PHYS003

Optimization of Distributed Phased Arrays: A New Approach to Sending High Power Signals

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Background image is the experimental setup (Credit: Author)

Introduction

Phased arrays are an "inexpensive and efficient” [i] solution to beamsteer signals. Used in satellites and missiles, they are now being used in newer technologies such as 5G Cellular Communications

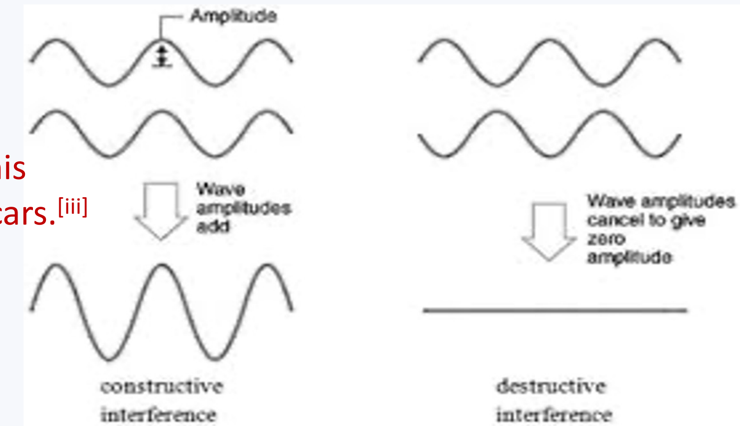
- Phased arrays benefits: increased signal strength (gain), directivity, interference minimization, and signal steerability[ii]
- 5G (millimeter wave transmission) needs line-of-sight to achieve high power and directivity

PROBLEM: As the size of a phased array increases, a necessity to increase power, the system becomes very expensive and inflexible. Distributed phased arrays can solve this problem, a critical requirement for newer technologies such as 5G and autonomous cars.[iii]

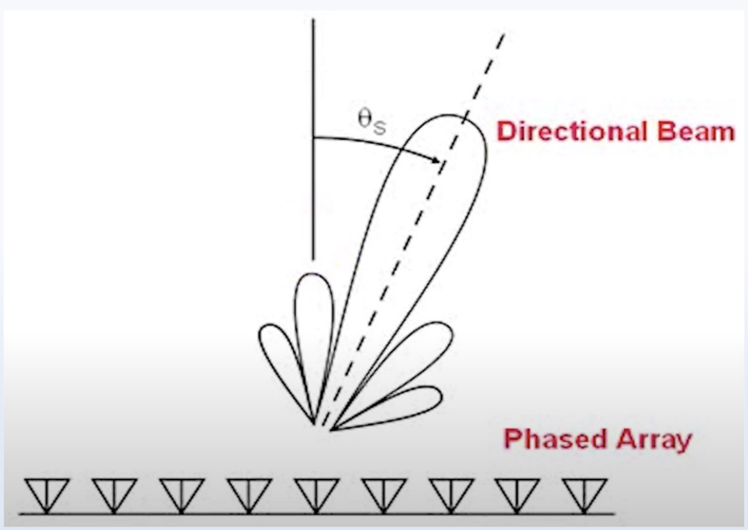
This project investigates novel optimization for phased arrays on 3D surfaces in 3 parts:

- **Mathematically Derive** Calibration Equations for Both Frequency and Phase
- Write **original code** for Matlab Simulations to validate calibration equations
- Build **Software Defined Physical Hardware model** to verify derivations and simulation models

Self-Developed CAD Model of a Drone with Phased Array Transceivers. Credit: Me



Interference figures. Credit: Alan Fenn, MIT Lincoln Labs, 2018



Directional beam of a phased array. Credit: Alan Fenn, MIT Lincoln Labs, 2018

- Phased Array Antennas use **wave coherency** to maximize signal power and direct beams in specific directions
- Phase direction is determined by specifying the **azimuth and elevation angle**
- A signal source is split into **N array elements** with each path having its own phase shifter to manipulate the phase of each element
- A **directional beam** is then formed with optimized phase settings
- Only applied to phased arrays with a **single oscillator**
- As the system increases in size, the cost drastically increases and becomes very **inflexible** [iv]
- **No current equations for frequency calibrations** (something required when having independent systems)

Methods Part 1 and 2: Calibrations

Calibration Equation

$$f = \frac{c}{\lambda}$$

$$t = \frac{d}{c}$$

$$y_1(x,t) = A\sin\left(2\pi \frac{c}{\lambda_1}\frac{d}{c}\right)$$

$$y_1(x,t) = A\sin\left(2\pi \frac{d}{\lambda_1}\right)$$

$$\phi_1 = 2\pi \frac{d}{\lambda_1}$$

$$\phi_2 = 2\pi \frac{d}{\lambda_2}$$

$$\Delta\phi = \phi_2 - \phi_1$$

$$\Delta\phi = 2\pi \frac{d}{\lambda_2} - 2\pi \frac{d}{\lambda_1}$$

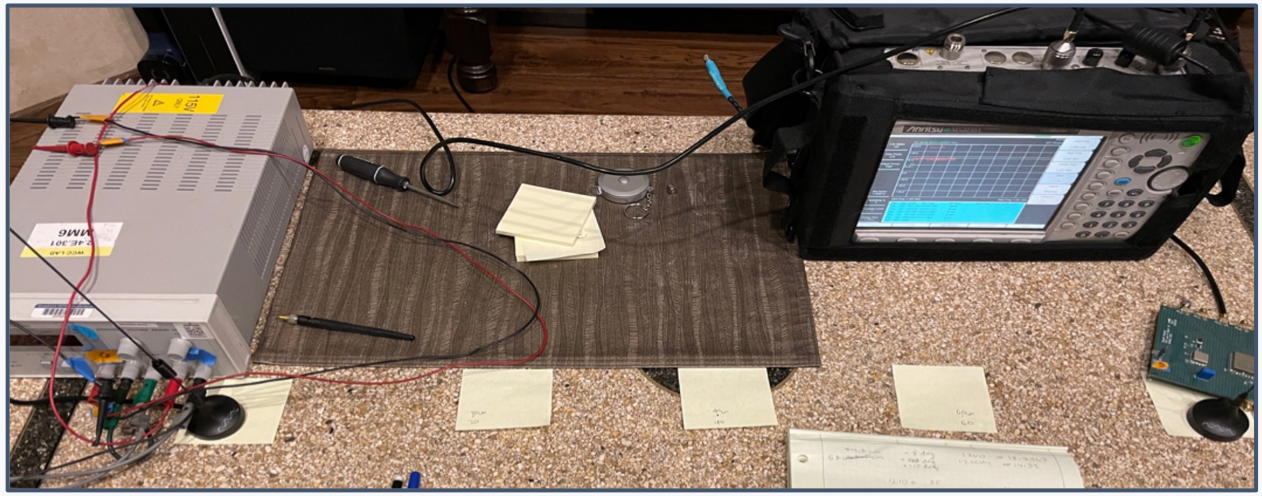
$$\Delta\phi = 2\pi d\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)$$

$$\Delta\phi = 2\pi d\left(\frac{\lambda_1 - \lambda_2}{\lambda_1\lambda_2}\right)$$

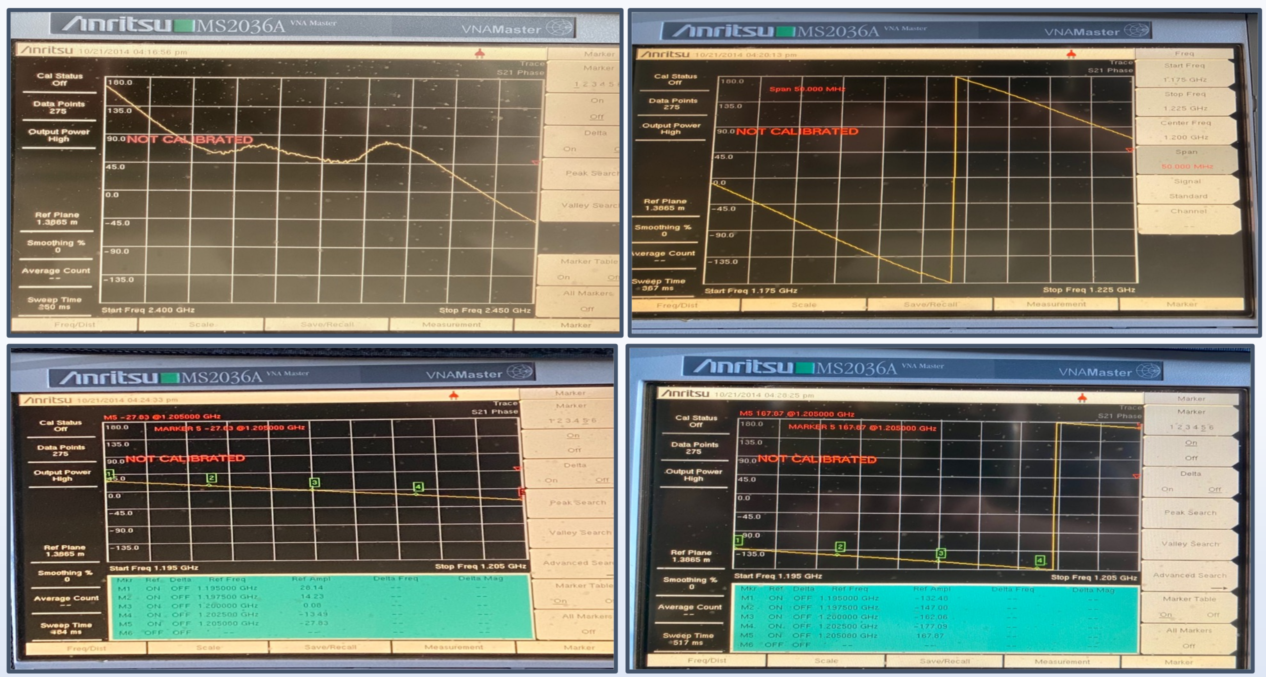
$$d = \frac{\Delta\phi}{2\pi}\left(\frac{\lambda_1\lambda_2}{\lambda_1 - \lambda_2}\right)$$

$$\boldsymbol{\Delta\varphi = \frac{\Delta\phi}{\lambda}\left(\frac{\lambda_1\lambda_2}{\lambda_1 - \lambda_2}\right)}$$

Calibration Testing

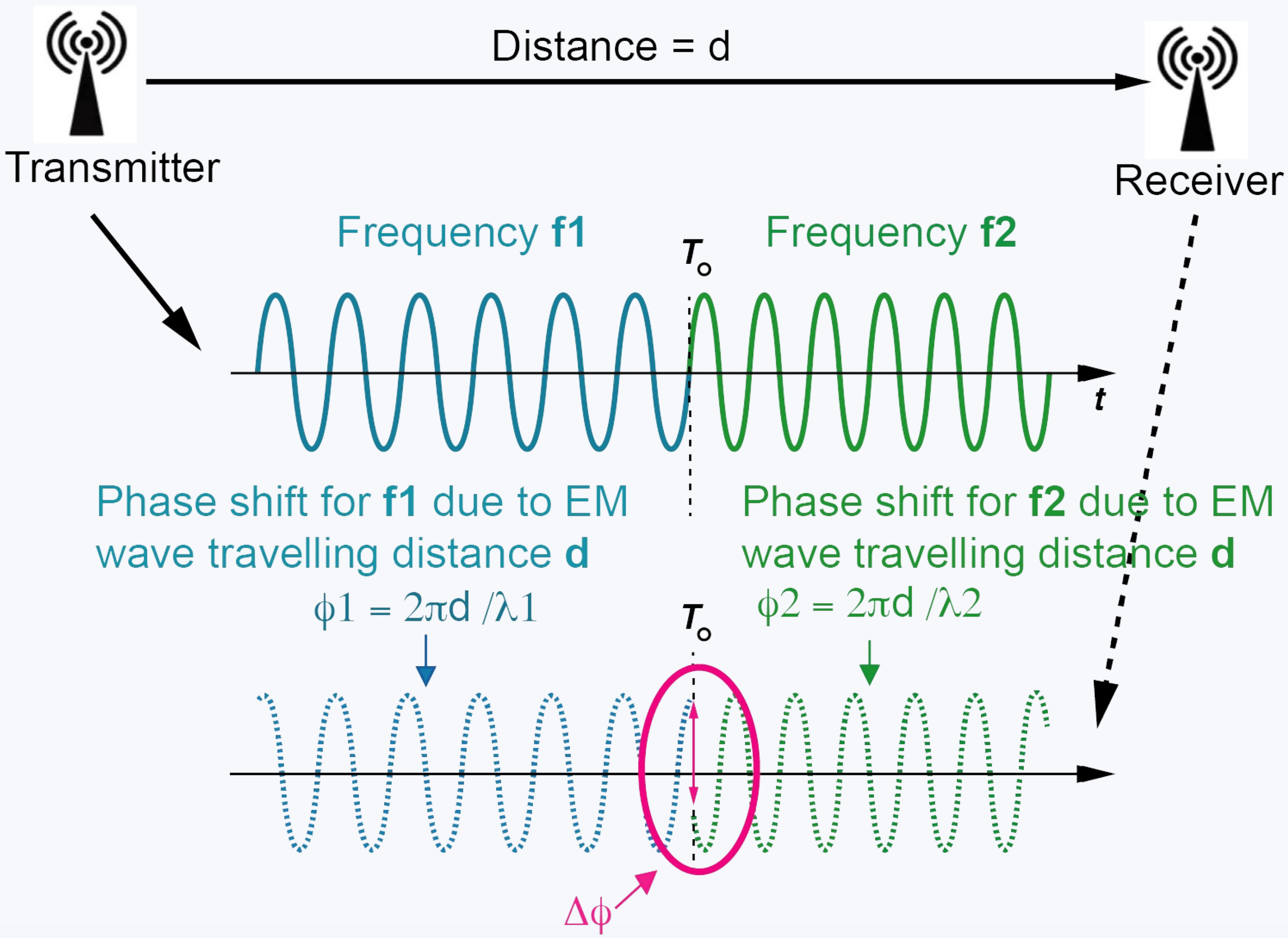


Calibration Setup. Credit: Author



Calibration Data. Credit: Author

Methods: Application of Theory



$$d = \frac{\Delta\phi}{2\pi}\left(\frac{\lambda_1\lambda_2}{\lambda_1 - \lambda_2}\right)$$

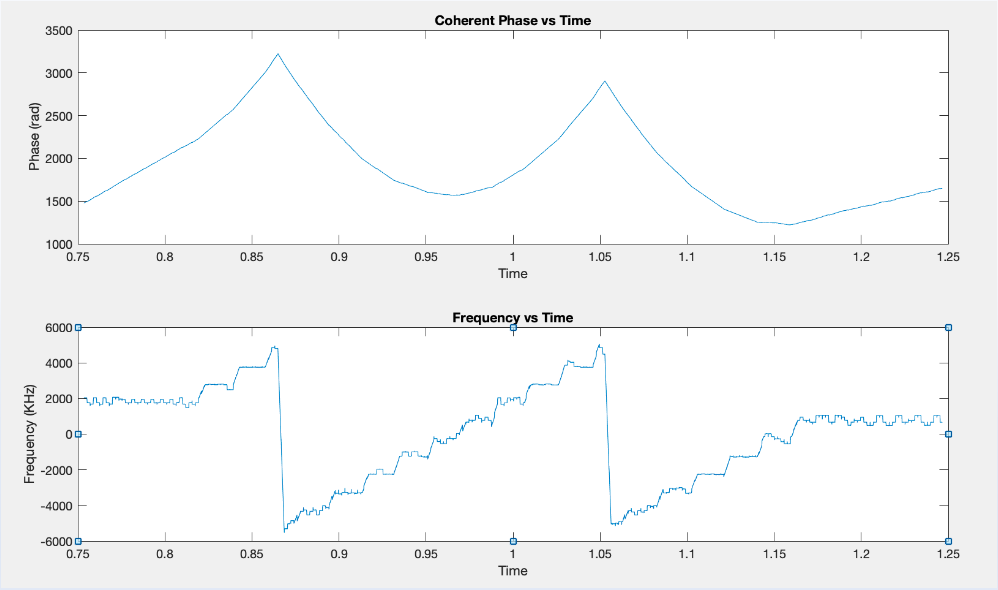
Phase Coherency Visualization. Credit: Author.

- To estimate the distance based on phased offsets, both the **transmitter and the receiver must have phase coherency**
- The phase delta in the receiver when **transitioning from one frequency to another** helps estimate the distance between the transmitter and receiver
- Based on differences in phase for the different frequencies, the **distance can be calculated**

Results Part 1 and 2: Calibrations

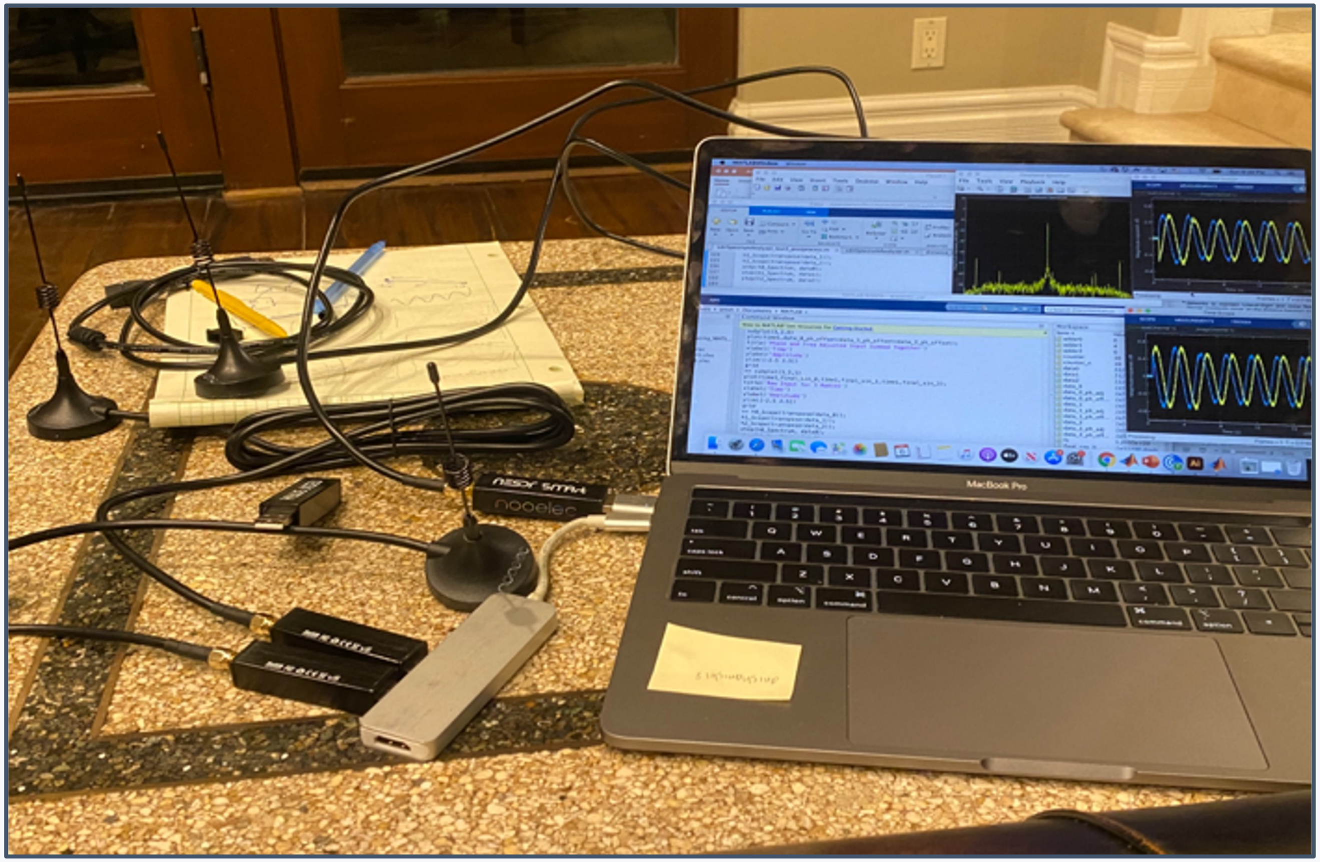
Actual Distance (m)	Phase @ 1210 MHz (deg)	Phase @ 1215 MHz (deg)	Phase @ 1220 MHz (deg)	Phase @ 1225 MHz (deg)	Phase @ 1230 MHz (deg)	Calculated Distance (m)	Percent Off (%)
4.62	-50.768	-82.735	-105.208	-137.147	-162.474	4.6312	-0.242%
4.72	159.79	133.776	106.698	76.199	49.82	4.6149	2.227%
4.92	-121.592	-159.468	172.592	142.078	116.214	5.0512	-2.667%
5.22	157.447	118.744	91.328	63.255	28.01	5.2614	-0.793%
5.62	-70.515	-98.696	-134.118	-171.817	161.628	5.4513	3.002%

- 4.52 meters was added to the actual distance to account for wire distance
- A **chi-square analysis** resulted in a p-value of 0.952
- With **99% certainty**, the distribution of calculated distances matches the distribution of actual distances
- Phase is coherent corresponding to time



Phase and Frequency vs Time. Credit: Author

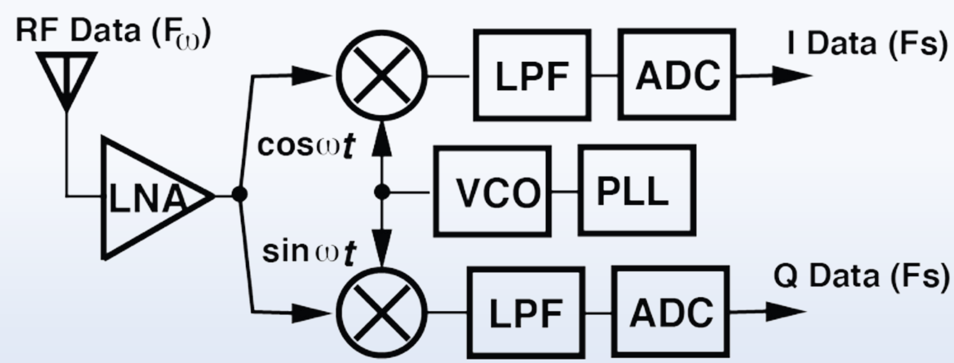
Methods Part 3: Hardware Prototype



1. Antenna **reads in signal** from Software Defined Radio
2. **MatLab program** displays wave
3. Original MatLab code **calibrates for frequency**
4. Original MatLab code **callibrates for phase**
5. **Final wave** is outputted

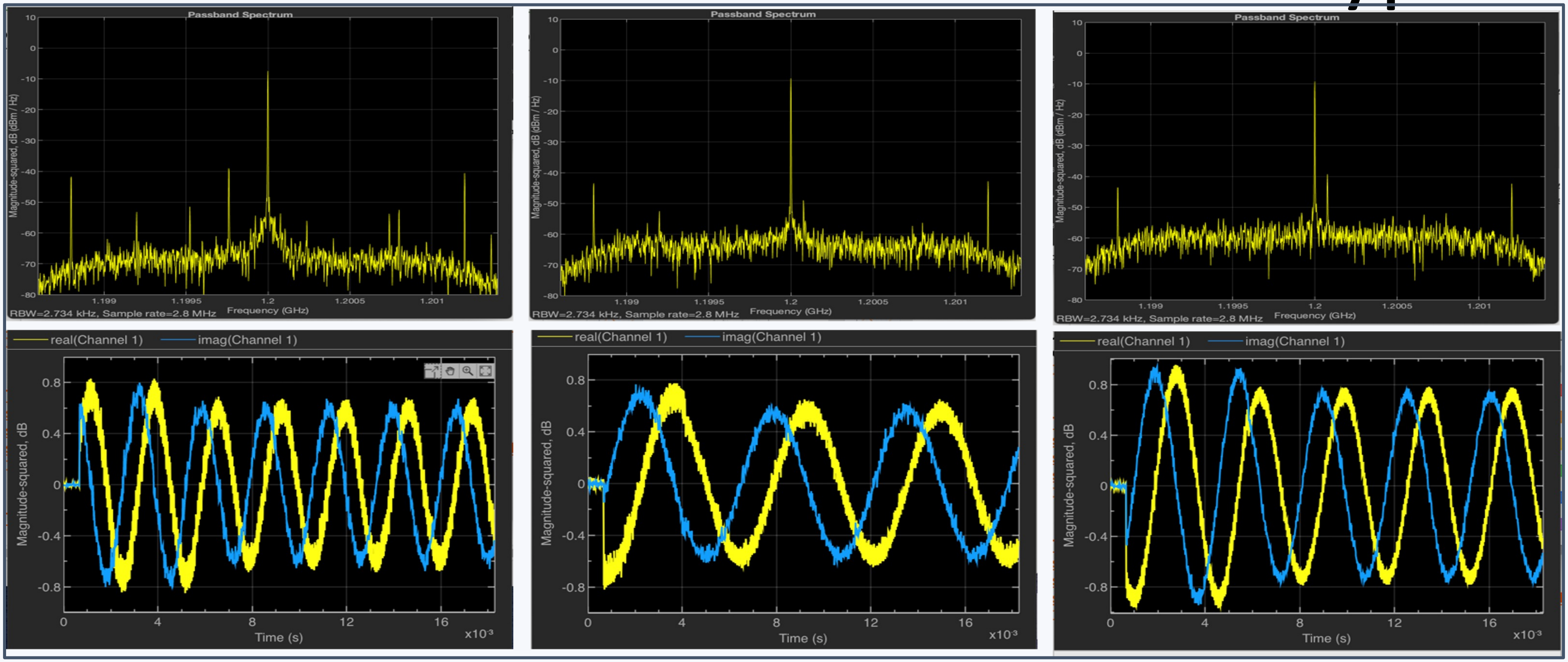
Experimental Setup with 3 software defined radios connected to a computer. Credit: Author

1. Transmitter **tuned at 1.2 GHz**
2. Each of the 3 antenna collects **independent** signals
3. **Down convert** signal by mixing with a 1.200001000 GHz signal -> results in a 1 kHz signal which is easier to manage
4. **Read wave at 2.8 MHz** so the final frequency window is 1.2 GHz $\pm$ 1.4 MHz



Software Defined Radio. Credit: Author

Results Part 3- Hardware Prototype



Frequency Spectrum and Wave Plot of each of the 3 Software Defined Radios. Credit: Author.

- Neither the frequency nor the phase of the signals are correlated
- Signals were **collected via 3 SDRs** and **visualized via Spectrum Analyzer and Timescope in MatLab programs**

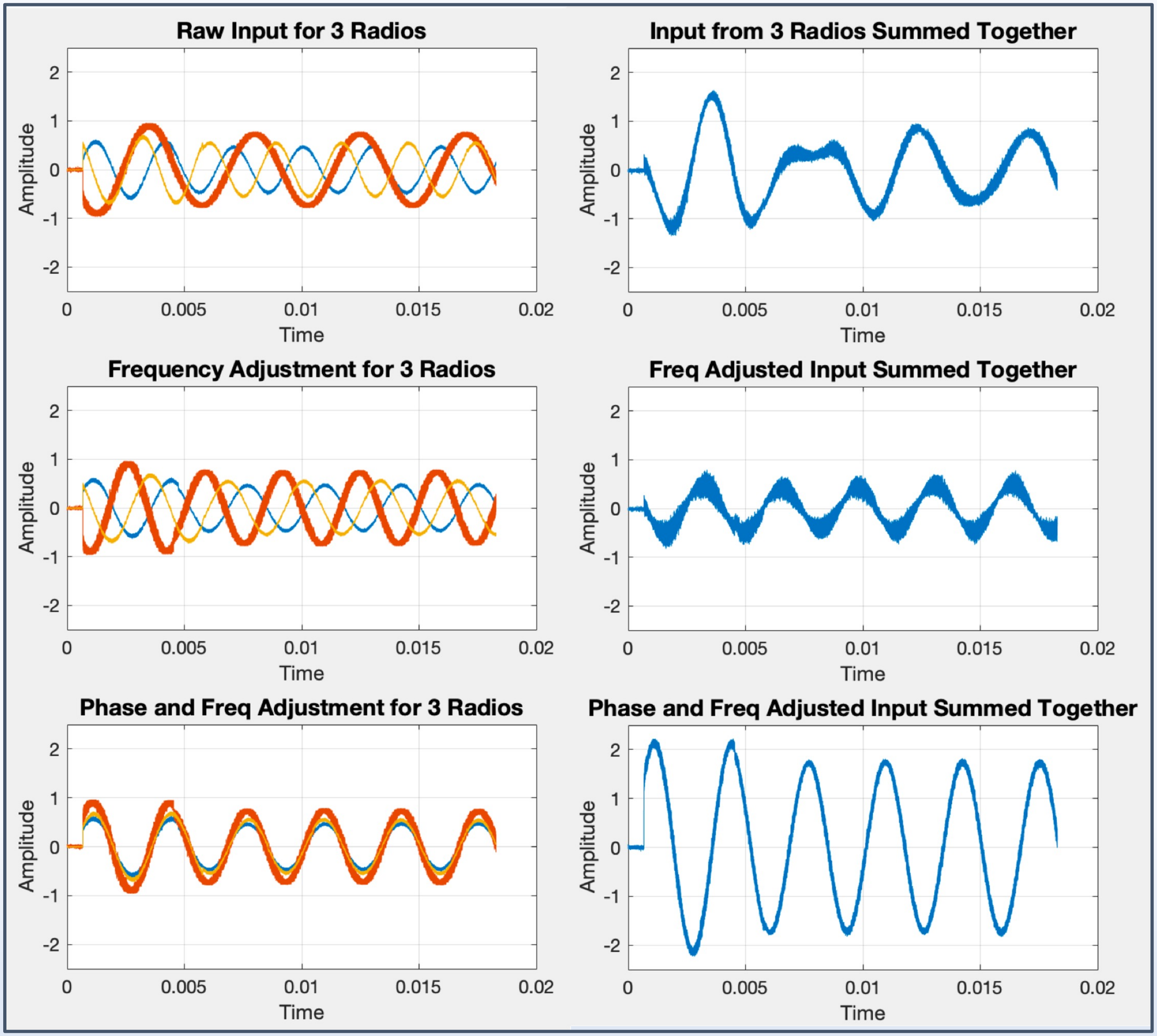
Phase Calibration

- Used the equation derived in the project to find unknown distance
- Distance and phase offset are **directly correlated**

Frequency Calibration

- Instead of collecting amplitude vs time, collect **phase vs time**
- Sample each wave at different rates to ensure data matches

Results Part 3- Power



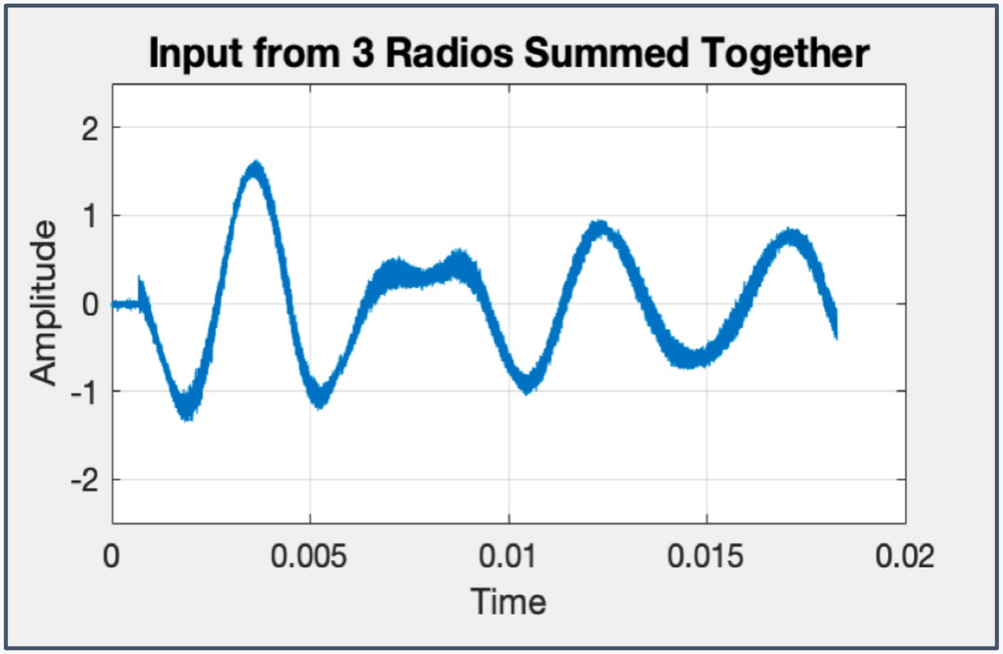
Phase and Frequency Adjustments of Waves. Credit: Author.

- The final power was approximately **6dB greater** than if the waves were summed randomly
  - Equivalent to 4 times as much power
- Calibrations are completed via a **header wave**
  - Receiver knows when to start reading data
  - This waves are already sent to receivers when searching for signals
  - Therefore, there is very minimal additional time delay for distributed phased arrays

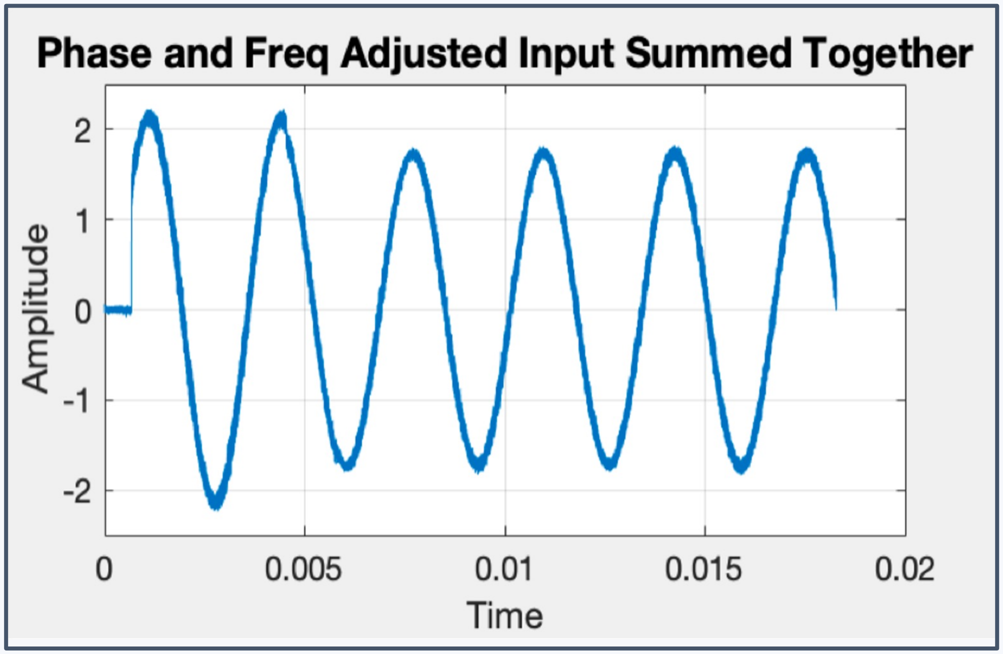
Discussion

Hardware implementation matches Theory

- Newly derived correlation equations correlate with the MatLab simulation and hardware test results—which was amazing to see ☺
- Newly calibration equations allow for **more accurate beam steering with higher power**



Initial Wave. Credit: Author.



Final Wave. Credit: Author.

Sources of Error

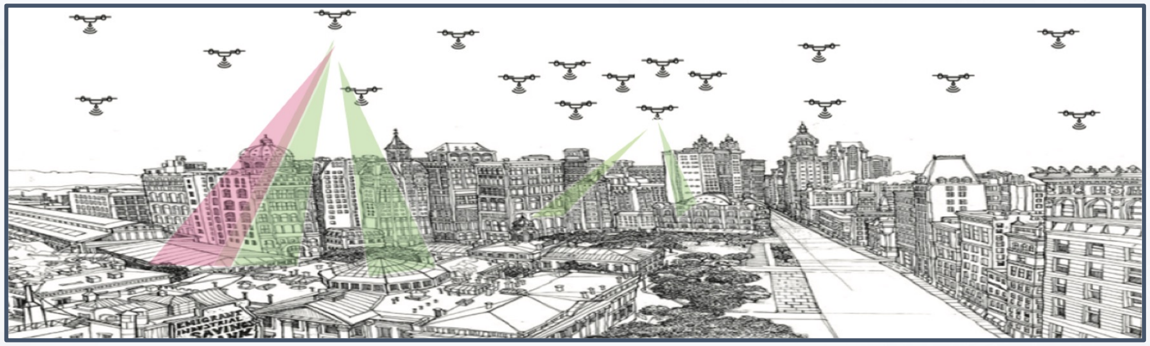
- Interference was minimized by **using a frequency of 1.2 GHz** -> no electronics use this frequency as it is periodic and would consequently interfere with 2.4 GHz
- Multipath was minimized by placing the system in the middle of a room -> **power decreases proportionally to** $\frac{1}{d^2}$ so the extra distance limits the noise
- The final wave is very sinusoidal so **error was minimized** in the project

Conclusions

Key applications for distributed phased arrays

- Distance from antenna to receiver can remain unknown → easier to **send signals to moving objects**
- Multiple systems of phased arrays can now synchronize
  - Necessary when using multiple drones for **5G communication networks**

5G Cellular Communication System Using Drones to Send Signals. Credit: Author.



Future Research

- This approach can open opportunities for studying and optimizing future adaptive and **AI based beam steering algorithms** for moving devices (people on the move)

Key Benefits

- More generalizable -> distance does not need to be known beforehand
- More flexible -> software based rather than hardware based
- More cost-effective -> Cost reduced from $480 to $90 [v]

References

[i] Ehyaie, D. (2011). *Novel Approaches to the Design of Phased Array Antennas.* Deepblue.lib.umich.edu. https://deepblue.lib.umich.edu/handle/2027.42/89713

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