Experimental Exploration of 5G-and-Beyond Wireless Systems and Rural Broadband

FINAL REPORT

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Table of Contents

1 INTRODUCTION

1.1 Project Context

*"ARA, an acronym for **A**gricultural and ru**RA**l communities, is an at-scale platform for advanced wireless research deployed across the Iowa State University (ISU) campus, City of Ames (where ISU resides), and surrounding research and producer farms as well as rural communities in central Iowa, spanning a rural area with diameter over 60km. ARA is envisioned to serve as a wireless living lab for smart and connected rural communities, enabling the research and development of rural-focused wireless technologies that provide affordable, high-capacity connectivity to rural communities and industries such as agriculture."* – ARA User Manual

1.2 Problem Statement

With the **A**gricultural and ru**RA**l communities (ARA) project recently being started in July 2021, there are limited teaching resources available for undergraduate and graduate students to utilize before joining the ARA project. These students are required to have a baseline knowledge of the use of ARA technology. Knowledge especially within SDRs and OAI will allow for meaningful contributions to further expand the solutions created by the use of ARA resources in rural communities. There is currently a lack of available teaching resources.

1.3 Solution to Problem Statement

Create 5G learning materials (wiki pages, quizzes, hands-on labs) to prepare undergraduate students for experimenting with advanced wireless systems using testbeds such as ARA, which supports 5G platforms such as OAI and USRP SDRs.

The 5G learning materials have 3 learning outcomes. Learners will:

1. **Understand the 3 main components of 5G network structures**
   a. User Equipment (UE)
   b. Radio Access Equipment (RAN)
   c. Core Networks
2. **Become familiar with ARA and apply ARA resources to 5G concepts**
3. **Test their knowledge by establishing their own 5G network with ARA resources**

1.4 Intended Users and Uses

- **Senior Design Students:** Incoming senior design students at Iowa State University who have an interest in 5G and beyond technology and are taking on projects related to ARA (agricultural and rural communities) resources can greatly benefit from these learning materials. These materials provide essential knowledge and insights therefore providing students with the ability to effectively utilize ARA resources in their projects.
- **Undergraduate and Graduate Students:** These materials also serve to prepare undergraduate and graduate students across various disciplines. By defining and teaching the foundational knowledge required to work with ARA resources it allows students to succeed in their academic pursuits to obtain knowledge in 5G and beyond technology.
- **General Public Interested in 5G Networking:** The learning materials are publicly accessible which allows anyone with an interest in 5G networking to explore and deepen their understanding. Whether you're a curious individual, a professional, or an enthusiast, these resources create a broader awareness of 5G technology especially in the realm of SDRs and OAI allowing for a potential impact on our interconnected world.

1.5 Work in Context

When looking at other 5G wireless and beyond teaching material online today, there are very limited options that directly help with understanding and obtaining the baseline knowledge required to work with ARA's resources. There is a lot of information that is out there that allows a user to learn about 5G and beyond material however it often requires previous understanding of 5G material, requires you to purchase the material, or it is not relevant to ARA's resources. The product that we have implemented helps to solve the issues that the user may experience by providing material that is easy to understand, open source, and directly related to the use of the ARA project. It helps provide a clear and efficient place for users to come to quickly obtain knowledge required to help contribute to the ARA project.

Pros	Cons
Open Source	Labs occasionally require ARA's resources
Easy to comprehend	Limited to certain areas of 5G material
Directly related to ARA's resources	

2 REVISED DESIGN

2.1 Requirements

Functional Requirements:

- Design must have a wiki page for each module to educate the user on the material being taught
- Design must have multiple quizzes for each module to ensure the user comprehends the information
- Design must have labs for each module which is broken into two parts. The first part is conceptual labs that give the user the chance to experiment outside of ARA's resources. Then a second part that requires the user to use module information with ARA's resources
- Design should have a capstone lab that uses OAI to simulate a 5G network and allow the user to see how information is transmitted
- Design must display the use of ARA's resources and its importance for 5G systems

Non-Functional Requirements:

- Design of the modules must be easy to navigate and visually pleasing to the user
- Design must allow users to easily comprehend material by using images and educational text
- Design must be completed using ReadTheDocs to ensure it remains open-source
- Quizzes must be easy to complete and display results in an understandable way
- Learning materials should be tested to effectively assess learning effectiveness

2.2 Engineering Standards

- **3GPP (3rd Generation Partnership Project)** - The name of the standard for 5G as a whole and the name of the body that creates the standard
  - **Open-Air Interface**: an open-source project spearheaded by the Mobile Communications Department at EURECOM. It is designed to implement the 3rd Generation Partnership Project (3GPP) standards on general-purpose x86 computing hardware and Commercial Off-The-Shelf (COTS) Software Defined Radio (SDR) cards, promoting innovation in mobile and wireless technology domains.
- **IEEE 802.X (Wi-Fi)** - ensures devices can communicate and interoperate within a local area network

2.3 Security concerns and countermeasures

The availability of storing learning materials on GitHub has provided an amazing open-source platform for this project. However, this accessibility comes with a security concern due to these materials being posted publicly. This poses a security concern because anyone will have the ability to copy and leverage our work with ARA to trick future users into releasing sensitive information. This can be countered by informing users to only provide information to ARA directly. The ARA Portal also serves as a countermeasure due to it requiring a rigorous and often lengthy process for entry. This deliberate approach ensures that only qualified individuals can benefit from the resources within. While the public nature of GitHub fosters collaboration and knowledge sharing, the controlled access to the ARA Portal safeguards sensitive information and intellectual property.

2.4 Design Changes from 491

Using the foundational design constructed in 491, our design went from being a mere idea to a practical product that can help foster further education within the 5G and beyond technologies related to ARA. Our design detailed in section 3.1 has remained simi-similar throughout the process; however has had to take on slight chances due to testing results and issues that occurred. We started with a rough layout of the design that detailed the functionality required to complete this project.

This space is designed to display information information about the topic selected from the tabs on the left. This information can consist of edcational information about a topic, quizes, and labs that are designed to help the user learn each topic.

Key for the image above	
Purple	Getting started page
Red	learning modules and quizzes
Yellow	Lab material
Green	ARA Technical Overview
Blue	About us

From this we were able to develop a new approach which allowed us to construct a new layout that would provide the user with more information while making it easier to understand and more graphi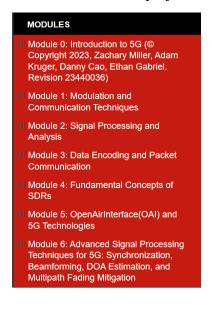cally pleasing. This is a major change from our first design because we have switched to a module-based system. Each module will contain 3 types of information which are wiki pages, quizzes, and labs. We switched to this method because we determined this was the best way for learners to be educated while retaining information that was provided. This new design created labs that require the use of ARA Sandbox. Each module has two labs, one that utilizes the ARA Sandbox and one that makes use of ARA's field equipment. The labs themselves will guide the learner through all the steps needed to utilize these resources. This design also does a better job of fulfilling non-functional requirements because it presents information in a more digestible way.

Key for the image above	
Welcome tab	Brief introduction to the project
Module 0	Basics
Module 1	Fundamental Concepts of SDRs
Module 2	Modulation and Communication Techniques
Module 3	Signal Processing and Analysis
Module 4	Data Encoding and Packet Communication
Module 5	Practical Applications and Systems
Module 6	OAI and 5G Technologies
Module 7	Cognitive Radio and Dynamic Spectrum Access
About us	Brief introduction to the team members

After many stages of testing and changes to the product we finally came to the final design that is constructed today which is displayed below. In this design we wanted to take a deep dive into the elements of SDRs and OAI and their relationship to 5G networks. We were able to construct modules that have wiki pages, quizzes, and labs that provide users with detailed information required to use ARA resources. These new modules allow for a detailed breakdown of complex information in a manner that allows users to easily understand. This was the best approach that was discovered when trying to relay information about 5G networks and ARA's technology. The finished product will provide users with an efficient way to comprehend information that will help them contribute to the ARA project.

MODULES

Module 0: Introduction to 5G (© Copyright 2023, Zachary Miller, Adam Kruger, Danny Cao, Ethan Gabriel. Revision 23440036)

Module 1: Modulation and Communication Techniques

Module 2: Signal Processing and Analysis

Module 3: Data Encoding and Packet Communication

Module 4: Fundamental Concepts of SDRs

Module 5: OpenAirInterface(OAI) and 5G Technologies

Module 6: Advanced Signal Processing Techniques for 5G: Synchronization, Beamforming, DOA Estimation, and Multipath Fading Mitigation

3 IMPLEMENTATION DETAILS

3.1 Detailed Design

3.1.1 Design Context

This project was split up into several steps to organize the massive amount of content. ARA and the underlying research needed to understand were put into modules designed by our team to teach the user about each fundamental component of 5G implementation and application. There are 6 modules, each module consisting of informational pages, certain number of quizzes (proportional to the amount of information in the module), and hands-on labs for users to become familiar with the commonly used technologies and software in ARA.

3.1.2 Design Complexity

Drawing on open-source information and research compiled by ARA researchers, our team populated each module with the necessary information to understand 5G foundational components. For each module, there are 4-5 informational wiki pages with some modules being even larger than the others (namely modules 3, 4, 5, 6). Each wiki page also has a corresponding quiz, providing knowledge checks for the user as they go through the site. We decided to give each module two labs, one conceptual lab for the user to be shown the processes talked about in the module and then one hardware lab where the user specifically interacts with ARA software to implement topics covered in the module. This includes users becoming authenticated with the ARA project and setting up their sandbox environment on the ARA portal to use 5G and radio technologies. Users need to complete labs and achieve desired outcomes as outlined at the end of each lab walkthrough before moving on to the following modules.

3.1.3 Engineering Tools Used

A list of all tools for learning, setup, and platform implementation includes the use of GitHub for version control, Sphinx and ReadTheDocs for text generation and formatting, GNU radio and other SDRs, Python, Matlab, and Simulink, ARA sandbox, Visual Studio Code for script writing and generation.

3.1.4 Features

Wiki pages (informative learning tool), multiple choice quizzes (ways for users to evaluate their learning), virtual experiments (ARA original content for user hands on interaction).

3.1.5 Learning Material Design

Breakdown of Website Layout

Module 0: Introduction to 5G

- **Learning modules:**
  - Overall Basic 5G Network Structure
  - User Equipment
  - Radio Access Networks
  - NG-Core Overview
  - Other Equipment Used to Deploy 5G Networks

- o 5G Networking in Rural Locations
- o 5G RRC Layer
- o MAC, RLC, and PDCP Layers
- o 5G Physical Layer
- **Experiments:**
  - o Get to Know Powder
  - o "Hello World!" in ARA
  - o AraRAN Experiments:
    - Experiment 1 - Transmitting, Receiving, and Visualizing Waveforms using UHD and GNURadio
    - Experiment 2: Monitoring Skylark MIMO Wireless link Performance
  - o Virtual Network Topology using GENI
- **ARA Infrastructure Overview:**
  - o Wireless Access Network
  - o Backhaul Network
  - o Compute
  - o Storage

Module 1: Modulation & Communication Techniques

- **Wiki page 1**: Understanding Modulation & Demodulation Techniques
  - o **Quiz 1**: Modulation Techniques and Communication
  - o **Lab 1**: Modulation and Demodulation Techniques
- **Wiki page 2**: OFDM: Principles and Implementation
  - o **Quiz 2**: OFDM: Principles and Implementation
- **Wiki page 3**: Frequency Hopping in Communication Systems
  - o **Quiz 3**: Frequency Hopping in Communication Systems
- **Wiki page 4**: Advanced Modulation Techniques in SDR
  - o **Quiz 4**: Advanced Modulation Techniques in SDR

Module 2: Signal Processing and Analysis

- **Wiki page 1**: Diving Deeper into Signal Processing
  - o **Quiz 1**: Diving Deeper into Signal Processing
- **Wiki page 2**: Sampling Theory and Application
  - o **Lab 1**: Signal Filtering
  - o **Lab 2**: Low and High Pass Filters – Hardware Lab
  - o **Quiz 2**: Sampling theory
- **Wiki page 3**: SDR Signal Processing: A Look Into Signal Analyzation
  - o **Quiz 3**: Digital and Analog Filters
- **Wiki page 4**: Convolution and Correlation

Module 3: Data Encoding and Packet Communication

- **Wiki page 1**: Introduction to Data Encoding in 5G
  - o **Quiz 1**: Introduction to Data Encoding in 5G
  - o **Lab 1**: Understanding Baseband Modulation Techniques in Digital Communications
- **Wiki page 2**: Fundamentals of Packet Communication
  - o **Quiz 2**: Quiz 2: Fundamentals of Packet Communication
  - o **Lab 2**: Data Encoding and Decoding with BPSK signals and LDPC codes
- **Wiki page 3**: Encoding Techniques for 5G
  - o **Quiz 3**: Encoding Techniques for 5G
  - o **Lab 3**: QPSK Communication System with Polar Coding
- **Wiki page 4**: Packet Communication Protocols and Standards
  - o **Quiz 4**: Packet Communication Protocols and Standards
  - o **Lab 4**: Advanced Packet Communication Simulation in 5G Networks
- **Wiki page 5**: Channel coding
  - o **Quiz 5**: Implementing Packet Communication with USRP SDRs

Module 4: Fundamental Concepts of SDRs

- **Wiki page 1**: Introduction to Software Defined Radios (SDR)
  - o **Quiz 1**: Fundamentals of SDRs
  - o **Lab 1**: Waveform Transmission
- **Wiki page 2**: Overview of UHD and GNURadio
  - o **Lab 2**: Receiving and Transmitting Data with the UHD Library
- **Wiki page 3**: Basic Concepts of Signal Processing in SDR
  - o **Lab 3**: Visualizing SDR data with GNURadio
- **Wiki page 4**: SDR Hardware Overview
  - o **Lab 4**: Exploring OFDM with USRP B210
- **Wiki page 5**: Concepts of Signal Reflection and Multipath
- **Wiki page 6**: Basics of Radar Systems in SDRs

Module 5: OpenAirInterface(OAI) and 5G Technologies

- **Wiki page 1**: Background and History of OpenAirInterface (OAI)
  - o **Quiz 1**: OpenAirInterface (OAI)
- **Wiki page 2**: How OpenAirInterface (OAI) Works and Its Advantages/Disadvantages
  - o **Quiz 2**: OpenAirInterface (OAI)
- **Wiki page 3**: Setting Up a 5G Network Using OpenAirInterface (OAI)
- **Wiki page 4**: How OAI Uses and Establishes Configuration Files
- **Wiki page 5**: Creating an IP Route Between gNB and NRUE Using SDRs
- **Experiments**:
  - o **Lab 1**: Setup, Ping, and Throughput measurement with iperf

Module 6: Advanced Signal Processing Techniques for 5G: Synchronization, Beamforming, DOA Estimation, and Multipath Fading Mitigation

- **Wiki page/Lab 1**: Synchronization
- **Wiki page/Lab 2**: DOA & Beamforming
- **Wiki page/Lab 3**: Multipath Fading

3.2 Implementation/Functionality Description

o We used Github, ReadTheDocs, and reStructured Text (Sphinx) to implement a website that will provide information on important 5G concepts such as modulation, encoding, Fundamentals of SDRs, and more. It is important to gain the knowledge of the fundamentals of 5G networking so that we help users understand how to use ARA resources.

3.3 Notes on Implementation

- There was initially some trouble deciding the best markup language to use for the site; however, due to client's request and the fact that Sphinx offered benefits of improved layout and design, we chose Sphinx over MkDocs.
- The number of modules has changed over time as well. It was initially at 7 modules, then it changed to 5 modules, and finally we settled with 6 modules. This is excluding Module 0 because this information is created by the previous senior design team. We are simply sending users to that website not claiming their work.
- Our initial thoughts on lab implementations were to write our own scripts and have users simply run them to visualize the process outlined in each module. We decided to change this approach by establishing our own sandbox in which users can create and edit their own scripts/waveforms/applications for module concepts. This decision was made to allow the user more freedom in implementing the concepts covered and applying their own creativity to the process.
- The final module was to incorporate Open-Air Interface (OAI) and utilize any source code (while applying our own changes) to show users the importance of OAI with ARA. Module 5 eventually introduced OAI to the user and included a capstone lab to use OAI in the implementation of a 5G network. Our thoughts were on teaching the learner about 5G and its components to have them then apply their knowledge and simulate the setup of a functional 5G network.

4 TESTING

The testing procedures that were conducted can be broken into six parts as seen in the sections below. Each of these elements are essential for ensuring tests are conducted on every element of the product. It starts with testing specific parts of the product to ensure that they work before they are added to the project. Then it moves on to testing the interface and ensuring the information is being hosted correctly. Once that is finished the focus shifts to conducting alpha and beta tests on the completed product. Once completed our product went through a final test ensuring it passes all conditions before it is considered completed.

4.1 Unit Testing

Testing Units:

- **SDR Software Modules:** Testing of signal processing and modulation algorithms/scripts.
- **USRP Hardware Interface:** Testing for communication between software and USRP hardware.
- **OAI Configurations:** Validation of custom OAI configurations in controlled environments.
- **Lab Experiment Scripts:** Testing the lab experiment scripts being walked through for accuracy and reliability.
- **GitHub/ReadTheDocs:** Testing the documentation updates pushed to our public GitHub repository triggers rebuilds on ReadTheDocs.

Tools used:
GNU Radio, UHD tools, OAI Software Suite, Network Analysis Tools (e.g. Wireshark), PyTest/Manual Testing of scripts, GitHub webhooks, and ReadTheDocs build framework.

4.2 Interface Testing

Software-to-Hardware Interface:
- **Composition**
  - This interface comprises the interaction between the SDR software modules (such as GNU Radio or custom Python scripts) and the USRP hardware.
- **Testing**
  - Verify that commands sent from the software are correctly executed by the USRP hardware, and that the data received by the hardware is accurately captured and processed by the software.
- **Tools**
  - UHD Utilities for direct interaction with USRP, automated scripts for functional testing.

Software-to-Software Interface:

- **Composition**
  - o Encompasses the communication and data flow between different software components, such as between GNU Radio and custom scripts or between different modules within OAI.
- **Testing**
  - o Ensure data transmission and command execution between software modules, verifying data integrity and correct functionality.
- **Tools**
  - o Custom test scripts, Python for automation, GNU Radio for internal module testing.

User Interface to Backend System Interface:

- **Composition**
  - o Involves the interaction between the graphical user interface (GUI) or command-line interface and the backend software and hardware systems.
- **Testing**
  - o Check that user inputs via the GUI or command-line are accurately translated into actions by the software, and that system status is correctly reflected in the user interface.
- **Tools**
  - o Manual Testing or potentially the use of GUI testing tools like Selenium.

4.3 Integration Testing

The critical integration paths for our design were broken down into four parts which are described in detail below:

DR Software and USRP Hardware Integration:

- **Justification:**
  - o The core functionality of the educational tool depends on effective communication between the SDR software and USRP hardware, and this integration is crucial for accurately conducting experiments and demonstrations in SDR technology.
- **Testing Method:**
  - o Tests will involve executing specific signal processing tasks using the SDR software and verifying the correct signal transmission and reception by the USRP hardware.
- **Tools**
  - o GNU Radio for software simulation, UHD Utilities for interacting with USRP hardware, and manual testing or potentially custom scripts for automating testing.

OAI Integration with USRP:

- **Justification**
  - o For advanced labs involving 5G simulations, the integration between OAI and USRP devices is vital.

- o This allows for realistic demonstrations of 5G network functionalities in the field, within an educational setting.
- **Testing Method**
  - o Setting up 5G network scenarios using OAI and USRP, and testing various network functions such as data transmission, handovers, and signal processing.
- **Tools**
  - o OAI software suite for network setup, network analysis tools like Wireshark for monitoring and troubleshooting.

Integration of Lab Experiment Scripts with SDR/OAI Systems:

- **Justification**
  - o The scripts guide students through the lab experiments and need to interact flawlessly with the SDR and OAI systems to ensure an effective learning experience.
- **Testing Method**
  - o Conducting lab sessions using these scripts, observing their interaction with the SDR and OAI systems, and collecting feedback on their effectiveness and ease of use.
- **Tools**
  - o Python or Bash scripts for controlling SDR and OAI operations, feedback collection tools for assessing user experience.

Documentation Hosting on ReadTheDocs Integrated with GitHub:

- **Justification**
  - o The integration between GitHub and ReadTheDocs is crucial for maintaining up-to-date, accessible, and version-controlled documentation.
  - o It's vital for ensuring that students and educators have the latest information and guides for the SDR and OAI based labs and experiments, designed by leveraging ARA's resources.

- **Testing Method**
  - o Verification of the sphinx html build for the document on a localhost/python server, and regular verified updates of documentation pushed to the GitHub repository.
  - o Verification of integration between GitHub and ReadTheDocs via the GitHub webhook, to host the documentation on ReadTheDocs.

4.4 System and Acceptance Testing

We split our group into 3 to satisfy system and acceptance testing. The groups were as follows:

GROUP 1	1. Chris 2. Josh
GROUP 1	1. Chris 2. Josh
GROUP 2	1. Jared 2. Lukas
GROUP 3	1. Zach 2. Varun

With these groups, as progress was made on our project, we internally tested the quality of the materials by following this order: Group 1 checks Group 2, Group 2 checks Group 3, and Group 3 checks Group 1. We also had our client/faulty advisor look at our work at each of our bi-weekly meetings. This process was repeated until no other problems remained, thus considering our deliverable as "Accepted".

4.5 Regression Testing

For wiki pages, we would complete a page with information. But there are times when we also update the materials to ensure that it doesn't bring any bugs or display things incorrectly after we build the project. This is the same for the quiz. For the quiz, we would ensure the questions make sense and the radio buttons would work and give us the correct output.

For some labs such as Matlab Simulink, we temporarily completed some sections of the lab. But there are many times where we added constant blocks and other blocks to ensure we can receive improve signals. Running the Simulink program and also checking the scope block within the software would verify if we received a valid signal or any errors.

4.6 Results

Overall, for our project, we are limited on what kind of testing methods we can employ because we are creating a website with learning materials. As such, we primarily employed alpha testing methods, aka internal testing methods. This involved each group in our team performing certain labs, looking through the website to ensure the material makes sense, performing the labs to make sure that they are receiving the correct outcomes and values, as well as proof-reading the website for grammar issues. Unfortunately, due to time constraints, we were not able to obtain usability data from users not in our senior design group. We are currently working on obtaining the data; if we are able to obtain it, it will be added to the presentation before our scheduled presentation time.

5 BROADER CONTEXT

Our project may seem very simple at first glance; however, it has required extensive research and time to obtain the information that is required for the product. The first step was to conduct research so the group could be considered experts in the topic therefore allowing us the ability to create learning materials and experiments. Our goal by the end of this project was to have a product that would impact the learning process for anyone that has an interest in ARA and 5G and beyond wireless systems. With this big-picture view in mind, here are some examples of when the modules are completed how users can use ARA to affect certain fields/areas:

Area	Examples
Public health, safety, and welfare	**In accordance with United Nations Sustainable Development Goals, our project incorporated by ARA meets SDG #4: Quality Education and SDG #9: Industry, Innovation, and Infrastructure.** With 5G accessibility available in rural areas, safety can be improved by increasing automation of unmanned technological equipment. This will decrease accidents with the faster latency provided by 5G (Real-Time Systems).
Global, cultural, and social	The entire world will be affected by an improvement in 5G simply because rural areas help feed a large percentage of the world. With 5G access in rural areas, they will be able to, for example, check the quality of crops and livestock remotely and efficiently.
Environmental	To increase accessibility, this will require more technology to be implemented, which can increase energy and therefore cost. Although solar power could be used, this adds another problem of energy efficiency and how much is required to power such technology in rural areas.
Economic	5G can be costly. This is part of the reason why 5G accessibility is still a problem in some parts of the world, especially in those with a lower population. The learning platform that we are creating is considered free for learners, which will be able to access ARA equipment and tools to perform experiments for free, provided that they are allowed access.

6 CONCLUSIONS

6.1 Progress Review

Over the last two semesters we have been committed to multiple aspects that have been crucial to the devolvement of our project. The elements that were crucial were our dedication to a schedule, preparation, and communication. These elements allowed us to develop a well-rounded project that hit all the requirements required. The first semester was focused heavily on researching 5G material that was required for the ARA project. This allowed us to become experts on material such as SDRs and OAI which are essential for 5G and ARA. Once we became an expert on the material, we were able to make an initial prototype to gain a general idea on how we want to design the project.

In the second semester we then were able to make changes to the design to make a project that is able to educate future users. In this process we were tasked with creating labs that directly use ARA's resources. During this process, it allowed us to get a hands-on experience within 5G and take a deep dive into the service that ARA provides. Our team was able to take in a complex request, conduct research, create a prototype, conduct testing, and build a final product that hits all requirements.

6.2 Value of Design

For senior design students interested in 5G and rural technology projects, our learning materials give them the knowledge they need to use ARA's resources effectively. This means better projects and learning.

Also, undergraduate and graduate students in different fields can use these materials to understand rural resources better. This helps them do well in their studies and learn about advanced technology like 5G. Moreover, anyone in the general public who wants to learn about 5G, even if they are not students, can use our materials. Therefore, our resources can also help more people understand 5G and how it connects to the world today, which could pave the way for new ideas and improvements.

6.3 Potential Future Steps

This project can continue benefiting its users by taking these potential future steps:

1. **Website upkeep**: Regular maintenance of our website is crucial to ensure it remains accessible and functional. This includes fixing any bugs that may arise, updating software, and further optimizing the user experience.
2. **Update wiki page content**: Keeping the wiki page content up-to-date is essential for providing accurate and relevant information to users. This involves adding new information as ARA technologies evolve and removing outdated content.
3. **Add more labs**: Expanding the number of labs available on our platform can enrich the learning experience for users. By covering a wider range of topics and technologies, we can cater to diverse interests and educational needs.

4. **Make labs more connected**: Enhancing the connectivity between labs can provide users with a more cohesive learning experience. This can be done by structuring labs to build upon each other, allowing users to progressively develop their skills and understanding as they move through the material.
5. In conclusion, senior design has provided us with an experience to discover technical skills that can be directly applied to our careers in the future. We are also very grateful to have been able to help ARA with their endeavors and thank all members of ARA that helped us be successful with this project.

6.3 Acknowledgements

In conclusion, senior design has provided us with an experience to discover technical skills that can be directly applied to our careers in the future. We are very grateful to have been able to help ARA with their endeavors and thank all members of ARA that helped us be successful in completing this project, especially Dr. Arsalan Ahmad, Dr. Hongwei Zhang, Dr. Mohamed Selim, Mr. Joshua Ofori Boateng, and Dr. Sarath Babu, among many others.

7 APPENDICES

7.1 Appendix 1 – Operation Manual

Because we created self-paced and self-directed learning materials, all the details explaining how to use our learning materials can be found at the following link:

https://5g-prototype.readthedocs.io/en/latest/module_0_old_5g/beforeyoubegin.html

7.2 Appendix 2 – Alternative/Initial Version of Design

Previous versions of our design are explained at length above in "2.4 Design Changes from 491".

7.3 Appendix 3 – Other Considerations
o N/A

7.4 Appendix 4 – Code
o The source code for our 5G site was built from our GitHub repo, which can be found at the following link:

https://github.com/ARAnextg/5G_prototype

7.4 Appendix 5 – Citations

<u>Module 0: Introduction to 5G</u>

- https://arawireless.readthedocs.io/en/latest/

<u>Module 1: Modulation & Communication Techniques</u>

- o **Wiki page 1**: Understanding Modulation & Demodulation Techniques
    - o https://www.youtube.com/watch?v=mHvV_Tv8HDQ
    - o https://en.wikipedia.org/wiki/Demodulation
    - o https://www.techtarget.com/searchnetworking/definition/modulation
    - o https://www.youtube.com/watch?v=Fe4XII0CK_8
- o **Wiki page 2**: OFDM: Principles and Implementation
    - o https://en.wikipedia.org/wiki/Orthogonal_frequency-division_multiplexing
    - o https://www.mathworks.com/discovery/ofdm.html#:~:text=What%20Is%20OFDM%3F,transmit%20at%20similar%20data%20rates
    - o https://www.youtube.com/watch?v=KCHO7zlU25Q
    - o https://www.techtarget.com/searchnetworking/definition/orthogonal-frequency-division-multiplexing
- o **Wiki page 3**: Frequency Hopping in Communication Systems
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    - o https://www.researchgate.net/publication/325962173_Modulation_of_Laser_Light
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- o **Wiki page 3**: Setting Up a 5G Network Using OpenAirInterface (OAI)
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- o **Wiki page 4**: How OAI Uses and Establishes Configuration Files
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