EE 488 COMMUNICATION SYSTEM DESIGN - MIDTERM REPORT

Analog Beam Steering with Codebook Facilitated Feedback for Optimal Beam Pairing

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Abstract – To better observe and compare the effects of optimal beam pairing on signal transmission by designing a protocol using 2x1 USRP devices in conjunction with labview that will facilitate scanning, locking, and readjusting beam pairs through the use of feedback protocols utilizing rudimentary codebook models.

I. INTRODUCTION

The Purpose of this project is to devise a protocol using NI Labview in coordination with 3 or more USRP devices (2Tx:1Rx) with weighted phase shifting at the transmitter side in order to successfully direct a beam in whichever direction is calculated and designated as the current optimal beam pairing angle through feedback from the transmitter. In addition, beam angle correction will be implemented in order to adjust for changes in user end orientation. By accomplishing these goals, we will achieve higher SNR in order to more accurately and effectively conduct QAM Modulated transmission of signals.

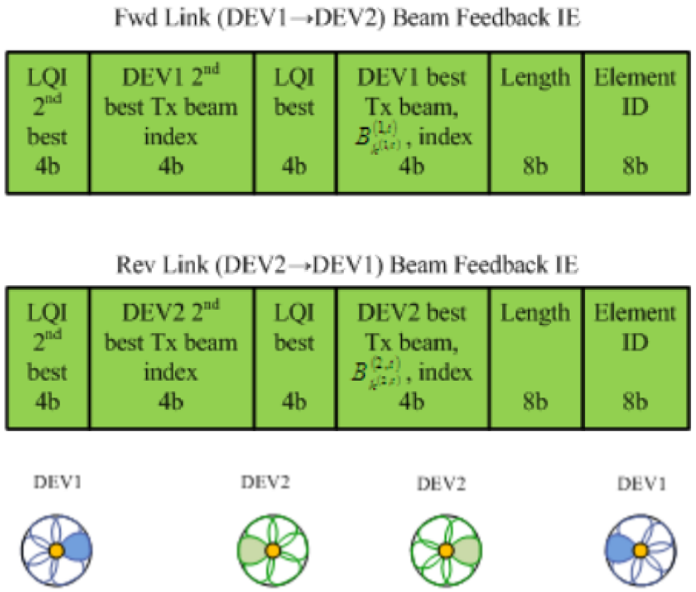
Design Constraints and Engineering Standards

While still in the design and testing phase of this project, it will be difficult to completely align with the current communications standards that are currently in practice. As a result, we can only study and try our best to take loose guidance of the standards wherever we can.

Table 1. Engineering Standards for Beamforming

Standards	**Description**
IEEE 802.11-09	Beamforming Protocols

It is important to note that while the standard previously listed deals with multiple input and multiple output, we can still pull some key ideas into our project when applying these techniques to our own single user protocol. One portion of the standards which will be important for us to study deals with the typical protocol necessary to establish the optimal connection with each receiver end device. It is explained that in the forward link, from device 1 to device 2, the best beam pair is selected. The same protocol is also followed for the reverse link. There also exists specific protocols for feedback



Fwd Link (DEV1→DEV2) Beam Feedback IE

LQI 2nd best 4b	DEV1 2nd best Tx beam index 4b	LQI best 4b	DEV1 best Tx beam, $B^{(1,t)}_{k^{(1,t)}}$, index 4b	Length 8b	Element ID 8b

Rev Link (DEV2→DEV1) Beam Feedback IE

LQI 2nd best 4b	DEV2 2nd best Tx beam index 4b	LQI best 4b	DEV2 best Tx beam, $B^{(2,t)}_{k^{(2,t)}}$, index 4b	Length 8b	Element ID 8b

Figure 1. Engineering Standards for Beam Level Feedback

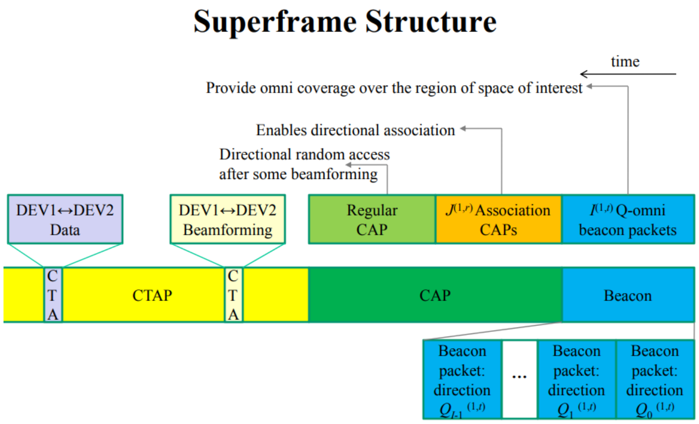


Figure 2. Engineering Standards for Superframe Structure

II. PRELIMINARY SYSTEM DESIGN

a. Hardware

It is necessary to identify that for the purposes of this experiment, RF transmission as well as reception will be carried out with VERT 2450 monopole Antenna which is rated for 2.4 to 2.48 GHz and 4.9 to 5.9 GHz. While most of the calculations will be done in reference to a dipole antenna configuration, it is believed that a monopole can be substituted without much deviance from the dipole far field calculations.

Figure 3: VERT2450 monopole antenna used with USRP device

The USRP-2943R and the USRP-2953 will be the radio models of choice. Transmitters will be hooked up to the Octoclock GPSDO with internal clock mode at 10 MHZ with a PPS trigger. Each transmitting USRP will be connected via two coaxial cables to the previously mentioned outputs.

b. Polarization

One of the many properties of electromagnetic transmission that we must take into account is polarization. Essentially, the plane of propagation is perpendicular to the poles of the antenna. In order to ensure that the most power is received by the receiver, the antennae must generally be parallel to each other. when the plane of propagation is perpendicular, very little to no power is successfully transmitted to the receiver. These properties ca=n be taken advantage of in beamforming.

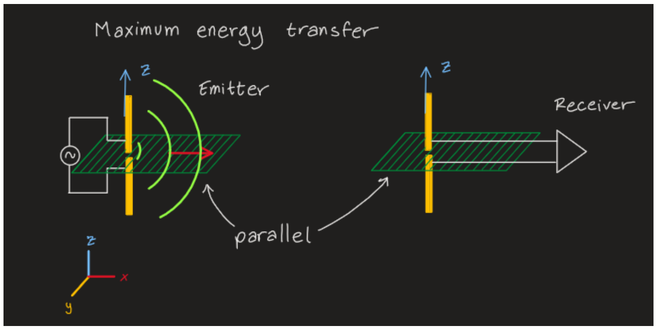


Figure 4: Maximum energy transfer with parallel antenna orientation.

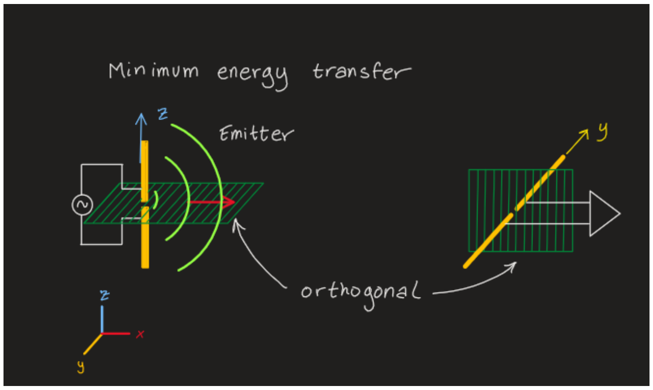


Figure 5: Minimal energy transfer with orthogonal antenna orientation.

c. Monopole vs Dipole

In order confirm that a Monopole behaves similar to a Dipole for the purposes of our far field calculations, we will recall the method of Images which we learned in EE 360 Electromagnetic fields which states that the both the polarization and propagation shape pattern of a monopole antenna mirror that of a dipole antenna. The only difference is that a dipole antenna will typically only propagate a field in the top half above the ground plane wherass a dipole will propagate between the two poles

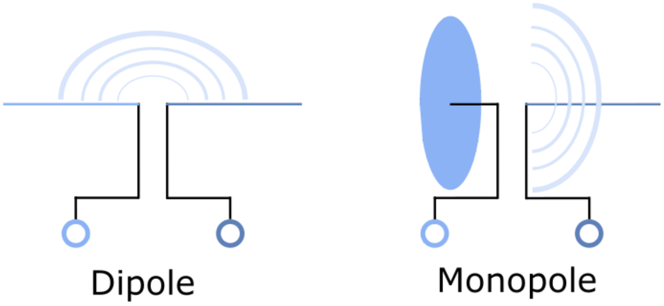


Figure 6: Monopole vs Dipole Antenna

d. Array Factor

In order to calculate the Array Factor needed to control the direction of the beams we must first consider the far field diagram of our configuration.

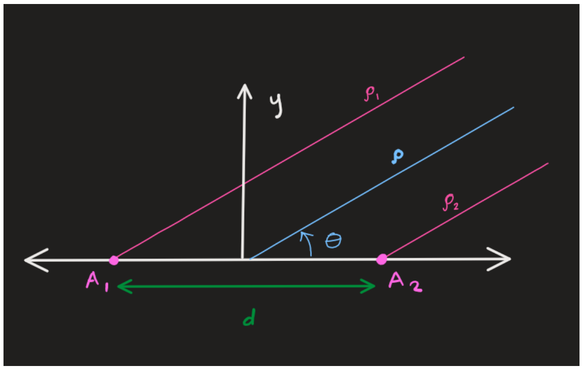


Figure 7: far field plane observed in the x-y plane with the tips of the monopoles reaching out of the page.

After more conditions are met, we are left with the derivation of two monopoles as:

$$\rho_1 \cong \rho + (d/2)\cos\phi$$
$$\rho_2 \cong \rho - (d/2)\cos\phi$$

$$E_\theta = E_0 \frac{e^{-jk\rho_1}}{4\pi\rho} + E_0 \frac{e^{-jk\rho_2}}{4\pi\rho}$$

where:

$$\rho \cong \rho_1 \cong \rho_2$$

Without going too deep into the referenced paper's derivations[4], we are left with an expression for array factor which is a function of phase difference ∝, azimuth φ:

$$A(\theta, \phi) = \left\{2e^{j\alpha/2}\cos\left[\frac{kd\sin\theta\cos\phi+\alpha}{2}\right]\right\}$$

Plugging in d = λ/2, θ = 90 and ∝ = 0, as well as taking into consideration that k = 2π/λ, we get:

$$A(\phi) = \cos[(\pi\cos\varphi)/2]$$

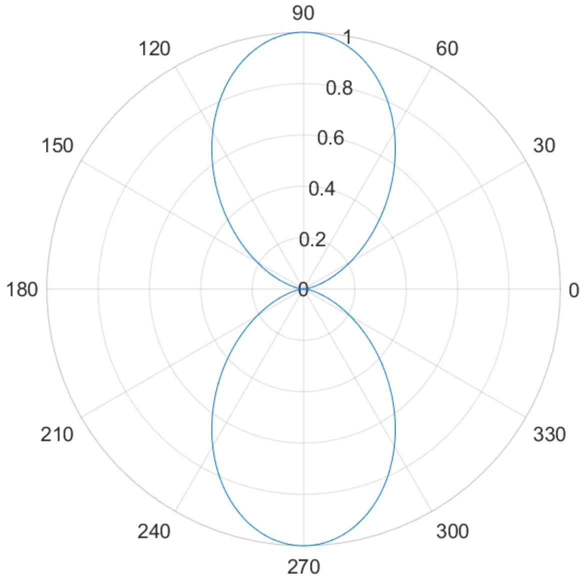


Figure 8: Beam Pattern for d = λ/2 and ∝ = 0. Simulated in matlab.

Plugging in d = λ/2 ,θ = 90, and ∝ = π, we get:

$$A(\phi) = \cos[(\pi\cos\varphi + \pi/2)/2]$$

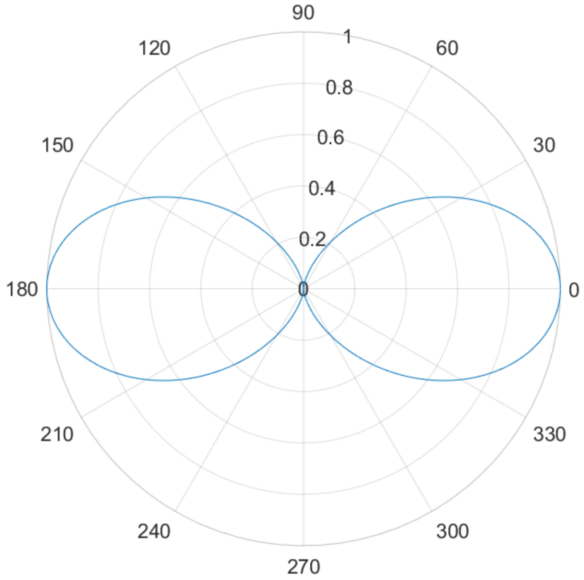


Figure 9: Beam Pattern for d = λ/2 and ∝ = pi/2. Simulated in matlab.

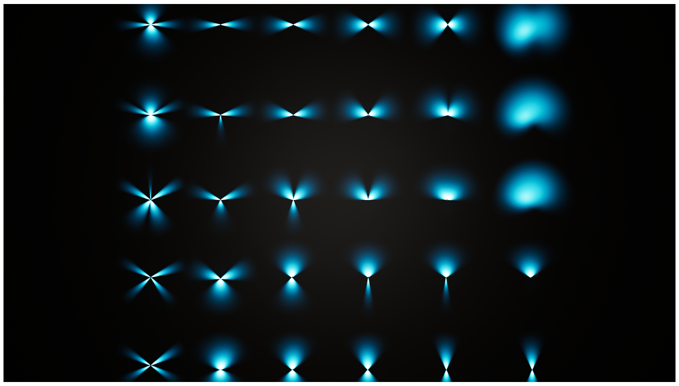
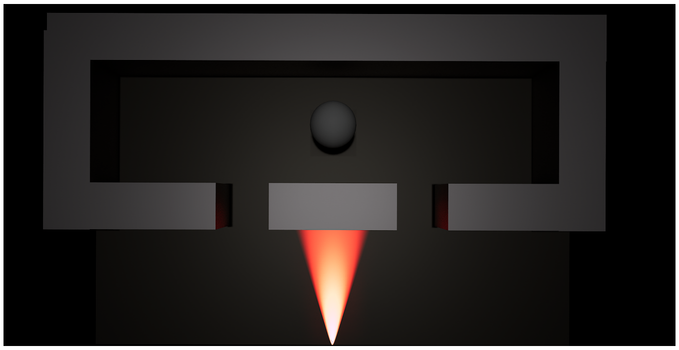
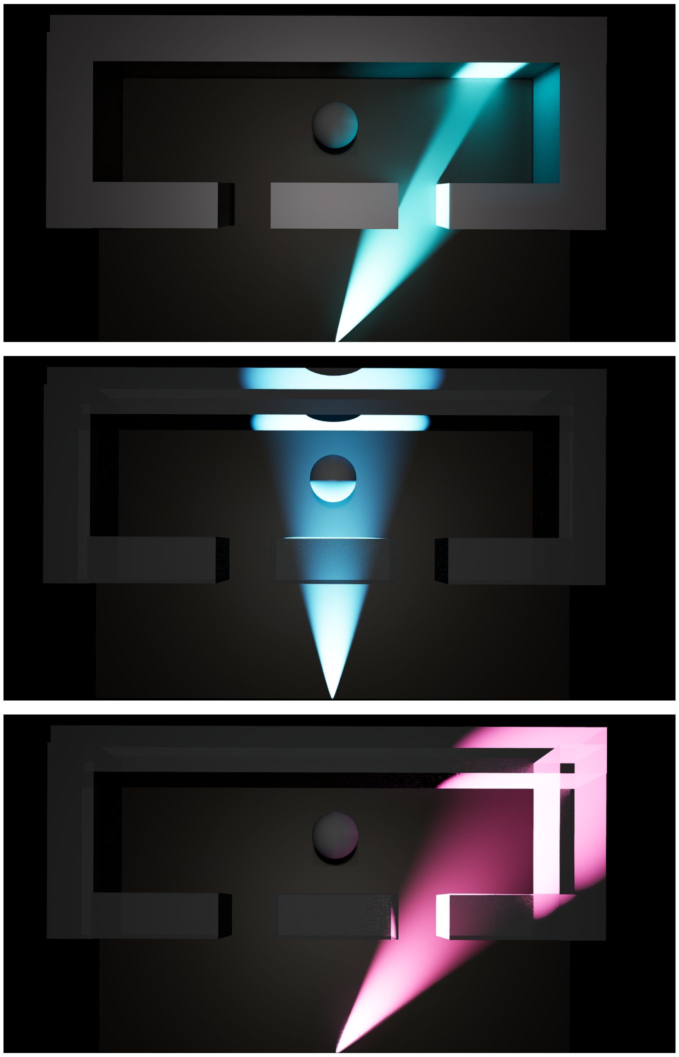


Figure 10: Beam Propagation patterns with respect to phase vs distance/wavelength.

e. Beam Pairing

Beam pairing is an important step of forming the transmission link between a transmitter and receiver. Successfully forming an optimal beam pair link is less straightforward than finding the exact physical position of the user. In some cases where there is an object or wall between the base station and the user, a beam pair may not necessarily be pointing at the user. If the objects relative permittivity is high, the signal for the most part will either be blocked completely or reflected to another path that is not a direct vector from Tx to Rx. One such case is a freeway overpass where metal rebar within a thick concrete structure inhibits the signal from following a straight path to the user. In other cases where the relative permittivity is low such as structures made from wood or drywall, electromagnetic propagation passes right through and you are able to link to the user in one straight path from the base station.





Figures 11.a beam obstruction when hitting an obstacle with high relative permittivity.
11.b optimal beam pairing with non direct path.
11.c optimal beam pairing with direct path through material with lower relative permittivity.
11.d: non-optimal beam pairing with non-direct path through material with lower relative permittivity.

f. Beam Steering (USRP)

Beam steering can be achieved through modifying the phase of the carrier signal right before RF transmission at the antenna. Unlike a multi antenna array with three or more antennae, a phase weight gradient will not have to be implemented in order for a two antenna TX array to work. For our purposes, one antennae will remain in phase while the other separated by phase difference $\propto$.

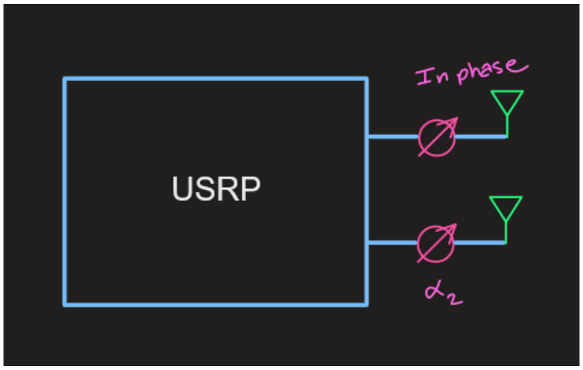


Figure 12: USRP with phase shifter + transmitter configuration for 2 array element beamforming

g. Synchronization of USRP Devices (Labview + USRP)

The two transmitting USRP devices will be configured alongside the Octoclock as shown in the diagram. It will utilize 4 coaxial cables (2 per device) in order to get clock frequency data as well as PPS triggering data. We will be using the octoclock's internal clock for the 10 MHZ reference.

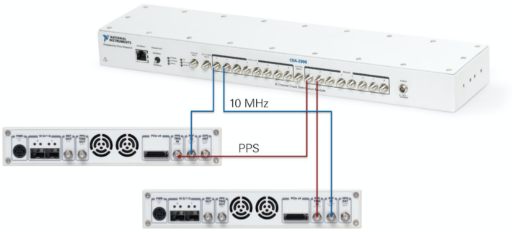


Figure 13: USRP configuration for operation with octolock PPS as well as 10MHZ ref.

(Larger format can be found in appendices)

In order to successfully synchronize the dual Tx devices we will have to configure the USRP devices through labview in a specific configuration.

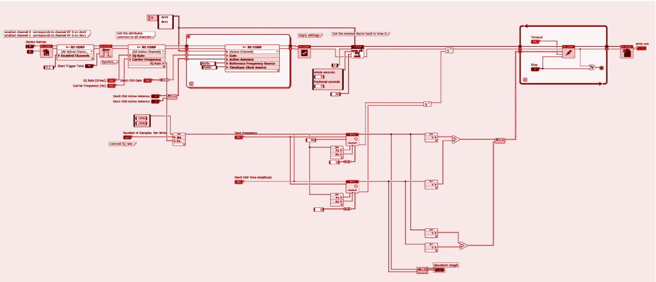


Figure 14: Labview code for synchronizing two USRP devices.

(Larger format can be found in appendices)

h. Essential blocks for Synchronization of USRP Devices (Labview + USRP)

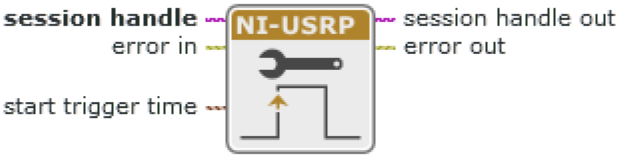


Figure 15: "Labview Configure Time Start Trigger" block for initiating trigger start and generation of the first sample.

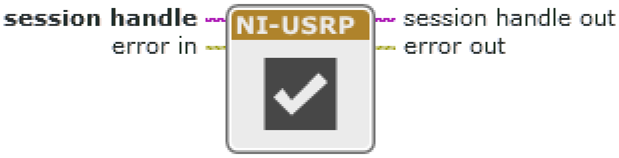


Figure 16: "niUSRP Commit" block for validation of properties to the USRP device.

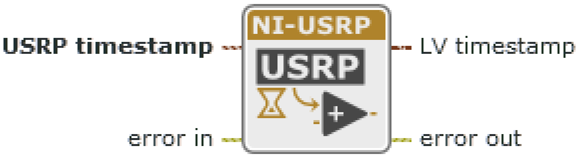


Figure 17: "niUSRP Commit" block for validation of properties to the USRP device.

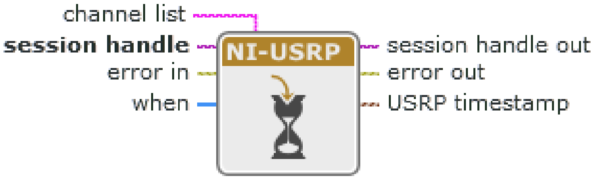


Figure 18: "niUSRP get time" block for getting USRP time of the onboard device timer

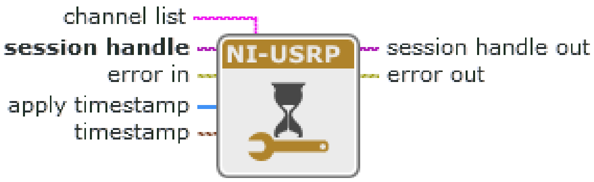


Figure 19: "niUSRP Set Time" block forgetting the time with the onboard timer.

i. Synchronized Dual Carrier Transmit

Using the methods stated above in order to synchronize the devices, we were able to transmit two carrier waves simultaneously over two channels by setting both channel outputs to the carrier waves.

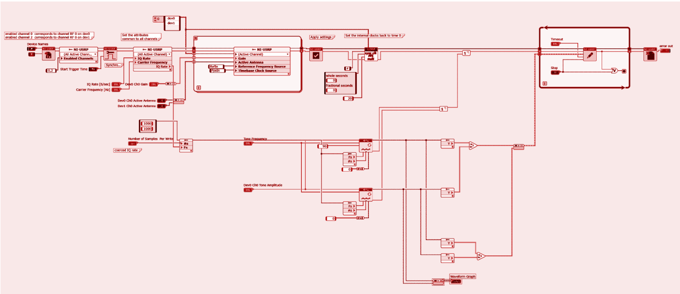


Figure 20: Labview code for synchronizing two USRP devices.

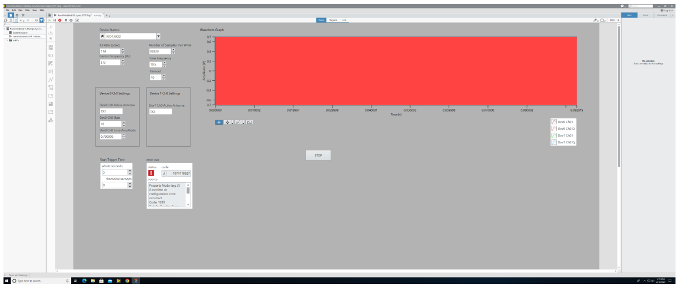


Figure 21: Labview code for synchronizing two USRP devices.

j. Phase Shifter Implementation (Labview + USRP)

In order to implement a user controlled phase shifter for the testing phase, a code was implemented in labview that added a phase shift to both the I and Q channels of the signal. This will be added after the modulation.

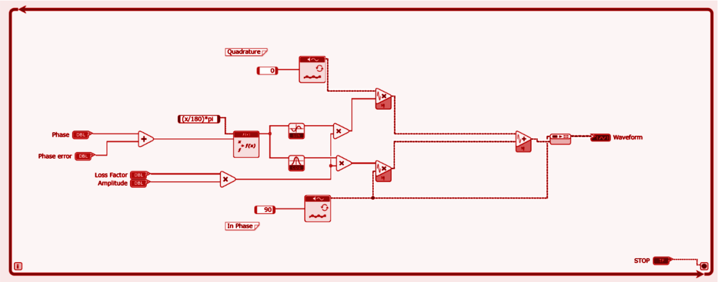


Figure 22: Labview code for phase shifting control.

(Larger format can be found in appendices)

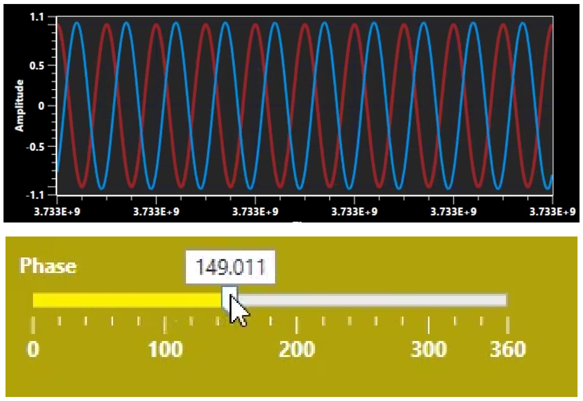


Figure 23: Labview front panel for phase shifting control.

k. 16-QAM Transmission (Tx:1 Rx:1 testing)

Using the Labview QAM transmitter gvi template, we were able to have a single 16-QAM transmission with the following parameters:

Table 2. Parameters for 16-QAM transmission

IQ Sampling Rate:	500k
Carrier Frequency [Hz]:	3G
Samples Per Symbol	4
PN Sequence Order	9
Alpha (Pulse Shaping Filter)	0.5
Filter Length (Pulse Shaping Filter)	6
TX filter	RRC

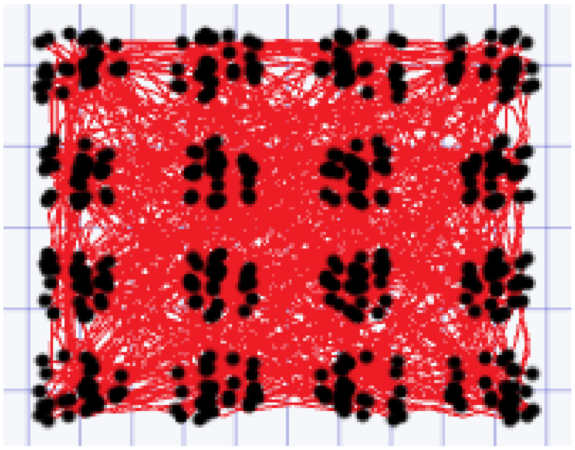


Figure 24: Results of single USRP transmitter.

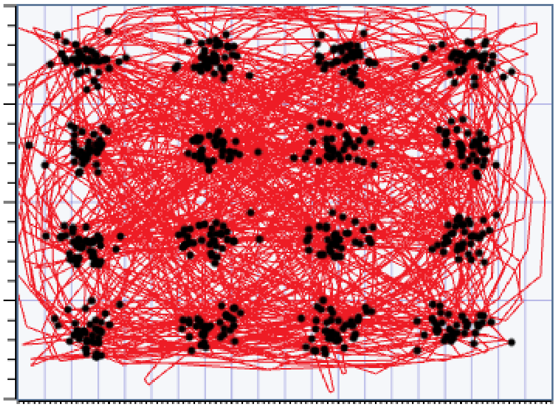


Figure 25: Results of single USRP receiver.

l. 16-QAM Transmission (Tx:2 Rx:1 testing)

Where there were no evident errors with dual transmission indicated by LabVIEW, the results of 2x1 Tx Rx were not conclusive. The resulting received signal was not discernible from the surrounding noise that was present on the Rx constellation before transmission. In order to determine if the problem was the synchronization of devices, we disconnected an antenna from one of the devices mid transmission which made no difference. In theory, removal of one out of sync transmission antenna would have corrected the issue and given us a clean transmission.

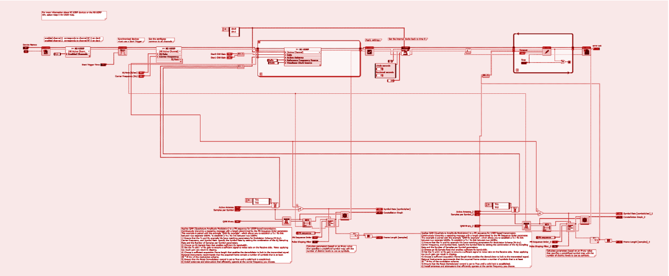
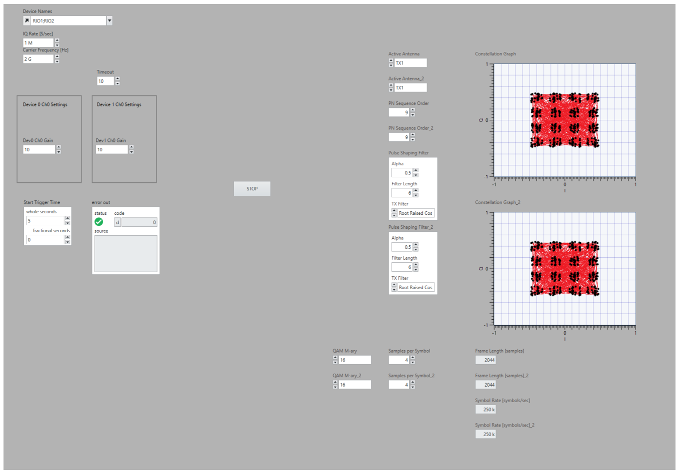


Figure 26: Labview code for dual device QAM Tx.



Device Names: RIO1;RIO2
IQ Rate [S/sec]: 1 M
Carrier Frequency [Hz]: 2 G
Timeout: 10
Device 0 Ch0 Settings
Dev0 Ch0 Gain: 10
Device 1 Ch0 Settings
Dev1 Ch0 Gain: 10
Start Trigger Time
whole seconds: 5
fractional seconds: 0
error out
status: ✓
code: d 0
source:
Active Antenna: TX1
Active Antenna_2: TX1
PN Sequence Order: 9
PN Sequence Order_2: 9
Pulse Shaping Filter
Alpha: 0.5
Filter Length: 6
TX Filter: Root Raised Cos
Pulse Shaping Filter_2
Alpha: 0.5
Filter Length: 6
TX Filter: Root Raised Cos
QAM M-ary: 16
QAM M-ary_2: 16
Samples per Symbol: 4
Samples per Symbol_2: 4
Frame Length [samples]: 2044
Frame Length [samples]_2: 2044
Symbol Rate [symbols/sec]: 250 k
Symbol Rate [symbols/sec]_2: 250 k

Figure 27: Front panel results for dual device QAM Tx.

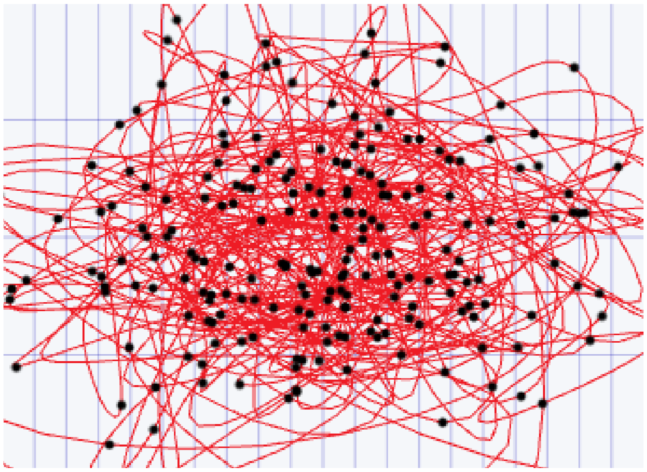


Figure 28: Receiver side results for dual device QAM Tx.

m. Codebook Design

While there is currently no groundwork in place for a codebook within our project for the time being, the concept that we want to base our codebook design on is fairly simple. There will be three possible modes for the antenna array that will be decided based on channel feedback from the transmission recipient. These modes of operation will enable the most optimal beam pairing to be established no matter the location of the end user. All three modes cover a 360 degree sweeping of the beam as well as enhanced modes that favor one sided transmission.

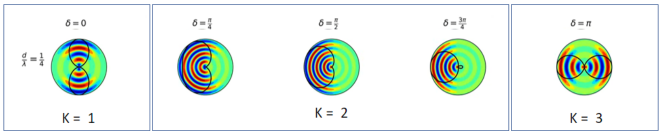


Figure 29: proposed codebook design for 3 mode beamforming.

The design that we are basing the codebook on is from a similar project that also uses a codebook design in order to establish optimal beam pairs. While their design uses 16 beam patterns, our design will only utilize 2 beam patterns minimum if omitting the single sided transmission configuration. Therefore it seems that only one bit will be required for feedback transmission.

Implementation of feedback can be implemented through beacon standards for 802.11 where device 1 and 2 beam pair as well as signal strength are included in the time block coding.

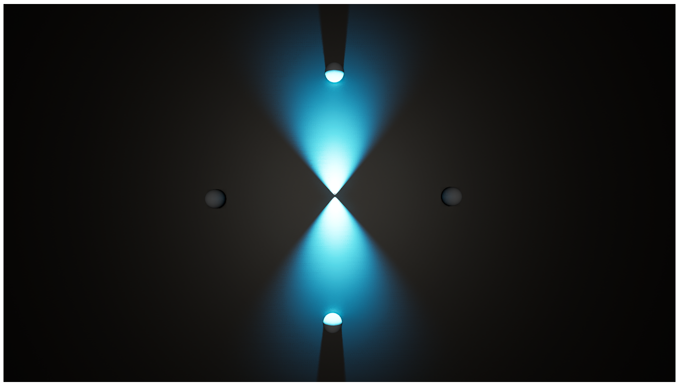


Figure 30: visualization of beamforming serving users 1 and 4.

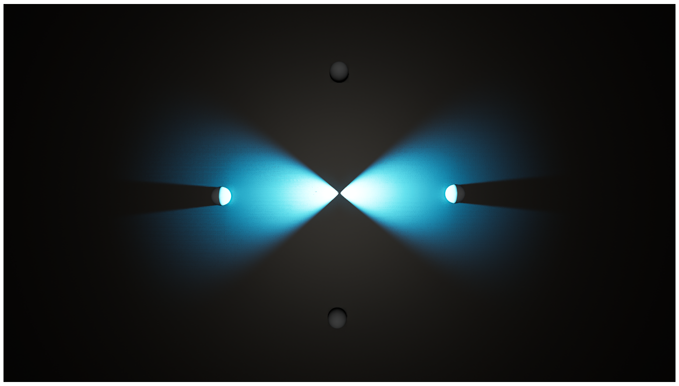


Figure 31: visualization of beamforming serving users 2 and 3.

III. Future Work

a. Dual Synced Transmission correction

One thing that we may have overlooked is that we had no real way to tell if our multiple transmitter transmission was actually transmitting a synced output. In retrospect, we should have enabled a single transmitter with the code and observed whether or not.

b. Connection of MIMO cable to Receiver

One of the most detrimental mistakes that we could have made upon feedback from our observing professor is that the MIMO cables for PPS trigger and the reference frequency needed to be connected to the receiver as well in order to show properly show the constellation.

c. Positioning of USRP

A final theory that we also had was that the inability to see a clear constellation may have even been due to USRP positioning when a beam was formed. Because there are points around the azimuth where attenuation was high (0 gain) we could have tried rotating the devices in order to see if it changed our result.

IV. Conclusion

In conclusion we have observed that it is possible to use multiple USRP devices in unison with the aid of an octoclock and PCIEx4 switch in order to synchronize transmission from two devices/channels. We have also derived and simulated the different beam formations possible through the implementation of a phase shifted secondary antenna which will later be implemented into the final system. QAM modulation of signals with up to 16 symbols has been successfully transmitted and received. A codebook design is also ready to be implemented in labview once a feedback system is further studied.

In testing the final design as far as forming a physical beam, we have not had any conclusive results due to a number of possible causes. While the semester is over, it may be in our interest in future opportunities to attempt to complete the project after reassessing our setup and current parameters.

V. References

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