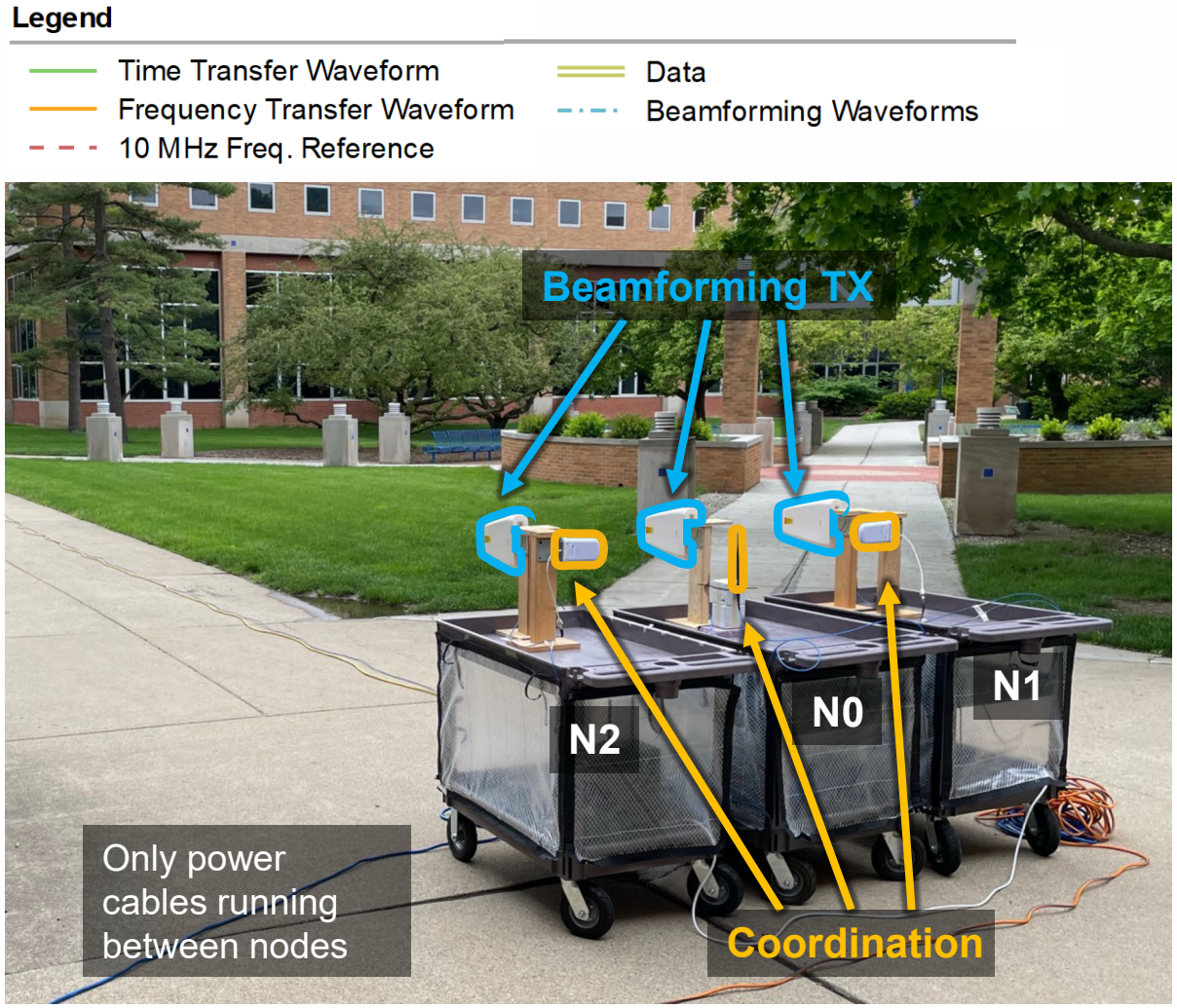




IEEE TMTT 68 (1) 2020
IEEE MWSCS 2020
IEEE IMS 2020

Experiments – Typical Configuration

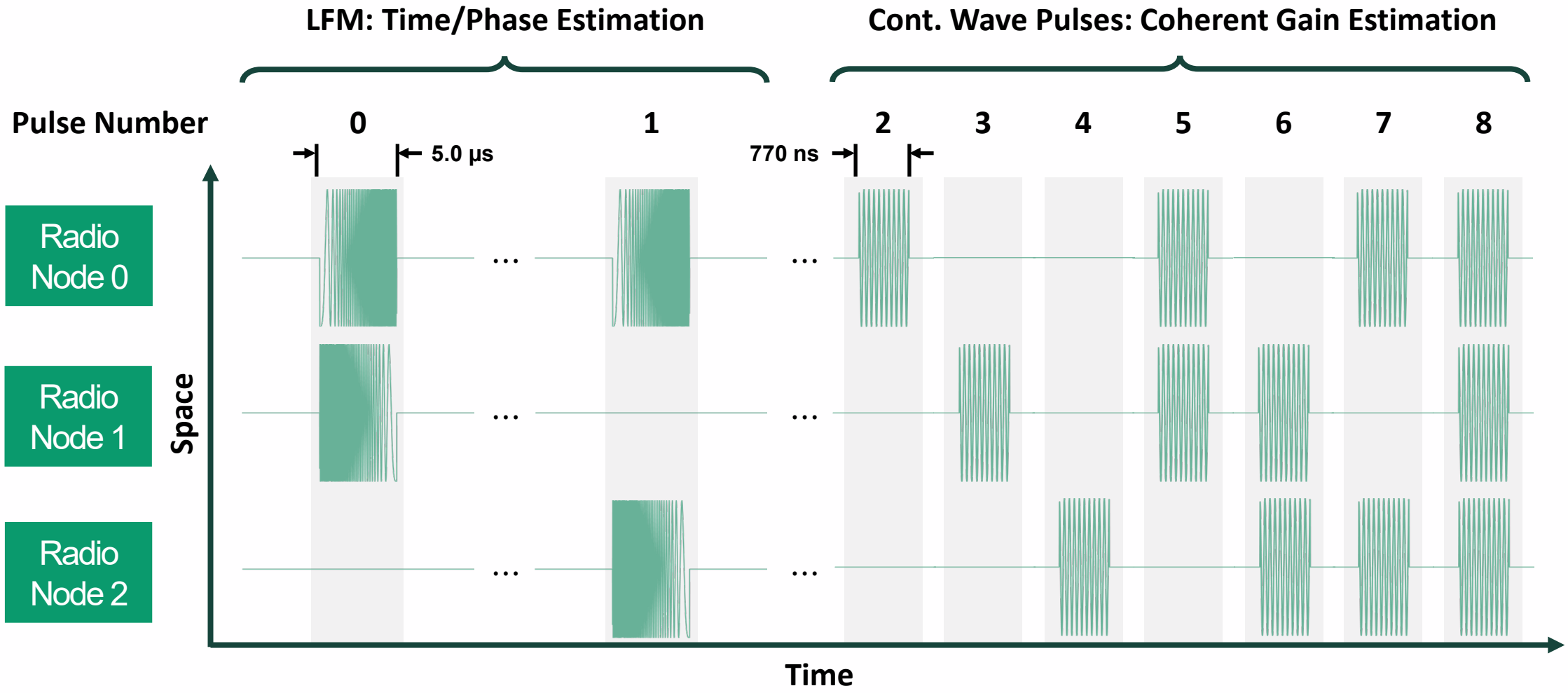




J. M. Merlo, N. Shandi, M. Dula, A. Bhattacharyya, and J. A. Nanzer, "Fully wireless collaborative beamforming using a three-element coherent distributed phased array," in 2024 IEEE International Symposium on Phased Array Systems & Technology (PAST), (Boston, MA, USA), Oct. 2024. doi: 10.1109/ARRAY58370.2024.10880359

Beamforming/Beamsteering Evaluation

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



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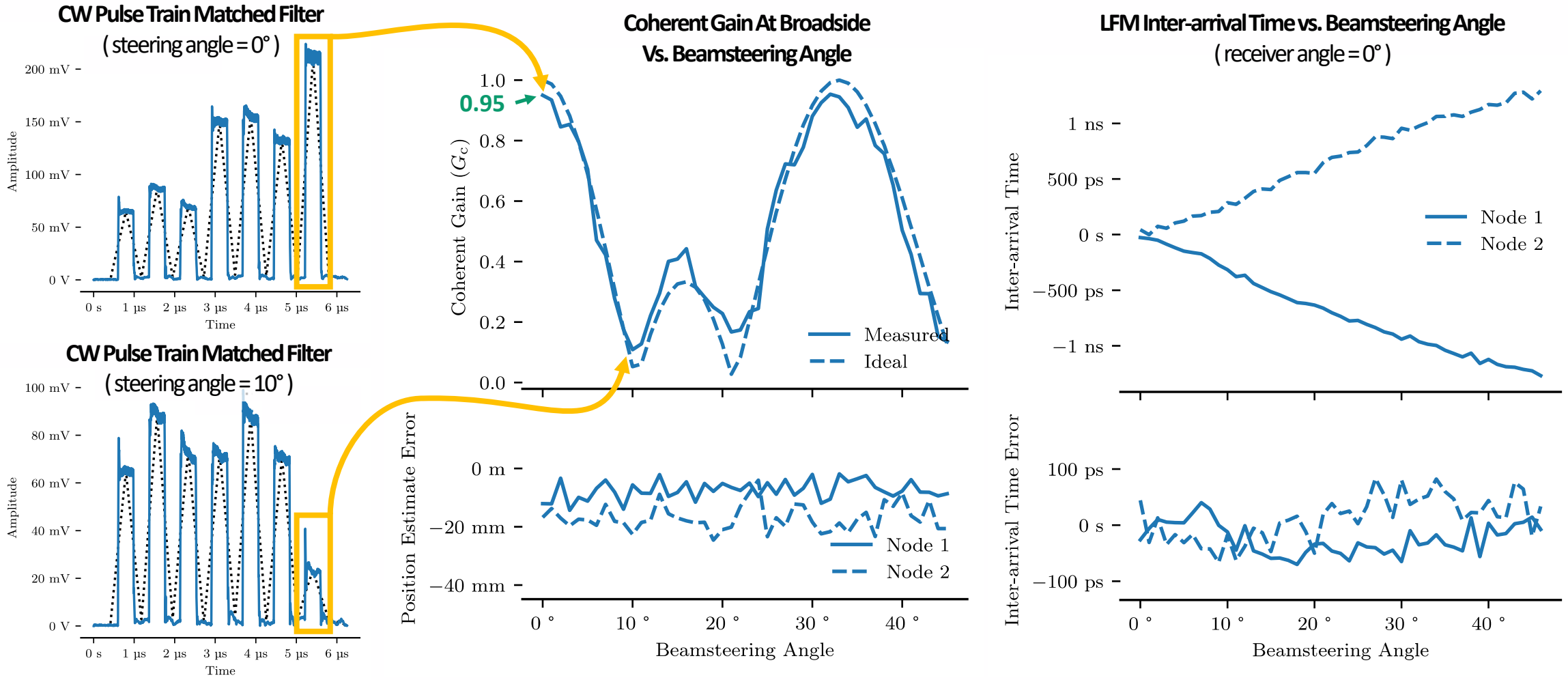
Beamforming/Beamsteering Evaluation

Beamsteering measurements at a static receiver



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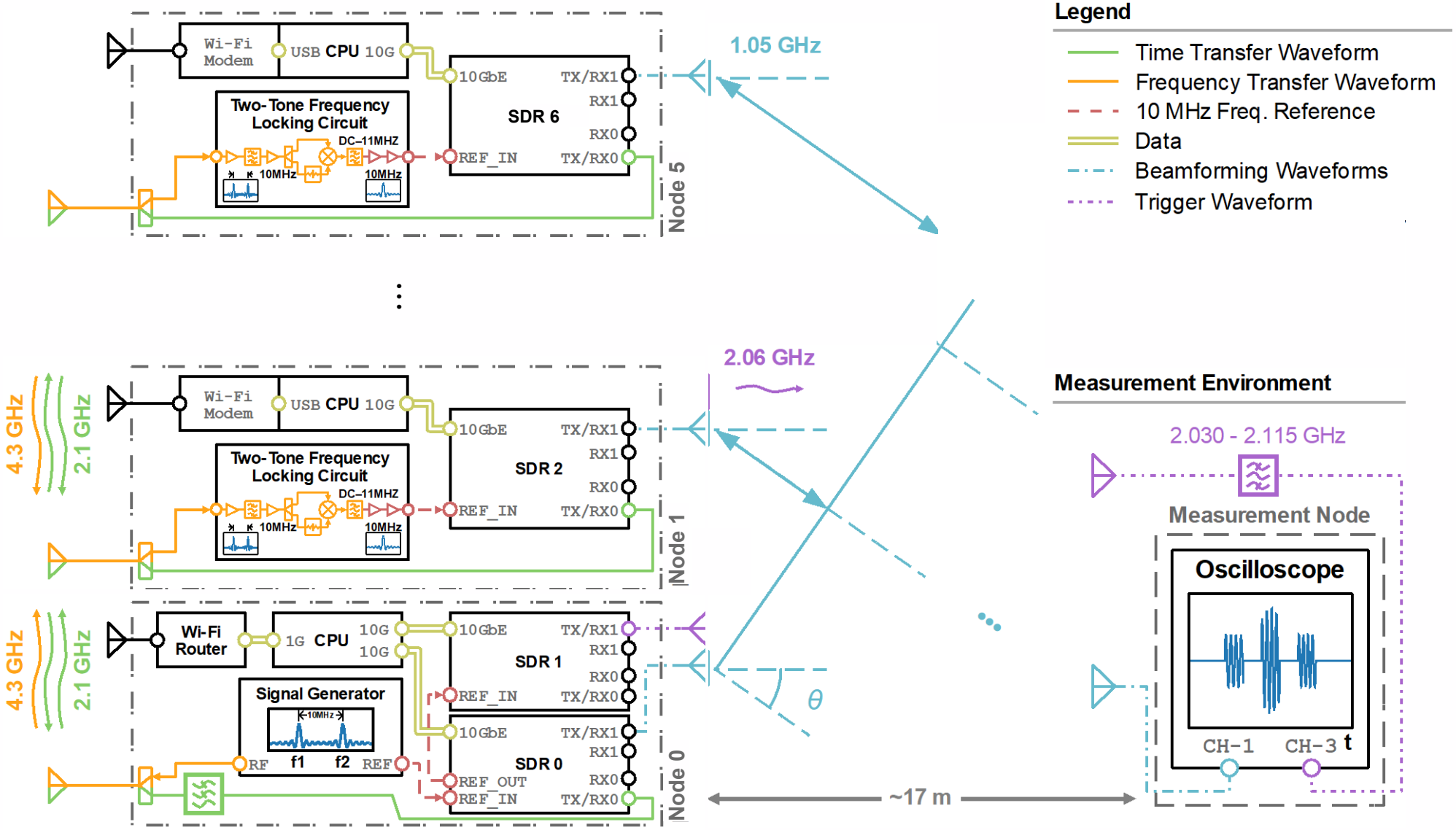
Six-node Beamforming with Decentralized Time Synchronization

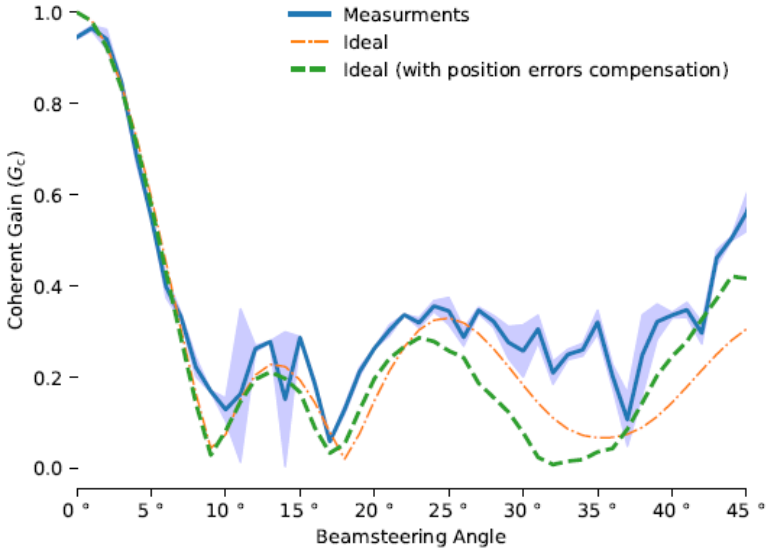


Six-node Beamforming with Decentralized Time Synchronization

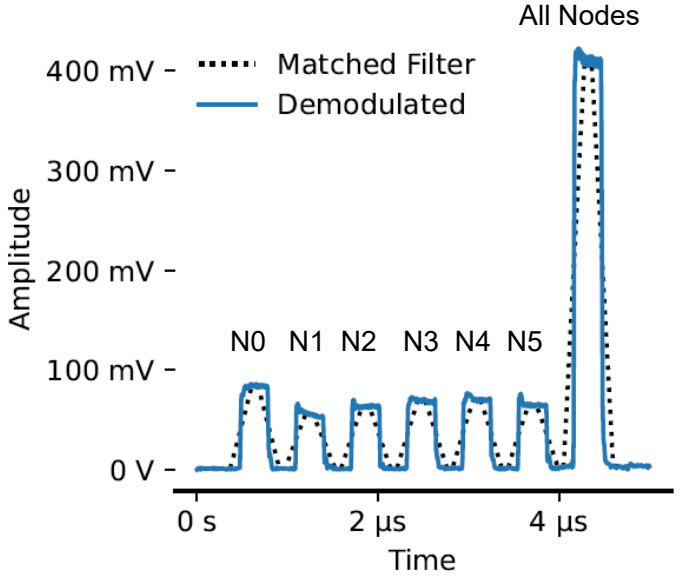
Six-node Beamforming with Decentralized Time Synchronization

- Receiver held static; beam steered from 0° to 45°
- Decentralized time synchronization; centralized analog frequency syntonization
- Average coherent gain > 98% at $f_c = 1.05$ GHz

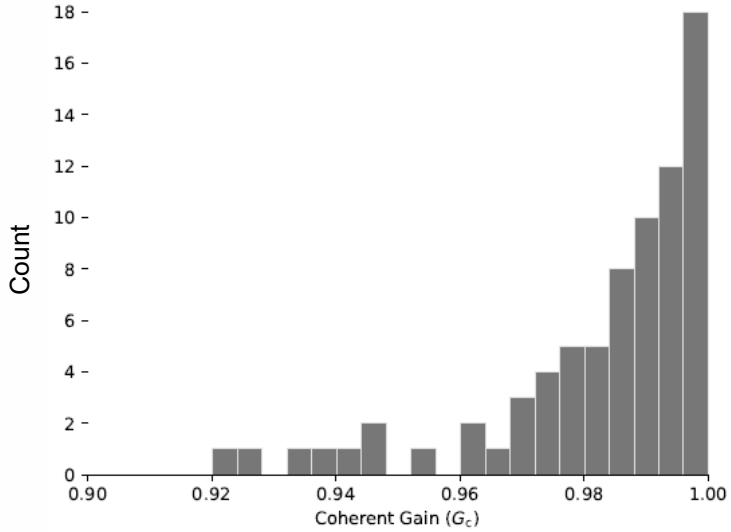
Array pattern while steering



Single pulse (fast time)



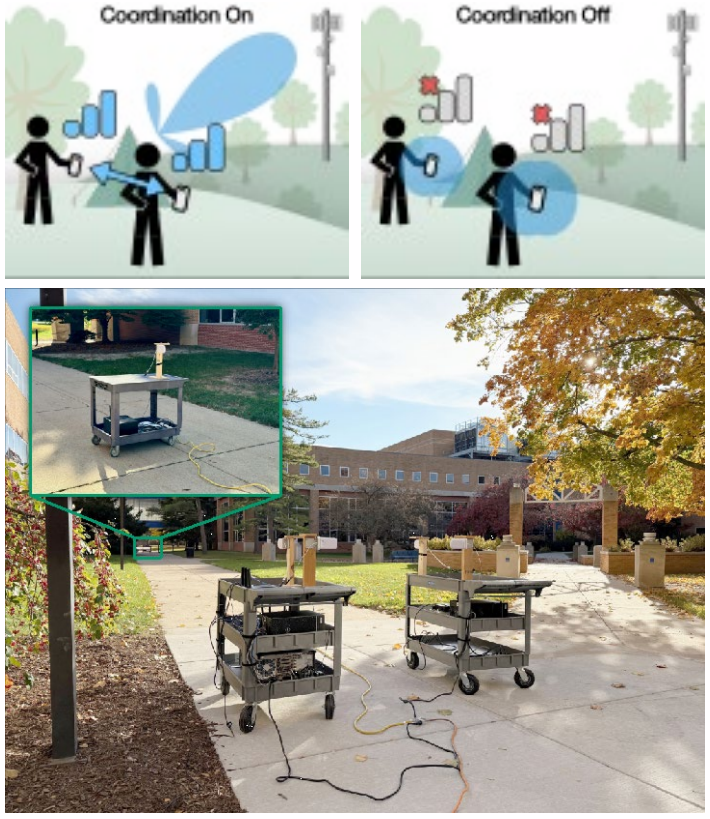
Histogram of coherent gain

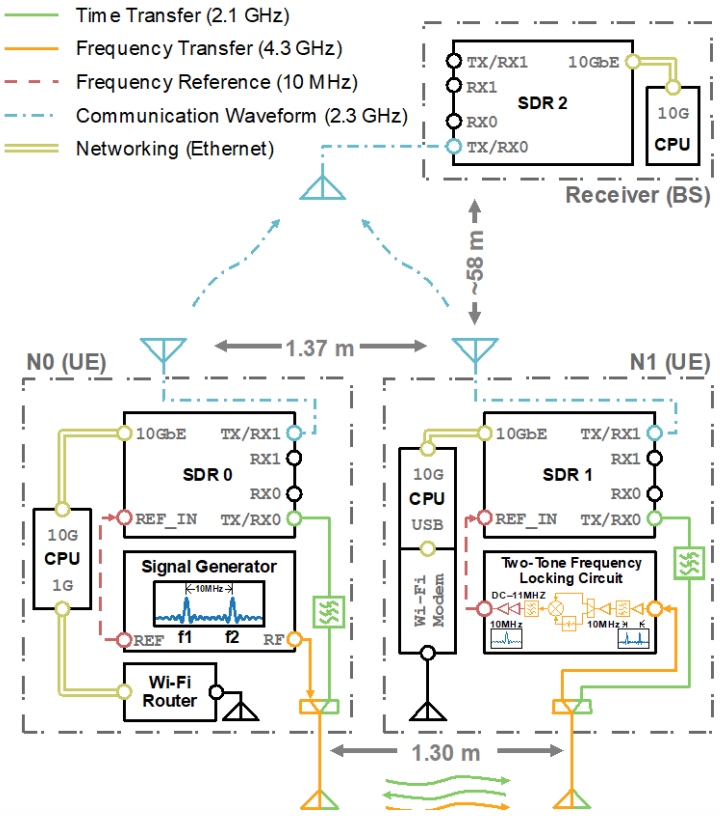


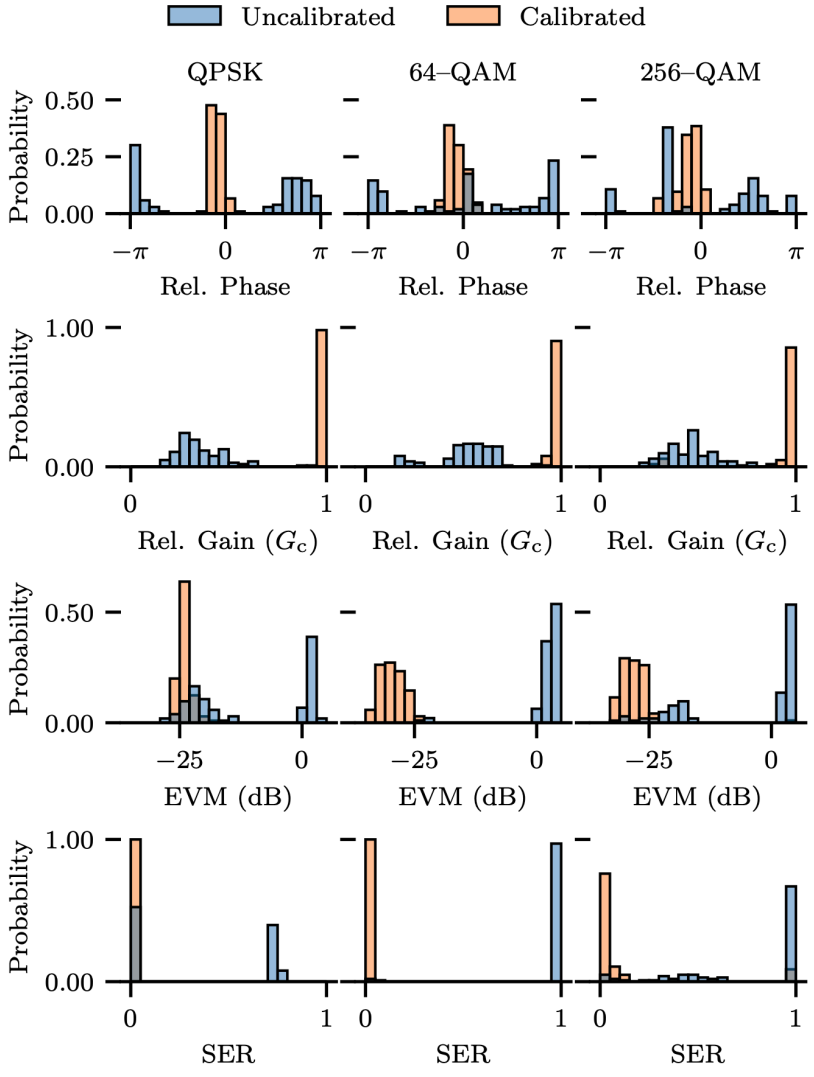
Shandi, N., Merlo, J.M. and Nanzer, J.A., IEEE JMW 2025

Coherent Distributed Communications

- Demonstrated initial proof of concept of a distributed communication system transmitting QAM symbols
- Demodulated on a single software-defined radio receiver



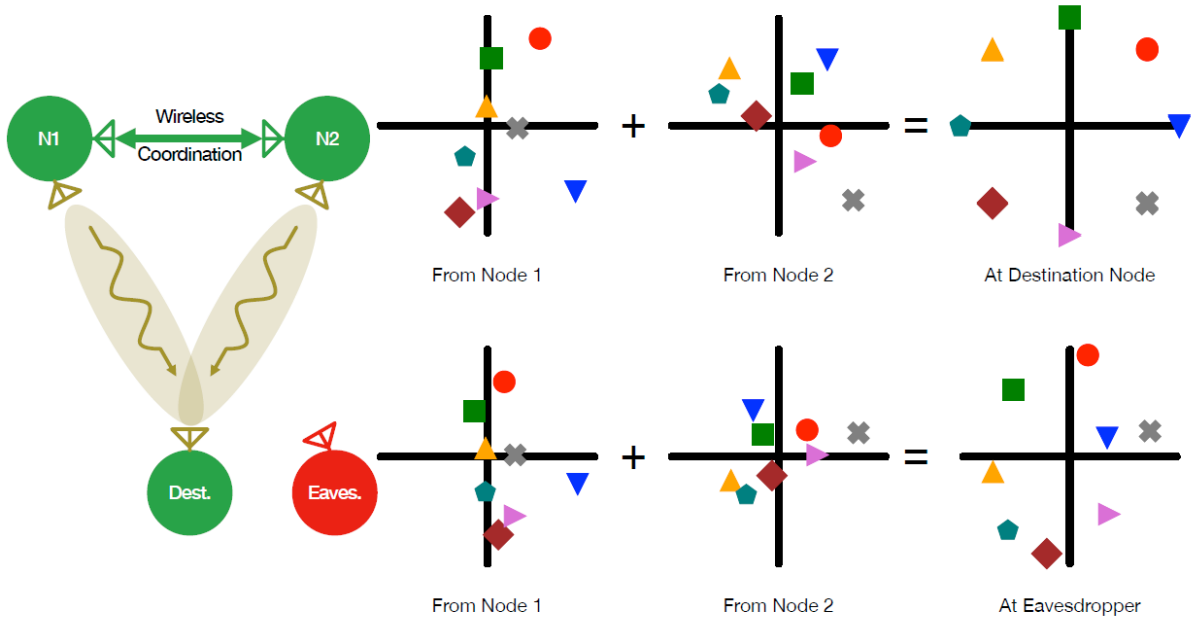


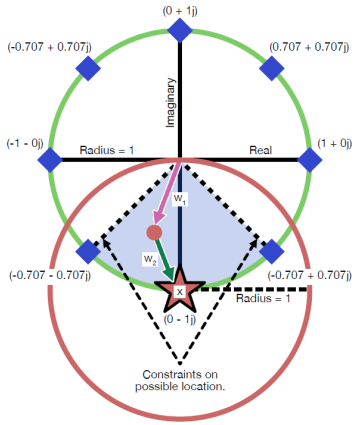


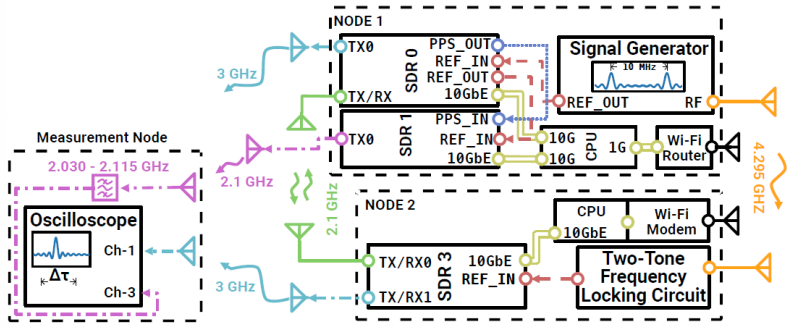
Merlo, J.M. and Nanzer, J.A., *arXiv preprint*

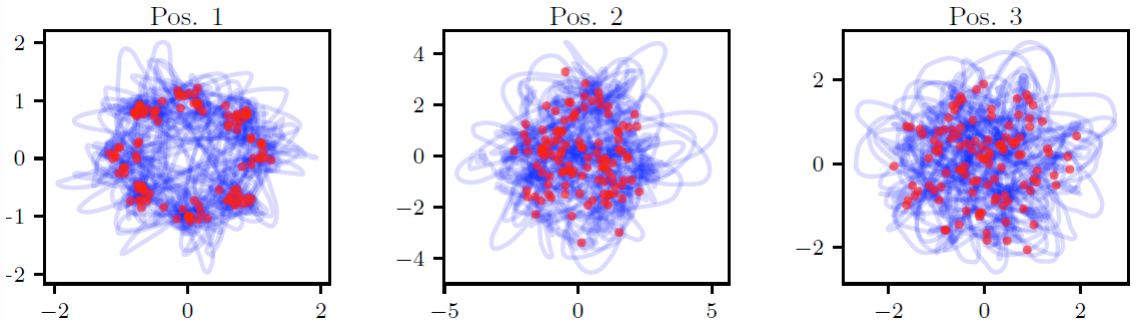
Distributed Communications for Wireless Security

- Coherent transmission of spatially decomposed signals
- Coherent reception at desired receiver, random constellations at other angle





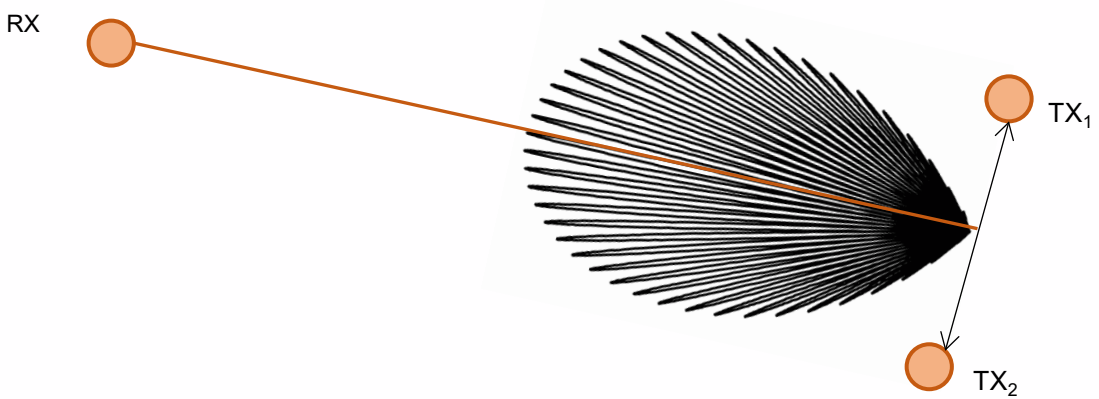


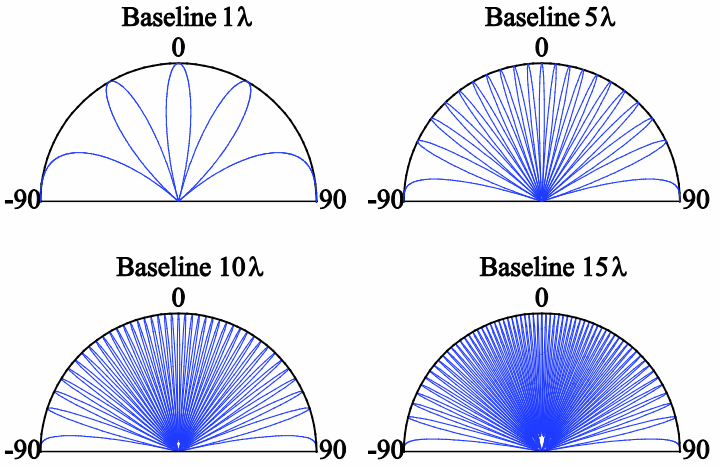


Schlegel, Merlo, and Nanzer, *arXiv preprint*

Grating Lobes

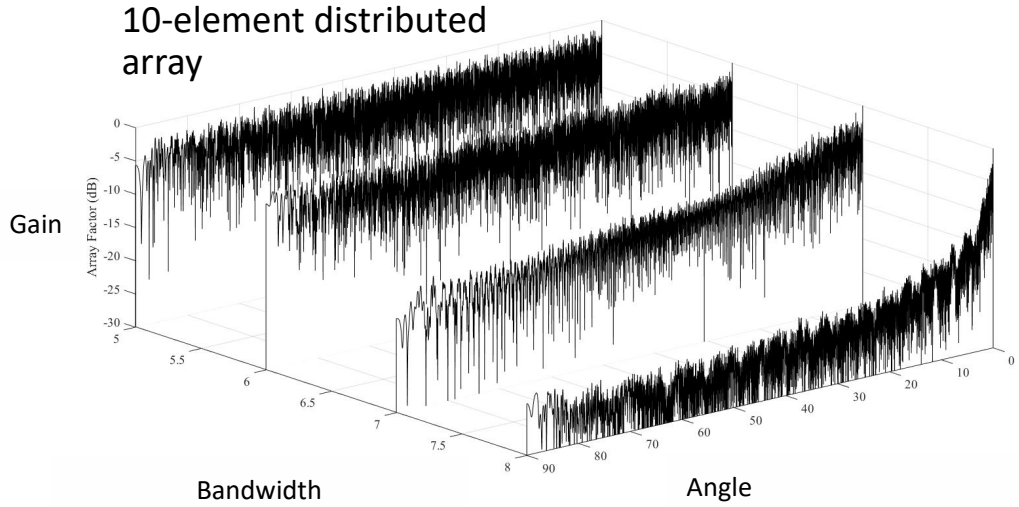
Spatial ambiguities are inherent in sparse antenna arrays





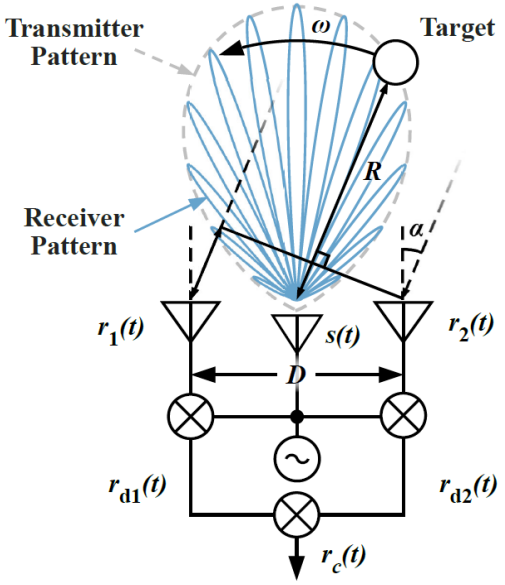
Typical approach: mitigation, e.g., via bandwidth

- Typically very wide bandwidths are needed
- Often reduces grating lobe energy far from mainbeam area, but can leave grating lobes near the mainbeam largely unaffected



Grating Lobes – Sensing

Using grating lobes for new radar measurements



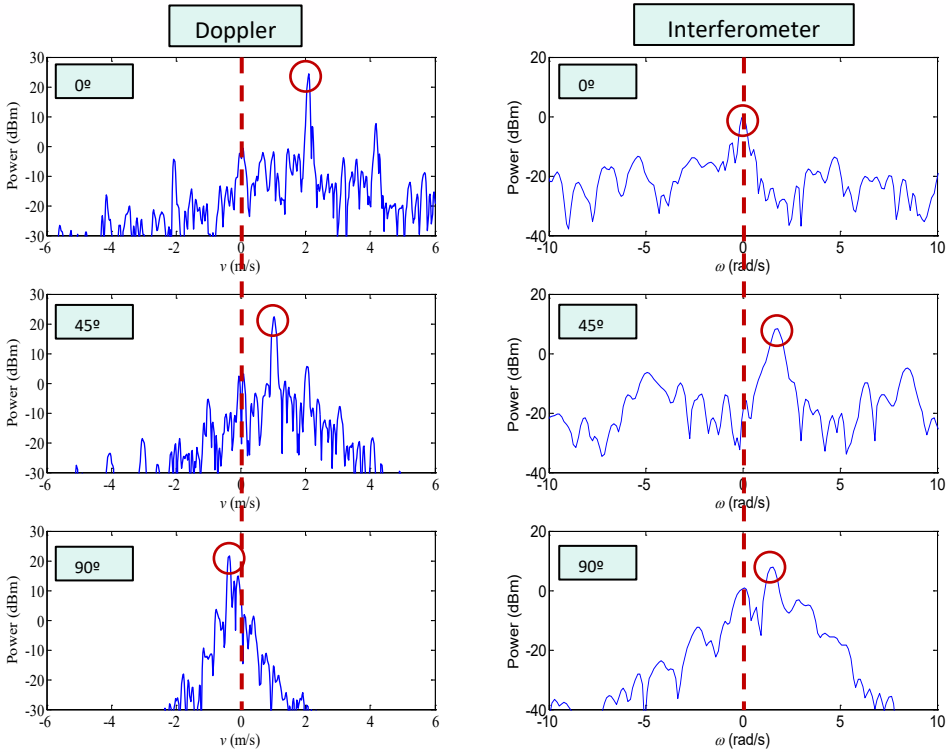
Interferometer Frequency shift

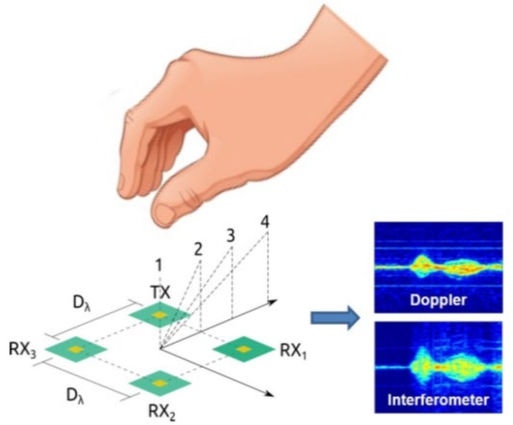
$$f_s = \frac{\omega D}{\lambda_c}$$

Doppler frequency shift

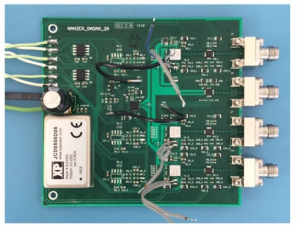
$$f_D = \frac{2v_r}{\lambda_c}$$

Joint Doppler/interferometer measurements

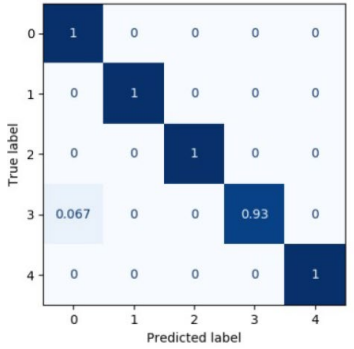




40 GHz interferometric radar



Gesture classification

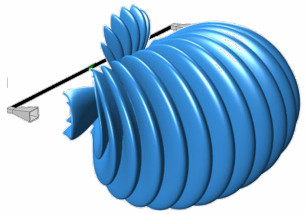


IEEE TMTT 58 (12) 2010
IEEE TAP 60 (11) 2012
IEEE TAP 62 (3) 2014)
IEEE MWCL 30 (3) 2020
IEEE TMTT 69 (1) 2021
IEEE MWCL 31 (8) 2021

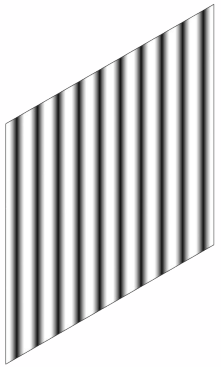
Grating Lobes – Sensing

Using grating lobes for fast Fourier imaging

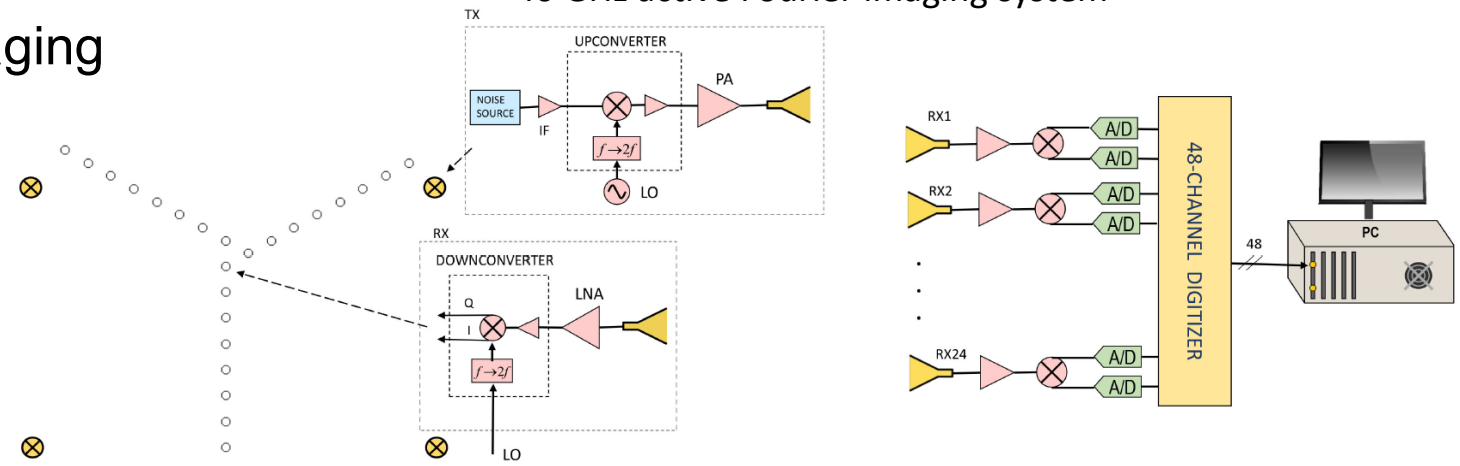
Interferometer radiation pattern

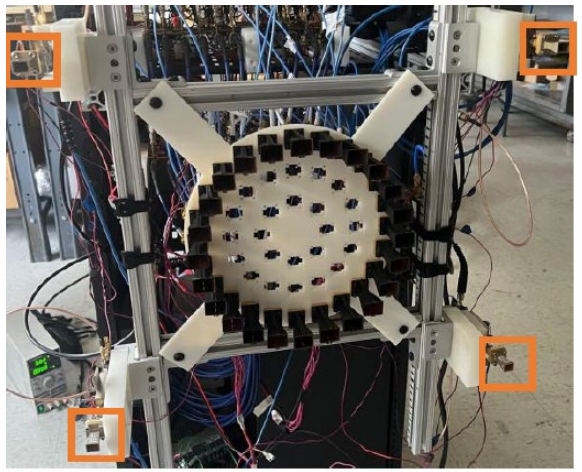


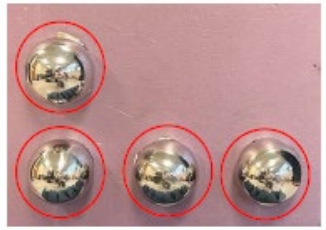
Far-field grating lobe pattern

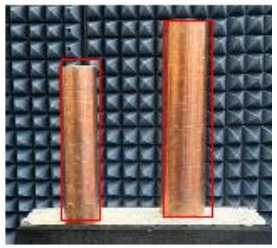


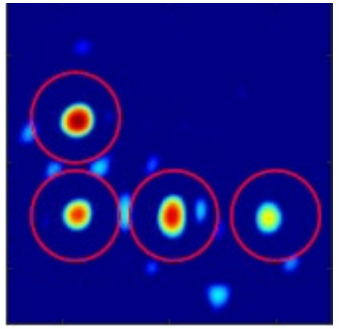
40 GHz active Fourier imaging system

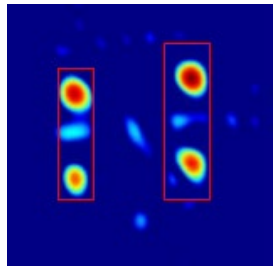




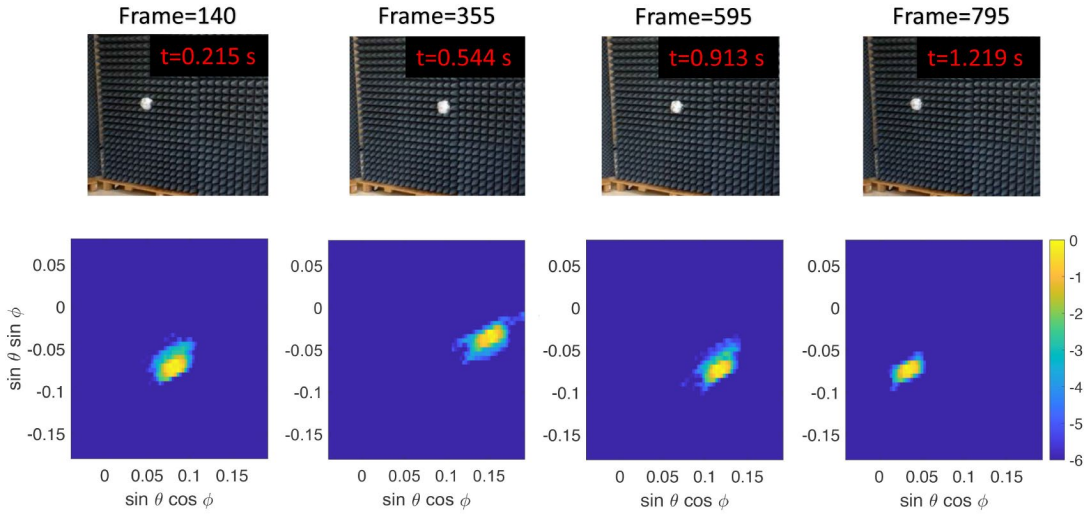








High-speed image reconstruction



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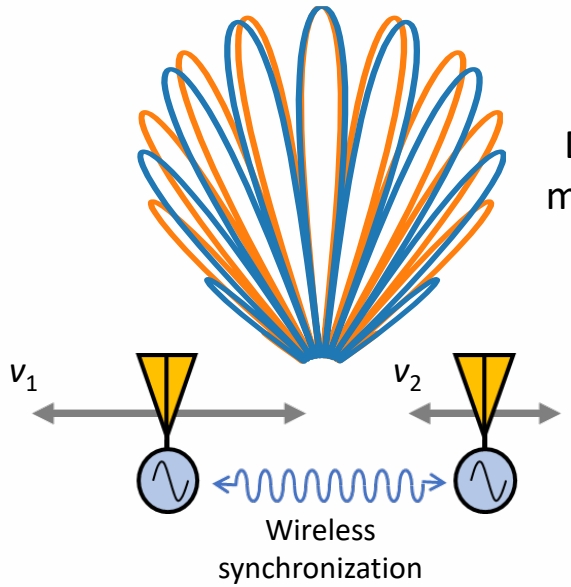
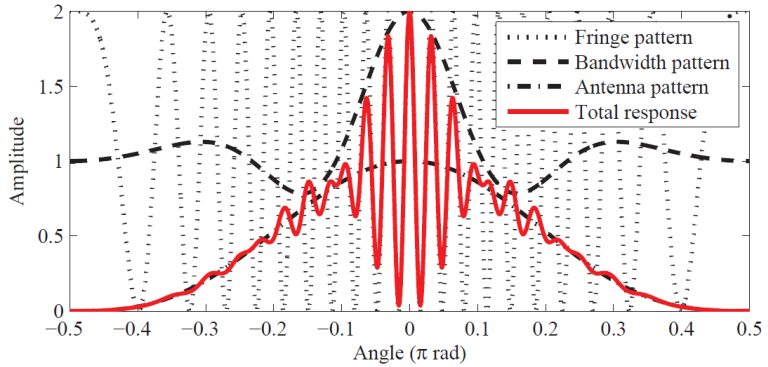
IEEE TMTT 68 (9) 2020
IEEE JoM 1 (3) 2021

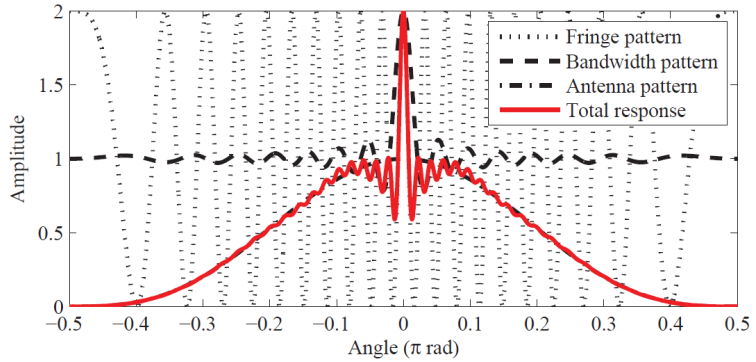
Mitigation of Grating Lobes Using Array Dynamics



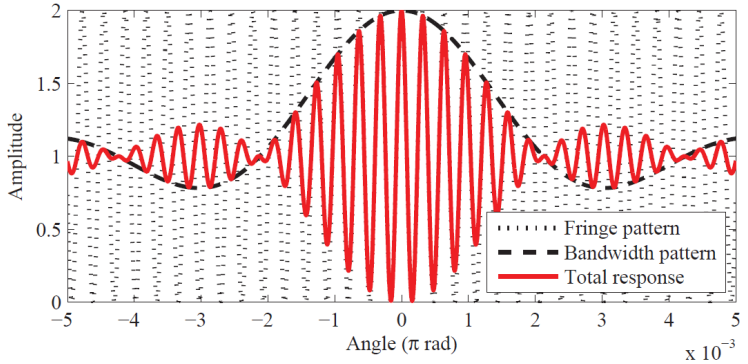
Dynamic array motion modulates array pattern



$D = 10\lambda$
$\Delta d_\lambda = 3$



$D = 10\lambda$
$\Delta d_\lambda = 15$



$D = 1000\lambda$
$\Delta d_\lambda = 150$

Combining spatial motion and frequency bandwidth

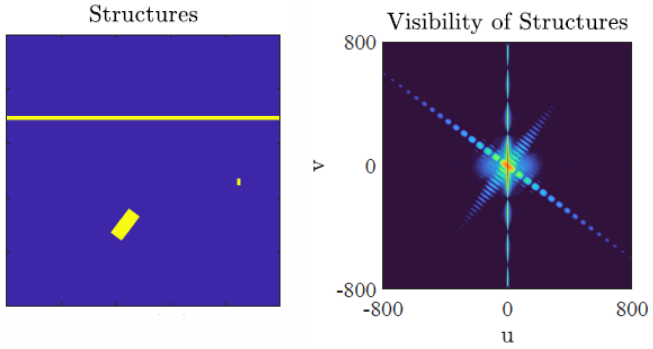
$$s_r(t,\theta) = \chi(t)A(\theta)\frac{\Delta d_\lambda}{2}\left[1 + e^{-j2\pi d_0 \sin\theta}\,\mathrm{sinc}\left(\pi \Delta d_\lambda \sin\theta\right)\right]$$

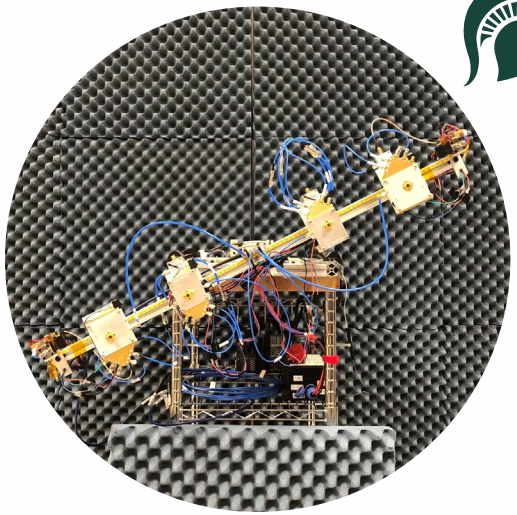
$$\Delta d_\lambda = \Delta d/\Delta\lambda$$

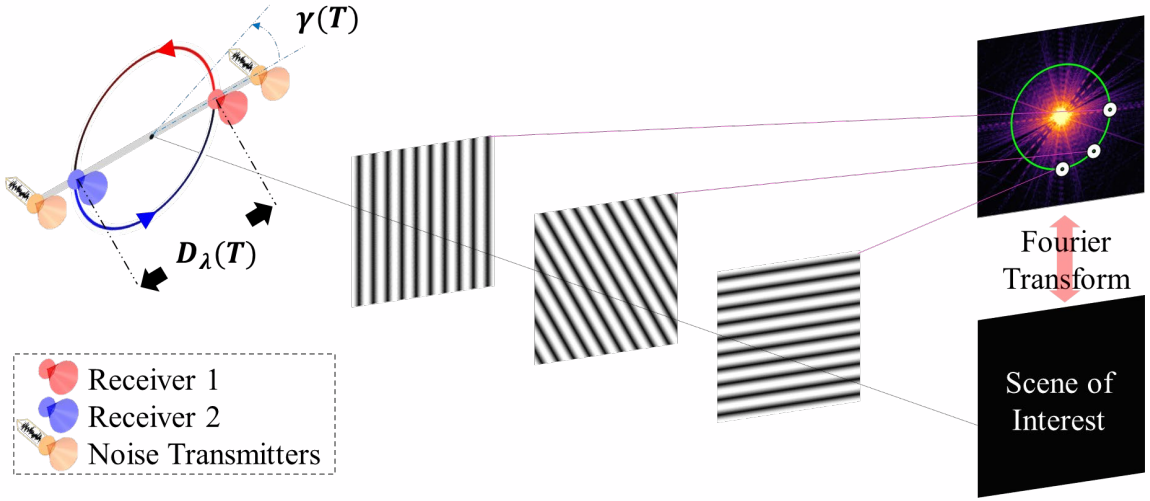
Fourier Domain Sensing

Using Fourier-domain sampling and dynamics for imageless object detection

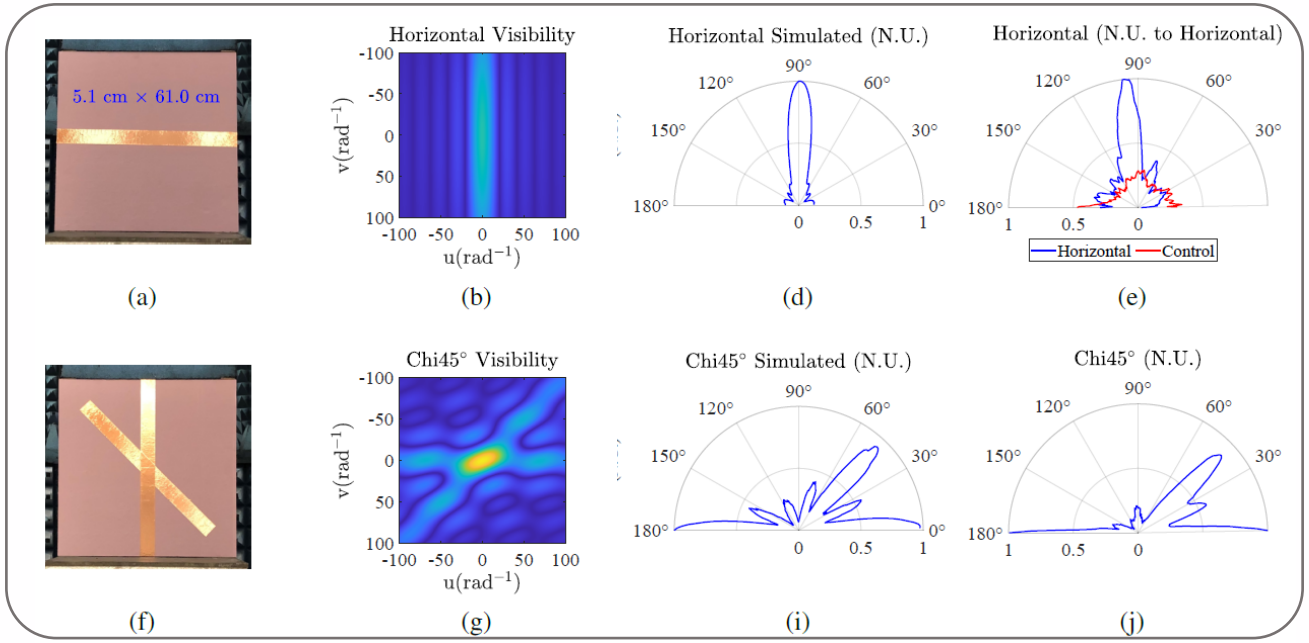
Fourier features







Fourier-domain feature detection



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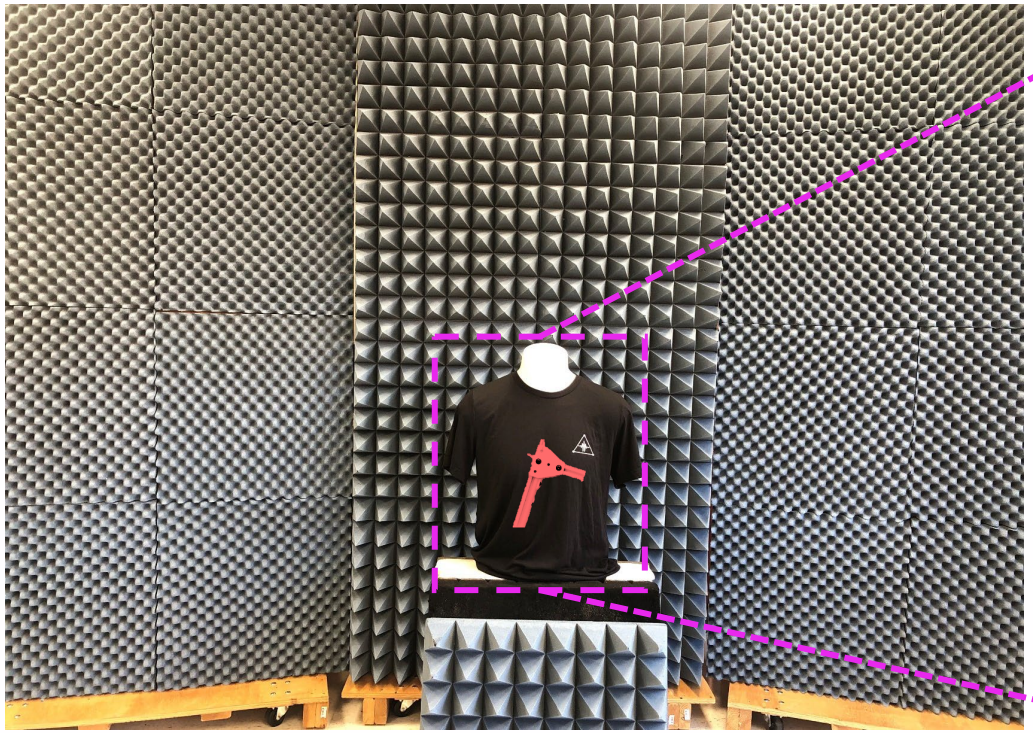
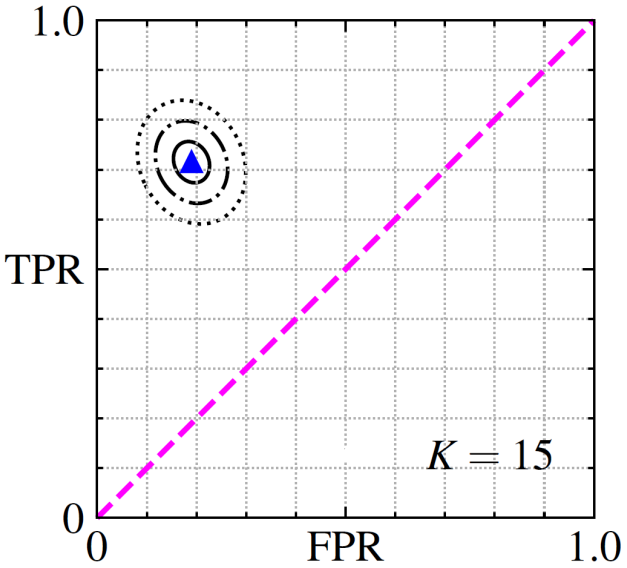
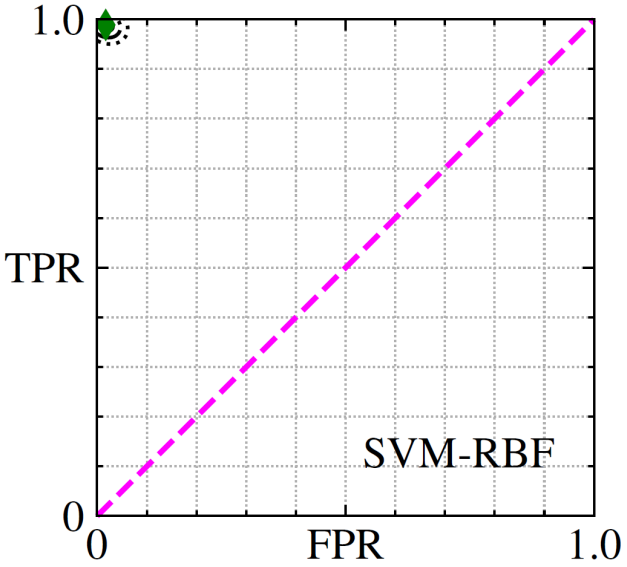
Fourier Domain Sensing



Gs: Gun-shape

nGs: non-Gun-shape





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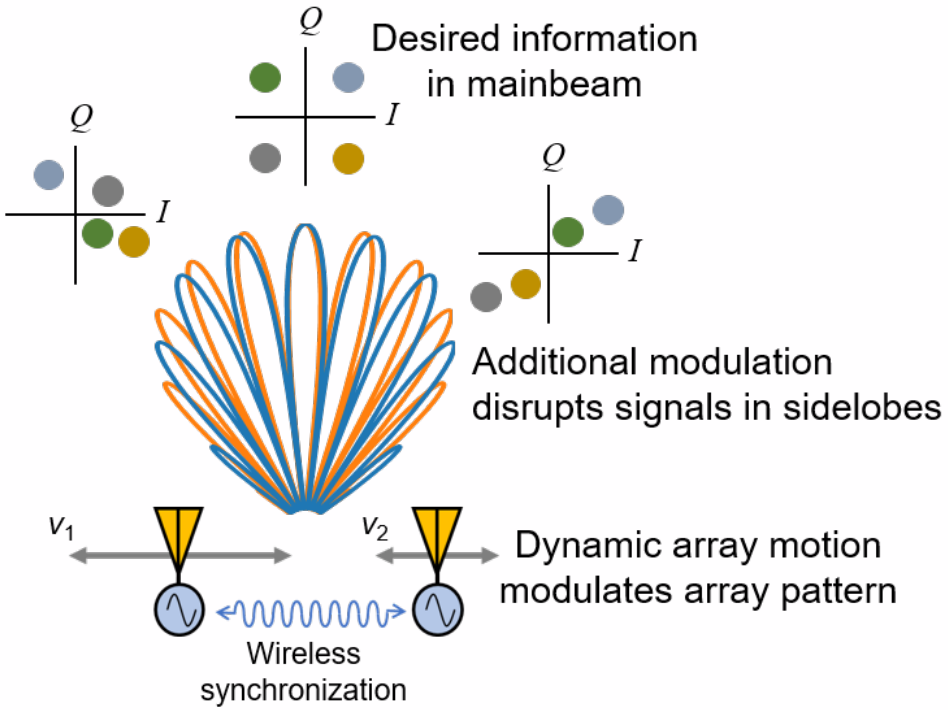
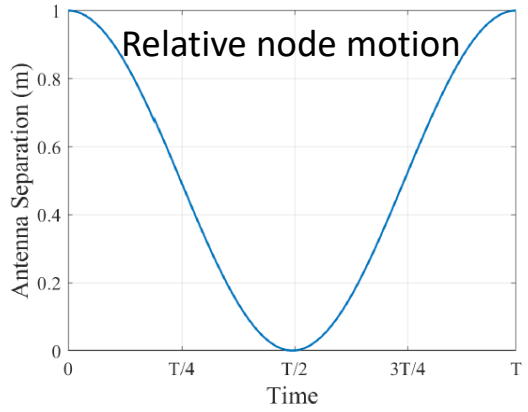
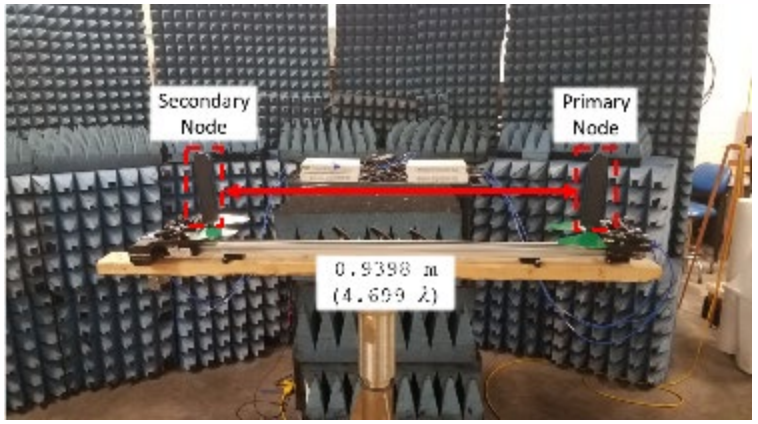
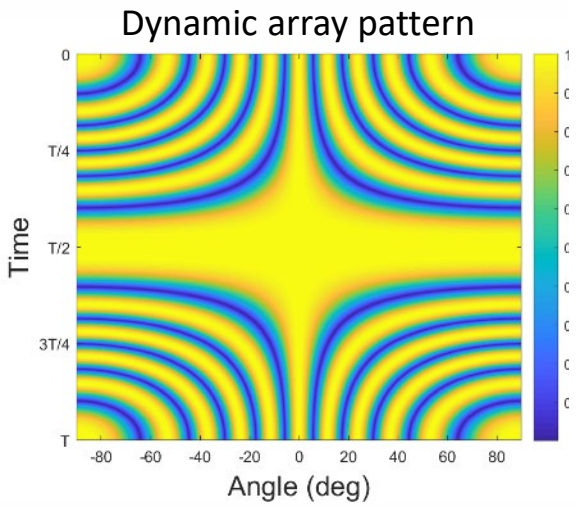
Directional Modulation

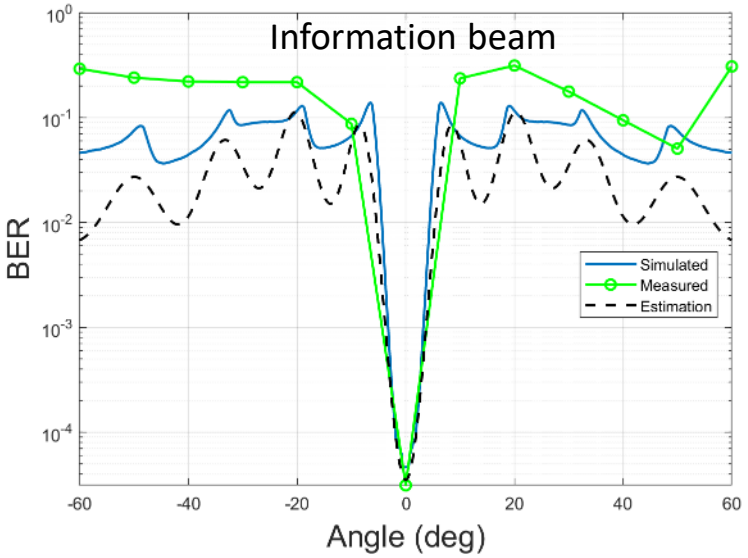
Using spatiotemporal dynamics for secure wireless





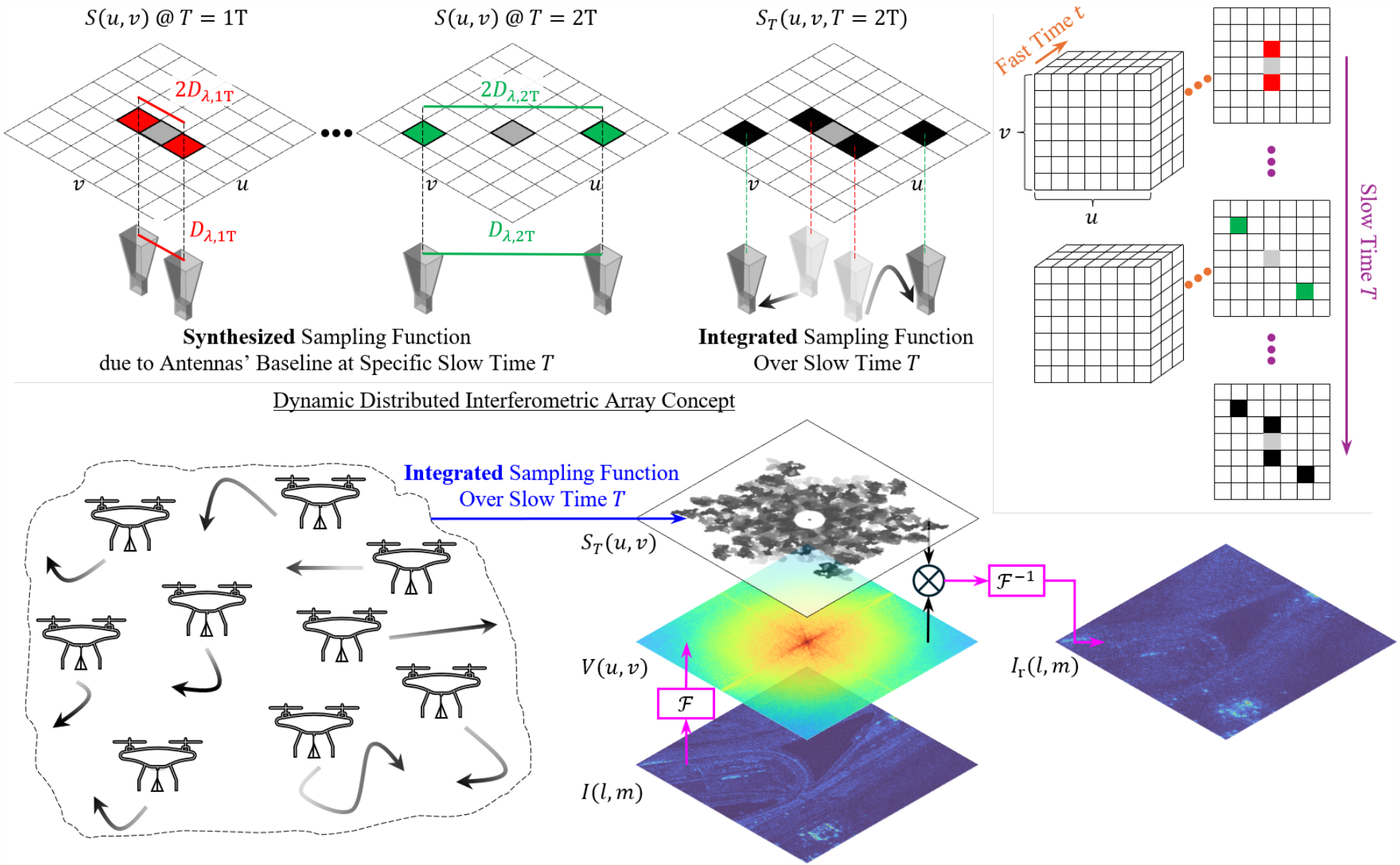




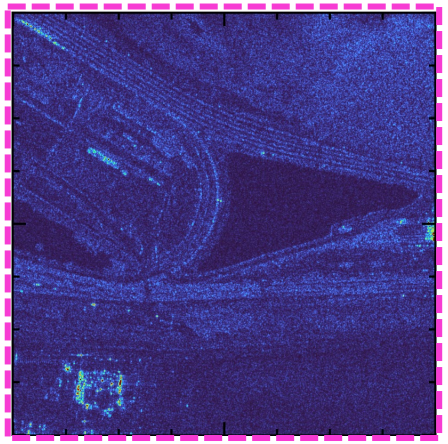


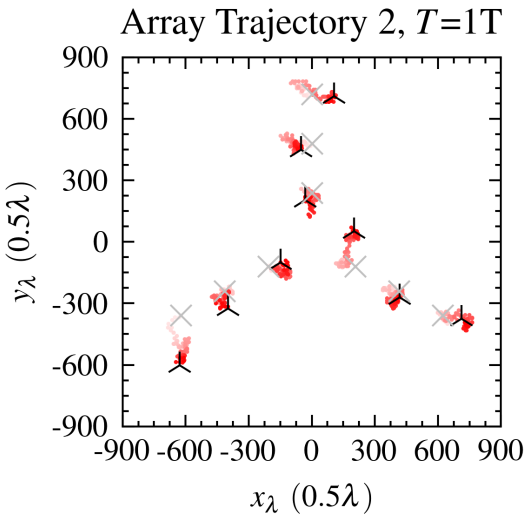
Distributed arrays: Signal gain in grating lobes reduces from N^2 to N

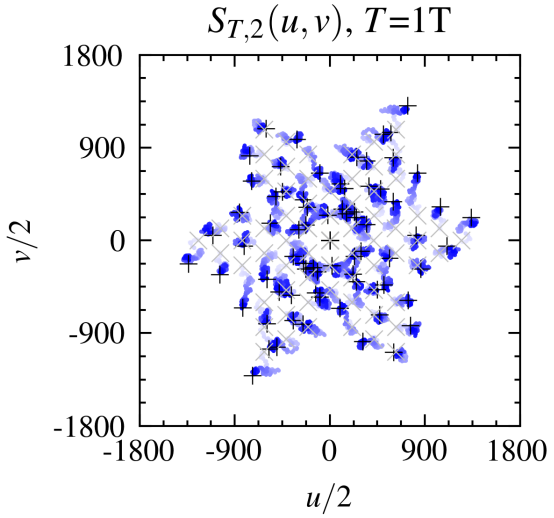
Increased Distributed Fourier Domain Sampling

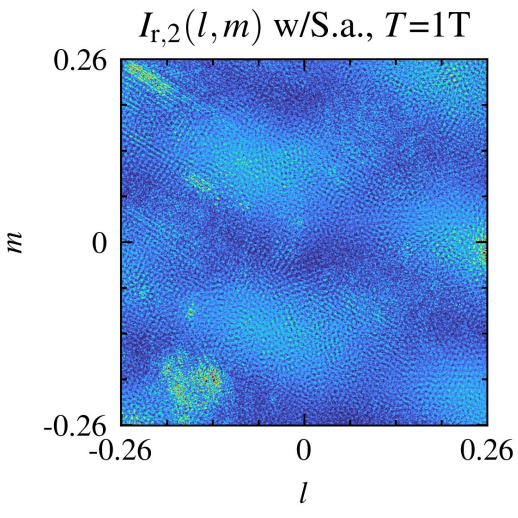


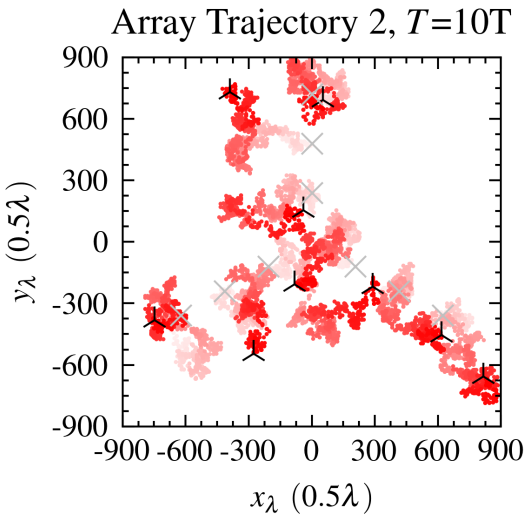
Increased Distributed Fourier Domain Sampling

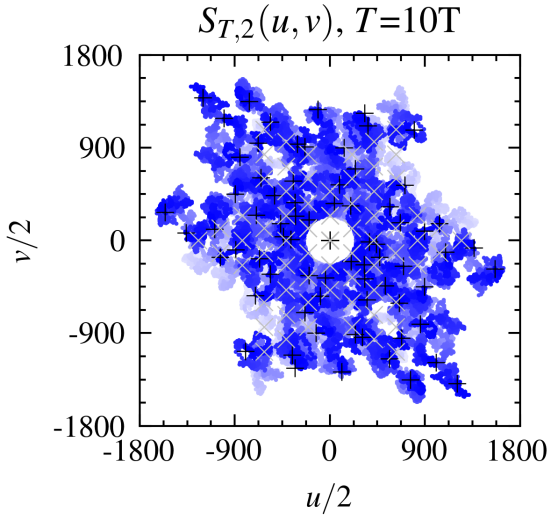


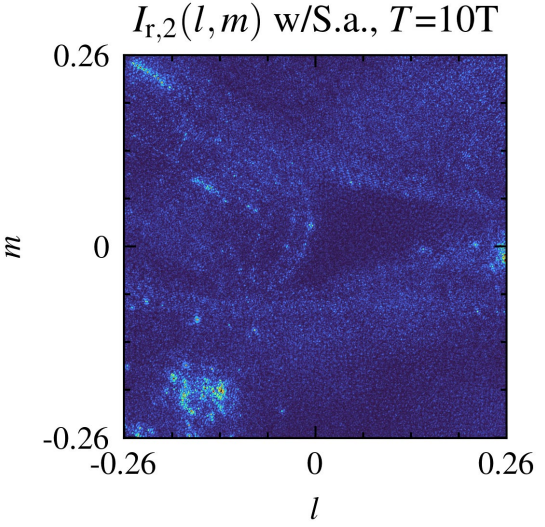






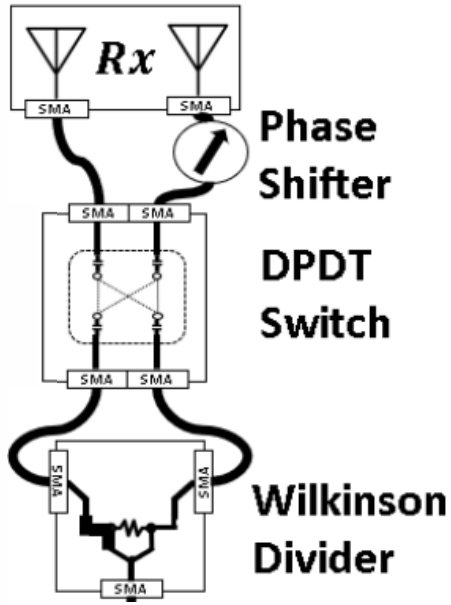


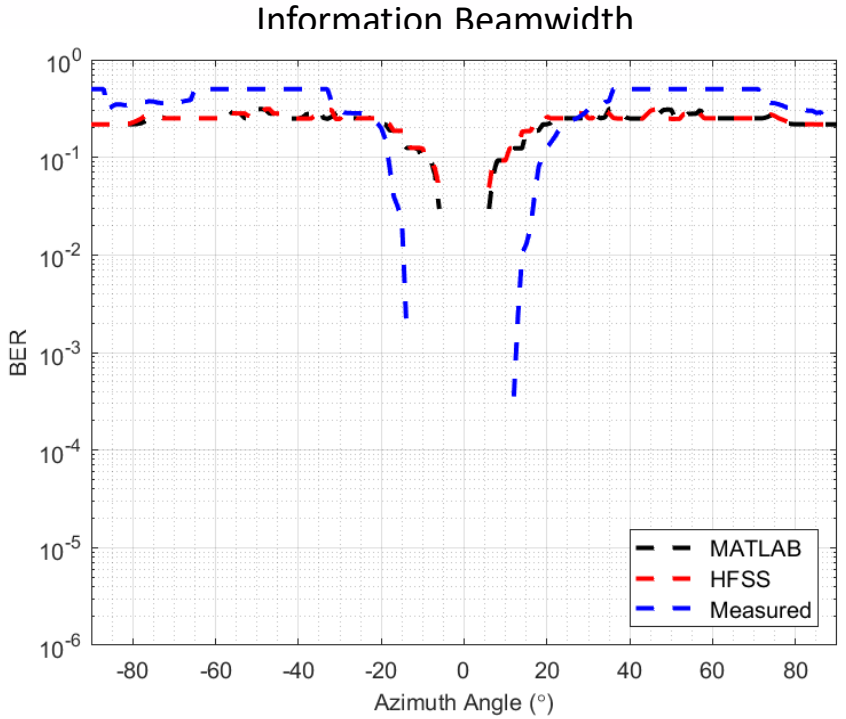




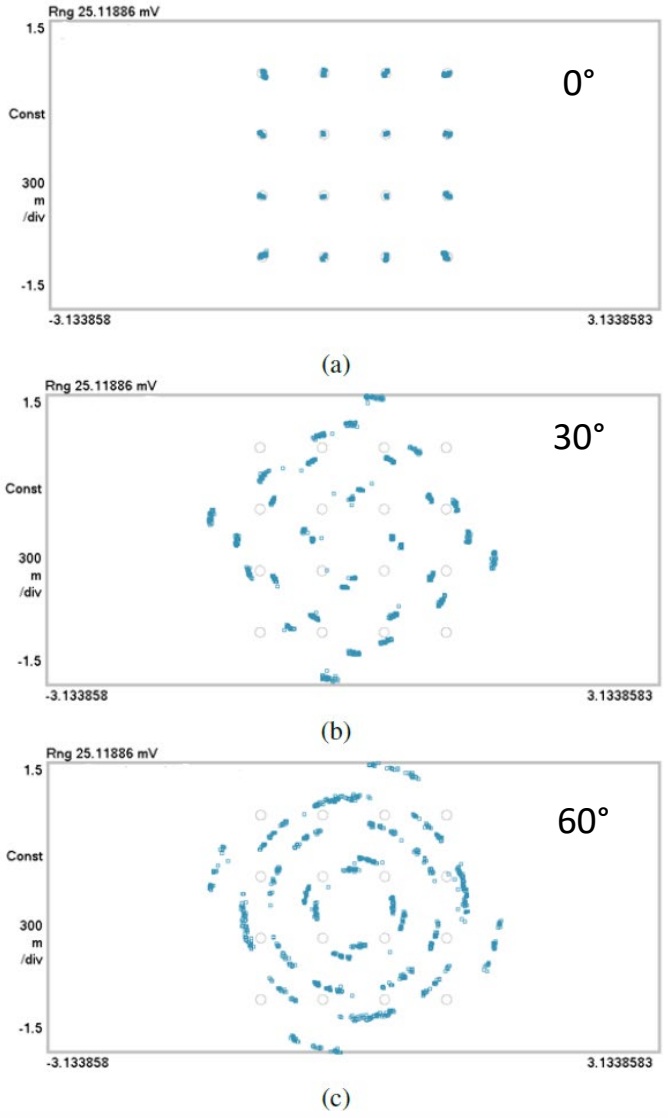
Array Dynamics

Dynamic amplitude/phase modulation in subarrays

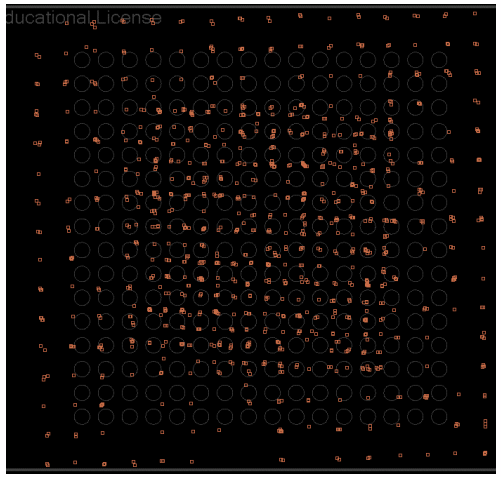


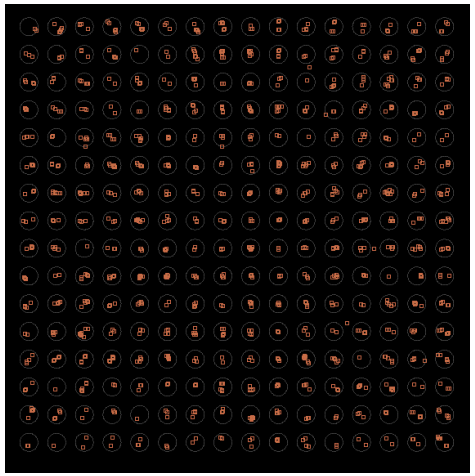


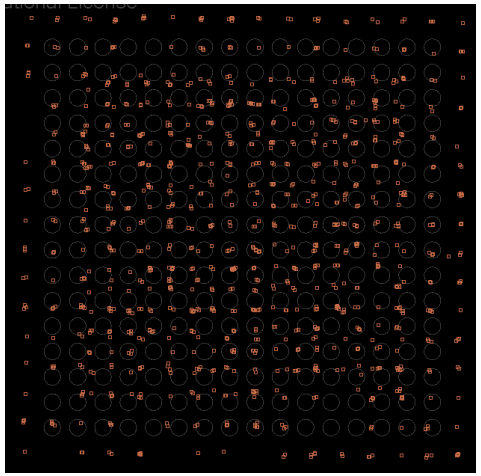
Received data

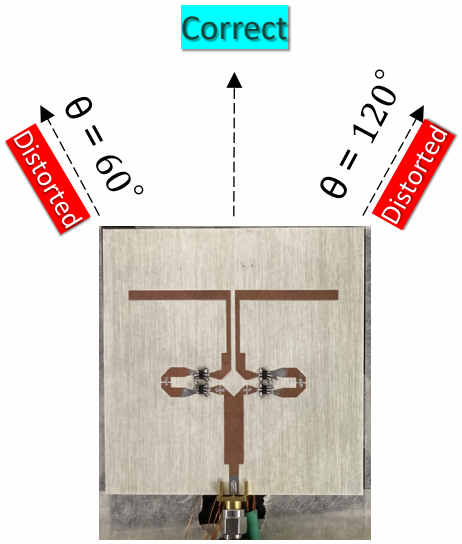


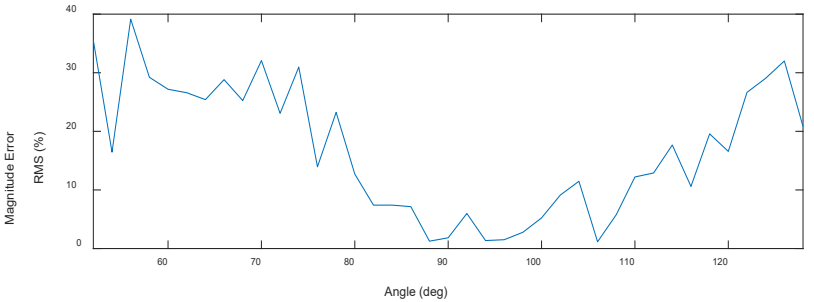
Single-Element Dynamics

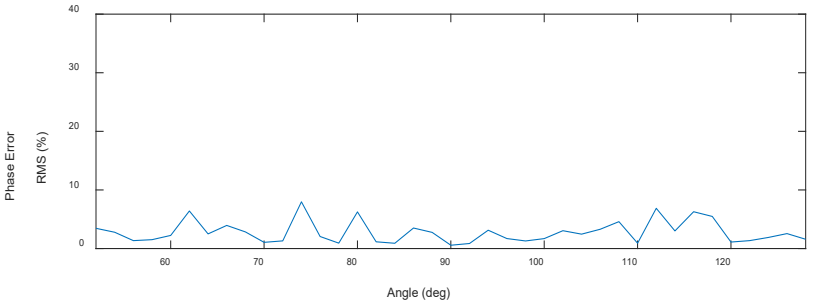


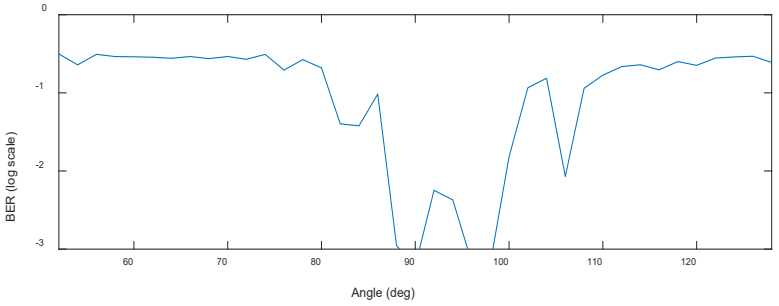












Summary

Microwave and millimeter-wave technologies have been developed to address the most fundamental challenges in coordinating distributed phased arrays

The unique nature of distributed phased arrays leaves possibilities for new measurement techniques and new directions of research