Student Name: Akash Anand

Title: Optimization of Distributed Phased Array Antenna Systems

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Introduction

Today's era greatly relies on wireless communications. From everyday objects such as mobile phones to massive rockets, almost all technology incorporates wireless technology and wireless communications—" The transmission of data or information from one place to another wirelessly" (TypesNUses 2019). Wireless communication allows for the almost instant transfer of information. Moreover, this communication can send signals hundreds of kilometers away. User interfaces have made the transfer of these signals very convenient, allowing "anyone to use them, wherever they may be" (TutorialsPoint 2020). However, as more and more technology enters our lives, people must find ways to continually improve wireless communications.

To send data in signals, wireless communications utilize modulation as shown in Figure 1a and Figure 1b. Specifically, the data transfer begins with an information signal with frequencies ranging over a specific bandwidth. The information signal is then combined with a carrier signal to contain a modulated wave. Modulation enables the signals to travel longer distances because low frequency signals contain too many losses from interferers to be properly demodulated into the original information signal (Gayenden, 2014).

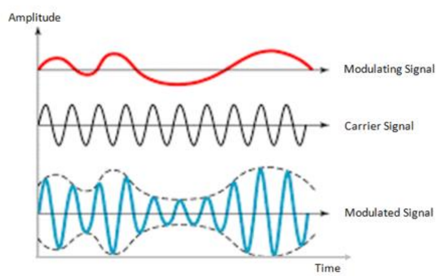

Figure 1a: Modulated Signal. Credit: Sasmita 2015.

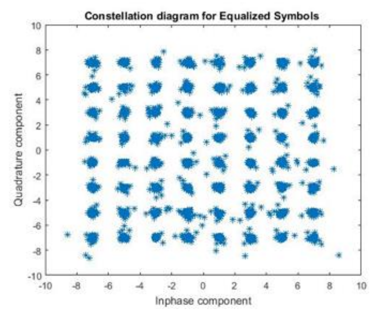

Figure 1b: Data Representation for a Signal. Credit: MATLAB 2015.

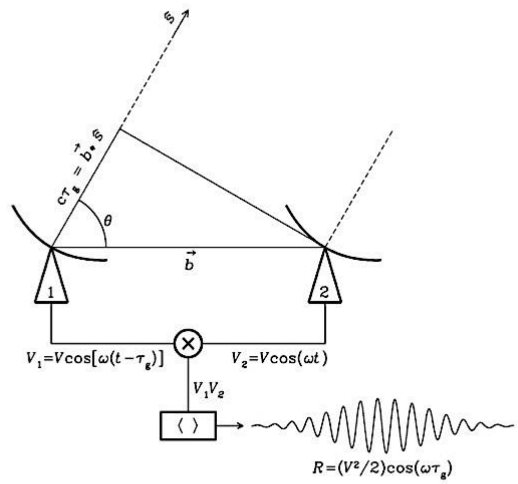

Figure 2: Simple Radio Interferometer. National Radio Astronomy Observatory 2015.

One common way to increase data transfer rates and decrease latency speed (the delay) is through beamforming. Beamforming requires multiple transmitters, which all send the same signal to a receiver. Each signal contains the same information and frequency; however, as each signal must travel a slightly different distance from the transmitter to receiver, they are out of phase with each other. As shown in Figure 2, the signal from receiver 1 must travel a distance $\boldsymbol{b} \cdot \boldsymbol{s}$ longer than the signal from receiver 2.

Phased array antenna systems capitalize on the high data transfer rates obtained by beamforming. There are two ways to incorporate beamforming: having multiple transmitters or having multiple receivers. Although these situations may appear as opposites, they are both incredibly similar and follow the same fundamental beamforming equation:

$AF(\emptyset) = \sum_{m=0}^{M-1} A_m e^{jm\left(\frac{2\pi d}{\lambda}cos\phi+\alpha\right)}$. This equation illustrates “an M-element equally spaced linear array that uses variable amplitude element excitations and phase scanning the array factor” (Dietrich 2000). This equation works for both the transmitter and receiver cases of phased array antenna systems because both scenarios have signals that are off in phase.

The four main benefits that arise from phased array antenna systems consist of “gain”, “directivity”, “interference minimization”, and “steerab[ility]” (Frenzel 2018). Gain is analogous to the amplitude of a signal. It refers to the power that a wave carries and

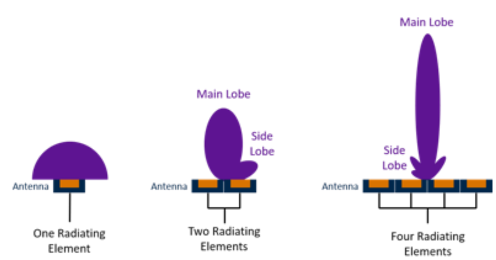

Figure 3: Beamforming of a Signal. Credit: Metaswitch.

" is proportional to the fed-in transmitter power [of each antenna], which can easily be measured on the feed line to the antenna" (Wolff 2016). Because the gain is proportional to "each antenna" (Frenzel 2018), having multiple antennas leads to massive increases in power gains. Although these power gains can also be obtained by having multiple transmitters not in a phased array antenna system, the phased array antenna system also allows for directivity. Directivity means that the signal points in a specific direction rather than emitting data everywhere.

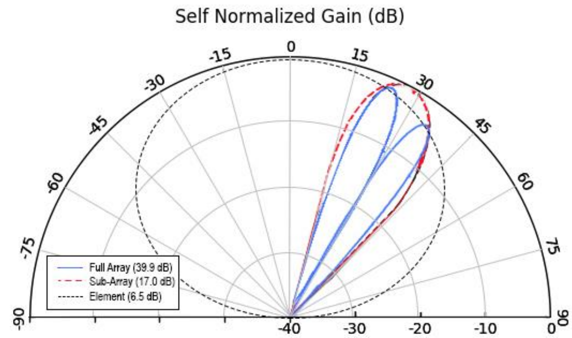

Figure 4: Hybrid Beamforming Beam Visualization. Credit: Corman 2018..

As shown in Figure 4, a phased array antenna system creates a narrow signal that point in a specific direction. Directivity comes with interference minimization. Specifically, as the signal becomes narrower, the signal is focused in a specific direction. Accordingly, interference will be decreased as the signal does not go in all directions. Lastly, phased array antenna systems also allow for steerability as shown in Figure 5 where the signals are focused in specific directions. By changing the phases of each signal, the system will send its signal in different directions. In fact, signals can be focused in every direction solely by changing the phases of individual transmitters. Ultimately, these systems lead to a myriad of benefits for wireless communications.

One crucial application of phased array antenna systems is 5G wireless communication systems. Fifth Generation networks require a direct Line of Sight between the transmitter and receiver as the signals will dissipate if they encounter any interferes such as buildings or trees. However, phased array antenna

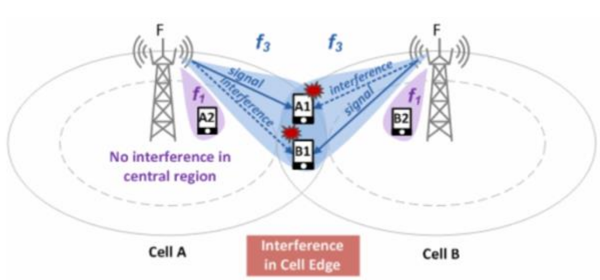

Figure 5: Interference in 4G WCNs. Credit: Do & Sun 2014.

systems allow for directivity, interference minimization, and steerability. Accordingly, transmitter systems can direct their signals specifically towards the Internet of Things devices. This minimizes interference, allowing for a coherent 5G cellular communication system. As shown in Figure 5, if interference was not subsidized by using phased array antenna systems, receivers would not be able to decipher their proper signals.

Due to the various benefits of phased array antenna systems, they are becoming increasingly popular and necessary to keep up with future technology. Already, these systems are used to collect cosmic data and for GPS (Jones 2011). Figure 6 illustrates the Square Kilometer Array (SKA), which is “the world's largest radio telescope [with a goal of] explor[ing] the Universe” (Carbon Creative 2020). The design of radio station phased array systems and GPS phased array systems have one crucial similarity: they are built on 2D surfaces. Current research is perfecting 2D phased array antenna systems. Research has investigated shaping the arrays in a myriad of geometrical shapes and incorporating machine learning for fine optimization.

Figure 6: Square Kilometer Array. Credit: Graham-Smith 2016..

However, depending on the size of the system, a single oscillator on a single platform (as current phased arrays are fabricated) can be very expensive, especially for new technology that requires much power such as 5G and autonomous vehicles. This project investigates a distributed phased array to solve this problem. A distributed phased array uses multiple independent phased array antennas. Each antenna can be set to its own frequency because they use independent oscillators. Moreover, by slightly offsetting the frequencies, it is possible to determine the appropriate phase offset needed for each phase to optimize the power and Half Power Beam Width.

This project will then confirm these results using hardware. Four digital phased array systems using a VCO, RF Amplifier, RF choke, 1-8 Splitter, and 180-degree Phase Shifters will be created. Each of these will alternate in frequency. A phase array design also needs many power sources, resistors, and capacitors. Specifically, the main power source will be the VCO that changes the battery voltage into a wave. The VCO will have a V Tune to control the power output. The signal will then be sent to a RF Amplifier which increases the power by 13 dB. Lastly, the signal will pass through a 1-8 phase splitter in order to separate the signal into 8 terminals. However, this will also result in a power loss of 12 dB. Moreover, the physical model will also be able to illustrate error when making parts by hand.

Methods

This research creates an evolution of phased array antenna systems from a single oscillator to a distributed system. A review of current models and designs of phased array antenna systems found that as the power and size of a phased array increases, the cost exponentially increases. However, majority of real-world technology, such as in 5G communication systems, require high-powered phased arrays. Consequently, this research utilizes distributed phased arrays to cheaply increase the size and power of phased arrays.

To accomplish this goal, the research was broken into 3 stages. First, the project will use E&M wave theory to create a series of equations for frequency changes. Second, the project will then simulate the transmitter layouts on MATLAB. Such simulations verify the accuracy of the novel frequency dependent phased arrays. Surfaces such as squares and circles will be modeled to show consistency among multiple designs. Third, to translate theory into reality, the project will then create a hardware phased array antenna system to physically study the properties of frequency-changing phased arrays.

The first step to optimize phased array antenna systems with frequency changes was to mathematically determine the distance between antennas via small adjustments in the frequency. Using wave theory, this was accomplished by calculating the phase offset at a point based on a small displacement in the frequency. Once the difference in phase is found, that value can be used to find the distance between the receiver and the antennas.

Second, investigation of various antenna array designs was conducted in MATLAB. Original MATLAB code was created to study phased arrays. Variables included in this study include the number of antennas, the distances between the antennas, and the pattern of the array. Several algorithms for combining phased arrays were reviewed and tested. These algorithms consisted of using different weights for each antenna of an array to strengthen the signals in specific directions while reducing noise in the surrounding environment. The total subsystem was optimized to maximize the intensity of the signals of interest.

The code was implemented by first initializing all the necessary variables consisting of the frequency of the wave, the speed of light, the distance between two elements, the pattern of the array, the number of elements, and the angle of interest. Using Euler's equations, the signal as a function of time was estimated. Similarly, the weights were also calculated based on the phase delays of the received signals at each antenna in various two-dimensional patterns. Then, a polar plot was created based on the beamforming gain as a function of the angle of the incoming signal. By digitally manipulating the phase at each antenna, the gain can be steered across each azimuth and elevation angle to be directed to any location. This was completed for two dimensional surfaces and adjusted to accommodate multiple oscillators.

The third part of the project used hardware to create an authentic frequency-changing phased array antenna system. Multiple YouTube videos such as those created by Hunter Scott were viewed in order to learn about the process and components required to build a phased antenna array system. To create any electrical engineering hardware, a thorough hardware design must first be created. This project used three software defined radios connected to a computer with MatLab to generate power graphs.

Finally, one must test the performance of the system. A network analyzer was first used to estimate the initial phase delta between each Phase Shifter. Then, a spectrum analyzer was utilized to obtain frequency distribution plots for the waves. These results were compared to the results obtained through the MATLAB simulation.

Data

Data

In this research, data was collected in three forms: mathematical models, simulation data from Matlab, and experimental data from the distributed phased array. The Matlab simulations illustrate the accuracy of using phase differences to find the appropriate distance of antennas as well as power benefits of distributed phased arrays.

The first step of mathematically describing distributed phased arrays was to model a wave using sinusoidal functions and Euler's equation:

$$x = Ae^{-j2\pi\frac{d}{\lambda}}$$

$$y_1(x,t) = Asin\left(2\pi\left(\frac{x}{\lambda} - ft\right) + \emptyset_1\right)$$

$$y_1(x,t) = Asin(2\pi f_1 t)$$

Then, substitution and wave theory was used to find the appropriate phase difference and distance between antennas:

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

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

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

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

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

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

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

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

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

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

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

Lastly, the model was extended to average multiple frequencies to obtain a more accurate distance measurement:

$$Suppose\ we\ test\ with\ 5\ frequencies\ for\ 2\ nodes: f_1, f_2, f_3, f_4, f_5$$

$$f_i\ corresponds\ with\ \phi_i$$

$$Each\ of\ the\ 10\ pairs\ of\ frequencies\ will\ have\ one\ \Delta\phi$$

$$\Delta\phi = \frac{\left(\sum_{n=1}^{10}\frac{\Delta\phi_n}{2\pi}\left(\frac{\lambda_a\lambda_b}{\lambda_a - \lambda_b}\right)\right)}{10}$$

Following the mathematical theory, a proof-of-concept was completed on MatLab. Using frequencies of 1500, 1501, 1502, 1503, and 1504 MHz and a distance of 30.0 meters, the appropriate phase difference was calculated. To model these number in the real world, a random error of based on the normal distribution with mean 0 and standard deviation 0.1 was added to each phase difference. The following function then calculated the distance:

```
function [d] = d_cal(f, ph)
%UNTITLED4 Summary of this function goes here
%   Detailed explanation goes here
N = size(f, 2);
```

```
PI=3.14159265358979;
c=299792458;

lambda = c./f;

count = 0;
total=0;

for iIdx = 1:N
    for jIdx = iIdx+1:N
        delta_ph = abs(ph(iIdx) - ph(jIdx));
        lambda1 = lambda(iIdx);
        lambda2 = lambda(jIdx);
        total = total + (delta_ph/2/PI)*((lambda1*lambda2)/abs(lambda1-
lambda2));
        count = count + 1;
    end
end

d = total/count;
end




PI=3.14159265358979;
c=299792458;
```

```
N=5;

ph0 = 3.76;
ph1 = .4;
ph2 = .2;
ph3 = .5;
ph4 = .3;

f=[1500e6 1501e6 1502e6 1503e6 1504e6];
lambda = c./f;

d_test1 = 20;
ph_test1 = 2*PI*(d_test1./lambda);
noise = randn(1,N)./15;
ph_noise1 = ph_test1 + noise;
d1 = d_cal(f,ph_noise1)

d_test2 = 25;
ph_test2 = 2*PI*(d_test2./lambda);
noise = randn(1,N)./15;
ph_noise2 = ph_test2 + noise;
d2 = d_cal(f,ph_noise2)


d_test3 = 23;
ph_test3 = 2*PI*(d_test3./lambda);
noise = randn(1,N)./15;
```

```
ph_noise3 = ph_test3 + noise;
d3 = d_cal(f,ph_noise3)


d_test4 = 28;
ph_test4 = 2*PI*(d_test4./lambda);
noise = randn(1,N)./15;
ph_noise4 = ph_test4 + noise;
d4 = d_cal(f,ph_noise4)
```

The actual, exact distance was 30.0 meters. Based on the inputted random error, the program found distances of 31.8480, 30.1802, 28.9894, and 29.4004 meters for the first four trials. After running the program 10 times, the average calculated distance was found to be 29.5422. Similarly, after running the program 100 times, the average calculated distance was found to be 29.92024. Following, the probability rule of large numbers, after 100000 trials, the average calculated distance was found to be 30.0000.

For the hardware, calibration was initially made to find the distance of the wire. This was found to be 4.52. Using this value, it was then possible to find the phase based on the frequency graph. The spectrum analyzer produced the frequency graph.

By inputting the phases in the new equations derived in the project, the distance values were calculated as shown in the following table.

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%**

A statistical analysis was then conducted to find the accuracy of experimentation. With a p value of 0.0012, it was found that there is statistical evidence that the distances found via the new equations matched the actual distance.

After this calibration data, the signal data was acquired using a spectrum analyzer for frequency analysis and a software defined radio for power measurements. These results are shown in the following figures.

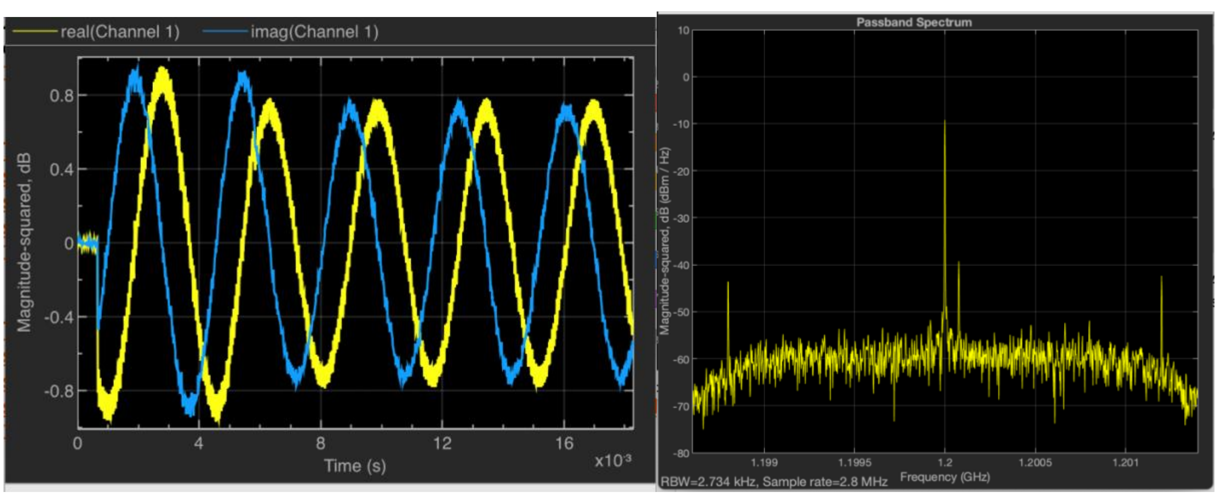

Figure 1: Wave path and frequency of antenna 1

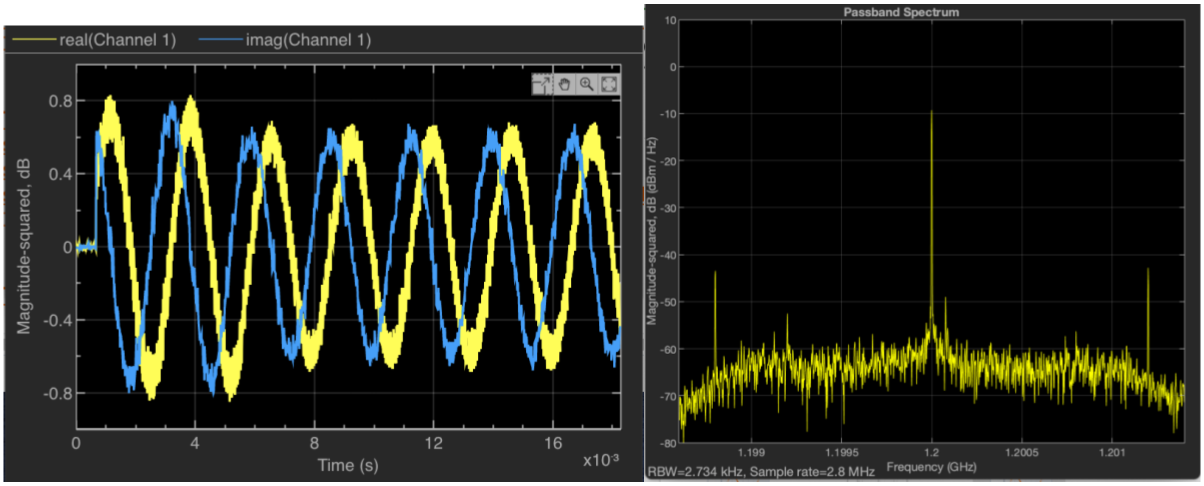

Figure 2: Wave path and frequency of antenna 1

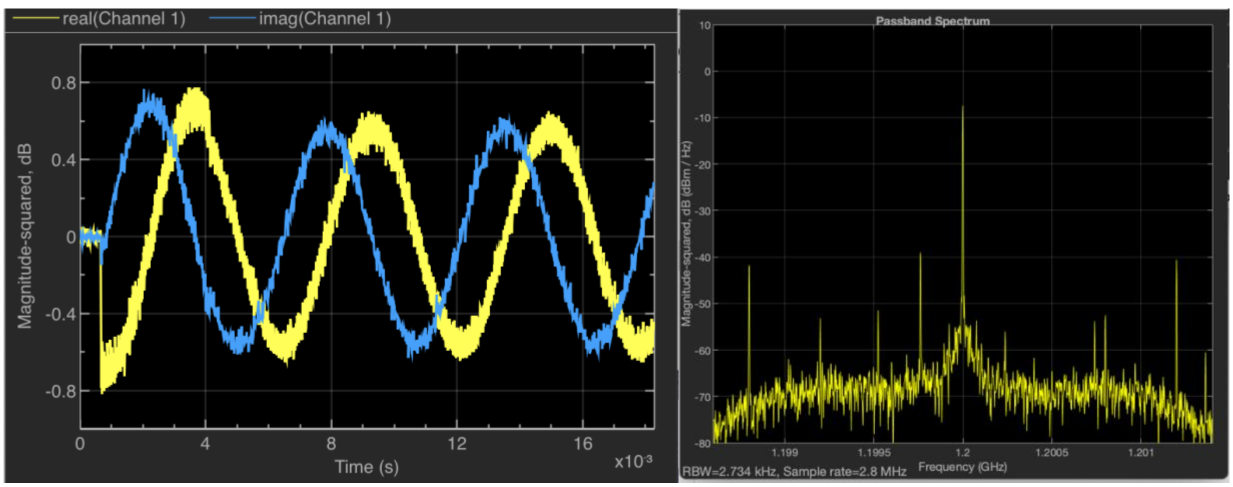

Figure 3: Wave path and frequency of antenna 1

Each frequency and wave plot are different because all of the signals are sent from independent subsystems. These independent subsystems are the main difference between current phased arrays and distributed phased arrays. Further, there is a blue and yellow wave for each subsystem because the software defined radios have two outputs, an imaginary part and a real part. These 3 waves were then added three different ways. They were added without any calibration, with frequency calibration, and with both phase and frequency calibration. The results are displayed below.

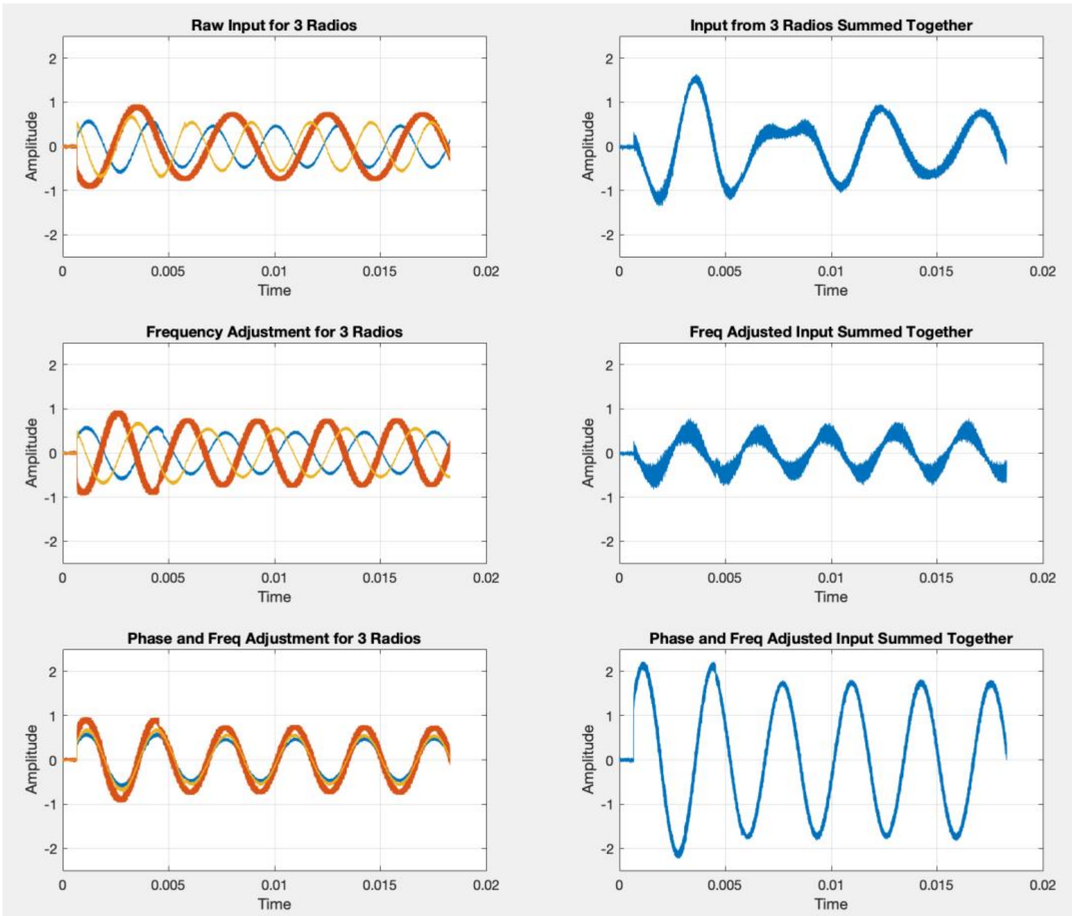

Figure 4: Summations of waves with different calibrations.

It is evident from figure 4 that the power drastically increases when the calibrations are implemented. Specifically, the amplitude of the wave approximately doubles. This corresponds to a 6 dB power gain which is equivalent to 4 times as much power.

Discussion

This research investigates a novel methodology to design distributed phase arrays. Key challenges to such systems that have to be overcome include the individual phase and frequency adjustments required for each distributed node to align the signal at the wave level. Based on the understanding of the wave equations, calibrations for phase adjustment and frequency adjustments were designed and implemented in Matlab. Phase offsets for each node were determined by calculating the distance for each receiver node to the transmitter. By sending a tone at different, close frequency, a phase shift could be calculated and the distance would be determined based on the derivations depicted in the methodology. Several readings are required for averaging as error from interference or multipath can occur. Frequency adjustments were made using a single frequency and measuring the change in phase over a small time period. This calibration signal can be provided before the data is sent so the receiver and transmitter and can align across all the distributed nodes. The frequency of 1200MHz was used since this portion of spectrum was relatively free from interference for the prototype system.

The frequency of 1200 MHz is unique because it is exactly one half of 2.4 GHz. This creates a very special property. Because waves are sinusoidal, a wave of 1200 has exactly a wavelength that is twice as long as that of 2.4 GHz. Accordingly, peaks are aligned in both waves. Therefore 1200 Hz frequency will create interference for the 2.4 GHz range so no devices use this frequency. The difference in noise is shown in the figures below.

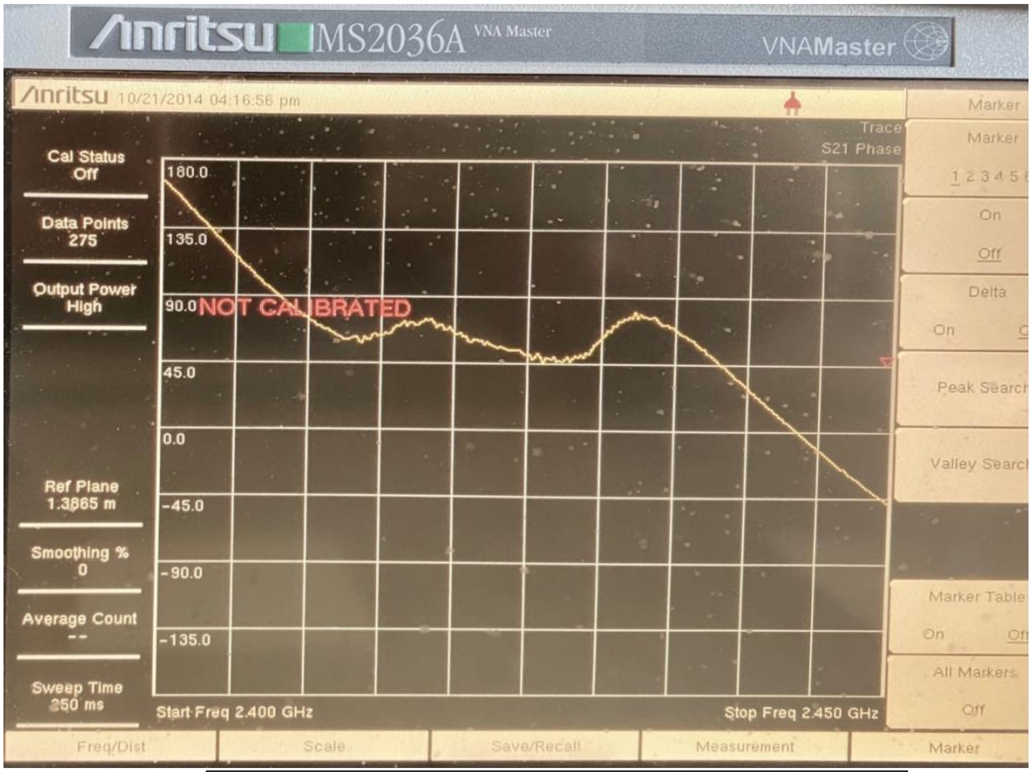

Figure 1: 2.4 GHz wave with interference

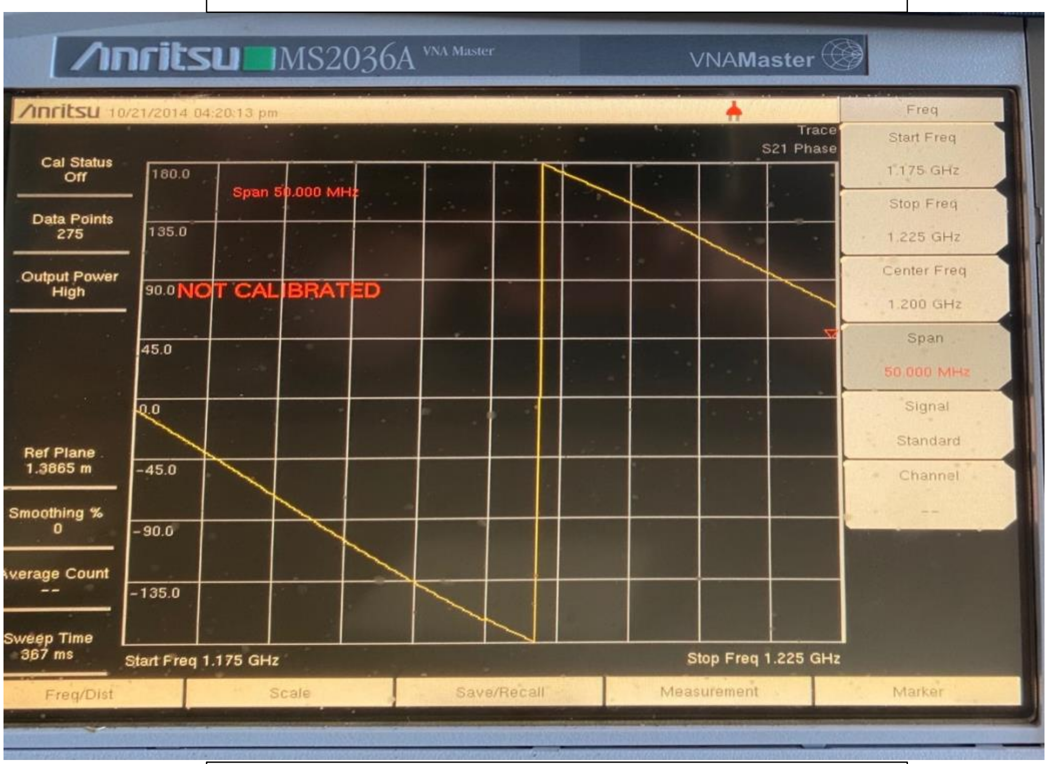

Figure 1: 1.2 GHz wave with minimal interference

The main benefit of a distributed phased array over a typical phased array antenna system is that distances can remain unknown and can change with time. For regular phased arrays, the phase offset is calculated directly for distance. Contrarily, as the transmitter must be known in a distributed phased array, the phase offset and frequency adjustments can be calculated via the novel equations derived in this project. This is extremely important for new research such as 5G cellular communication systems designed that use millimeter waves and need very high gain- typically designed with phased arrays. Current research is attempting to utilize drones for these networks to maintain Line-of-Sight and more flexibility (Fig 10). However, drones constantly move, so the distance between transmitters on the drones and receivers on the ground continually changes. Distributed phased arrays mitigate this problem as they do not need a known distance and allow for drone movement with changing distance.

Distributed phased arrays do have some additional challenges. As the antennas are spaced far away (more than lambda/2 apart), grating lobes appear. A grating lobe is a side lobe with the same magnitude as the desired lobe. This creates additional noise surrounding the larger phased array system. To account for these, current research is developing special software to eliminate these grating lobes. Moreover, distributed phased arrays need extra calibration so specific calibration signals are required before data is transmitted or received. The frequencies and distances must be calibrated for the system to work properly. The newly derived equations in the project provide sufficient calibration to move past this barrier.

The ultimate goal of phased arrays is to provide optimal phase shifts to maximize power for moving systems as efficiently as possible. This project eliminated the need for a known distance in phased arrays and introduced a method to calibrate frequency across several radio subsystems. However, it does not entirely account for moving devices, noise from interferers, and multi-path.

As the wavelengths are very small, minor mathematical errors can negatively impact signal gain. An exciting new step would be using AI to calibrate phase and frequency offsets in signal, based on training and various input of signals that are provided. This new optimization may improve on all sources of errors in a similar manner.

One of the most amazing findings from this project was seeing that the actual phased array hardware I built matched my proof of concept. The prototype verifies that the calibration equations were functional and valid. However, there are small errors, due to machinery discrepancies and possible interference and multipath.

In conclusion, my project paves the path for the widespread deployment of distributed phased arrays. Distributed phased arrays will be used in new technologies like 5G and distance detection in autonomous cars. These systems have three main benefits:

1. This would allow for higher gain which is necessary to send fast data streams and to send data far distances.
2. With these calibration techniques, it is not necessary to know the distance between the antenna and receiver. This is especially important to send signals to moving objects.
3. The generalizable equation and model allows for the next stage of research which is adaptive beamforming algorithms. These algorithms will make it possible to continuously change the angle of the beam which is the next step to send fluent signals to moving objects, like a person walking down a street or a drone overhead.

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