CONTROL TECHNIQUES IN BEAM STEERING AND VECTOR MODULATION APPLICATION

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Electrical and Computer Engineering

Summer 2017

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ACKNOWLEDGMENTS

I have been blessed with having such a strong support group surrounding me during my life. I always knew that I would always have colleagues, friends, and family there to celebrate my accomplishments and raise me up when I am in dire need of positivity. This past couple of years have been extremely trying but crucial to my development as both a scholar and a person. While I cannot thank everyone individually I would like to take a minute and acknowledge a group of people that were crucial in my development here at the University of Delaware.

I would first like to thank a few members in the Department of Electrical Engineering. I would like to thank Dr. Dennis Prather for the opportunity to work towards my Masters in Electrical Engineering. Your dedication to your students and to the field of engineering is inspiring and I hope to one day bring that kind of inspiration to others. I would also like to thank Dr. Janusz Murakowski for his patience with me as I worked towards completing my masters. Your knowledge and ability to explain complex ideas in a simple manner was immeasurably helpful to me in my time here. I would like to thank Morgan McElhiney for being a friend to me from day one and being such a great tutor to me in the lab. I would also like to thank all of the other members of Dr. Prather's group for being accepting of me in my time here.

I would not have made it to where I am today without the never-ending support of my friends and family. I would first like to thank my friends Chris Rodriguez and William Reeck for always being there for me since my freshman year of college, they have always been supportive of my decisions and I am incredibly grateful for them.

Next thank you to Dylan Spence who was always there to help me not only at an academic level but at a personal level as well, I owe a great deal of my success to his support. I would like to thank Kenneth Elliot and William Bartlett for being such great friends and always being supportive of me. I would next like to thank Zach Nerwinski, Mathew Luddington, and Kyle McParland for their immense support as I worked towards my thesis this year and always being there to talk. I would like to thank all of UD Swim club for giving me one more opportunity does something I truly love and giving me the drive to excel every day. Thank you as well to all friends that have supported me in anyway over the years, while I could not name everyone there are countless others that have helped me to succeed.

Lastly I would like to thank the most important people in my life. I would like to thank my sister Lauren Ashley Jerothe for always putting up with me even though we are always at each other's throats. Thank you to my parents for their never-ending love and support that has gotten me through all the tough times life has thrown at me. To my Dad, retired Colonel Douglas Jerothe, thank you for your words of wisdoms through the years and setting the example of what it means to be a leader. To my Mom, Patricia Jerothe, thank you for always being there for me when life had me down and instilling the confidence in me to pursue greatness. Without these two in my life I know for a fact I would not be the man I am today and for that I thank them for everything.

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ABSTRACT

In the modern world researchers are continuously looking for faster, and more efficient forms of communications. A need for the ability to maximize the channel bandwidth available while maximizing the signal to noise ratio will be critical in the years to come. As the society becomes more dependent on wireless technology, and communications the required data rates to sustain our needs will skyrocket in the coming years. There are a number of emerging solutions to this problem, one of which is to look to higher frequencies where more bandwidth is available due to a lack of use. In order to achieve this solution a system must be built that can both achieve a higher range of frequencies without compromising the wireless fidelity of the signal being transmitted. Over the years an attempt to solve this problem has come in the form of many different types of Beamforming. Analog beamforming is the most basic form of beam steering and has the benefits of a maximized signal to noise ratio (SNR). While Digital beamforming is more flexible in allowing you to deal with different ranges of frequencies it however has an extremely high power usage that is currently expensive to be commercially viable. This leads to the idea of creating way to induce both analog and digital beamforming into a single system. A system which can have to flexibility to work in almost any frequency range offered by digital systems while achieving the same degree of accuracy and power that come with an analog system. A commercially viable system efficiency would be able to satisfy the needs of growing demand by supplying a near limitless bandwidth supply with a high signal fidelity. At the University of Delaware, it is hoped that the Vector Modulator will be able to fulfill the technological demands of a growing world while being more economically friendly compared to competing ideas.

Chapter 1

INTRODUCTION

In today's technological world, efficient forms of beam steering are key in order to optimize the already stretched resources of bandwidth and data rates. Due to the ever-increasing interest in wireless communications and technology, there is an exponential increase in need for bandwidth and higher data rates. [1] The overarching reason for this comes from the ability to communicate wirelessly on a large scale. Telecommunication companies have made high-powered wireless devices such as phones and computers affordable to the average person. This dramatic increase in development is not likely to stop in the near future, as data rate usage will continue to soar to in the coming years

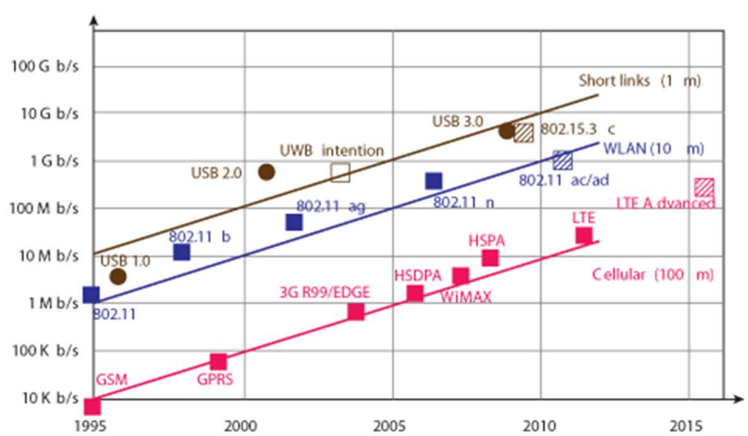

Figure 1.1: Growth of Data Rate Usage [1]

Figure 1 is a graph showing the overall demand for transmission speed from 1995 to the present date. The log plot of data rate seen in every aspect of wireless communications short links, WLAN, and Cellular data. It is also noticeable that as new technology is developed to increase data rates, it is not likely enough to supply sufficient increases within the next few years. Estimation of future data usage started back in the early 2000’s and if compared to a prediction of data usage today shows that not only are the predictions accurate, but likely to increase at the same rate over the next 10 years.

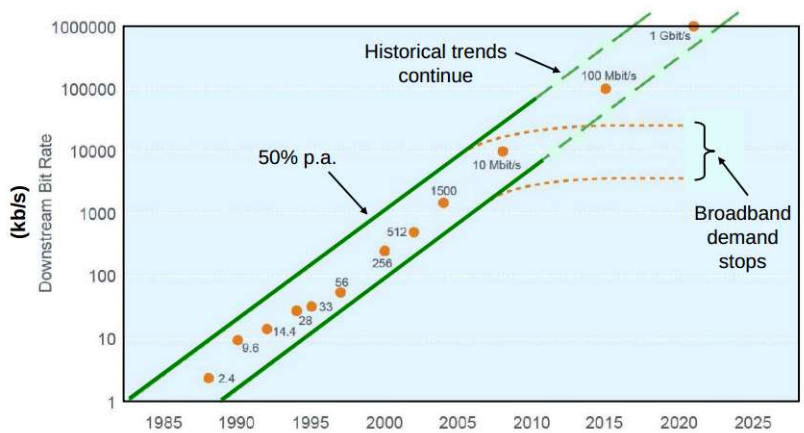

Figure 1.2: Downstream Bit Rate predictions [1]

In order to meet the needs of an ever-growing population it is necessary to expand our wireless capabilities into new frequency ranges, namely the frequencies between the ranges of 30-300 GHz or the millimeter wave spectrum. [2] Communication devices operating in this frequency range are referred to as millimeter wave technology due to operating at wavelengths spanning 1mm to 10mm. It is postulated that millimeter wave communication devices, specifically the 60-90 GHz range, would open up a large untapped source of bandwidth that would be able to alleviate the worldwide shortage created by the increased wireless communication use.

In order to achieve this goal, you must not only have the ability to economically create such a technology, but also be able to transmit data at these operating frequencies with an acceptable Signal-to-Noise loses and the ability to maintain wireless transmission fidelity. The potential of millimeter wave technology has raised a great interest in researching beamforming technology capable of transmitting at these frequencies. Over the years, many different forms of beam steering have been utilized, each with its own advantages and disadvantages. It has become necessary to evaluate each of these methods in detail to determine a form of beam steering that is sufficient for operating at a millimeter wave frequency. If one is not readily available, we hope the following discussion will convince you that it is possible to take already existing methods and combine them in such a way that you are able to maximize their advantages and minimize their disadvantages.

1.1 Introduction to Beamforming

A beam former is to be defined as a system with an array of transmitters and receivers that perform adaptive signal processing. [3] A system generates a radiation pattern, or beam, to propagated signals to a given location or receive radiation patterns from another. The signals being propagated through the radiation pattern are encoded with the data requisite intended on being sent to the desired location. In this thesis, I will focus primarily on the physical forming of these radiation patterns and how it pertains to different methods of controlling these beams. There are many reasons for why one would want to use beam forming as a means of spatial filtering as can be seen in Table 1. For the purposes of this thesis, I will focus on the use of beamforming technology as a form of communication.

Table 1.1: Applications of Adaptive Signal Processing [3]

Application	**Description**
RADAR	Phased Array Radar, Air Traffic Control
Communications	Direct Transmission/reception, Satellite comm
Imaging	Ultrasonic, optical, tomographic
Geophysical Exploration	Earth crust mapping, oil exploration
Astrophysical Exploration	Extraterrestrial Imaging
Biomedical	Heart monitoring, tissue hypothermia, hearing aids

1.2 Beamforming Theory

Beamforming is in essence the constructive sum of a set of signals emitted from a set of small non-directional antennas in order to form a large directional signal. Once the signal is generated it can either by physically steered by pointing the antenna in the direction you wish the, or it can be electronically steered without mechanically touching the antennas. In order to have a clear signal at the receiver it is important to have a precise method of beam steering to allow for the signal's maximum power output to reach its destination. [4] Transmitted signals are after sent via cables, such as conventional coaxial or fiber optical, to a radio transmitter. These transmitters and antennas are designed with electrical conductors that can create electromagnetic fields around them. Once the signal is received, the transmitter then converts the signal into electromagnetic waves that can be propagated through space.

The propagated signal forms a field in front of the antenna called a “radiation pattern,” which is the strength of a signal in each direction from the center of an antenna array. The individual elements of the antenna array all radiate waves with different amplitudes and phases. Due to the differences in amplitudes and phases these waves interfere with each other both constructively (causing peaks) and destructively (causing nulls) to form the overall radiation pattern for the full array. The radiation pattern of a specific array is the same for both the transmitted and received signals.

One of the more common forms of antenna arrays in communications is known as the “Directional Antenna Array.” Often designed in a circular fashion, a directional antenna spreads the radiating elements over a larger distance. By adding more radiating elements the antenna has a greater degree of control over the constructive and destructive interference tendencies of the array. As such, there are two parts to the field propagated from a directional antenna. The central narrow field, or “beam”, is an area of highly constructive interference that is aimed in the direction of the desired receiver. To the side of the central pattern are ripples of much smaller patterns called “side lobes.” These are the areas of less constructive and destructive interference and ensure that the central beam’s strength is. Figure 3 demonstrates a simulation of such a system in which the aperture of the antenna has a diameter equal to 3 times the operating wavelengths.

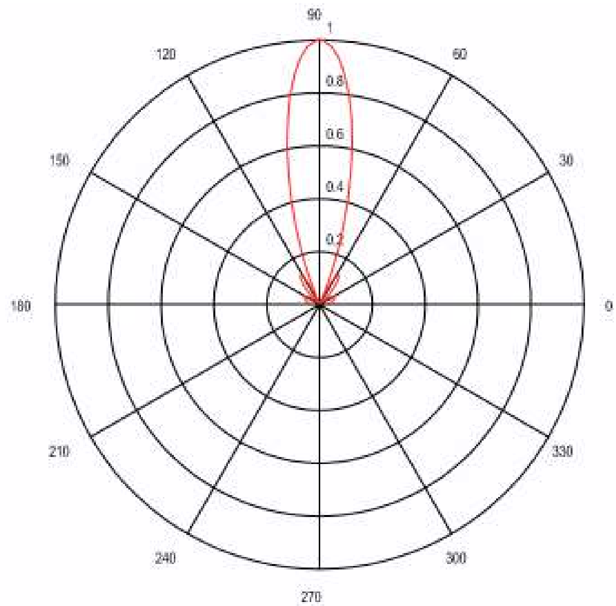

Figure 1.3: Field Strength vs Direction for typical antenna [4]

When discussing the theory of beamforming it is important to mention the relevant of research in millimeter wave communications. Current prototypes developed by communication companies demonstrate feasibility to use millimeter waves in 5G cellular networks. Having a range of 30-300 GHz allows for exciting new possibilities for broadband applications. In particular, it has been shown that for a standard 60 GHz indoor communication system it is possible to achieve a maximum data rate of 6.576 Gbps given suitable modulation and coding schemes. [5]

1.3 Mathematical Background of Beamforming

Wireless communication devices are based upon electromagnetic waves radiating from an antenna source and being transmitted to a receiving unit. This propagation is described by in the introduction of Maxwell's equations in an isotropic and homogeneous medium:

$$\nabla \bullet \overline{E}(\overline{r},\, t) \;=\; \frac{\rho_{vol}(\overline{r},\, t)}{\varepsilon},$$
$$\nabla \bullet \overline{H}(\overline{r},\, t) \;=\; 0,$$
$$\nabla \times \overline{E}(\overline{r},\, t) \;=\; -\frac{\mu\, \partial H(\overline{r},\, t)}{\partial t},$$
$$\nabla \times \overline{H}(\overline{r},\, t) \;=\; \frac{\varepsilon\, \partial E(\overline{r},\, t)}{\partial t} + J(\overline{r},\, t).$$

In these equations $\overline{r}$ represents the positional vector, t is the time variable of the system, ρ_{vol} is the charge density, $E(\overline{r},\, t)$ is the electric field, and $H(\overline{r},\, t)$ is the magnetic field. [5] These equations are effectively referred to as Maxwell's equations. Maxwell's first law describes the presence of charges, whether static or dynamic, in a given volume creates a divergent electric field. Maxwell's second law states that magnetic monopoles do not exist. Maxwell's third and fourth equations are known also as Faraday's and Ampere's laws, respectively. The last two laws of Maxwell's equations are the most important aspects when it comes to obtaining wave propagation for wireless technology. Since wireless technology assumes free space there are no charges or charge densities or currents. On the other side a time-space varying electric field causes an H-field to be generated, which in turn generates an E-field and the two begin to influence one another.

It is through Maxwell's equations we can couple the E-field and H-Field of Maxwell's equations together and derive the equation of a wave propagating in free space. The mathematical curl is taken of Maxwell's first law in order to create an identity that can be used to decouple the E-field and H-fields:

$$\nabla \times \nabla \times \overline{E}(\overline{r},\, t) \;=\; -(\frac{\mu\, \partial}{\partial t})\nabla \times \overline{H}(\overline{r},\, t)$$
$$\nabla \times \overline{H}(\overline{r},\, t) \;=\; \frac{\varepsilon\, \partial \overline{E}(\overline{r},\, t)}{\partial t}.$$

Through substitution we are able to determine the governing equation that allows us to decouple the E-field and H-field. Through further mathematical simplification the curl taken of Maxwell's first law can be simplified into:

$$\nabla \times \nabla \times \overline{E}\left(\overline{r},\ t\right) = \nabla(\nabla \bullet \overline{E}) - \nabla^2 \overline{E}.$$

With this simplification and the coupling of the E and H-fields we can find the time dependent wave equation of any Electromagnetic wave propagating in free space. In this case, as stated before, free space refers to an isotropic and homogeneous medium. It is through this method one is able to derive the speed of light in free space as well.

$$\nabla(\nabla \bullet \overline{E}) = 0$$
$$\nabla(\nabla \bullet \overline{E}) - \nabla^2 \overline{E} = -\nabla^2 \overline{E}$$
$$-(\frac{\mu\,\partial}{\partial t})\nabla \times H\left(\overline{r},\ t\right) = -\varepsilon\mu \frac{\partial^2 \overline{E}}{\partial t^2}$$
$$\nabla^2 \overline{E} - \varepsilon\mu \frac{\partial^2 \overline{E}}{\partial t^2} = 0 \quad \text{(Time dependent Wave Equation).}$$

With the fundamentals of electrodynamics for electromagnetic waves, it is necessary to begin to look into the fundamentals of Antenna technology and determine the power of waves propagating in free space. Antennas are defined as “part of a transmitting or receiving system that is designed to radiate or to receive electromagnetic waves.” [6] To begin we must look at the E and H-Field as complex fields E_s and H_s :

$$\begin{aligned} \bar{E}(\bar{r},\ t) &= Re\{E_s(r)e^{j\omega t}\} \\ \bar{H}(\bar{r},\ t) &= Re\{H_s(r)e^{j\omega t}\}. \end{aligned}$$

Using these radiating fields it is then possible to quantify the radiated power of the beam itself at any point of space by using the real part of the Poynting Vector. [7] The real part of the Poynting vector represents the active power density, associated with the field being radiated from the center. Using the Poynting vector the average power radiated by an antenna over the space can be quantified as:

$$P_{rad} = \oiint W(r) \bullet ds = \oiint \frac{1}{2} Re\{E_s(r) \times H^*{}_s(r)\} \bullet ds$$

Where $H_s^*(r)$ represents the complex conjugate of the magnetic field vector radiated from the antenna system.

At this point it becomes necessary to talk about the different regions that describe the full field radiated by an antenna system. The first boundary that describes the radiated field of an antenna system is bounded by the antenna surface itself and a small sphere surrounding it, this is known as the *reactive near-field* region. The spherical region surrounding the antenna has a radius of $0.62\sqrt{D^3{}_{max} / \lambda}$ where D_{max} is the largest dimension or diameter of the antenna array and λ is the operating wavelength of the signal. In this region, the active radiated power can be ignored. The radiation near field or Fresnel region is the region in which the active power first becomes non-negligible, however its field distribution depends on the distance from the antenna. The operating surface of this region starts at $0.62\sqrt{D^3{}_{max} / \lambda}$ and extends to $2D^2{}_{max} / \lambda$. The final region and most important boundary of the radiating field is known as the far-field or Fraunhofer region. This boundary lies beyond the boundary of $2D^2{}_{max} / \lambda$ and is in general the operating region of most antenna systems. The reason for this is because the Poynting vector's imaginary component approaches a negligible value faster than its real component allowing you to ignore the reactive power of the system. In this region, you can express the two primary components of a Transverse Electromagnetic Wave (TEM) as:

$$\begin{aligned} E_s(r) &= \eta_0 H_s(r) \times \hat{r} \\ H_s(r) &= \frac{1}{\eta_0} \hat{r} \times E_s(r) \end{aligned}$$

These physical boundaries describe all of the working regions of an antennas radiation and how the geometry and operating wavelength relate to the average radiated power. This concept can be physically represented in the following figure showing each of these radiation regions and how they relate to one another.

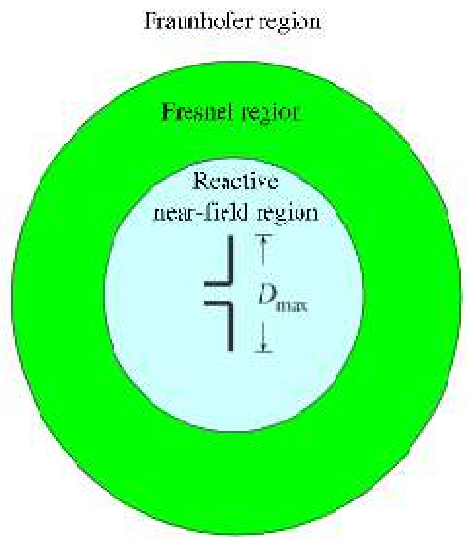

Figure 1.4: Operating Boundaries of a standard Antenna Array [7]

1.4 Radiation Properties

As stated in Section 1.2 the information being sent to the receiving unit forms a "radiation pattern." [7] The intensity of the pattern in the far-field, the optimal region of operation, is represented by the term $W_u(\theta,\ \varphi)$ where θ the zenith angle of the field and φ is the azimuth angle. One can determine the power gain coefficient of the antenna by using $W_u(\theta,\ \varphi)$, which is comprised of the Pointing vector, and applying the component of direction:

$$W_u(\theta,\ \varphi)\ = r^2 Re\{\vec{W}(r) \bullet \hat{r}\}$$
$$G(\theta,\ \varphi) \triangleq \frac{4\pi W_u(\theta,\ \varphi)}{P_{input}} \approx \frac{P_{output}}{P_{input}}$$

The gain as such is the ratio between the intensity of the radiation and the actual power input into the system. Another form of the gain coefficient can be determined by taking the product of the antenna efficiency and the directivity, $D(\theta,\ \varphi)$, of the antenna. The efficiency, e, is the ratio of the power radiated over its input. The input power does take into account the fact that there will be potential loss due to infinite conductivity and dielectric absorption of the device. Meanwhile the directivity of the antenna is a similar ratio to that of the gain, except instead of using at the input power it is required to use the radiated power:

$$e \triangleq \frac{P_{rad}}{P_{input}} = \frac{P_{rad}}{P_{rad} + P_{loss}}$$
$$D(\theta,\ \varphi) \triangleq \frac{4\pi W_u(\theta,\ \varphi)}{P_{loss}}.$$

Having a physical understanding of the radiation pattern is just as important as having a basic mathematical understanding of its background. There are different characterizing elements of the radiation properties that define the pattern as a whole. Figure 1.5 gives a physical interpretation of these elements of radiation. The null zone is an area of the pattern where the radiation is negligibly small, where ideally it would be zero. [8] This zone is important in suppressing signals capable of interfering with the main signal, thus reducing noise because the directivity angle of the null zone is generally very narrow compared to the main beam. Any area bounded by two null zones is called a lobe. [7] The main lobe, or the main beam, contains the maximum amount of radiation being directed, meaning that any information being sent is ideally contained within this lobe. Unfortunately, it is impossible to contain all of the radiation of the system to a single direction, which gives rise to side lobes, which are lobes adjacent to the main lobe caused by a leak of radiation from the main beam. Side lobes are generally specified as being a dB value down from the main lobe. The beam width of a signal is described by two values. The Half Power Beam Width (HPBW) is the angular range where the radiation intensity is greater than one half the maximum value both horizontally and vertically. Any receiver would ideally be within this range during transmission of data. [7] The First Null Beam Width (FNBW) is the entire angle spanned by the main lobe of the radiation pattern.

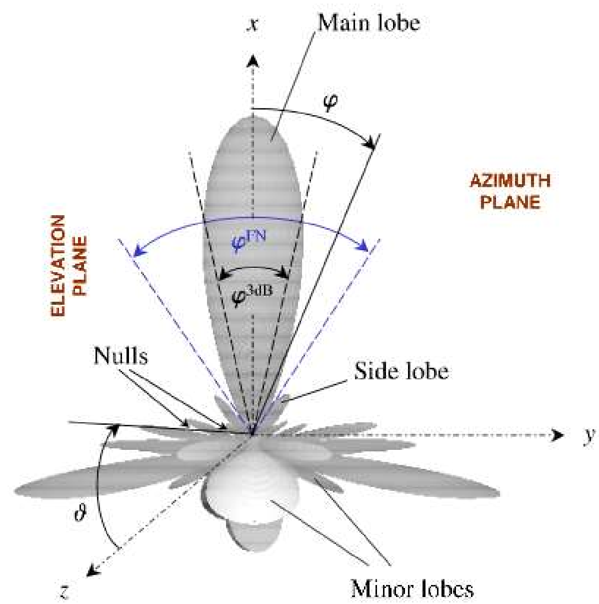

Figure 1.5 Theoretical Radiation Pattern [8]

In order to fully understand beamforming and the relevant technology, a basic understanding of how antennas transmit signals is imperative. Both mathematical basis of antenna theory and the physical interpretation of the radiation pattern play large roles in the design and operation of antennas. In order to maximize the efficiency of any beamforming system each system design must be tailored to the exact intention of operation.

1.5 Beamsteering Characteristics

The physical characteristics of each component is important to the overall performance of the system. The main characteristics that are of concern are: insertion loss, steering range, steering resolution, steering speed, and bandwidth phase deviation. Insertion loss is defined as loss that arises as a result of inserting a signal into a transmission line.[2] Often these losses can arise from impedance mismatches and back reflection at the point of insertion, which causes for a percentage of the power being input to be lost before it is actually used. In simpler terms, it is the difference between the inserted power and the power coupled into the system. Mathematically it can be defined as follows with the resulting value being in dB:

$$\text{Insertion Loss} = 10\log\frac{P_{ref}}{P_{in}}.$$

The Insertion loss in particular is a critical element to any beam steering technique. If a system loses a noticeable amount of power upon insertion, then the overall efficiency of the system will suffer and become less commercially viable. Both the performance and the overall power efficiency of the system is higher with a lower insertion loss. By lowering the insertion loss, there is less power that is required to achieve the energy requirements of the system leading to a cheaper operating cost and lower power consumption.

The steering of a system is broken into multiple aspects. The steering range of a system is the maximum angle away from center (the bore sight) that a beam can be steered. In the literature, there are two classifications for steering ranges, they are either full 360-degree range or have a specified angle. The steering speed of a system is how fast beam steering can be performed over the desired transmitting area. If the system is performing in a static environment the sensitivity of the beam steering is less important and will require a slower beam steering speed. Meanwhile if trying working in a dynamic environment with multiple moving receivers, it is necessary to have a system that can steer quickly enough to continuously transmit to the desired receiver. The bandwidth phase deviation (BPD) refers to the uniformity of the beam being transmitted. Ideally you want as low of a BPD as possible so that the frequency remains as close to constant across the entire operating bandwidth of the antenna.

When considering what type of beam steering technique to use, these characteristics are ultimately the deciding factor when deciding the viability for different applications. As stated before, there are many different forms of beam steering technology that have already been researched thoroughly. Each method has its own unique advantages and disadvantages that can be briefly seen in Table 1.2. Each technique will also perform differently depending on the frequency range of operation. While there are a number of techniques listed on Table 1.2 the majority of this thesis will be focused on two techniques in particular. Analog and Digital Beamforming. These two methods are the basis of most modern-day communications and the most commercially viable for worldwide communication devices. In later chapters, it will be discussed how to realize a hybrid form of Beam steering using these two techniques in order to create the next generation of communication devices.

Table 1.2: Example Techniques of Beam Forming [2]

Technique	IL	S-Res	Complexity	BPD	Size	Cost
Mechanical	*None*	*Continuous*	*Low*	*None*	*Large*	*Low*
Analogue BF	*High*	*Predefined*	*Moderate*	*High*	*Medium*	*High*
Digital BF	*High*	*Fine*	*High*	-	-	*High*
Reflectarray	*Medium*	*Predefined*	*Moderate*	*High*	*Large*	*High*
Parasitic	*Low*	*Predefined*	*Low*	-	*Freq dependent*	*Low*
ILAs	*Low*	*Predefined*	*Low*	-	*Medium*	*Low*
SBA	*Medium*	*Predefined*	*Low*	*None*	*Large*	*High*
TWA	*None*	*Continuous*	*Low*	*High*	*Small*	*Low*
R-Arrays	*Low*	*Fine*	*Moderate*	-	*Medium*	*Medium*
Metamaterial	*High*	*Predefined*	*Moderate*	-	*Medium*	*Medium*

Perhaps the most basic characteristic of all systems, when it comes to commercial use is the cost of the system. [2] When discussing the use of one technique over another often cost becomes the deciding factor. As if you can implement one technique over another at a lower cost, even if the performance suffers, it is often that the cheaper option is taken in the interest of profit. The size and the complexity of the system often effects the cost of the system as well, larger bulkier systems are generally more expensive to create, mount, and utilize compared to smaller systems. Meanwhile the complexity of a system is rated as low, moderate, or high. Size also limits the capability of utilizing each system, larger systems cannot be implemented into newer reconnaissance platforms such as UAV's and other forms of drones due to their weight. Meanwhile if a system is too complex for a particular application the cost to profit ratio is limited. Commercialization of smaller, compact, and less complex systems becomes more feasible the smaller the size of the system. By reducing the size, one increases the range of possible utilizations a system is capable of while also reducing the overall cost of the system.

Chapter 2

COMMON FORMS OF BEAMSTEERING TECHNOLOGY

2.1 Introduction into Analog Beamsteering

Analog Beamforming (ABF) is the oldest and most well-known methods of beam steering in wireless communications. In some applications ABF is preferred over other methods due to its simplicity. The full system itself requires no conversion of signals so there is less power consumption. The steering range capable of an ABF system is extremely precise and capable of accuracy within fractions of a degree. Their cost is cheaper compared to other forms of technology such as Digital Beamforming. [9] They also require minimal hardware, which decreases the risk of the system becoming inoperable.

While simple and a great tool in wireless communications, there are several downsides to ABF that must be taken into consideration when choosing appropriate applications. One such consideration is the adjustment of the phase and amplitude, while very precise, is difficult to adjust quickly. This leads to a system that can only be used in near static environments as its steering speed is not fast enough to track moving targets. ABF systems also have the drawback in that they are only able to produce a single beam and can only handle a single stream of data. This draw back limits the abilities of the system to interface with multiple receivers impossible.

As stated before ABF systems are one of the better researched forms of data transmission technology. As such there are multiple methods that have been created over the years. The following two sections will discuss two forms of ABF technology; Mechanical Beamforming systems and Phased Array Beamforming systems.

Mechanical Beamforming is the oldest and well researched form of beam forming to date. Mechanical beam steering designs make use of a fixed beam of transmitted data at the boresight of the antenna. In order to direct the beam of transmitted data to its intended receiver the entire antenna dish must be rotated until its boresight puts the intended receiver in the radiation pattern of the beam. [10]

The only information needed in order to steer the dish itself is the location of the receiving unit. The antenna array system takes this information from the data supplied and extracts the receiving unit's location. Then, the mechanical devices responsible for steering the antenna dish are provided with the coordinates of the receiving unit and position the bore of the dish to be in "line of sight" of the intended destination of the data.

There are several drawbacks to such a system that makes it obsolete in today's modern communication world. These systems are very large and cumbersome; they are not easy to produce and they are full of mechanical devices that are prone to mechanical failures due to faulty manufacturing, wear and tear, or environmental influences. The size of these dishes makes uses in commercial technology very difficult. This comes from the size of the systems and difficulty of production. Later research lead to the miniaturization of such systems, which eventually led to more effective ways of steering data encoded beams to their destinations. Currently this type of analog beam forming sees most of its application in the military such as radar.

2.2 Electronically Steered Phased Array Analog Beamsteering

Phased Array analog beam steering technology evolved out of necessity as systems became larger and more difficult to maneuver. With Phased Array ABF, the beam of the transmitted signal does not have to be directly pointed at the receiving unit. The system as a whole operates similarly to a mechanical ABF system,

The difference between mechanical ABF and phased array ABF lies in how the beam is controlled. In phased array ABF, the beam can be steered through non-mechanical means such as the introduction of electric currents. The application of an electric current causes phase shifts in the beam depending on the strength of the current applied. By changing the phase of the beam, it is then directed in the desired direction of transmission. This shift of technology was made possible with increased capabilities of analog to digital converters, in regards to their speeds and resolution potential. [11]

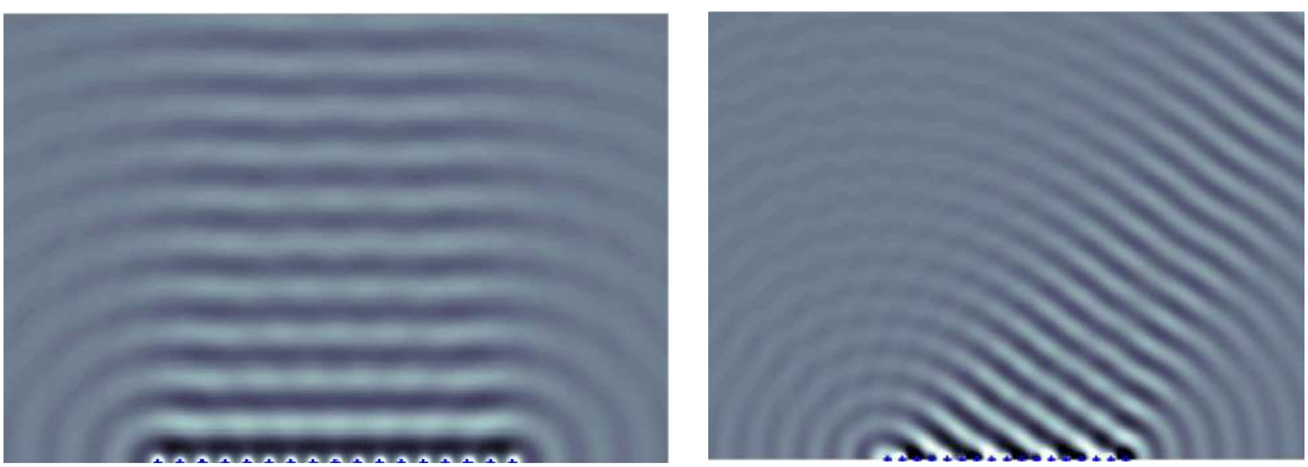

Figure 2.1: Example of Phased Array ABF effects on waves [14]

The phased array antenna is constructed from a number of similar radiating elements, each of which has independently controlled amplitude and phase. The different phases and amplitudes supplied by each radiating element begin to interfere both constructively and destructively. It is through the interference that the radiating beam is formed and steered to the appropriate direction. The spacing between the antennas causes a delay and signals begin to interfere with each other, which must be taken into account. This phase delay applied is then a function of the delay of time and the carrier frequency of the signal equaling $\Delta\phi = 2\pi f_c \Delta t$

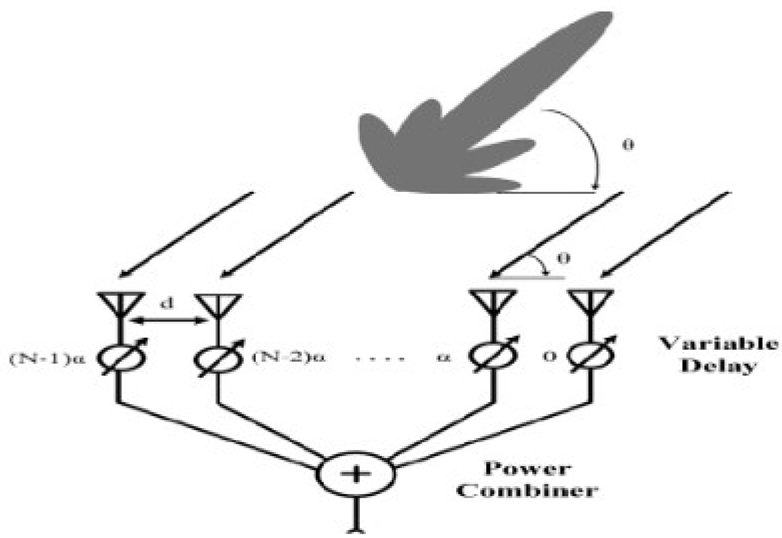

Figure 2.2: Conceptual design for an electronically steered ABF System [14]

Generally, cellular operation is in the spectrum of 800 MHz to 3 GHz. This particular spectrum is used because it holds the best propagation and implementation characteristics for most radio band and mobile broadband applications. However, with the growth in demand for mobile broadband it has become apparent that in the near future that this small swath of bandwidth will not be sufficient to sustain the data needs of the digital industry. Millimeter wave technology hence is the most logical solution to such a problem as there is already data supporting its potential use as a successor to the current frequency range of communication.

Phased Array ABF has received a great deal of attention in transmission of millimeter waves in open area outdoor environments. The small wavelength of millimeter waves allow for the potential of large beamforming gain from systems consisting of smaller multiple phased array antennas. [12] These systems are cheap and easy to produce on a large scale, however, are not ideal for indoor household use. Meanwhile many different wireless personal use of millimeter wave systems have been researched but they are limited in range and are unable to sustain the signal in different environmental factors, such as wind or rain.

Current research into the use of phased array ABF in the millimeter regime involves its use in wireless backhaul systems to support the overtaxed data flow systems currently in place. The idea would be to break up the current data traffic hierarchy into smaller zones, current communication towers would be considered the macro cell while the installation of smaller towers would be called Pico cells. Each Pico cell would consist of its own phased array antenna system capable of performing phased array ABF, and each would be positioned between 50m to 100m from one another. This would be essential for millimeter beamforming because the loss of signal due to atmospheric effects and environmental effects.

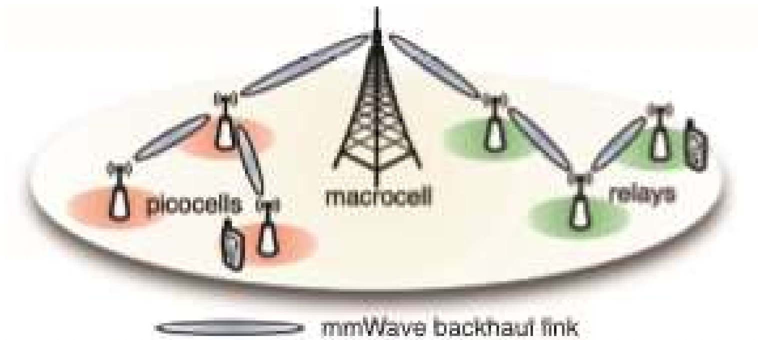

Figure 2.3: Data backhaul system consisting of multi-tier transmission cells [15]

While Pico cells help to reduce the risk of outage from effects such as wind it cannot eliminate the possibility of occurrence entirely. Thorough testing of the system showed that in environments of extremely high wind there is a strong possibility of data outage to occur from the Pico cells even if they are located next to the desired receiver.

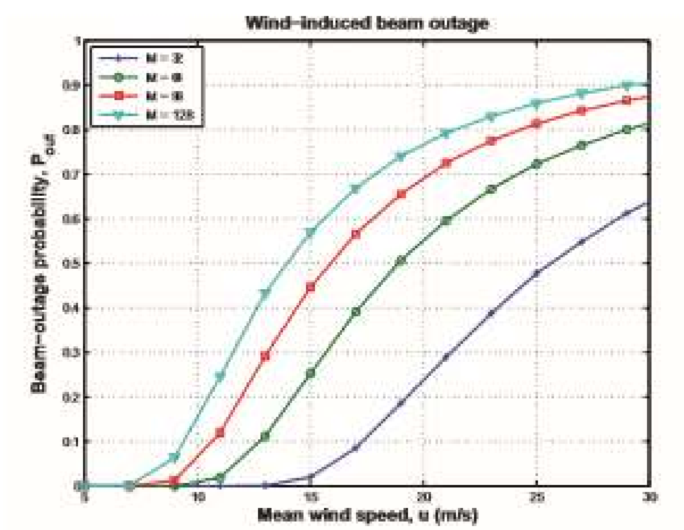

Figure 2.4: Probability of data outage in wind environments [15]

It is apparent from the Figure 2.4 that especially in very windy environments the Pico cell method of data transmission is susceptible to beam outage, however this is true of most forms of communications in modern technology. However once tested in communication friendly environments it shows that communications via millimeter wave signals are a viable alternative to current technology.

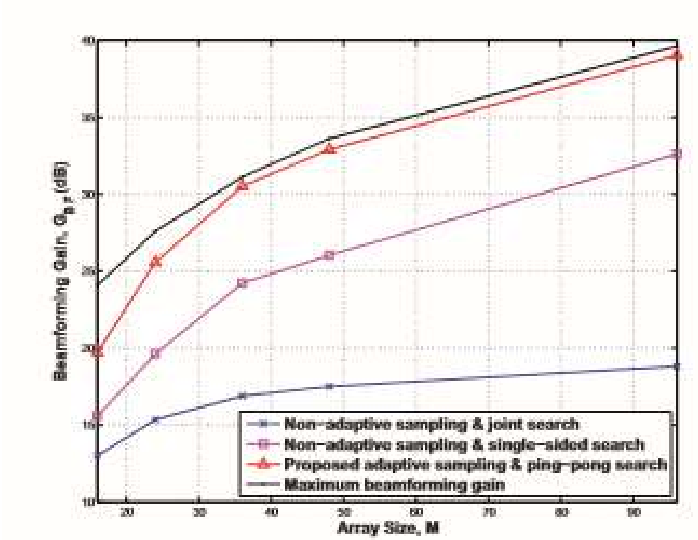

Figure 2.5: Beamforming Gain at Millimeter Wave frequency [15]

Figure 2.5 shows tests of the beamforming under multiple types of sampling. However it can be seen that through adaptive sampling the phased array system proposed would be capable of nearly reaching the simulated maximum gain possible for any phased array ABF system of similar array size. This data also supports a much earlier claim that as one increases the size of the array, the maximum gain possible increases as well.

2.3 Introduction into Digital Beamsteering

Digital Beamforming technologies (DBF) have received a great deal of attention in recent years. This is because wireless communication are devices becoming more sophisticated and more widespread, which consequently means new technologies must be created in order to support the increased data rate usage. It must also offer support to a large number of devices accessing the network at the same time due to increased consumer usage.

Digital Beamforming is a combination of antenna technology and digital technology. DBF takes an RF signal and converts it into a series of binary signals representing the cosine and sinusoidal channels. From these two channels the phases and amplitudes of the signals can be recovered and sent to the individual antenna array elements. By using a combination of weighting functions and summing them together the system is able to create the beam profile necessary to transmit the signal to its desired location.

Unlike straight ABF, the down-converting and digitizing of data is done at the individual array element, or even at the sub level. [13] By digitizing and processing the signals separately it allows for a variety of benefits over ABF. The first and most important benefit is the reduction of noise and distortion among the individual signals. This is due to all the signals being decorrelated from one another at the time of processing. There are other benefits to DBF over ABF that include; an improved dynamic range of the steering, you are able to control both the amplitude and the phase of the signal faster and more efficiently, lastly you are able to create multiple signals since each signal is processed on an individual level.

While the benefits of DBF are undeniable and necessary with growing usage of wireless communications, there are some downfalls to DBF that make it less of an optimal choice in certain applications. The first, and most notable, is the cost of DBF systems, which are markedly more expensive than analog systems and as such makes it less ideal to use. DBF systems are also more complex than ABF, allowing more room for mechanical or electrical failure within their designs. Lastly DBF can only steer the phase of a signal in discrete values, or integer values. This lack of precision causes DBF to become unappealing in situations where the system is tracking a moving object. [14] While these faults can be detrimental in specific applications, research is ongoing in order to create a less expensive and less complex system that meets all the needs of a growing digital world.

2.4 Digital Beamforming Theory

In order to transmit a digital signal to a particular region assume that $x[m]$ represents the data of the information signal. In any given system of N antennas in an array the phase delay of each antenna (θ_n) must be controlled precisely. However, one can determine the complex weight of the signal using only the phase delay of the antenna arrays: [15]

$$
\begin{aligned}
&w_n^* = \cos(\theta_n) + j\sin(\theta_n) \\
&n = 0,1,\ldots N-1.
\end{aligned}
$$

The phase of the complex weight can be changed in ways that vary different aspects of the beam pattern, such as the side lobe level, bandwidth, and null placements. The first step in digital transmission beam forming is the Complex Weight Multiplication step (CWM). In this step the imaginary and real part of the complex weight is multiplied together in order to give two signals for each antenna signal:

$$i_n[m] = x[m]\mathrm{Re}(w_n^*) - - - - - > i_n[m] = x[m]A\cos(\theta_n)$$
$$q_n[m] = x[m]\mathrm{Im}(w_n^*) - - - - - > q_n[m] = x[m]A\sin(\theta_n).$$

At this point the signals for each antenna have been created and it becomes necessary to do a Digital Up-Conversion. During the signals up-conversion the signals generated are multiplied by a sinusoidal signal of fixed amplitude and a frequency of ω_{IF} and its 90 degree phase shifted version and results in the output of signals fi_n and fq_n. After simplifications of the previous equations, the signals are expressed as:

$$fi_n[m] = \frac{A_n x[m]}{2}(\cos[\omega_{IF} m + \theta_n] + \cos[\omega_{IF} m - \theta_n])$$
$$fq_n[m] = \frac{A_n x[m]}{2}(\cos[\omega_{IF} m - \theta_n] - \cos[\omega_{IF} m + \theta_n]).$$

These two equations can then be added together in order to determine the bandpass signal $f[m]$. This signal will have the desired phase delay and will be the foundational equation that the signal beam will be formed from:

$$f[m] = fi_n + fq_n = A_n x[m]\cos[\omega_{IF} m - \theta] \ .$$

The final step of digital signal processing then occurs when converting the digital bandpass signal into one that is analog for the purposes of beam steering. When doing this the signal is converted using a digital-to-analog converter that has a specified sampling frequency f_s. The sampling frequency comes into play because analog signals are time dependent and the digital signal must be converted to a time dependent signal. In this case $m = f_s t$ where the constant f_s can be ignored arbitrarily taken as 1 in the final equation of $x(f_s t)$. The resulting signal of the conversion from the digital domain into the analog domain then becomes:

$$f_n(t) = f_n[m]\big|_{m=tf_s} = A_n x(t)\cos[\omega_{IF} t - \theta_n] \ .$$

The resulting equation contains all necessary components to constructing the required beam pattern to transmit the desired data to its location. However, it sometimes becomes necessary to limit the operating frequency at the output of the DBF transmitter due to costs or the operational speeds of the DAC. In order to compensate for such an occurrence an RF mixer can be placed at the output of the signal transmitter. The modulator is able to scale up the frequency of the output signal to one that is more suitable for antenna signal generation. This operation can be mathematically preformed simply by multiplying the output signal by the required local oscillator and its frequency, w_{LO} :

$$f_n^{'} = A_n x(t)\cos[\omega_{IF} t - \theta_n]\cos[\omega_{LO} t] \ .$$

From here much of the same manipulation of equations can be applied much like the digital up-conversion step. Once fully simplified the passband signal is represented by the equations:

$$f_n' = A_n x(t)\cos[\omega_{RF} t - \theta_n]$$
$$\omega_{RF} = \omega_{LO} + \omega_{IF}.$$

In Figure 2.6 the block diagram which summarizes the mathematical model for digital beam forming from information encoding to signal generation is shown.

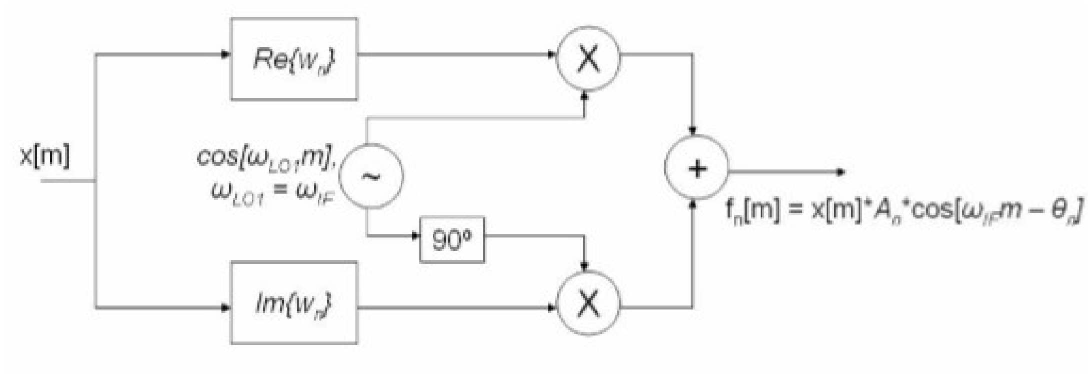

Figure 2.6: Mathematical Model of Digital Beamforming [18]

2.5 DIGITAL BEAM FORMING SYSTEMS

In digital beam forming, the RF information that is being transmitted is first captured in the form of a digital stream. DBF is based on the conversion of RF signals at each antenna element into two different baseband signals, an I and Q signal. The combination of the I and Q baseband signal then represents the amplitude and phase of the signal received at each element. [16] The elements weights can then be adjusted so that by adding together all the antenna array elements one is able to steer the beam direction in the proper direction. There are two domains in which digital beam forming can be split, one can perform it in the time domain or the frequency domain. For the purposes of this thesis we will only discuss digital beam forming in the time domain as it relates more closely to later chapters.

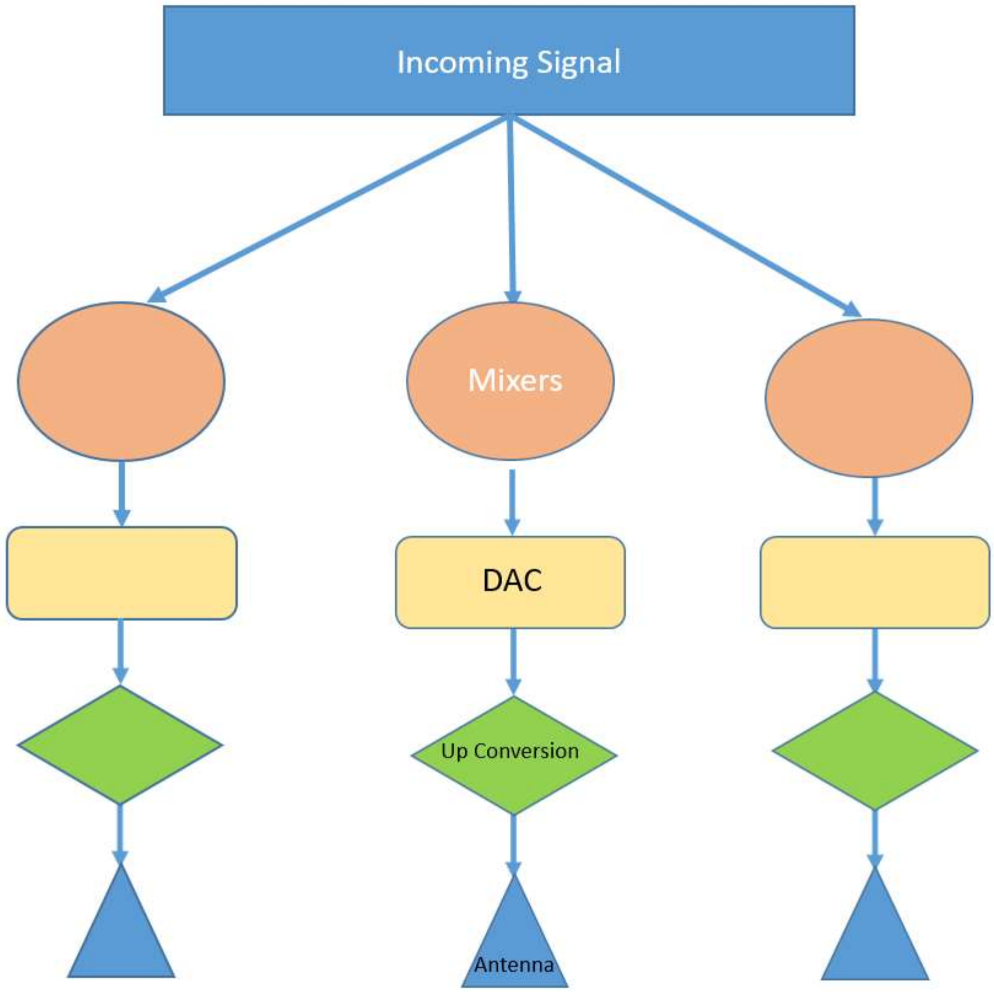

Figure 2.7: Conceptual design of a standard DBF System

Figure 2.7 shows a possible digital beamforming conceptual design that can be used for time domain related DBF. The first step of DBF is to ensure that the signal is digitized and weighted. Each signal sampled digitally by the DBF system undergoes a set of signal processing steps that is discussed in more detail in the following section. Once this processing is done, it is sent to a DAC system where the digitally sampled information is converted into a form capable of transmission via the antenna array. At this stage the now analog signal is up-converted to the desired frequency of transmission and sent to the antenna array. With this information, the antenna array forms the beam pattern necessary by adding the weights of the signals together.

The digital sampling of each weight however causes the system to be able to form beams only in discrete directions, as is related to the delay of the signal across samples [17]:

$$\tau_i(\theta) = k_i\Delta$$
$$k = 1, 2, 3.....L,$$

Where k is an integer up to the number of elements in the system and Δ is the sampling interval of the digital system.

The minimum delay of the signal must be equal to the interval number of the sampling signal in order for digital processing to take place. As the sampling size increases in the digital domain the system is capable of being steered in more directions. For practical use of DBF the array sample must be much higher than required by the Nyquist criterion, so that the array is able to reconstruct the wave form back from the samples given. This, however, causes an increased complexity and a larger power draw to the system. The requirement for high sampling rates can be averted by using digital interpolation, which simulates the samples generated by the high sampling rates. The array is sampled at the Nyquist required rate or higher, then zeros are added to the sample sequences to create a new sequence that is as large as a sequence that was sampled at a high rate. Once the beams are formed with these sequences the signal is passed through a Finite Impulse Response system to remove the added encoded zeros that caused a higher sampling.

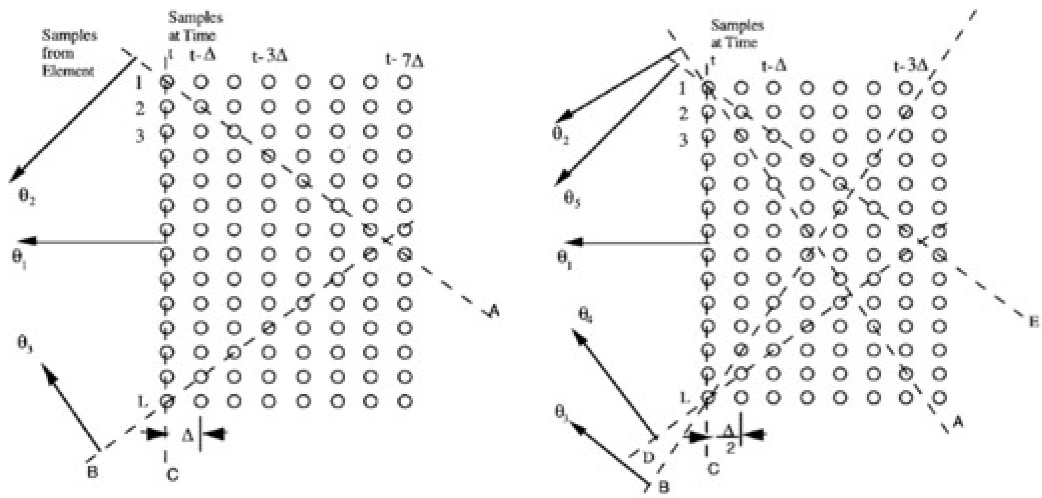

Figure 2.8: Example Sampling of Digital Beamforming Systems [20]

Once the digital sampling of the signal is complete the shape of the beam is determined by the size and shape of the array to be transmitted. Larger arrays produce a narrower beam, which is the most desirable outcome in beamforming techniques. Narrow beams have less loss of power over distance traveled, which in turn reduces the required power to operate the overall beamforming system. Much like interpolation tricks the signal into being sampled at a higher rate, extrapolation is used to simulate larger array systems, which in turn improves beamforming quality.

The combination of interpolation and extrapolation allows for smaller more compact systems to operate on a similar level compared too much larger and more cumbersome systems, at the cost of increased system and circuit complexity. Satellite systems benefit greatly from the use of interpolation and extrapolation. Satellites often use such system architecture when it comes to their digital beam forming systems. The reduced size and weight allows for assets to be launched into orbit with rockets that consume less fuel reducing costs of system "installations." Other more common uses of DBF often include cellular communications, radar systems and other military applications.

Chapter 3

MULTI-INPUT MULTI-OUTPUT BEAMFORMING SYSTEMS

3.1 Introduction into Multi-Input Multi-Output Systems

One of the greatest breakthroughs in wireless communications and beamforming technologies is the Multi-Input Multi-Output System (MIMO System). The MIMO system is capable of de-multiplexing the source data stream into multiple channel streams, allowing for multiple channel outputs. [18] MIMO systems are a vital part of today's communications systems as they allow multiple users and receivers to talk to one another and to independent receivers at the same time. The Department of Defense often utilize this technology as it allows for instantaneous coordination among different units allowing for adaptability in the changing environment of the battlefield.

There are several other benefits to MIMO transmission systems that make it suitable as technology in the 5G era. The array gain of MIMO transmission systems compared to standard Single-Input Single-Output systems (SISO) are much improved which causes the SNR at the receiver to be ideal. [19] There is also a reduction of interference in MIMO systems compared to typical SISO systems. Using multiple antennas allows the system to separate each spatial signature, which leads to more robust signal transmission. The Diversity Gain is the system's ability to combat signal fading, a form of signal attenuation. MIMO transmission technology is able to reduce the loss due to fading by using multiple antennas to the same channel to the same receivers. By doing this there is an increased probability that at least one if not multiple signals will reach the receiver without fading significantly.

While MIMO transmission systems are helping usher in a new era of wireless communications it is also posing new challenges when it comes to digital processing. With the complexity of MIMO transmission, compared to SISO, the processing algorithms become more complex as antennas are added at both the receiver and the transmission end. However if this challenge can be overcome it is shown that the efficiency of the MIMO transmission system will increase as antennas are added to both the transmission and receiving end. [20]

3.2 MIMO System Design and Theory

The foundational idea behind Multi-Input Multi-Output transmission systems is to use multipath propagation, which was originally an impairment to any wireless communication device, as an advantage. As stated before MIMO systems consist of multiple antennas and receivers in order to transmit or receive multiple signals at the same time. Standard MIMO systems make use of; Space Time Transmit Diversity (STTD), Spatial Multiplexing (SM) and Uplink Collaborative MIMO. In STTD the data being transmitted is copied multiple times and transmitted through multiple antennas. By doing this you are able to effectively increase the power of the channel without dramatically increasing the input power thus improving the SNR. [21] Uplink Collaborative MIMO utilizes the ability for multiple antennas to transmit on the same channel, which effectively increases the capacity of the transmission link. Spatial Multiplexing has the ability to transmit parallel streams of data to user equipment's (UE) by exploiting the multiple paths waves take to their destinations. The benefits it creates to the capacity of the system vary depending on the RF conditions and distance to target receiver.

Figure 3.1 represents the conceptual idea of how multiple transmitters and receivers would interact with one another in a standard MIMO system. Here Txn_1 represents the transmitting antenna and Rxn_2 represents the receiving antenna. While $h_{n_1 n_2}$ is the signal being sent from the transmitting antenna to the receiving unit.

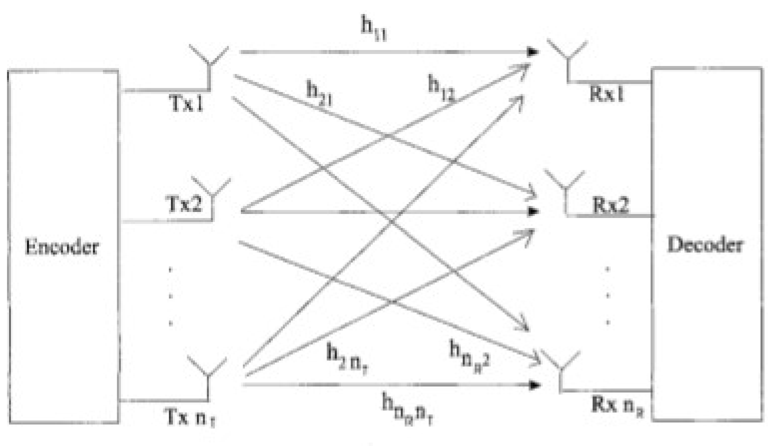

Figure 3.1: Conceptual Diagram of MIMO Transmissions [24]

With the addition of more antennas to the transmission and receiving units it is obvious that the maximum transmission rate or system capacity will increase. Assume a simple scenario in which there is a single user with N receivers and M transmitters. You can use the N x M channel matrix $[H]$ to find the matrix of the received signal using:

$$[y]=[H][x]+[n]$$

$$[H] = \begin{bmatrix} h_{11} & h_{12} & \rightarrow & h_{1M} \\ h_{11} & h_{11} & \rightarrow & h_{2M} \\ . & . & \rightarrow & . \\ h_{N1} & h_{N2} & \rightarrow & h_{NM} \end{bmatrix}.$$

Here $[x]$ represents the M x 1 matrix given by the transmitted signal while $[n]$ gives the column vector of additive Gaussian white noise. In order to normalize any noise, it will become necessary to multiply $[K]_n^{-1/2}$ by the receiving vector $[y]$ in order to yield $[K]_n^{-1/2}[H]$ and a noise vector. When trying to determine the channel capacity of a system it is easiest to convert the MIMO system into parallel non interfering SISO channels through the decomposition of the channel matrix. [22] The equation for estimating the constant system capacity is given by the formula better known as Shannon's law.[23]

$$C = (N)BW\log_2(1 + SNR))$$

In the preceding equation BW represents the bandwidth available to the system, and N represents the spatial streams. This capacity equation defines the maximum data transmission available with negligible error within the transmitted data. When comparing between SISO, SIMO, MISO, and MIMO transmitters it is easily noticeable that MIMO transmitters have the best transmission rate as is seen in figure 3.2. Simply by adding more antennas and more receiving units the throughput of any transmission system can be dramatically increased, which in turn increases the efficiency of the system.

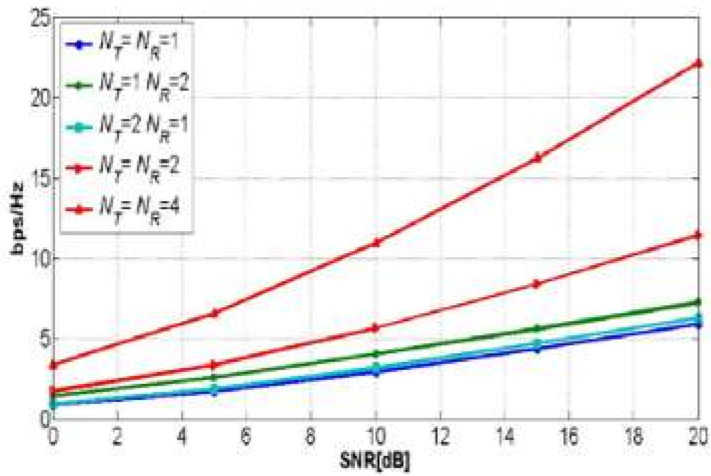

Figure 3.2: SISO, MISO, SIMO, MIMO comparison of data transmission speeds with no known CSI [26]

One of the biggest operational impairments of the Multi-Input Multi-Output System is the presence of "Fading Channels." These fading channels are brought on by the presence of multiple reflections and communication paths between two or more communication terminals. In MIMO systems, there are two different types of fading channels; selective fading and non-selective fading. In non-selective fading the frequency components are attenuated by the same amount without creating any distortion of the signal, however there is signal loss. In the case of non-selective fading channels, the signal loss can be corrected by boosting the signal strength of the antenna while equalizing the attenuated signal to ensure signal fidelity. These cases are generally narrow band signals and less used in commercial products such as Wireless LAN.

The alternative is to have a system with selective fading of the signal. In this case there is no signal loss because the frequency components are attenuated in smaller segments, however this ends up causing a distortion of the signal causing a communication impairment. [18] Most systems today experience selective fading channels because they are broader band devices, which means that techniques for signal restoration used for non-selective fading channels are not enough to repair the signal distortion caused by the multipath communication channels. In order to eliminate the signal distortion, the transfer function of the communication channel must be equalized by applying its inverse at the receiving end of the communication device. Doing this eliminates all impairment caused by signal distortion.

3.3 Existing MIMO Systems and Results

Multi-Input Multi-Output transmission systems as stated in previous sections played a key role in ushering in the 4G Cellular communications. Electronic research companies, such as Samsung Electronics Co, have once again turned to MIMO system research in order to expand wireless communication capabilities into the 5G era. To do this Samsung is researching into the possibility of using millimeter-wave frequency bands in order to increase the bandwidth compared to current day 4G cellular network technology.[24] It is hoped that by 2020, which many people believe will be the beginning of the 5G era, mobile devices will be able to offer a 1 Gb/s data rate at any location in the network. Meanwhile in more populated areas, data rates would be anywhere between 5 Gb/s and 50 Gb/s. [24]

In order to achieve this goal, it has become necessary to look for alternative sources of bandwidth not previously used, leading to heavy research into MIMO systems that operate in the millimeter frequency band. There are however concerns with the use of millimeter-wave frequency bands in order to enhance mobile cellular communication devices. At higher frequency ranges, signals are more prone to loss due to penetration of structures, precipitation and foliage in the path of the wave's propagation. It is believed at Samsung that a highly directive MIMO scheme can be created in order to overcome these unfavorable propagations losses that stands as a challenge to millimeter wave frequency bands being used in cellular communication.

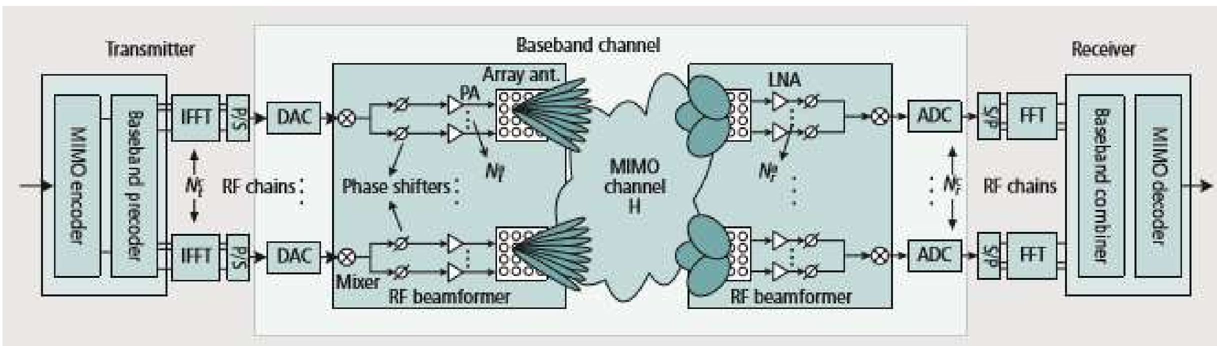

Figure 3.3: Architecture of Samsung mm-Wave MIMO transmitting system [27]

The above architecture is an example of a conceptual design used by Samsung in order to create a hybrid digital/analog Multi-Input Multi-Output mm Wave transmitting system. In the transmitting portion of the system all coding of information is done in the digital domain. Doing this increases the performance, provides for a better operational degree of freedom and it also allows for potential multibeam techniques to be implemented. The drawbacks however, cause a need for separate Inverse Fourier Transform blocks in order to encode the information into each RF chain. After digital processing the carrier is sent to a Digital-to-Analog converter (DAC) where the now analog system is controlled via phase shifters. Controlling of the signal via phase shifters creates a narrower beam which compensates for the natural large path loss of mm Wave band frequency. Today similar system designs have been implemented in academic environments, such as the University of Delaware, in order to present the solution of mm Wave band frequency communications.

Samsung R&D has taken the conceptual design presented before and created a prototype hybrid mm Wave beam former. Samsung states the main purpose of the beam former is to test the feasibility of mm Wave communications and to lay out a template for which can be followed for later versions of the technology. The transmitting array antennas have two available channels and the array comprises of 32 antennas arranged in a uniform planar array. Designed to operate at a carrier frequency of 27.925 GHz, the array is connected to an RF unit where a series of phase shifters control the signals sent to the antennas and thus creates the desired beam pattern to be transmitted. The prototype attempts to cut down on system complexity and cost by employing sub-array systems, where eight antenna units are connected to an RF unit. This allows for the use of only four RF units for 32 antennas. The creation of sub arrays causes reductions in antenna gains at any desired angle other than boresight, reduces the scanning range, and increases the side lobe levels of the beams. The prototype has the ability to code at different modulation rates, namely QPSK and 16QAM. The overall gain of the system is 18 dBi while the Full Width Half Max of the beam at boresight is 10 degrees horizontally and 20 degrees vertically. The specifications of the system parameters of the prototype can be seen further in Table 3.1 while the prototype antenna array is shown in Figure 3.4.

Table 3.1: Key System Parameters of the Samsung mm-Wave beamforming prototype [27]

Key system parameters	Values
Carrier frequency	27.925 GHz
Bandwidth/FFT size	520 MHz/4096-FFT
Subcarrier spacing	244.14 kHz
Cyclic prefix size	0.18 × OFDM symbol
Modulation, coding (data rate)	QPSK, LDPC 1/2 (264 Mb/s) 16QAM, LDPC 1/2 (528 Mb/s)
Maximum transmit power	31 dBm (with 9 dB back-off), 1.26 Watts
Array antenna configuration per channel	8-element by 4-element (32 antennas) Uniform Planar Array
Array gain	18 dBi
FWHM	10° (Horizontal)/20° (Vertical)
Beam scanning range	±30° (Horizontal)
Effective isotropic radiated power (EIRP)	Max 49 dBm (Nominal 41 dBm)
Adaptive beam searching and switching time	45 ms

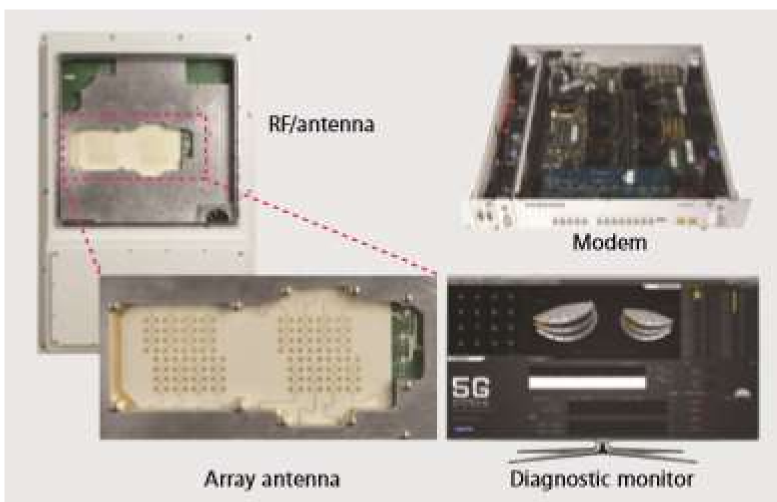

Figure 3.4: Samsung mm-Wave Prototype

Testing of Samsung's Prototype was done in outdoor settings to ensure that mm Wave cellular communication devices could operate around environments that could cause path loss to the propagated signal, such as in city environments. In a laboratory setting the system was able to produce a peak data rate of 1.056 GB/s, between two 528 Mb/s channels, with negligible block error rate (BLER). These same results were produced once in an outdoor environment, with BLER results being confirmed to be less the .01% at data rates of 528 Mb/s for up to 1.7 km away from the signals transmitter. The results of their tests can be seen in figure 3.5 and show that mm-Wave is not only feasible, but producing encouraging results, for highly mobile devices.

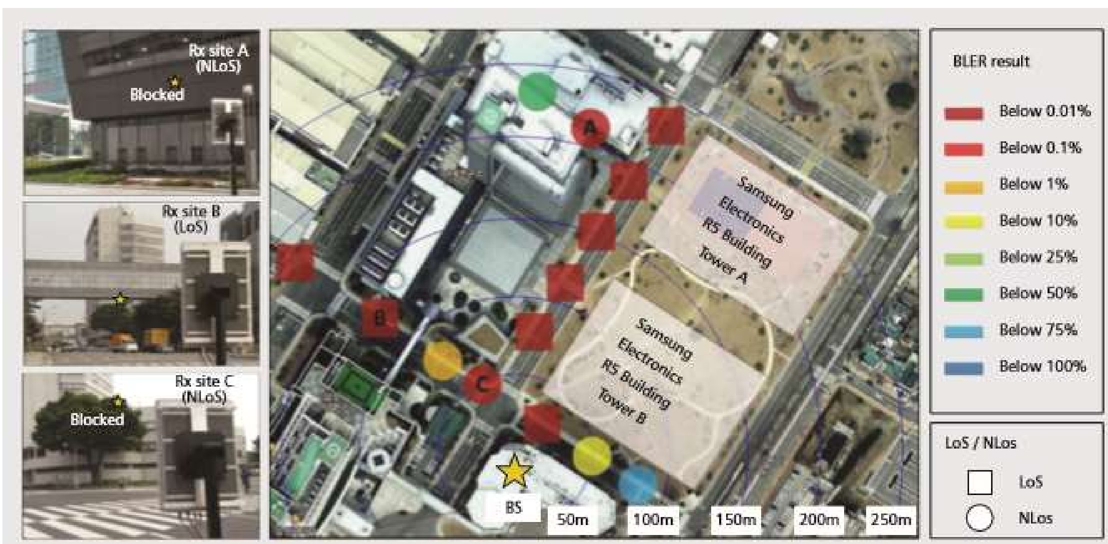

Figure 3.5: Samsung mm-Wave Prototype Outdoor Tests [27]

3.4 MIMO Application

The applications of Multi-Input Multi-Output transmitters can be tied to that of any basic radio transmitter. Military application, cellphone companies, and household applications are all among the different areas that the introduction of the MIMO system has greatly improved. Continued research in these fields yield more applications and benefits of the MIMO system as opposed to standard Radio transmitters.

One of the key aspects of military applications is the ability for the tracking and monitoring of different targets. Whether used for homeland security or as a means of tracking enemy combatants on the battlefield, the ability to register and identify these targets is key to the operation of the military and strategic planning. Standard radio transmitters are capable of Radio Frequency Identification (RFID) of these targets; however, it can only be used to identify one target at a time. MIMO systems are capable of locating and identifying multiple receivers at once. This is made a reality because each antenna in a MIMO system are able to act independently of one another and therefore send or receive independent signals.

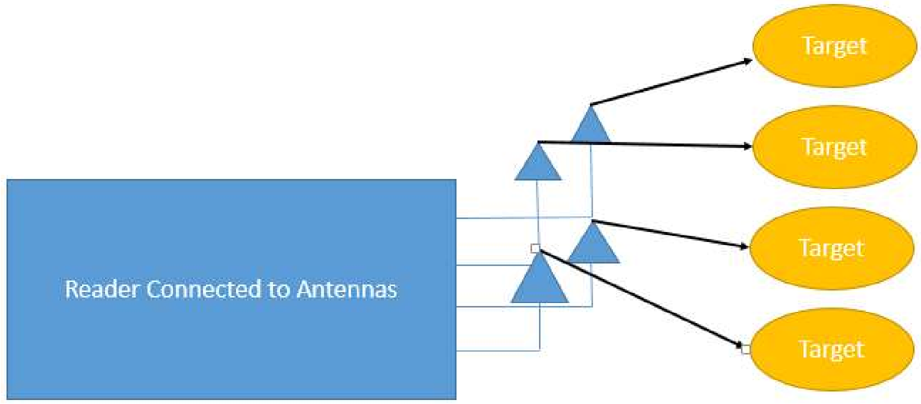

Figure 3.6: MIMO in RFID application

Cellphone companies and internet services use MIMO systems in technologies such as 4G cell service and modern day Wi-Fi connections such as WiMAX and Wi-Fi 802.11n. The introduction of MIMO technology into the Cellphone industry helped to give rise to the 4G era. The scalability of MIMO systems allow for 4G networks to reach download speeds of up to 100 Mb/s for highly mobile devices. Meanwhile for low mobility devices, download speeds can reach upwards of one Gb/s.[25] For home digital systems MIMO systems allow for a greater range of operation for Wi-Fi systems as compared to single radio performance. This idea can be seen in Figure 3.4 as it demonstrates the range and performance difference of Single Radio Wi-Fi compared to MIMO dependent Wi-Fi.

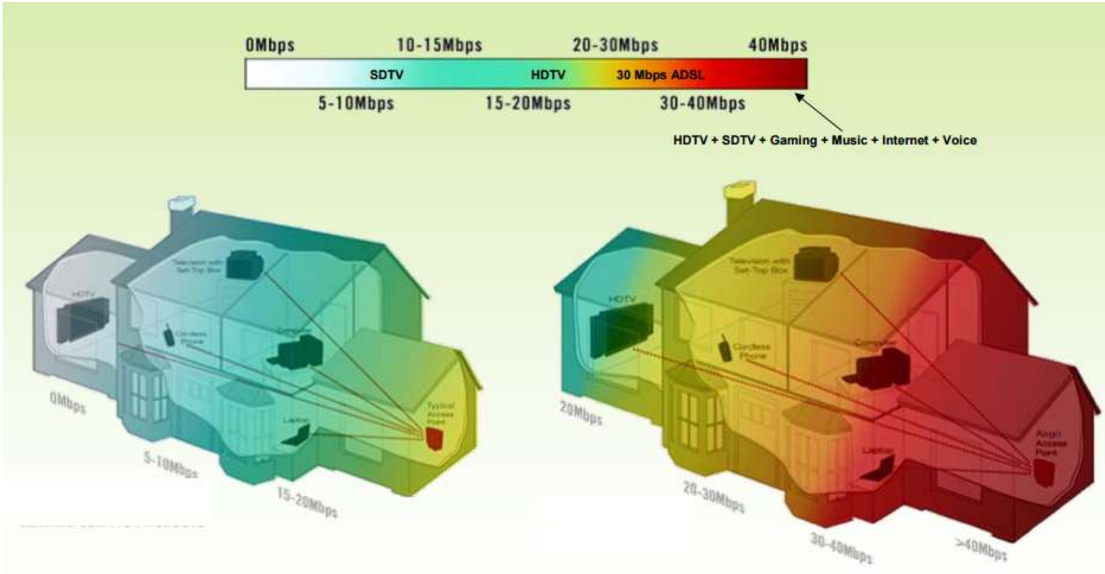

Figure 3.7: Wi-Fi Comparison, Single Radio (left) vs MIMO (right) dependent [28]

While there are many other aspects that have been improved by the introduction of MIMO technology, these are the most prevalent uses as it pertains to common everyday use. The military's use of MIMO systems in either defense of strategic assets or on offense for tracking high value targets has increased the efficiency of military operation while helping to ensure the safety of both US soldiers and foreign civilians alike. Meanwhile everyday usage of cell phone and Wi-Fi technology have seen an increased boost in speed and power efficiency from MIMO usage ensuring a stable wireless communication network in an ever-growing consumer base.

Chapter 4

THE OPTO-ELECTRONIC MIMO TRANSMITTER

4.1 Introduction into Opto-Electronic MIMO Transmitter

While Digital and Analog beam forming are currently sufficient to meet many of the communication needs of the world, the increasing use of wireless technology makes it imperative that research for the next generation wireless communications begin now. The Electrical Engineering Department at the University of Delaware has taken such an opportunity to begin research on an Opto-Electronic Multi-Input Multi-Output Transmitter. As mentioned in previous chapters while there are three methods of modulating signals to encode information, it is possible to use multiple forms of modulation at once to increase bit rate transmissions. This MIMO transmitter utilizes vector modulation, a form of Quadrature Amplitude Modulation, as its main form of information encoding. Vector modulation utilizes both phase and amplitude modulation to encode information on a carrier signal. On the beam forming side it is also possible to utilize aspects from both analog and digital beam forming in order to achieve a simultaneous multi-beam transmitter with pinpoint precision and near instantaneous beam steering capability.

When looking towards the future of communications a hybrid form of beam steering utilizing both analog and digital beam steering continues to receive a great deal of funding due to its potential. This sort of technology would have immense applications in not only the commercial sector, but in military applications and satellite communications. It is the University of Delaware's hope that we are able to pioneer the next phase of wireless communications with the Opto-Electronic MIMO transmitter, opening up a new realm of possibilities in both modulation techniques and beam-steering technologies

4.2 Opto-Electronic MIMO System Design

The Opto-Electronic Multi-Input Multi-Output transmitter is a system that takes the aspects the optical domain, the analog domain, and the digital processing of RF transmissions. The idea of the antenna system is to use the advantages of each aspect while minimizing the flaws and weaknesses by masking them with the strengths of the other domains. Figure 4.1 is the conceptual diagram of the Opto-Electronic MIMO transmission system.

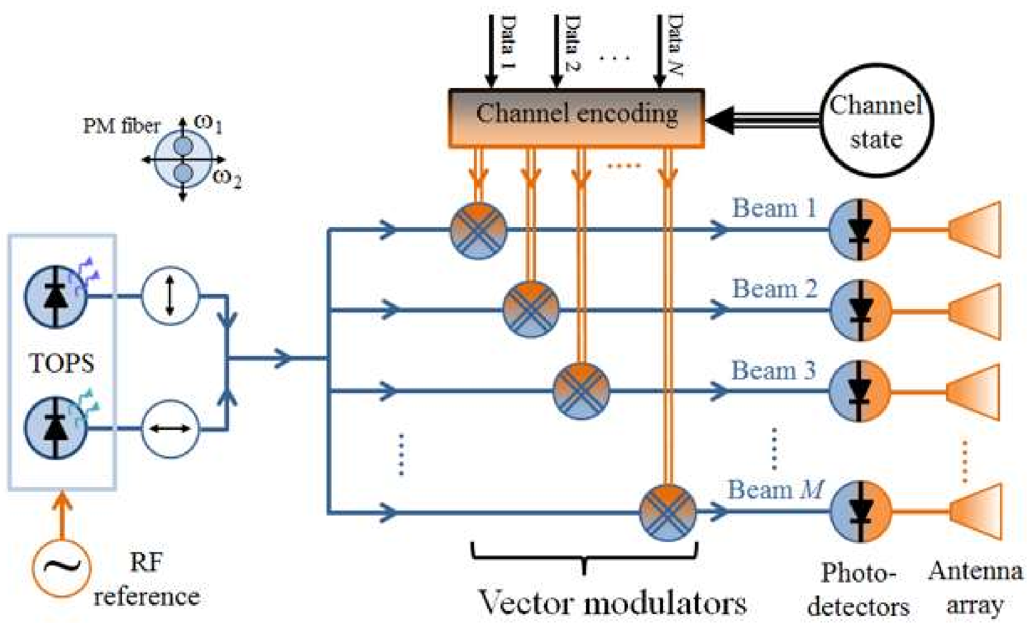

Figure 4.1: Opto-Electronic Multi-Input Multi-Output Transmission system [30]

The carrier wave for the MIMO transmission system is done with a device developed at the University of Delaware, known as the Tunable Optical Paired Source (TOPS). This Optoelectronic system is based on side band injection locked lasers that allow for the generation of low-noise carrier signals. [26] In application a master laser is driven through an optical filter in order to separate it from its side-bands. These sidebands are then amplified by a semiconductor optical amplifier before it is injected into a slave laser. The offset frequency of these two lasers are then tuned to be approximately the desired frequency of the output laser by locking on to the one of the injected sidebands. The slave laser is then recombined with the original master laser and directed towards a high-bandwidth photodetector. The resulting radio frequency of the TOPS system is an ultrawide-bandwidth carrier signal with orthogonal modes creating low loses and has the ability to be tuned from 0.5 GHz to 110 GHz. It is believed with high performance components that the system would be able to reach an excess of 300 GHz in a compact package.

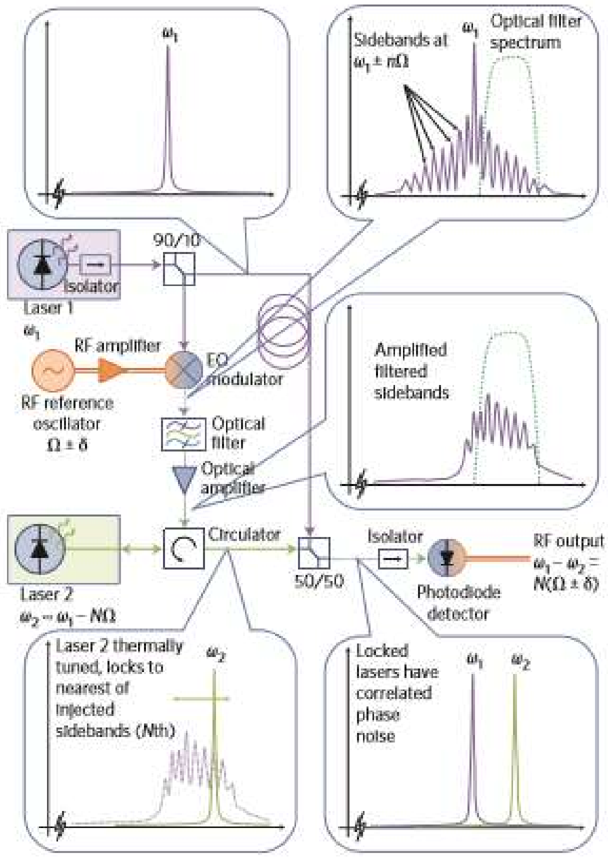

Figure 4.2: TOPS design

Once the orthogonal mode is generated it is then coupled together into a Polarization-maintaining fiber to ensure that the two signals do not lose their orthogonality. [27] The two orthogonal modes at this point will be referred to as the "slow-axis" and the "fast-axis." While the two modes differ in wavelength they will travel together which allows for the minimization of any outside effects. It is at this point the optical beam is driven through a device called a vector modulator. The vector modulator is another device being made-in house at the University of Delaware and will be discussed in greater detail in the following section. The still optical signal at this point has been encoded with the information to be transmitted. It is then directed to an amplifier or directly to a photodetector where the optical signal is converted into an analog signal that can then be transmitted via an element of the antenna array.

The resulting system yields a transmitter that can be used as a multiple user wireless MIMO that contains aspects of analog, optical, and digital processing. The carrier signals to be encoded are optical, the data channels are created through the digital aspect, while the beamforming is done in the analog domain meaning the accuracy is only limited by the performance capability of the Digital-to-Analog Converter. The system itself can operate with any RF frequency and because of the TOPS system the different frequency bands are easily accessed by tuning the output desired. The resulting beam is thus scalable, non-blocking, and capable of simultaneous transmission to as many user interfaces as there are digital channels and antenna arrays available.

4.3 Signal Encoding and Vector Modulation Design

As stated in the previous section the Vector Modulator design proposed in this Thesis is one that has been conceptualized by Dr. Janusz Murkowski within the research group of Dr. Dennis Prather. The vector modulator is a modulator designed to convert data streams to be sent to different User Equipment (UE) to yield an RF Beam signal with the correct amplitude/phase profiles. In order to do this the vector modulator uses aspects of the digital domain and the analog domain to increase the precision and the power efficiency of the system. [28] Consider the channel encoding system within the Opto-Electronic MIMO design.

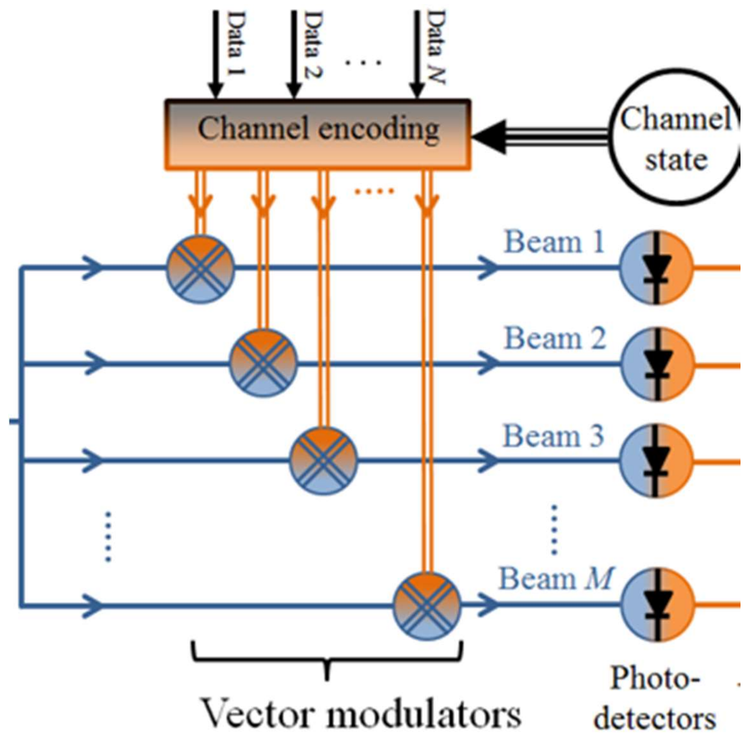

Figure 4.3: Channel Encoding of Electro-Optical MIMO [31]

The encoding of the channel will first take place in the digital domain. The Opto-Electronic MIMO design is capable of supporting n^{th} number of data channels, as seen in Figure 4.3. Each existing data channel has a corresponding amplitude and phase profile linked to a desired UE's location represented by the complex vector X_n where *n* represents the number of data channels being transmitted. Thus, the complex vector of the data transmission can be represented by:

$$X(t) = \sum_{n=1}^{n} D_n(t) X_n^* \ ,$$

Where D_n represents the symbol streamed to the n[th] UE. From this point $X(t)$ will have *M* number of complex entries, where *M* represents the number of antennas on the designed system. Each entry will then have a corresponding RF wave profile to be transmitted once the vector X has been converted into the analog domain for the vector modulator.

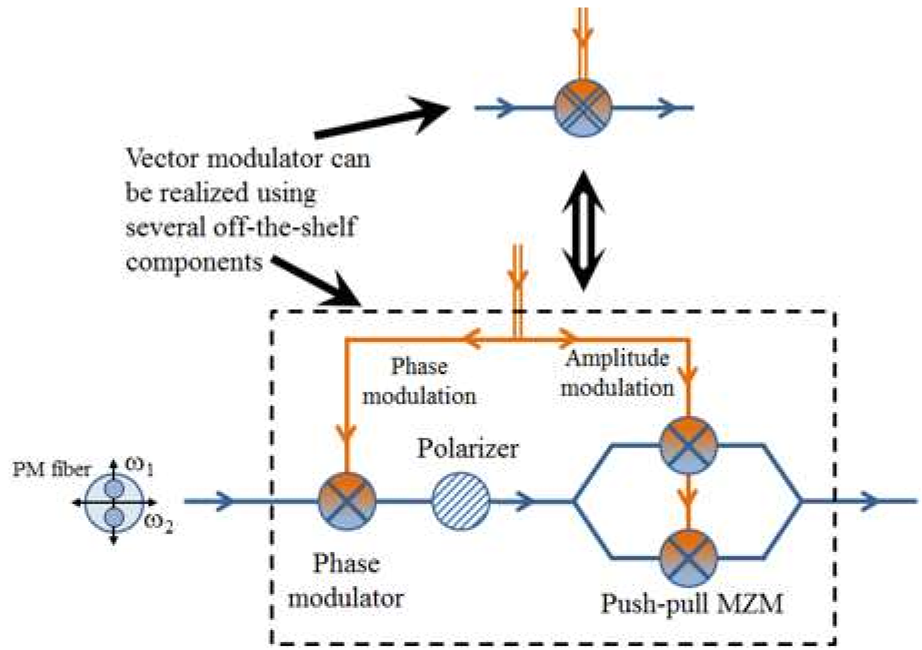

Figure 4.4: Vector Modulator Conceptual Design [31]

Once converted into an analog signal the RF wave profile is modulated into the carrier signal via the vector modulator. The vector modulator conceptual design (Figure 4.4) shows that there are several components; a phase modulator, a polarizer, and an amplitude modulator. As stated in the previous section, the optical signal being carried by the PM fiber carries beams in both the “slow” and “fast” axis. From the optical input, it enters the phase modulator which is made of Lithium Niobate. Lithium

Niobate is specifically chosen due to its polarization dependent electric optical coefficients. In Lithium Niobate the r_{33} polarization, which the *z* direction parallel to the applied electric field, has a coefficient of 33. The r_{13} direction has a coefficient of 10 meaning it under goes one third of a phase shift as the mode parallel to the E-Field causing two different modes to leave the phase modulator.

After leaving the phase modulator the two modes of the optical signal must then be tilted onto an axis of 22.5 degrees before being introduced into an inline polarizer. This is to ensure that equal **TE** and **TM** components of the E-field are keeping the strength of the E-Field uniform. However, in order to project the two beams into the same mode a loss in the optical strength is incurred, the cost in optical power is around a 3dB loss.

Lastly, the two modes will pass through a type of amplitude modulator, such as a Mach-Zender Push-Pull modulator as seen in the conceptual design. It is then the amplitude profile of the RF wave is imparted into the signal. At this point the signal has been encoded with the information being transmitted to the UE and is sent to the photo detector as described in Section 5.2. It is hoped that it will be possible to realize the design of the vector modulator on a single monolithic chip in order to reduce the size, cost and overall production time of the system. If able to utilize this method, the University of Delaware will attempt to control the amplitude of the modulation utilizing an adjustable polarizer instead of a set polarizer at 22.5 degrees. Changing the polarization from 22.5 degrees will affect the modulation eliminating the need for a Mach-Zender amplitude modulator.

4.4 Opto-Electronic MIMO Theory

To give an example of the theory behind the Opto-Electronic MIMO we will use the situation of two data streams being transmitted at the same frequency to two separate UE's. Assume the simplest case in which line of sight to the UE is available and that there is no scattering involved. As stated in the previous section $D_n(t)$ represents a symbol to be transmitted. One can have *n* data inputs organized into a vector. Through linear matrix multiplication the channel encoding can be performed through the equation:

$$\vec{F} = \vec{X}\vec{D}, \ \vec{D} = \begin{pmatrix} D_1 \\ D_2 \\ \vdots \\ D_N \end{pmatrix}, \ \vec{F} = \begin{pmatrix} F_1 \\ F_2 \\ \vdots \\ F_M \end{pmatrix}.$$

$\vec{F}$ represents the vector complex numbers in which yield the proper RF beamforming profile. $\vec{X}$ represents the channel-state information of the data streams. The representation of the complex numbers take the form of real (amplitude) and imaginary (phase) values. The phase values can be written as the following:

$$2\pi\frac{d_s}{M}, 2\pi\frac{2d_s}{M}, 2\pi\frac{3d_s}{M}, \dots, 2\pi\frac{(M-1)d_s}{M}, 0.$$

In this equation, *s* represents the number signal being sent to the corresponding UE, in this scenario *s* is either 1 or 2 with only two UE's being active. We begin to formulate the equations that create the RF wave profile:

$$\vec{D} = \begin{pmatrix} D_1 \\ D_2 \end{pmatrix} \qquad \vec{X} = \begin{pmatrix} \exp\left(2\pi j \frac{d_1}{M}\right) & \exp\left(2\pi j \frac{d_2}{M}\right) \\ \exp\left(2\pi j \frac{2d_1}{M}\right) & \exp\left(2\pi j \frac{2d_2}{M}\right) \\ \vdots & \vdots \\ \exp\left(2\pi j \frac{Md_1}{M}\right) & \exp\left(2\pi j \frac{Md_2}{M}\right) \end{pmatrix}.$$

Taking these equations and applying them to the complex value *F* from before we find that the complex input to the modulators. However, considering the interaction of the vector modulator with the photodiode one must multiply the equation by the RF carrier $\exp(j\Omega t)$, which results in the equation:

$$\vec{F} = \begin{pmatrix} D_1 \exp\left(j\Omega t + 2\pi j \frac{d_1}{M}\right) + D_2 \exp\left(j\Omega t + 2\pi j \frac{d_2}{M}\right) \\ D_1 \exp\left(j\Omega t + 2\pi j \frac{2d_1}{M}\right) + D_2 \exp\left(j\Omega t + 2\pi j \frac{2d_2}{M}\right) \\ \vdots \\ D_1 \exp(j\Omega t) + D_2 \exp(j\Omega t) \end{pmatrix}.$$

To demonstrate modulating with this system, consider now the simplest form of modulation, On-Off Keying modulation. In this form of modulation, the data inputs D_1 and D_2 can only take one of two values, 0 (off) or 1(on). If both D_1 and D_2 are 0 then the antenna system is "off" and there is no wave being transmitted from the antennas, meaning the corresponding UE will receive no wave or a 0. If on the other hand D_2 is on, then the antenna will transmit the waveform:

$$\vec{F} = \begin{pmatrix} \exp\left(j\Omega t + 2\pi j \dfrac{d_2}{M} \right) \\ \exp\left(j\Omega t + 2\pi j \dfrac{2d_2}{M} \right) \\ \vdots \\ \exp\left(j\Omega t \right) \end{pmatrix}.$$

This same theory can be used in more complicated situation such as QAM modulation, or in situation in which line of sight is not available. This includes a system or design in which more than two data streams are being transmitted or a system with more than two antennas as adding each to the preceding equations is summed into the overall complex value of $\vec{F}$.

4.5 Summary of Opto-Electronic MIMO System

With an exponential rise in data rate usage and it is critical to begin researching the next generation of wireless communication technology. The overused bandwidth available to a rising consumer base will cause a slowing of data transmission speeds and bog down the communication networks that are currently in place. The Opto-Electronic Multi-Input Multi-Output is one of the many solutions currently under research that could help alleviate this strain on the bandwidth.

With the Opto-Electronic MIMO one is able to utilize all of the best aspects of Optical, Digital, and Analog processing of data. With optical inputs, one will have a lower insertion loss, lower interference, and lower attenuation levels over currently existing methods such as coaxial cables. Fiber optics are also much smaller, weigh less and due to their efficiency draw less power thus being cheaper over a long period of time. With the digital processing of the complex vector wave profile one is able to quickly change the profile of the RF wave and handle multiple beams at the same time, allowing for tracking of multiple targets. The analog components of the system allows for the overall design of the MIMO system to be cheaper, smaller in design, and less complex to operate. It will also give the user pin-point precision of the beam steering technology. When used in conjunction with the Tunable Optical Paired source it also has the ability to reach frequency ranges of up to 90 GHz and possibly even beyond. Having such a wide range of operation would open up a new untapped potential bandwidth supply opening freeing up wireless communication systems for years to come.

Chapter 5

OPTO-ELECTRONIC MIMO TRANSMITTER APPLICATIONS

The Opto-Electronic Multi-Input Multi-Output Transmitter has numerous potential applications in all aspects of life. The MIMO Transmitter is a commercially viable design that could be used to either create new technologies or be implemented into currently existing technologies to expand their current operating capacities. Wireless Communication companies would be able to implement the MIMO system allowing a continued effort to advance from a 4th Generation network into the realm of 5th Generation. Research institutions specializing in Meta-Material research would be able to implement aspects of the MIMO transmitter to allow for discrete beam steering and a reduction in both size and power consumption. The MIMO transmitter could also see potential military application in two different fields. In communications, it would see application in naval vessel communication systems and Electronic Warfare (EW) defensive suites. On the battlefield, it is possible for the MIMO transmitter to see use in devices used for Non-Lethal target eliminations that operate in the range of 90 GHz such as the Active Denial system and any potential system derived from it. These are just a few of the countless areas of research that would benefit from the continued research of the MIMO Transmitter system. It is the hope of the University of Delaware that Industry, The Department of Defense, and other academic research institutes are able to recognize the potential of the Opto-Electronic Multi-Input Multi-Output Transmitting Antenna System.

5.1 Industrial Applications

As stated in Section 4.4 Multi-Input Multi-Output transmissions systems were and continue to be, a vital element in wireless communications today due to the emergence of the 4G network and the continued improvement of data rates compared to increased congestion caused by consumer usage. The developed Opto-Electronic MIMO system could be easily implemented into already existing industrial uses of current MIMO technology as current MIMO technology often does not utilize optical processing, which has reduced loss, interference, and is cheaper overall then your standard coaxial inputs. The introduction of the Opto-Electronic MIMO system in place of current existing technologies would not only boost the efficiency and capabilities of current communications technology, it would also be more reliable and easier to manufacture on a mass scale, with the vector modulator being capable of being realized on a single monolithic chip.

The Opto-Electronic MIMO system would also be crucial when advancing 5G wireless networks. This is due in part because of the tunable optical paired, the source system that be paired with the Opto-Electronic MIMO transmission system. The vector modulator can support as high or as low of a frequency carrier as is supplied by the source, the Opto-Electronic transmission system has a much larger range of operation than a standard MIMO system. [21] With an operating range anywhere between 0.5 GHz and 90 GHz there would be an untapped source of bandwidth that the system can provide. This along with simultaneous transmission of signal to multiple UE's and the ability to quickly adjust the frequency of the signal carrier make the Opto-Electronic Transmission system capable of improving an already well understood 4G network.

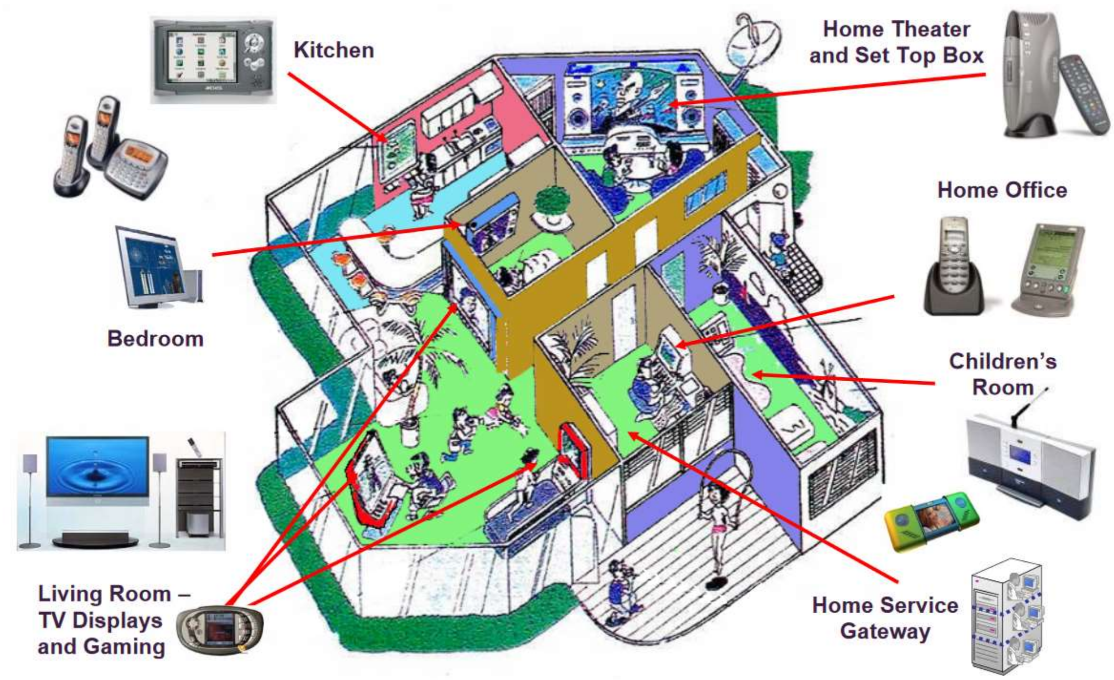

Figure 5.1: Common Household Wireless Enabled Devices [32]

The Opto-Electronic MIMO system would also be able to upgrade currently existing fiber optic based internet and Wi-Fi enabled technologies. Considering how many different Wi-Fi enabled devices are available to a consumer, at prices most can afford, the data channels have become bogged down because current technology is unable to support the sheer number of devices that require connections to data sources. The Opto-Electronic MIMO would be an upgrade to such systems due to its ability to quickly steer its data transmitting beams between receivers. With a near instantaneous steering capability, the MIMO system is able to transmit the data requested by the receiver with minimal loss. This will limit the time required by the transmitting device to relay the information requested by the receiver which will reduce power and help eliminate unnecessary bandwidth usage by the transmitter.

5.2 Applications within Meta-Materials

Another area of interest in antenna technology involves the use of new materials to influence the direction of propagation. This field of research is known as Meta-Material Enabled Antenna Arrays. [29] Meta-Material Enabled Antennas, by definition, is the use of novel materials with unique electric properties to enable near negligible transmission loss of signal.

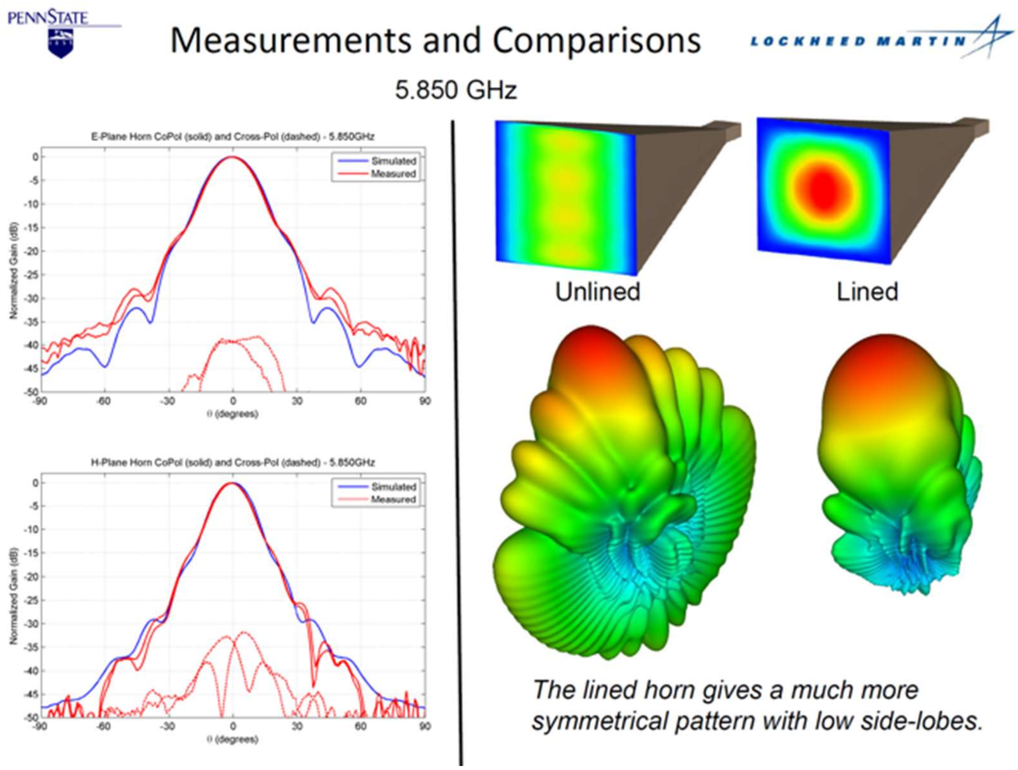

Figure 5.2: Comparison of Transmission loss due to side lobes (Non-MM enabled Left, MM Right) [33]

Universities such as Penn-State have been looking into the use of meta-material enabled antennas for both military and commercial application. One of the benefits of these new and unique materials are capable of creating a near negligible loss antenna array. Figure 5.2 demonstrated the difference in transmission loss between a non-MM lined antenna and a MM enabled antenna. In non-MM enabled antennas, the transmitted field loses strength because the field is unbounded in the Y direction thus side lobes to developed. This reduces the overall range of the antenna and requires a greater power input to ensure the signal is strong enough to reach its intended receiver. One way to reduce this loss is to line the top and bottom of each antenna with a Meta-Material designed to allow for electric current to flow through it.

Such is the design of one Meta-Materiel antenna being created at the Penn State University. The antenna uses a wire material to line the top and the bottom of the horn antenna that is capable of conducting an electric current. One is then able to direct the field by increasing or decreasing the electric charge as seen appropriate for the application of the antenna horn. Figure 6.3 shows this design in application to an existing antenna systems. This antenna system was used in order to come up with the results that were used in Figure 6.2 to compare losses of MM-enabled antennas vs Non-MM enabled antennas

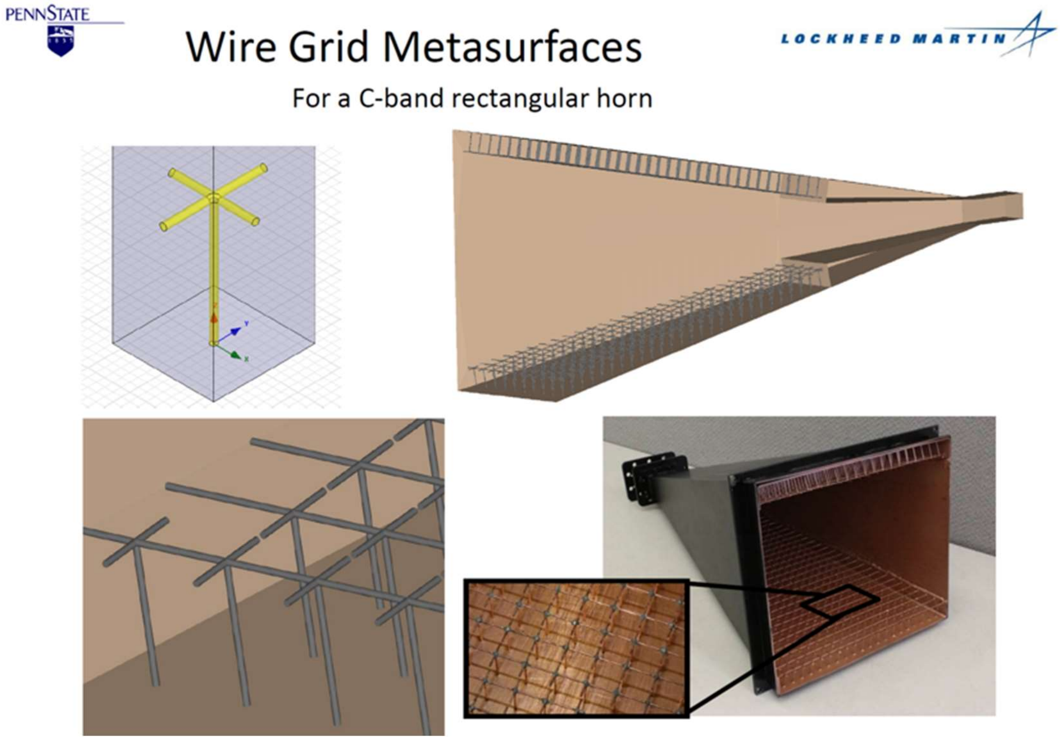

Figure 5.3: MM-Enabled Antenna Conceptual Design [33]

It is possible to use the vector modulator in these sorts of application to allow for a greater potential of each antenna array. In current designs Penn State is looking to create an MM-Enabled Antenna in which the RF beam is driven by phase controllers that are mounted on top of mechanical actuators. If however, one replaced the phase controlling mechanical actuators with vector modulators it would be able to create a system with all of the following benefits. Low loss feed paired with analog steering, broadband with multiple RF frequencies simultaneously, simultaneous beamforming, condensed size, and a frequency range limited only by limits of photodiode. The introduction of the vector modulator into a system such as this would allow for a much greater potential while taking advantage of the unique capabilities of meta-materials.

5.3 Military Communications and Non-Lethal Applications

A system such as the Opto-Electronic Multi-Input Multi-Output system would benefit the US armed forces as both a form of communication and as a potential use in Non-Lethal Weapons Technology. It would be able to operate at a frequency level that allows for use as a Non-Lethal weapon (95 GHz) in systems such as the Active Denial System (ADS) and the Radio Frequency High Powered Microwave Vehicle and Vessel Stopper. [30] Both systems utilize electromagnetic signals as a form of deterrent to enemy combatants. It is crucial to develop the means to fill the gap between verbal warnings and physical violence at potential enemy combatants. Meanwhile the military is making strides in creating a personal sensor platform that could be used to monitor soldier vitals on the field of combat and provide real time updates on squad conditions, which could be further enabled by a MIMO system such as the Opto-Electronic MIMO system.

On the field of battle, it is crucial for up to date status on all soldier's current situation, both mentally and physically, be carefully monitored in case of injury and need of immediate attention. In order to do this the military has begun research on personal monitoring platforms designed to constantly communicate with the forward base, sending information on soldier status over the period of an operation. [31] Current extractions depend on verbal communication from squad leaders as to the physical status of an injured soldier. Creating a system to constantly monitor those vitals during an operation would allow for evacuation to be deployed the moment command sees a soldier is critically wounded, or if the whole squad has for some reason been incapacitated and has no ability to communicate with command. The Opto-Electronic MIMO system would allow for such a system to exist, as it would allow for the capability of command systems to communicate with multiple personnel vital monitoring units at once allowing for command to make quick and informed decisions in the best interest of all military personnel involved with the mission.

The Active Denial System is a major project in creating a Non-Lethal riot suppression device designed to have no permanent health detriments. The ADS would see over sea uses in areas where terrorism is of particularly high concentrations. The ADS functions as a "portable" directed energy weapon that produces a beam that operates in the L, S, or W bands. A beam with a diameter of one meter is than directed towards the intended target. This beam than penetrates the skin to *1/64^th^* of an inch to reach the pain sensors of the body, the Nociceptors. The Nociceptors are then heated up by the beams penetration of the body causing a burning sensation that causes the target to flinch and react to trying to get away from the "fire" their body is being subjected to.

Figure 5.4: The conceptual idea of operation (left) with current ADS design (right) [35]

The ADS system, however, has several drawbacks that make it less ideal to operate on the field of battle. As seen in the preceding figure the ADS is extremely bulky and must be mounted on the back of a vehicle. The entire system itself is very complex because of how difficult it is to form beams in the L, S, and W bands. For this reason, it is too expensive to produce on a mass scale and has an extremely high power consumption. This makes it impossible to miniaturize such a device to be capable of being hand-held by foot soldiers. Another drawback in performance involves the reaction time between beam contact and human deterrence. Once the beam makes contact with the human target it takes time for the Nociceptors to realize that the human body is in pain, thus there is a gap in time allowing for the target to act normally for up to two seconds (3). Introducing the vector modulator and the Opto-Electronic system into such a system would allow for a reduction of current size of the system allowing for it to be mounted on standard Humvee transport systems instead of much larger vehicles. The Opto-Electronic system would also reduce the power consumption of the system and thus reducing the overall cost. Lastly, if used in conjunction with a Planar Radiation Antenna System, it is possible to negate any delay in reaction from the Nociceptors by "painting" a large area with a less concentrated beam in order to begin heating up the Nociceptors. From this point using the Opto-Electronic system to then pinpoint the desired target and they will feel the effects immediately of the ADS system. It would also be possible to target multiple target utilizing the MIMO qualities of the Opto-Electronic system.

While the ADS system operates to neutralize human targets in an open field or who are operating a vehicle, it is not capable of physically stopping a vehicle from reaching its intended destination as the driver is still capable of operating the vehicle even under distress. The Radio Frequency High Powered Microwave Vehicle and Vessel Stopper System (RFVVS) is designed to stop a vehicle in its tracks by disrupting its internal electronic systems. It functions very similarly to the ADS as it forms a beam of high powered microwaves and points it at the vehicle in question. The high-powered microwave then disrupts the electronics of the engine and causes the vehicle to lock down and become immobilized until the beam is released from the target. At this point the vehicle is then able to operate as normal due to no damage being down to any component of the vehicle.

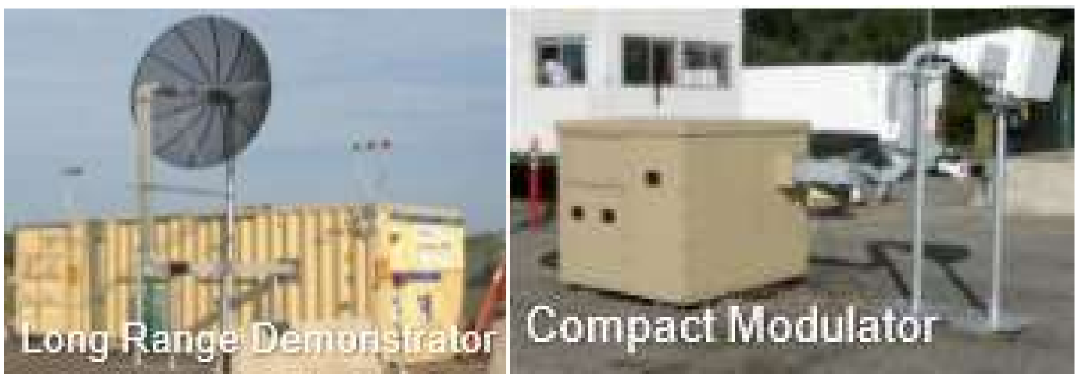

Figure 5.5: Laboratory Test System (left) vs Compact Modal (right) [34]

Several models of the RFVVS system have been created in an attempt to reduce both the size and the cost. The original laboratory test system, seen in the preceding figure, weighed up to 9,500 lbs. [30] More recent models have shown that weight down to can be reduced 4,500 lbs, however, in order for it to be capable of rapid deployment the goal weight of the system is set to about 2,000 lbs. This would allow for the system to be mounted on ground vehicles or even smaller water crafts, allowing for a highly mobile system capable of operating in almost any environment.

Much like the ADS introducing the vector modulator into the RFVVS system would potentially help the system slim down and reach its mark of 2,000 lbs. Not only that, but power consumption would be lower, cost of production would be much cheaper, and open up the system to the capability of becoming a multi-target acquisition system further creating more defensive possibilities.

While these are just a few of the multitude of systems that could benefit from the advancement of the Opto-Electronic MIMO, these systems stand to gain greatly if such a system was introduced into military use. Being used as both a form of communication and a potential avenue of Non-Lethal Weapons this system would be an advancement of current military defensive capabilities, protecting troops from further harm and reducing collateral damage on foreign soil.

Chapter 6

CONCLUSION

Today's modern society has seen an exponential increase of wireless data usage in the span of merely 20 years. This increase in data usage was predicted as far back as in the year 2000 where in William Webb's "The Future of Wireless Communications" Webb discusses the increasing traffic in wireless communications and the potential needs in the future years to come. [32] Below is a table listing some of the requirements when the book was written, compared to some of the requirements that he believes will be necessary in future years to come.

Table 6.1: Webb's Predications of Wireless Communication Needs [36]

	2000	2010	2020
To mobile devices	100 Kbps	1 Mbps	6 Mbps
To homes	1 Mbps	10 Mbps	60 Mbps
Within homes	1 Mbps	10 Mbps	60 Mbps

These predictions were made originally in 2000 and shows what he believes would have been the increase data usage through the year 2020. He states however that in order to achieve this level of speed in wireless communications the operating frequency must surpass that of 40 GHz in order to open enough bandwidth to accommodate the increasing population in the digital world. It is currently estimated that video traffic constitutes for approximately 51% of the mobile traffic volume in our day. Experts believe that that number could reach as high as 67% as Ultra HD (UHD) and 3D video. [24] With this said, we must look to the future of beamforming technology and increasing our capabilities in data transmission in order to create systems capable of operating at the higher frequency bands, enabling us to increase our bandwidth capabilities.

The future of beamforming technology lies not in creating a whole new method of transmitting data, but in taking the methods we currently have and combining them in new efficient ways. By utilizing digital and analog beamforming you are able to create systems that have the advantages of both methods while masking the deficiencies of each system. By taking advantage of the cheap, precise and simplistic designs of analog beam forming and meshing them with the diverse operating abilities of digital beam forming technologies. This concept is used often in Multi-Input Multi-Output systems which have enabled the jump into the 4G era of technology.

Moving forward, however, you can further enable these Multi-Input Multi-Output systems by exploiting the optical component of the transmission systems. Such as with the Tunable Optical Paired Source you are able to generate carrier signals that operate up into the realm of 90 GHz, which opens up the ability for transmitters to access a large cache of unused bandwidth that previously had been impossible to operate with before. Systems such as the Opto-Electronic MIMO system would help to enable 5G technology to become more widespread and commercially viable for the everyday household user.

The Department of Defense and Armed Forces would also benefit greatly from the enhanced capabilities of newer beam forming technology. The ability to operate at any frequency up to 90 GHz would open up many new secure channel capabilities for security sensitive information. Current technology such as the Active Denial System would be greatly enhanced by reducing the size and cost of the overall system, as well as increasing the performing capabilities of the system itself and allowing for potential multibeam propagation. This system is just one of many that would benefit from the creation of a highly diverse frequency range of operation of this newer technology.

It is the hope of the University of Delaware that through the research of the Opto-Electronic Multi-Input Multi-Output system that it will help introducing the era of 5G technology on a commercial basis. It has been demonstrated by many current wireless communication systems that it is essential to find a more efficient form of beam technology that will allow us to operate in the ranges and environments necessary without losses in signal transmission and fidelity of the information. Without the ability to effectively transmit data at higher frequencies data rates will continue to become bogged down as more wireless communications are introduced to the digital world due to growing demands in the market and cheaper more efficient ways of production.

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