2016

SENIOR PROJECT EE 460
MIMO Link

ELECTRICAL ENGINEERING DEPARTMENT

CALIFORNIA POLYTECHNIC STATE UNIVERSITY

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Abstract

The goal of this project is to utilize the multiple input multiple output (MIMO) wireless communication technique by incorporating multiple antennas to develop a 4x4 MIMO link. Ideally, this would consist of antennas at both ends of the link, 4 transmitting and 4 receiving. The MIMO system should then be able to send and receive a message signal. Additionally, at the various stages of the system, data can be acquired to observe exactly how the increase in the number of antennas affects the performance of the system to form an overall base of performance, from start to finish. MIMO addresses the capacity (capacity = b/s/Hz) issue with single input single output systems (SISO). The capabilities of MIMO communication systems as compared to a (SISO) is a linear improvement in capacity without increasing transmit power, the trade-off being complexity introduced through the multiple transmitters and receivers. In this type of communication system, the transmit power is evenly split between the antennas of the system. Furthermore, MIMO enhances the dimensions of communication through the use of multiple channels, so that bits can be sent in a parallel fashion. By using multiple channels, the same data can be sent through these channels to increase probability of successful transmission should one of the channels fail.. By developing a 4x4 MIMO link, the hopes are that the system will make a contribution by proving these theoretical concepts. Additionally, the system can later be used on campus for teaching purposes through demonstrations of its capabilities and functionality. Hopefully, it will inspire student curiosity by imploring them to develop their own unique and improved versions.

I. Introduction and Background

Wireless Communication Basics

Wireless communication utilizes the wave properties of electromagnetic fields. Figure 1.1 describes the basic means of wireless communication.

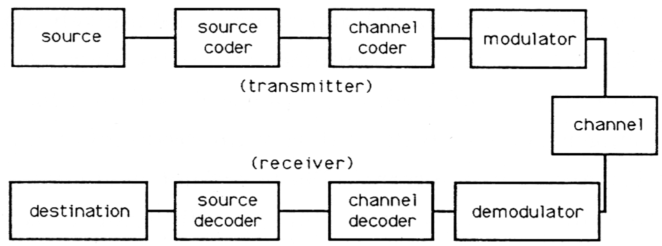


Figure 1.1: Wireless communication general diagram

The desired message is first encoded into a wave that optimizes the transmission medium. Next, the desired signal goes through the modulator and becomes the envelope function of the carrier frequency so that the data may be transmitted. The now modulated signal is transferred from the transmitter antenna to the receiver antenna using an electromagnetic wave. Once the receiver gets the signal it is demodulated and decoded using the same information the transmitter used to encode and modulate the signal at first. Once the signal is decoded the message from the transmitter has been transmitted to the receiver.

Wireless Communication's Main Problem

Wireless communication does not always deliver data to the receiver correctly. There are a few reasons for errors with the main one being multipath fading. Multipath fading is largely due to collisions between the transmitted signals and objects. The collisions between objects cause the signals to arrive at the receiver at different times. The delay between the received signals can cause parts of the original signal to be amplified or deleted due to the constructive and destructive interference of the signals. The interference causes multiple errors which makes the received message unusable.

II. Overview

MIMO addresses the need for faster and more reliable data transmission. The target customers for MIMO would be AT&T or Sprint to give them an advantage over Verizon in cellular device communication. Subsequently other customers like the military or satellite companies might want to buy our product if it works well.. The market would be communication solutions.

Product Description

Multiple Input Multiple Output (MIMO) communication system utilizes multiple antennas on both the transmitting and ends to send data accurately. The problem MIMO addresses is multipath propagation. Multipath propagation is one of the key reasons for fading. Figure 2.1 shows how transmitted signals hit obstacles and then converge at the receiver. The collisions between the signals and the obstacles cause the signals to arrive at the receiver at slightly different times. The delay causes some parts of the original signal to decrease or at times cancel out at the receiver. These changes in the signal cause the signal to noise ratio (SNR) to decrease, which means the number of errors that occur while transmitting increases. MIMO communication systems, shown in Figure 2.2, create different signals by using multiple antennas on both the transmitting and receiving ends. These antennas make the SNR extremely small so the data can be received very accurately compared to other types of communication systems.

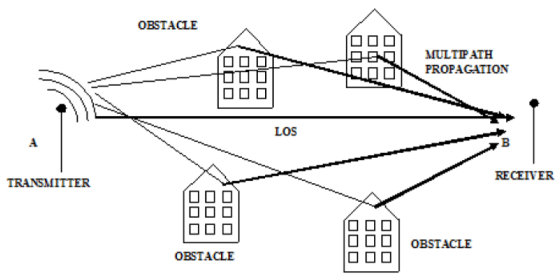


Figure 2.1: Multipath propagation illustration

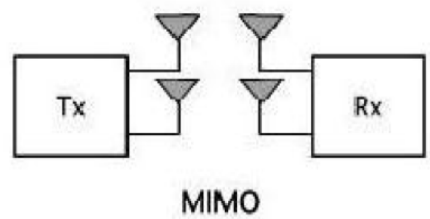


Figure 2.2: 2x2 MIMO communication system

For this senior project, a 4x4 MIMO link should be constructed; this will consist of 4 antennas on both the transmitting and the receiving end. This project is more research based than it is a consumer product, so the goal is to take all the theoretical knowledge obtained through research and prove the capabilities a MIMO communication system. As mentioned in the abstract, as the project proceeds the goal is to collect data as the size of the MIMO link grows (at 2 antennas, then 3 ect.) and observe how increasing the link up to four antennas affects communication parameters such as power consumption, the SNR and the capacity of the communication link. Finally, once the final 4x4 link is constructed, the deliverables will consist of the system and data acquired at various stages of the project that will hopefully show that as the number of antennas grew, all these parameters met expectations (power remained constant, SNR decreased, and improvement on the capacity of the communication link).

Market Research

Present solutions are currently single input single output (SISO), multiple input single output (MISO), and single output multiple output (SIMO). Figure 3.1 describes the different ways the different communication systems transmit information over a distance. SISO uses only one transmitter and receiver, which is inexpensive, but the reliability of the transmitted data is poor because the data is very susceptible to interference. To get a greater improvement multiple antennas are introduced. SIMO and MISO incorporate multiple antennas on the receiver and the transmitter end, respectively.

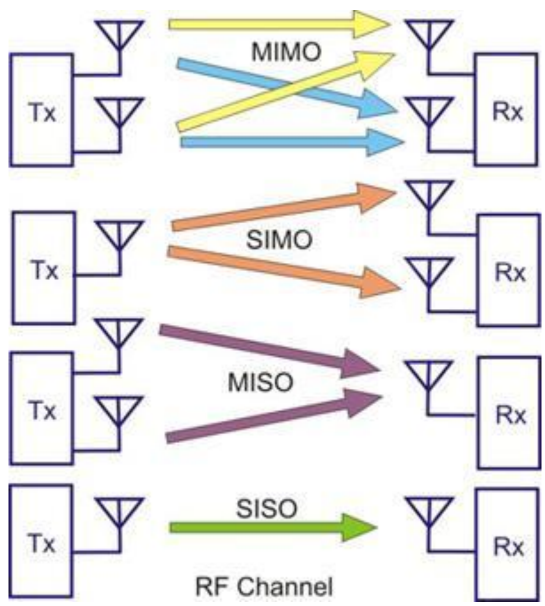


Figure 2.3: Comparison of different communication types

SIMO is the forefront of communication because it is very easy to implement and fading can be minimized using listening stations to negate the effects of interference. However, the main drawback is there is a more processing power required at the receiving end. To fix this problem and make cellular communication more realizable MISO was created. MISO forces the complexity and processing power on the transmitter end of the communication system by having multiple antennas only on the transmitter side.

MIMO is different because it uses multiple receivers and transmitters. Since MIMO uses multiple devices on the transmitting and receiving ends the number of channels is exponentially higher than the competing solutions. The large number of channels makes the signal to noise ratio (SNR) much greater than SIMO and MISO. Furthermore, MIMO operates under constant power where the power is evenly split between the multiple antennas; the drawback in increased SNR comes from the increased complexity of the system.

Historically, MIMO has played an important role in the advancement from 2G, to 3G, to 4G with the next advancement (5G) projected as early as 2020. The advancement periods have followed a consistent time frame of about 10 years. This is an important fact as estimates made by the Pew Research Center now determine that over 90% of adults in America now own a cell phone, and cell phones are quickly becoming the most adopted consumer technology in the history of mankind. Clearly, a MIMO system that promotes advancement into the next generation of communication has the potential of being very successful.

III. Customer Archetype

The findings of our research can be marketed primarily to cellular service providers. What we are developing and selling will not affect the daily life of our customers, however it will greatly impact our customers' customers. Our findings on MIMO will allow for advancements to be made in digital communications; this will allow for major improvements in modern cell phones. Many of the problems cellular service providers face deal with 'coverage' (this refers the amount of geographical area the cellular service provider can provide service). The findings in MIMO can allow cellular companies to expand their coverage due to the mitigation of multipath. As an example, Verizon Wireless which provides wireless communication services such as broadband, LTE and 4G communication relies on a strong communication network to provide all these services, plus stay on top of the market.

The MIMO communication theory is a well-known concept that is already in use by some powerful contenders of the communications market. Four organizations are given below that incorporate MIMO into their products and services. These four companies are all original equipment manufacturers that offer strong communication products (such as antennas, access points, ect.) that may be contracted by big companies such as AT&T or Verizon.

Organization
NetGear
EION
Charter Spectrum

Aruba

In terms of the size of the market, the assumption is made that MIMO will eventually become a dominant system to the point of becoming the future of communications. MIMO will most likely push older systems of communication such as SISO and MISO to become obsolete. With this assumption, it is likely that top communication service providers such as AT&T[12], Verizon Wireless[13], Motorola (among other Fortune 500 companies) that each operate in the customer base of over 100 million will push the MIMO market into a possible 500 million customer base just from these companies alone. The customer base levels of these companies were obtained from their websites' investor relations documents.

Expanding outside of these companies, there are nearly 7 billion people in the world and an estimated 6.8 billion people use cell phones. Naturally, there are many companies competing to develop the main communication method used in the modern cell phone. This market is considered to be so large due to how many people its products will affect. It is a safe assumption to make that the number of people using cell phones will increase. We can also assume that of the people currently using cell phones, the majority of them will upgrade to a new cell phone in the future. These assumptions state that the market for cell phone use will only increase. A study from Pew Research Center showed that in 2011 35% of U.S. adults had smartphones; as of October 29, 2015, the percentage of U.S. adults using smartphones increased to 68%.

IV. Market Description

Detailed description of Product

Ultimately, the goal is to achieve a 4X4 MIMO system. Currently T-Mobile has the fastest coverage using a 4X4 MIMO system; which allows for 4G LTE coverage. A 4X4 MIMO system will allow for the fastest and broadest coverage of any other wireless data transmission technique. The main advantage of having a MIMO communication system is it may solve the issue of multipath. Multipath occurs when there are multiple paths for a transmitted signal to travel along; this causes the signal to arrive at the receive end at different times causing interference. MIMO can be implemented by using several antennas at the sending end and the receiving end. The more antennas, the higher the signal throughput will be.

Current Limitations on Wireless Communications:

In previous techniques for wireless communications, people have struggled to transmit data with high SNR and high resolution. Many techniques encounter the issue of 'multipath'; multipath is defined by transmitted signal reaching the destination by the means of more than one intentional path. This can be an issue when it comes to signal clarity. Multipath may cause various types of interference as well as phase shifting. This can cause many issues in successful signal transmission. Another issue in wireless communications is energy consumption; many current methods for wireless communications consume quite a bit of power. Traditionally, signal capacity in a single-input-single-output system can be generalized by the Shannon's Law, the theoretical error-free channel capacity: $\text{Capacity}=BW\log_2(1+SNR)$. This suggests that to achieve a high signal capacity, one could simply increase the bandwidth or signal-to-noise ratio. However, increasing the bandwidth makes the signal more susceptible to be distorted from multipath fading. Also, cell phone providers may not be able to acquire a large bandwidth frequency band; the Federal Communications Commission (FCC) regulates the frequency bands in the United States to avoid conflict. This entails that cellular providers cannot simply use a large bandwidth exceeding their licensed bands without violating the FCC rules. As for increasing signal-to-noise ratio, power amplifiers are very expensive-both to purchase and to operate. To put into perspective, 1% of the world's power consumption is in power amplifiers alone. The tradeoff of increasing power is not worth the increase in capacity. For example, a 10% increase in signal-to-noise ratio has a smaller increase in capacity than a 10% increase in bandwidth.

Key Strengths of MIMO:

MIMO uses antennas and multiple paths to achieve a clear signal; essentially, it can use the issue of multipath to its advantage. MIMO can mitigate the multipath issues by requiring that the signal must propagate along various signal paths intentionally. This suggests that the more transmit and receive antennas, the clearer the signal will be. The reason for this is that with more antennas, the less unintentional paths available. The issue of multipath is present in almost all other forms of wireless communications.

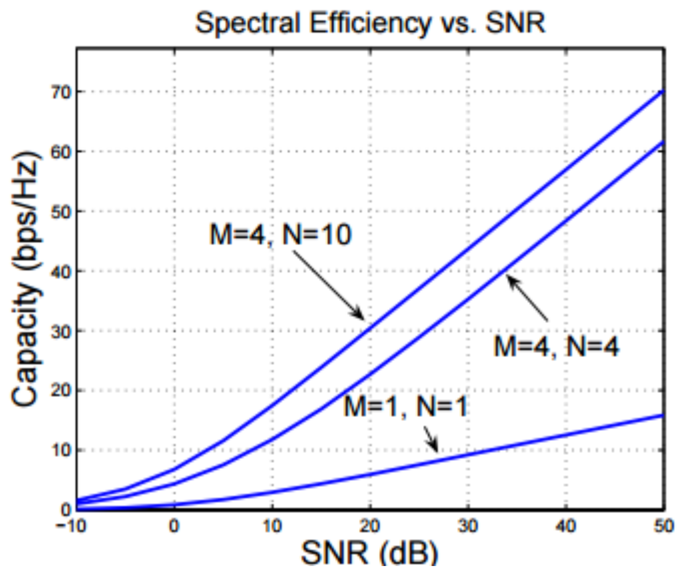


Figure 3.1: Capacity versus Signal-to-Noise Ratio. M signifies number of transmitters, N signifies number of receivers. For the case where M=1 and N=1, the system is a SISO system.

The key difference between MIMO and SISO in the relationship between signal-to-noise ratio is that a MIMO system has a linear relationship between capacity and signal-to-noise ratio, whereas a SISO system, the traditional system, has a logarithmic relationship denoted by Shannon's limit mentioned earlier. This results in a higher capacity when using a MIMO system. Using more transmitters and receivers results in higher capacity for the same amount of signal-to-noise ratio.

Not well-serviced areas of the market:

Looking at some of the network providers in other countries it can be seen that there are a couple of companies that still do not provide top network solutions such as LTE and 4G. These companies would benefit greatly from the MIMO communication system as it would propel them to more high tech technology. These companies would be ideal targets of the MIMO communication system[11].

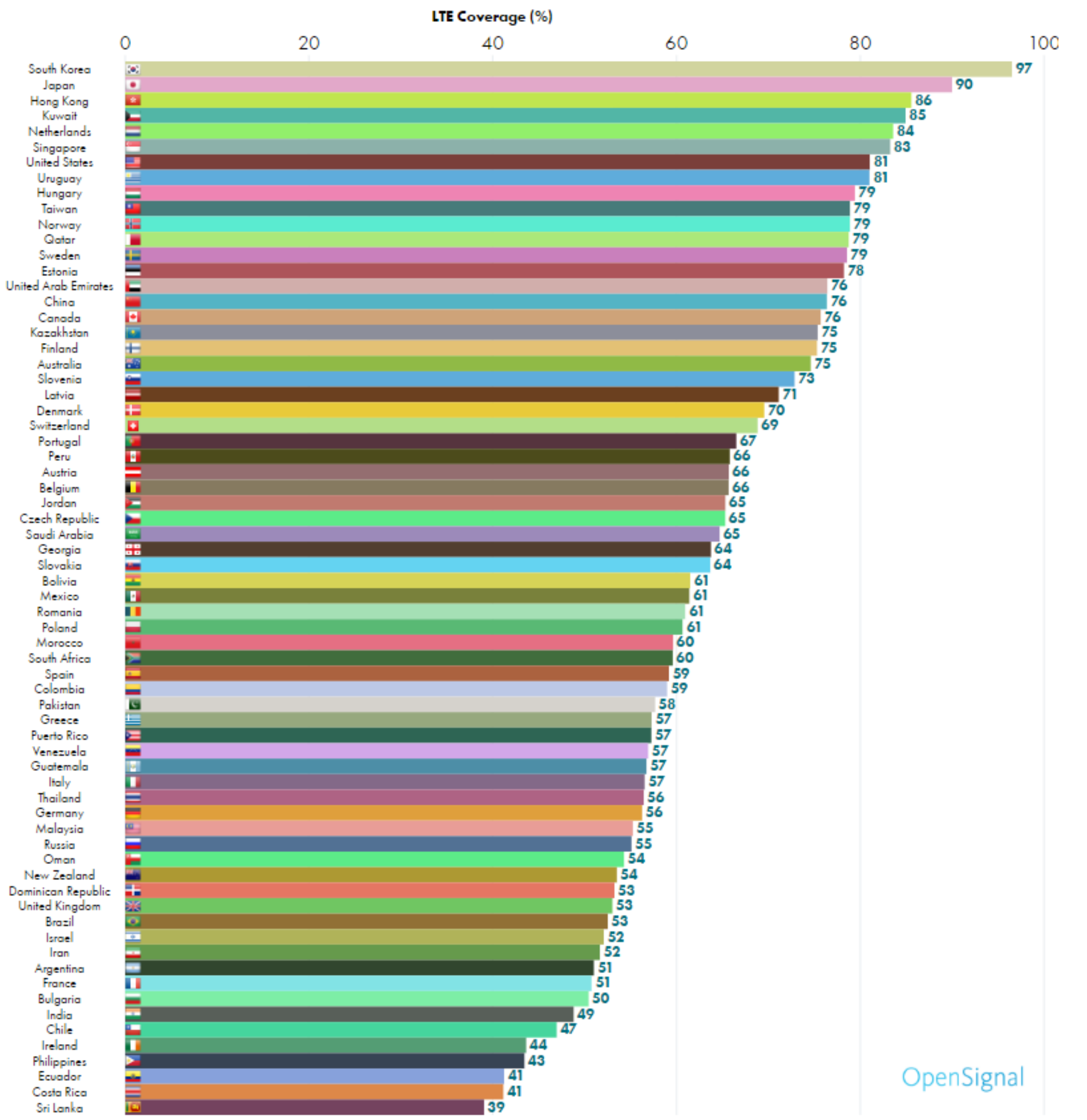


Figure 3.2: LTE Coverage, documented by OpenSignal in Q3 of 2015

The 4G LTE system is capable of MIMO communications. Currently the best targets would be companies in countries with little LTE coverage[14]. Some companies include Vodafone, Orange, and Telekon. These companies operate in multiple companies so collaborating with them will help facilitate the expansion of MIMO technology in new countries.

Window of Opportunity:

The window of opportunity for MIMO is a little abstract if marketing to cellular providers. Let's start with what will happen if MIMO were to be implemented into cellular communication: If it proved to be a useful means of data transmission, cellular providers and phone designers would need to make changes such that MIMO could be accommodated. This could be a relatively slow process waiting for everyone to get a new phone with MIMO capabilities. Currently, 15% of the phones on the market are able to use 4G LTE technology, a standard capable of utilizing MIMO. It will take years for users to turn-over to phones with MIMO capability.

Essentially, the window of opportunity for our product is now until most people have phones with MIMO capabilities. MIMO is a technique that can obtain 5G data transmission. Currently, the majority of people have phone with 4G LTE capabilities. This means that cellular service providers would be willing to purchase our product now; this is why we say that the window of opportunity is currently open. The article "Long Term Evolution: Simplify the Migration to 4G" by Cisco explains the events that followed once 4G was introduced into a world running on 3G. Complete transition from one level to the other can take over several years. Assuming a similar transition from 4G to 5G means the window of opportunity could remain open during this transition period of several years. This window will close once MIMO has been introduced to cellular service providers. The figure below displays that 5G will be available to consumer phones in the 2020s. For comparison, 4G LTE is a very recent technology, not appearing in many smartphones until 2014 and 2015. Some estimations predict that 5G technology will be in the hands of consumers around 2026, as seen in Figure 3.3.

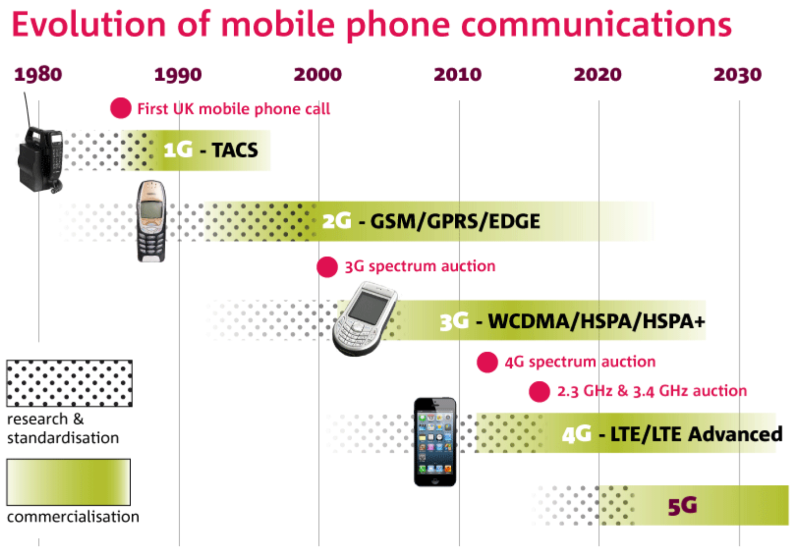


Figure 3.3: Predicted Time Line of 5G technology commercial launch.[15]

Key Partners:

The key partners for us in the archive of this MIMO project are companies that build wireless electronic parts, as well as software and analysis tools. Although Keysight is not sponsoring this project, they will be one of our main potential partners. Keysight has a software simulator called SystemVue which will play a major part in the design and simulate part of our MIMO project. SystemVue allows for us to implement design theories and testing their parameters without actually building the design with actual hardware. Keysight also creates Vector Signal Generators (VSGs) and Vector Signal Analyzers (VSAs) which will be used to test and characterize our final design. The VSA can be used to analyze modulated signals; this is especially useful when characterizing the transmit end of our MIMO project. The VSA will be used to characterize components like the oscillator or the antennas.

We will need various hardware parts to complete this project. It is essential for us to partner with companies that supply hardware components like Digikey, Mini-Circuits, Skyworks, Texas Instruments, etc. These companies will help when it comes to physically building our device.

Potential Customers

Due to our product not being one that a consumer would purchase, we have a very specific and selective market. For starters, the main customer for our MIMO product may be cellular service providers such as AT&T, Sprint, Verizon, etc. We would primarily market to the second most successful service provider like AT&T or Sprint. The reason for this is that they may be willing to pay more in order to become the top provider with the most coverage. Marketing to a company like Verizon may promote a monopoly.

Another potential customer of MIMO may be the military. Marketing to the military is very different than marketing to a cellular service provider in that they do not have competitors we would want to sell to. Marketing to the military, we would want to show them how and why our product is more valuable than any other they could potentially use. The two branches of the military that could benefit from MIMO are the Air Force and the Navy. These two branches of the military are constantly relaying information back and forth. MIMO signals can be encoded which allow for only the intended recipient to be able to decode it. The benefits of MIMO, however, are not limited to the Air Force and the Navy.

Advantages and disadvantages of MIMO

Data throughput and range can be increased while power consumption stays relatively constant. As discussed earlier, what makes MIMO better than many other wireless communication techniques is that it can potentially eliminate the issue of multipath propagation. It can achieve this by using multiple antennas at both ends to eliminate the unintentional paths for the transmitted signal to follow. The more transmit and receive antennas, the higher the signal throughput. This implies that to have the highest signal throughput, one would want to increase the amount of inputs and outputs, however, this can become an issue. The main issue with increasing the number of antennas is it means we will need a lot more room than SISO implementation.

V. Business Model Canvas Graphic

The Business Model Canvas

Designed for: MIMO Link

Designed by: William Tran, Patrick Kezer, Jeannie Whitmore, Rodrigo Mendez

Date: 11/28/16

Version: 2

Key Partners

- United States Telecommunications Companies
  - AT&T
  - Verizon
  - Sprint
- European Telecommunication companies
  - Vodafone
  - Telekom
  - Orange
- Measurement and Simulation
  - Keysight
    - SystemVue software to simulate system
    - Purchase network analyzers, vector signal analyzers, vector
  - Anritsu
    - Purchase network analyzers, vector signal analyzers, vector
- Hardware
  - Digikey, Miini-Circuits, Texas Instruments

Key Activities

- Customer Visits
- Consultation and Design
  - Existing and new designs
- Exposure at Conferences
  - Internation Microwave Synopsium (yearly)
  - European Microwave Conference (yearly)
  - International Conference and Business Expo on Wireless & Telecommunication (yearly)

Key Resources

- Hardware and Software Research and Development
- Applications & Marketing
- Measurement Hardware
  - Vector Signal Generators
  - Vector Signal Analyzers,
  - Vector Network Analyzers
- Design Software Licenses
  - Advance Design System
  - SystemVue
  - EMPro
- Intellectual Protection
- Financial Grants, loans

Value Propositions

- MIMO, optimizes speed, range and reliability of wireless communication versus older communication models.
- Assist telecommunication companies to become a leader in the next generation of communications standards; be faster and more furious in the 5G environment.

Customer Relationships

- Personalized relationship
  - Emails, visits to the customer's company
- Mass customization

Channels

- Web Platform
  - Webinars
  - Social Network
- Traditional media & community media
  - Press releases
  - Magazine articles and advertisements

Customer Segments

- Main: Telecommunications Service Providers, in prospective launch order
  1. United States:
     - AT&T
     - Verizon
     - Sprint
     - Virgin Mobile
  2. Europe
     - Vodafone
     - Movistar
     - Telekom
     - Orange
     - Telia
     - O_2
  3. Russia
     - MTS
     - MegaFon
     - Beeline
  4. China
     - China Mobile
     - China Unicom
     - China Telecom
  5. India
     - Airtel
     - Vodafone
     - Idea Cellular
- Secondary: Internet of Things
  1. Wi-Fi, Bluetooth Products

Cost Structure

- Fixed Costs (salaries)
- Web Maintenance - $6000/year
- Advertising
- Rent and Occupancy Cost
- Travel and Business Relations Costs
- Licensing

Revenue Streams

- Sales of Antenna Designs
- Sales of Transmitter and Receiver Hardware Designs
- Consulting Services
  - Be contractors to companies for modulation/signal processing assistance

VI. Marketing Requirements

MIMO Link	Channel
2x2	Cable, Wireless
3x3	Cable, Wireless
4x4	Cable, Wireless
4x2	Cable, Wireless
4x3	Cable, Wireless
4x4	Cable, Wireless

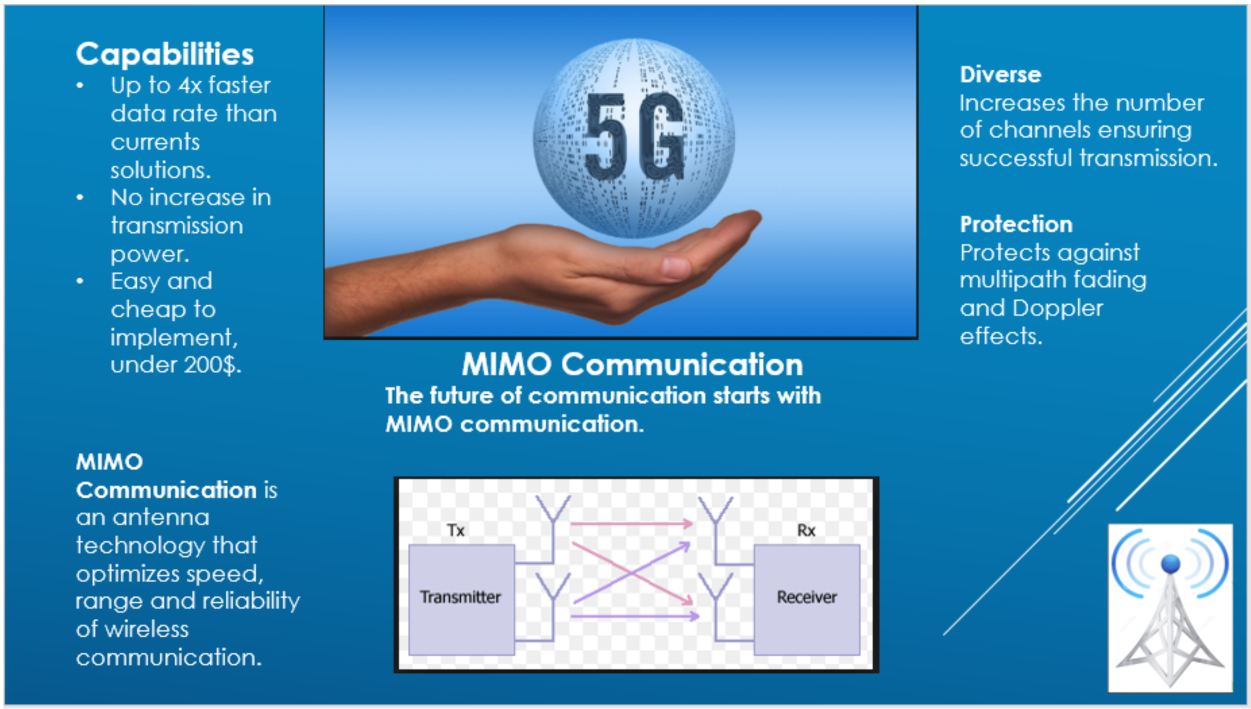
Table 5.1: MIMO Link and Channel Testing

The team will design the following systems in the above table. The more specific details are listed below.

Frequency specification:

Frequency of MIMO transmitters and receivers will be chosen in-between 100 MHz and 6 GHz in amateur radio bands to satisfy FCC communications standards and available measurement equipment. 2.4 and 5GHz are filled with Wi-Fi. 1.3 GHz is satellite GPS. Choosing a band with outside interference may save cost on designing a jammer or interference.

Marketing Datasheet:



Cost & Design

Less than $200 for transmitter and receiver system. This includes amplifiers, splitter, 2 to 5 antennas on the transmitter side. On the receiver side, a low-noise amplifier, splitter, and 2 to 5 antennas will be needed. Amplifiers should provide 10 to 15 dB gain. Noise figure should be under 5 dB. Cables should be tested at different lengths: 50 cm, 1 m, 1.5 m, 2 m. If the board does get to PCB layout, a micro strip-splitter maybe useful to create an n-way splitter.

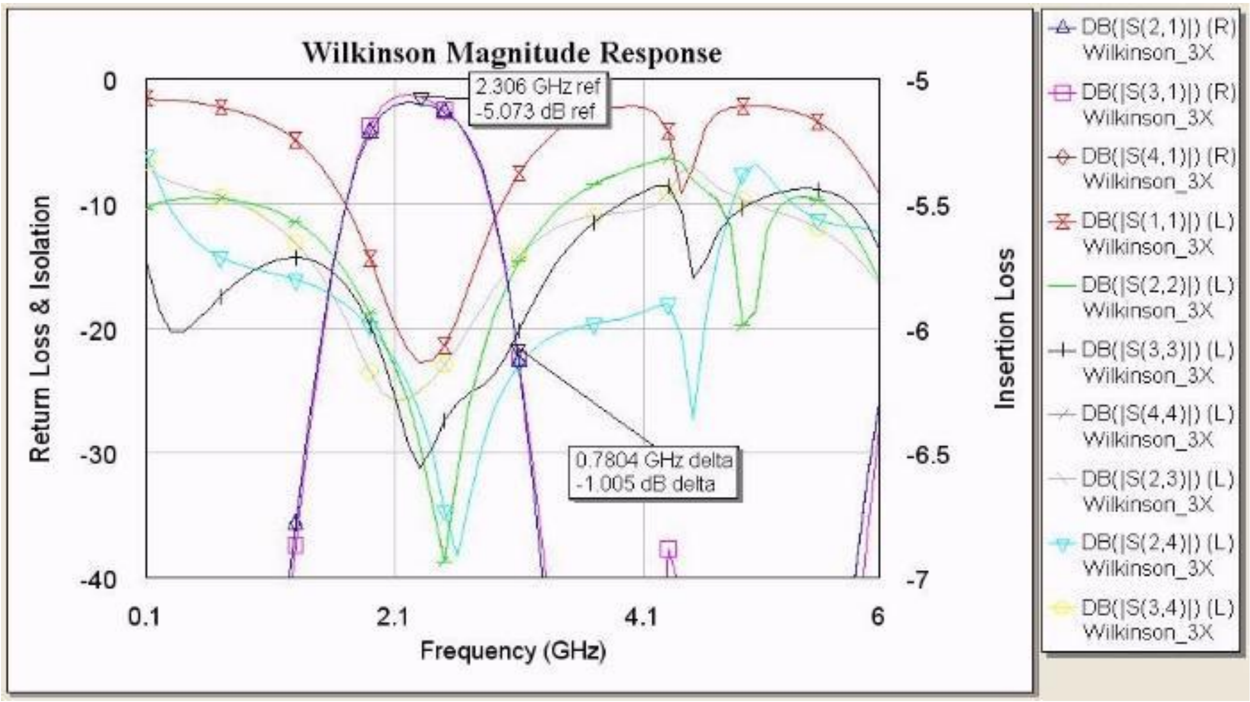


Figure 6.1: n-way Wilkinson splitter

For experimental purposes, the prototyped system does not need to be well-designed (well-designed 50 Ω transmission lines on a printed-circuit board with good return loss, 15 dB for example). Antenna design does not need to be industry-quality (high dBi,), under 10 dBi for the antenna is fine. Antenna can be spaced apart for a set frequency. Testing will see what the ideal spacing is for a set frequency and antenna type. Antennas can also be positioned 90 degrees out of each other (ex 45 degrees, 135 degrees) for polarization. Antenna distance, 0.5, 1 1.5, 2, 3, 4 ,5 meters. Also optional is obstacles, purposeful multipath (metal sheet interfering, longer cable for one side), jammers/other signals/noise (like Wi-Fi). The jammer antenna can be directional; the one requirement will be that it faces the receiver.

For each of the antenna designs, it is preferable to start with wire antennas (such as Yagi, Quagi, or cantennas) before advancing to microstrip antennas. This will cut down on costs, as coax and copper wires are available in the research laboratory. A design consideration to keep in mind is that the GHz antennas are not as large as the MHz range antennas; this may limit the available design antennas.

Modulation techniques will be QAM, 16-QAM, 64-QAM, 256-QAM, 1024 QAM (a stretch). We are not designing the modulation hardware; that is for the vector signal analyzer (VSA) and vector signal generator (VSG) to handle. For research purposes, we will use techniques such as Orthogonal Frequency Division Multiplexing (OFDM) to preprocess the transmitter signal. This is currently one of the signal processing methods used widely in current MIMO cellular implementations; by doing this, communications researchers from both the university community and industry will be able to interpret practical, applicable data instead of simplified cases.

Build The level 2 diagram (higher levels are mentioned later) will consist of the amplifier and antenna. The modulation and demodulation of the message is performed by the VSA and VSG.

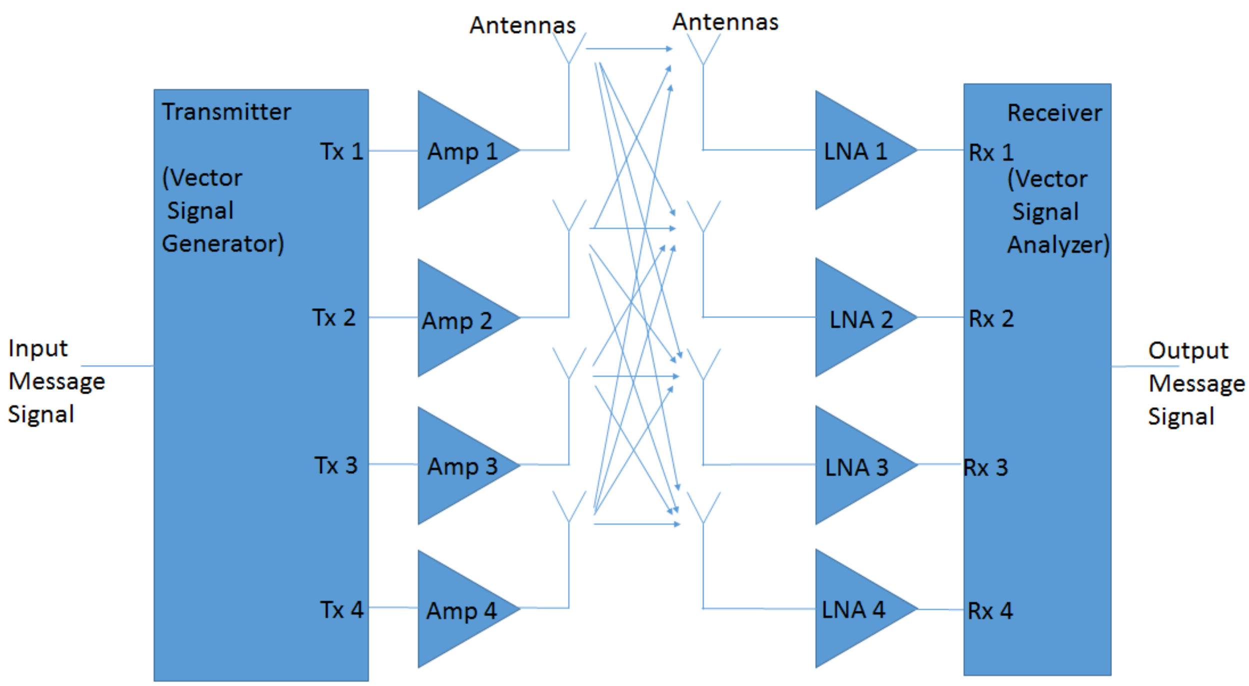


Figure 6.2: Level 2 Block diagram, the hardware-level view. Above is the 4x4 MIMO configuration.

Figure 6.2 displays the hardware build: 8 antennas and 8 amplifiers. To test 2x2, 2x3, 3x3 and other cases, some transmitters and receivers will be disabled using software for the VSG. As seen here, the receiver side will use low-noise amplifiers. The message signals are generated and inside the vector signal generator. The VSG is the N9381, available in the communications laboratory. The VSA is the N9391 also available in the laboratory.

VII. Block Diagram, Requirements, and Specifications Section

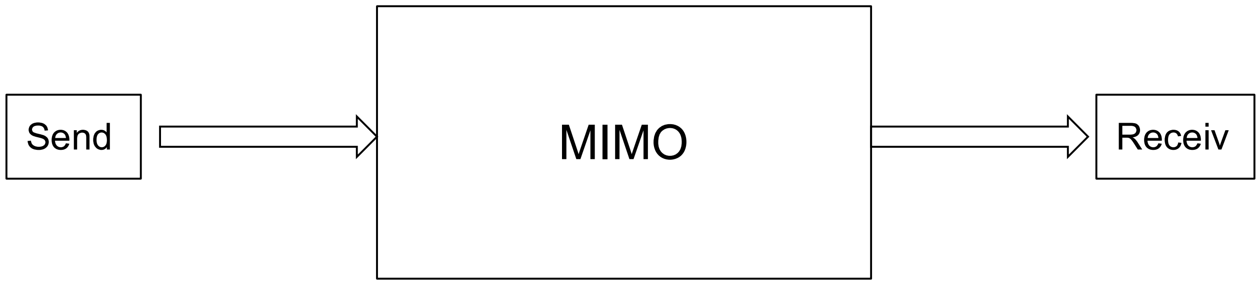


Figure 7.1: Level 0 Block Diagram

The high-level block diagram shown above depicts the input and output of the MIMO communication system. Basically, the sender will have a message to send to the receiver (an example of a similar scenario would be someone trying to send a text message through a phone or placing a call). The MIMO system takes in a message signal, process it through the transmitting antennas, through a medium and delivers it to the receiving antennas of the receiver. The receiver should receive the text or call promptly.

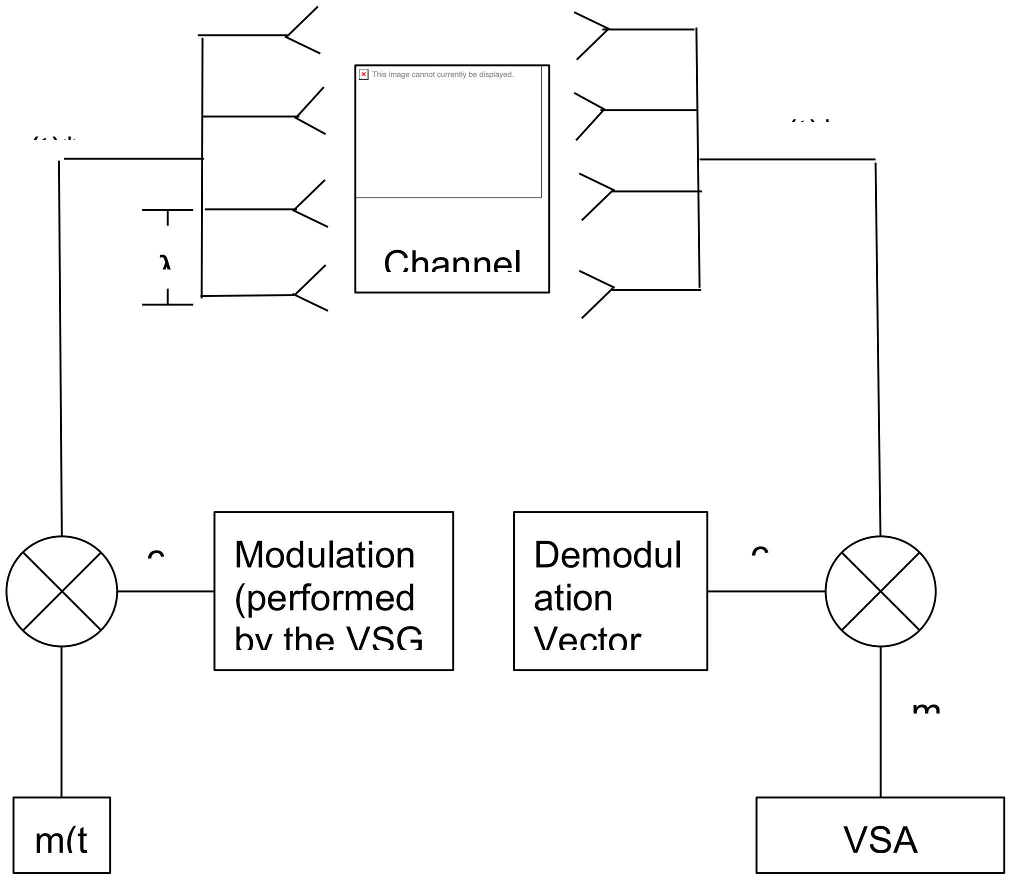


Figure 7.2: Level 1 block diagram.

The lower-level design above shows a more detailed explanation of how the MIMO system should be configured for the course of this senior project. The implementation utilizes the Keysight Vector Signal Generator (M9381A) and Vector Signal Analyzer (M9391A) available on campus. As shown above, a message signal from the outside world is the input to the system; for this implementation the message signal can be generated by a function generator. This message signal first goes through the VSG, where it is modulated with the types mentioned in the Modulation Techniques section. The VSG will provide the carrier signal which will be in the amateur radio bands of 900MHz-6GHz to modulate the message signal. Shown in the diagram as an example is amplitude modulation. Once the signal is modulated it reaches the transmitting antennas where four multiple copies of it are transmitted through the various channels of the system.

The channel information block is an overview of how each channel will affect its own signal and is represented by a matrix of transfer functions. During implementation, test messages can be sent from the first antenna and the responses by the receiving antennas can be recorded to determine how each channel can affect the message in terms of attenuation and phase shift. Once the modulated signal traverses the channel, it reaches the receiving antennas where it is demodulated by the VSA and displayed. The VSA should display the exact same message signal outputted by the function generator, m(t).

Testing and Verification:

Testing the MIMO system involves two tests. The first test deals with the functionality of the MIMO system. Starting with a SISO link system as reference, the number of antennas on the transmitter and the receiver side should be increased (2x2, 3x3, ect.) up to a 4x4 system. Since transmission power is to remain constant in reference to the SISO system by splitting the power evenly between the antennas, it must be verified that each MIMO configuration operates properly under this power constraint. A test message can be propagated through the system to ensure proper operation of the system., passing the first test

Before testing the MIMO system first the testing equipment needs to be configured to use multiple transmitters and receivers. To verify the transmitters and receivers are operational sample MIMO configurations given by Keysight, where the testing equipment is from, will be used to set up and test the configuration. Once this configuration is verified the MIMO system can be created and the second test can begin.

The second test deals with the theoretical operation of the MIMO system. Once it is verified that the MIMO link is functional, the channel capacity of the currently implemented system must be verified. In reference to the SISO link, the data rate of the message signal should be capable of being increased while still properly receiving the message signal at the receiver. By checking each MIMO configuration, this increase in the data rate that can be sent through system should be linearly related to the number of antennas currently operating on the transmitter and receiver ends of the link. In other words, a 2x2 MIMO system should see twice the increase in the capacity of the SISO system, while a 3x3 link should see thrice the increase in capacity. This will prove the theory of the MIMO system and ensure proper operation, passing the second test.

Marketing Requirements translated to Engineering Requirements

Marketing Requirements	Engineering Requirements
Transmission power should not be increased in reference to a single transmitter and receiver antenna link (SISO)	Antennas should have transmission power equally divided.
Message should be clearly perceived by the receiver.	The capability to detect the message signal at the receiver should be equal to equivalent SISO systems.
System should provide an increase in data rate related to number of antenna links.	Number of antennas on the transmit and receive side linearly increases capacity of SISO. 2x2 MIMO doubles it, 3x3 triples it etc.
Prototype costs should aim for less than $200	Budget accordingly. Estimation, may differ from BOM forecast based on vendors and available materials in the research lab: $20 Amplifiers $10 Antennas $20 Printed Circuit Boards $20 Resistors, Capacitors, Inductors $40 Coax wire and copper wires $30 Copper Clad Boards $20 SMA Connectors
Antennas need to operate within the 900MHz-6GHz amateur radio band, and	Anritsu VNA will be used to characterize amplifiers and splitters. 5% error margin is

amplifiers and splitters need to provide appropriate gain	required to obey FCC laws. The output on the transmit antenna will not exceed 1 W of power, to obey FCC laws.

Team Members and Contributions:

Rodrigo Mendez

Responsibilities for this project will include documentation of the progress, such as collecting data and appropriately differentiating the data collected from the various configurations of the MIMO. For example, data from the 2x2 MIMO will be collected and appropriately analyzed through plots displaying performance. This data will be crucial to the overall project as it will be included in the final research paper to be submitted. Collaboration with other group members will be included for appropriate analysis of theoretical concepts.

William Tran

Responsibilities for this project will be the designing, construction, and characterization of the hardware, and determining the RF characteristics of the propagation path. This will include characterizing antennas, splitters, amplifiers, wires, the wireless transmission, as well as noise analysis using the VNA, VSA, and VSG.

Jeannie Whitmore

Responsibilities for the project are configuring the VSA and the VSG to generate signals and analyze signals respectively. Some subtasks include finding example MIMO configurations that use the testing equipment from Keysight and getting all the correct software downloaded.

Patrick Kezer

Responsibilities for the MIMO research include configuration of the VSG and VSA in software and hardware. Working with Jeannie to use pre existing MIMO examples to develop our own set of configurations to test and characterize. Mathematical computations of component loss and gain via SystemVue and MATLAB. System modeling and implementation via SystemVue.

VII. Schedule, Cost, and Plan Section

Due Dates	Deliverables
11/28/2016	EE 460 Final Report
2/16/2017	Design Review
3/17/2017	EE 461 Report
5/17/2016	EE 462 Demo
6/2/2017	Senior Project Expo
6/9/2016	Final Report

Table 7.1: General Due dates for senior project

Key	color
Work in Progress: Rodrigo	
Work in Progress: Patrick	
Work in Progress: Will	
Work in Progress: Jeannie	
Work in Progress: Team	
Finish by	
Due date	
Advisor meetings	

Figure 7.3: Key for Gantt Chart

Fall 2016													
Week	W0	W1	W2	W3	W4	W5	W6	W8	W9	Break	W10	W11	Finals
Month	Sept	Sept	Oct	Oct	Oct	Oct	Oct	Nov	Nov	Nov	Nov	Dec	Dec
First date of week	22	26	3	10	17	24	31	7	14	21	28	5	12
Idea Pitch	22-Sept												
Abstract and Background													
Product decription													
Customer Archetype													
Market Description													
Market Requirements and Specifictions													
EE 460 Report (Frist Draft)						28-Oct							
Schedule													
Analysis of Senior Project													
Preliminary Design Analysis													
EE 460 Report (Final Draft)											28-Nov		
EE 460 Project Presentation												5-Dec	

Figure 7.4: Fall 2016 Gantt Chart

Winter 2016												
Week	Break	W1	W2	W3	W4	W5	W6	W8	W9	Break	W10	Finals
Month	Dec-Jan	Jan	Jan	Jan	Jan	Feb	Feb	Feb	Feb	March	March	March
First date of week	19-8	9	16	23	30	6	13	20	27	6	13	20
Parts, Test configurations, and SISO Measurements												
Select and get antenna parts												
Find MIMO test configurations												
Get Software and Cables for Testing												
Verify MIMO Basic Configuration												
Gather SISO Data												
2x2 MIMO												
Modify MIMO test configuration to 2x2 MIMO												
SystemVue MIMO models for 2x2 MIMO												
Build 2x2 Antenna system for MIMO transmission												
Testing 2x2 MIMO system both closed and open air												
4x4 MIMO												
Modify MIMO test configuration to 4x4 MIMO												
SystemVue MIMO models for 4x4 MIMO												
Build 4x4 Antenna system for MIMO transmission												
Begin Testing for 4x4 MIMO closed system												
Reports and Presentations												
Senior Project Report First draft												
EE Department Design Review							16-Feb					
Weekly Advising Report												
EE 461 Report											17-Mar	

Figure 7.5: Winter 2016 Gantt Chart

Spring 2016												
Week	Break	W1	W2	W3	W4	W5	W6	W8	W9	Break	W10	Finals
Month	March	Apr	Apr	Apr	Apr	May	May	May	May	May	June	Jun
First date of week	19-8	3	10	17	24	1	8	15	22	29	5	12
4x4 MIMO												
Finish Testing 4x4 Closed system												
Test 4x4 open air transmission												
Reports and Presentations												
Final Draft Senior Project											9-Jun	
Weekly Advising Report												
EE 462 Demo								17-May				
Senior Project Expo										2-Jun		

Figure 7.6: Spring 2016 Gantt Chart

High Risk Items that May Affect Schedule

A significant amount of time needs to be spent making sure the testing equipment is configured correctly. If the configuration is incorrect the signals cannot be generated or analyzed for either the 2x2 or 4x4 MIMO. Testing both systems also could take longer than expected since there are multiple aspects that need to be tested. Finally, the building could take a bit longer due to antennas not functioning the way they are designed to.

Cost

			Senior Project:	MIMO Link								
			TEAM:	William Tran, Jeannie Whitmore, Patrick Kezer, Rodrigo Mendez								
			DATE/REV:	NOV 28, 2016 VERSION V1.0								
Sub	**Sub**	**Sub**	**Sub**	**Description**	**Qty**	**P/N**	**Document**	**MFG**	**MFG P/N**	**LT-Weeks**	**Cost per Unit (USD)**	**Extended Cost (USD)**
Box Build - MIMO Link- Research Build					1	1000		Custom				
1	Final Assy - 4 x 4 MIMO Link				1	1001	Instr	Custom	---	6		
	1	Transmitter Assembly			1	1002	Instr	Custom	---	3		
		1	Quagi Antenna, 1.3 GHz		4	1003	Custom	Custom	---	2		
			1	SMA-M Connector	8		Spec	Amphenol	132195	1	$ 2.41	$ 19.28
		2	Transmitter Amplifier		4	1004	Spec	Mini Circuits	---	2		
			1	Power Amplifier	4		Spec	Mini Circuits	ERA-3+	1	$ 1.67	$ 6.68
			2	SMA-M Connector	8		Spec	Amphenol	132195	1	$ 2.41	$ 19.28
	2	Jammer Assembly				1005	Custom	Custom		1		
		1	Cantenna, 1.3 GHz		1		Spec	Pringles	Tall Can Pringles, any flavor	1	$ 2.00	$ 2.00
	3	Receiver Assembly			1	1006	Instr	Custom	---	3		
		1	Quagi Antenna, 1.3 GHz		4	1007	Custom	Custom	---	2		
			1	SMA-M Connector	8		Spec	Amphenol	132195	1	$ 2.41	$ 19.28
		2	Receiver Amplifier		4	1008	Spec	Mini Circuits	---	2		
			1	Low-Noise Amplifier	4		Spec	Mini Circuits	MAR-7+	1	$ 1.36	$ 5.44
			2	SMA-M Connector	8		Spec	Amphenol	132195	1	$ 2.41	$ 19.28
											MIMO Link Total	$ 91.24
2	General Construction Materials				1	2001	Custom			1		
	1	Semi Rigid Coax, 50Ω			1	2002	Spec	RFSuppliers	RG402/16 feet	1	$ 28.50	$ 28.50
	2	Pb-Free Solder			1	2003	Spec	Jameco	Pb Free Sn99.3/Cu0.7 250G	1	$ 24.95	$ 24.95
	3	Resistor-Capacitor-Inductor Kit			1	2004	Spec	Elenco	RCK-465	1	$ 32.61	$ 32.61
	4	Copper Wire			1	2005	Spec	OOK	24 Gauge 100 ft Copper Wire	1	$ 7.89	$ 7.89
											Construction Materials Total	$ 93.95
Box Build - MIMO Link- Commercial Build					1	1002		Custom				
3	Testing Equipment				1	3001	Instr			8		
	1	Vector Network Analyzer			1	3002	Instr	Anritsu	Anritsu VNA MS2661a	6	$ 1,950.00	$ 1,950.00
	2	Vector Signal Generator & Vector Signal Analyzer			2	3003	Instr	Keysight	Keysight PXI N9318, MIMO configured	8	$ 130,000.00	$ 260,000.00
	3	DC Power Supply			1	3004	Instr	HP	6206B	2	$ 45.00	$ 45.00
	4	BNC-SMA Adapter			8	3005	Spec	Show Me Cables	1578 BNC-F to SMA-M	2	$ 3.99	$ 31.92
	5	SMB Cable			16	3006	Spec	Vcablemart	RFC-SMB/SFS-SMB/SFS	2	$ 3.48	$ 55.68
											Testing Equipment Total:	$ 262,082.60
											Research Total (1 + 2) :	$ 185.19
											Commericial Total (1 + 2 + 3):	$ 262,267.79

Table 7.2: Estimation of the cost of Senior Project

The overall cost of our project is $185.19, which underneath the $200 allowance given by the EE department. If this was a commercial project, the cost of doing the MIMO research would be $262, 267.79 instead of $185.19. The 4x4 MIMO build has all the necessary parts to build lower-order MIMO (eg. 3x3, 2x2, 2x3, ect).

Resources

The internet and professors such as Clay Mckell will be used to get more information on MIMO. Also the new keysight VSA and VSGs that were donated to Cal Poly will be used to test the 2x2 and the 4x4 MIMO systems.

Key Skills Needed to Complete the Project

A strong understanding of the underlying principles of MIMO is necessary for the project. Mastering the multichannel interface and setting up the MIMO configuration is essential for any testing. Finally, well-developed probleming solving skills and a strong work ethic are necessary or else the project will never get done.

VIV. Analysis of Senior Project Report Section

Advisor: Dennis Derickson

1. **Summary of Functional Requirements:** As stated previously, this project is to build several unique MIMO systems and test them. The results of these test will be recorded, analyzed, and compiled into a final research report. Our findings will provide insight primarily to cellular service providers who may use our results to design the optimal method for cellular communication.
2. **Primary Constraints:** The first challenge we faced we doing this project was the understanding of digital communications. Digital Communications is considered to be a rather abstract concept and can be quite hard to grasp. Another aspect of this project that will prove to be difficult is understanding which MIMO implementations are the most important to analyze. MIMO designs are already in existence and being used today; determining ways to better these systems is a difficult task.
3. **Economic:** Target $200 budget for the construction of all systems. Construct the hardware with materials available in the lab, and order the rest from vendors. Materials available in the lab include coaxial connectors, coaxial cables, wires, and some amplifiers. With the modulation and demodulation of the signal taken care of by the

VSA and VSG, we will aim to construct the RF path. The ordered parts may include printed circuit boards, amplifiers, splitters, and antennas. Since this is a research project, students will be unpaid. The main people that will benefit from our product are not the consumer, but whichever company uses our research to develop MIMO. Fortunately, our project will be primarily be done on the VSGs and VSAs in the Networks Lab. We will need to implement discrete hardware components such as antennas, amplifiers, combiners, and splitters. The cost for these external components will be quite small.

4. **If Manufactured on a Commercial Basis:** Our final product is not something that a typical consumer would purchase, however, how it is implemented may have a very large effect on the common consumer. In 2015, a total of 403 million smartphones were purchased; the total number sold increased by 9.7% in the fourth quarter of that year. Currently the average production cost for smartphones is $220, the implementation of MIMO will raise that cost slightly (the main difference is adding antennas).
5. **Environmental:** Lead-free designs will be used in the construction of the MIMO hardware. The European market disallows anything with Lead inside the design; if the product were to include lead, our customer base will disclude the entire European communications market. Furthermore, the power of the antennas will not exceed more than 1 watt for each transmission antenna. This is to comply with the Federal Communications Commission's standards.
6. **Manufacturability:** The manufacturing process for smartphones has already been developed quite some time ago. If MIMO were to be implemented in the common modern phone, the manufacturing process would change very little. As stated in the previous section, the main change for cellular devices would be the increase in antennas. The manufacturing process would need to be adjusted such that the implementation of additional antennas could be accommodated. This change in process does not pose much of a threat to achieving MIMO integration into cellular devices.
7. **Sustainability:** The designs will involve hardware that is not too new, but not obsolete either. This will ensure that hardware such as power amplifiers will be available to purchase over the course of 5 to 10 years. An upgrade that we could implement are multi-frequency amplifiers, this could allow for the design to last longer when put into a cell phone. Upgrading the system would be a step that our customers would take. They would choose alternative ways to use MIMO.

8. **Ethics:** There are a few ethical dilemmas that this MIMO research can encounter. The first covers the thought of 'who can this research be sold to?': Many people believe that MIMO is the future for digital communications. Depending on how MIMO is implemented, we may be encouraging a monopoly for cellular service providers. If a cellular service provider uses our research to implement the best method for digital communications, many consumers would change their provider to that company. Economic monopoly has been a major ethical issue for quite some time. Depending on how successful MIMO is, many companies that cannot compete will lose customers. Eventually, most of the companies will cease to exist which will result in thousands of unemployed people. We are well aware that the concept of a monopoly is illegal, however there are many 'loopholes' that companies take advantage of. As stated before in the 'Market Description' section, one of our potential customers are several branches of the military. When selling to the government, one often faces many ethical dilemmas due to the secrecy of the government. On one hand 'could our research assist in saving lives?' on the other hand 'will our research be put to unethical use that will lead to the loss of innocent lives?'
9. **Health and Safety:** The implementation of MIMO poses little to no health threats. Even though MIMO itself does not directly pose any threats, cell phones still do. There have been many studies link cell phone use to an increased risk of certain types of cancer. Many people are concerned with the radio waves that come with cell phones. The increased number of antennas may facilitate an increase in the intensity of these radio wave, however this is unlikely. As a safeguard, the research will comply with FCC standards of no more than 1 Watt of power delivered to the transmit antenna. Higher power may be detrimental to the health of living organisms around the RF device. For example, radiation from WiFi bands have been found to have negative effects on the body, such as altered brain tissue and lower sperm count.
10. **Social and Political:** The implementation of MIMO should be in accordance to the Federal Communications Commission's standards. This means that the research will utilize amateur radio bands, and avoid bands not available to the public. Violating the FCC standards may result in heavy fines. The social analysis is that cellular providers are able to view this research equally. For companies that already use a MIMO implementation in their system, this may be seen as detrimental to their business, as competitors may gain insight to MIMO technology. For cellular companies that have not utilized MIMO, this will provide valuable knowledge to their research and development

groups. For researchers, this MIMO research may confirm their theoretical MIMO models and prove to be beneficial to the research community.

11. **Development:** For much of the system modeling we used a software called SystemVue from Keysight. SystemVue is a software which can model complex systems; often used for communication links. Due to how extensive SystemVue is, we will need to spend a large amount of time to become quite familiar with the software.

Preliminary Design Analysis

As stated in many of the previous sections, our project is not to build one single design; it is to design, build, characterize and record. We are attempting to write a research paper which aid others to better understand MIMO and how it can be used to improve digital communications. Throughout this project we will be testing various parameters such as: transmitting to receiving antenna ratio, filtering techniques, modulation techniques, etc. For this project, we will be using the Vector Signal Generator (VSG) and Vector Signal Analyzer (VSA) from Keysight to create and analyze the signals, however several other discrete components will be required such as amplifiers and antennas.

X. References

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