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Patch Antenna Calculations and Fabrication Made Simple for Cyber Security Research

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Abstract

Recently, radio frequency research has received increased attention from the cyber security community, identifying significant issues that compromise confidentiality and integrity of various wireless systems. Most cyber security researchers do not have vast and requisite expertise in antenna design and commonly use commercially purchased antennas as an alternative. To bridge the knowledge gap in antenna design, this paper introduces an open-source Antenna Calculator tailored for patch antennas, which are not only easier to manufacture than other topologies, but also more affordable compared to alternatives like horns, despite some offering higher gain. The calculator is designed primarily as an educational tool to supplement cyber security courses that focus on wireless security, equipping students and researchers with the knowledge to build their own antennas and apply them in observing effects of various cyber security scenarios. Directional antennas such as patch antennas are useful for proving that certain cyber security attacks are possible over long distances, compared to the short-range proof of concept approaches. This paper elaborates on several manufacturing methods for patch antennas and their relevance for cyber security courses. Results of antennas designed using the presented tool are reported, followed by an exploration of the importance of RF accessibility in education and potential application in the cyber security domain.

Introduction

Cyber security researchers publishing in the Radio Frequency (RF) and Software Defined Radio (SDR) domains have voiced that using a higher gain directional antenna would improve distances at which their cyber security research can be executed. Antennas employed in these areas are primarily commercially available monopoles and dipoles, which are known to have a relatively low gain. Antenna design was not necessarily the immediate area of expertise of the hitherto mentioned researchers based on the comments from [1-5]. A current trend in cyber security research focuses on passive attacks (e.g., wireless eavesdropping) and active attacks (e.g., impersonation and control). Within this topic, a high gain antenna would assist in verifying whether the identified flaw in the device under assessment could be executed at a distance where the risk is significant for the business that uses it. That is, utilizing an antenna capable of communication at greater distances increases the risk that a system could be compromised. As RF research becomes increasingly prevalent in related fields, it is important that accessible open-source tools for antenna design are made available.

The availability of open-source tools for antenna design is an invaluable resource for individuals interested in cyber security research. The reason behind this is that for both educators and students, the requirement of significant prerequisite knowledge for understanding information required for antenna design is often a substantial barrier to entry. This challenge can be particularly demotivating for students who are just beginning to explore the field. To combat this issue, and its potential effect on retention, these open-source tools are meant as a supplement to higher education concepts in a manner that is accessible to students and educators at different levels of proficiency, as well as students with less income or the ability to procure expensive custom antennas.

This paper presents an open-source Antenna Calculator [6] that aids in designing several common topologies. One benefit of streamlined open-source tools such as the Antenna Calculator is that it can serve as the connection between education and other fields, such as cyber security. While convenient, this tool is not meant to oversimplify the design process, but rather it is meant to reduce the barrier of entry for students and educators alike who want to learn antenna design and apply it to fields such as cyber security where it can be utilized for further discovery of new cyber security concepts. This reduction of complexity is accomplished by providing access to necessary information to get started, thereby enabling users to learn by experimenting, gaining practical experience, and learning the real-world applications in an effective manner.

The educational advantage of the Antenna Calculator tool is that it would provide students with aforementioned practical experience in complex RF concepts in an approachable and accessible way as well as decrease the intimidation factor that can often accompany learning new subjects with significant pre-requisite knowledge. This tool can be integrated into the existing curriculum, allowing students to gain a foundational understanding of RF concepts that can be expanded upon as they progress through their studies.

The Antenna Calculator is a tool that enables the calculation, design, and manufacture of antennas in a classroom environment as well as for professional use. Additionally, the paper discusses various manufacturing techniques that can be used for constructing an antenna. The main objective of the tool is to address the lack of readily accessible, high gain, directional antennas operating at frequencies of interest, while also making the process accessible to professionals and hobbyists alike. This tool is especially useful for those in the education sector, including students and cyber security researchers, who may not have detailed knowledge of antenna design. The open-source Antenna Calculator tool is available on GitHub [6], providing a wider range of people with the ability to create antennas for educational or research purposes.

This paper first introduces the Antenna Calculator, which allows students to calculate the required dimensions of a patch antenna based on the desired frequency and substrate material. It then discusses various manufacturing methods including utilizing copper tape, CNC, router, mill, chemical etching, and professional manufacturing. Afterwards, educational applications are explored by comparing the use of antennas to teach basic principles of electromagnetics. The use of patch antennas that have enabled cyber security research in aforementioned passive and active attacks are highlighted, and then the paper concludes with a discussion of future work, presenting several areas for future improvements.

Antenna Calculator

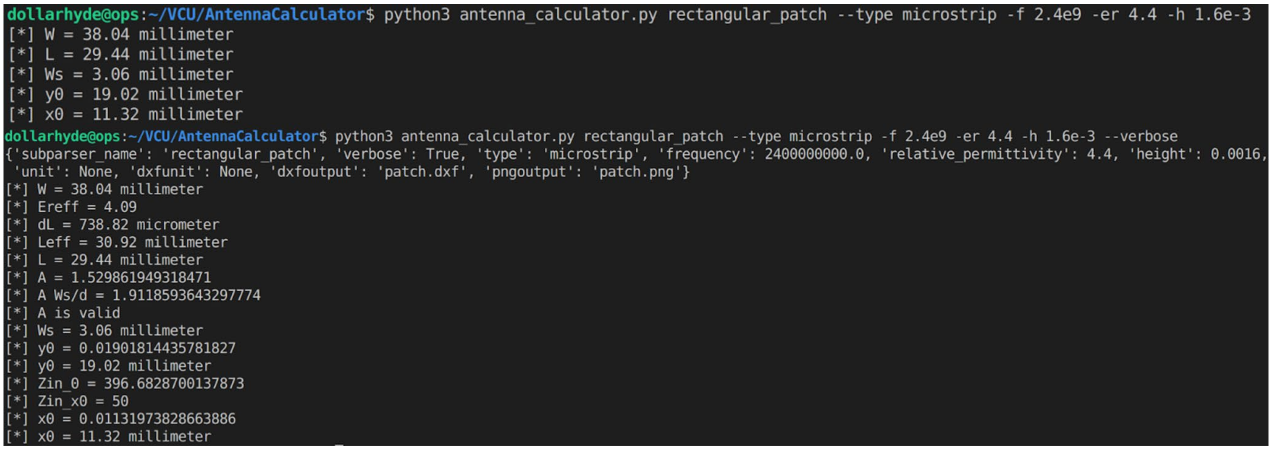

Figure 1. The calculator used to generate parameters for a microstrip-fed 2.4 GHz patch antenna (top), and the verbose option for displaying all calculated parameters (bottom).

The Antenna Calculator, shown in Fig. 1 with example calculations, is an open-source, command-line based tool written in Python. This tool offers a significant advancement by automating necessary calculations needed to determine the precise location of the 50 Ω point for impedance matching of the antenna with the rest of the system. Unlike existing calculators that only provide output of patch width and length, this tool provides crucial parameters such as microstrip width for microstrip patch antennas and placement of the probe for probe-fed patch antennas, which are necessary for constructing the entire antenna accurately. Without these parameters, connecting the antenna correctly can be a challenging task, potentially leading to reflections and decreased performance.

The documentation for the tool, also hosted in the GitHub repository at [6], covers how to download and use the Antenna Calculator. This tool currently provides calculations for the physical parameters for the creation of a variety of common antenna types; including a rectangular patch antenna fed either by a probe or microstrip based on the transmission-line model, a half-wave dipole, and a quarter-wave monopole. This paper focuses on the patch antenna calculator and output because of the versatility of manufacturing techniques. However, when using the tool, the help menu, as seen in Fig. 2, can be used to explain the input parameters and arguments needed for other topologies.

The calculator for patch antenna requires, as input, the desired antenna feed type, the resonant frequency, relative permittivity of the substrate on which the antenna in question is built, and the height (thickness) of the substrate. As output, the calculator provides parameters necessary for construction of the patch antenna: patch width, patch length, horizontal and vertical parameters of the connection point for both probe-fed and microstrip-fed antennas, and strip width for microstrip-fed antenna. The calculator provides the ability to export the antenna dimensional parameters in several formats for ease of manufacture. For example, the rectangular patch antenna design can be exported to a letter sized paper as a PNG image used for tracing copper tape to apply to single-sided FR-4, or printed using a laser printer on vinyl to transfer to double-sided FR-4 for chemical etching fabrication as in Fig. 7. The calculator tool can also export the design as a DXF file as seen in Fig. 4 for PCB/CNC fabrication, or as a Gerber file as seen in Fig. 8 for professional fabrication methods. Additionally, the export functionality can take input both immediately from the calculator tool or from the user to create antennas that vary from the initial calculations based on the transmission-line model. A benefit of this design method is that templates can be modified and reprinted as experimental tuning occurs to get desired results. It also allows for tuning and testing with an inexpensive technique (e.g., copper tape) to be used as a prototype for a more time and material consumptive method such as chemical etching.

The manufacturing example of patch antennas is just one facet of the calculator's potential. The Antenna Calculator is in continued development with aims to expand its capabilities to include other designs such as planar and nonplanar designs, including horn antennas. The Antenna Calculator also includes calculations for monopole and dipole designs which are simple to fabricate with wire. In this example, patch antennas serve as an excellent example to demonstrate manufacturing methods and further lower the barrier to entry by providing necessary step by step instructions for manufacturing.

```
dollarhyde@ops:~/VCU/AntennaCalculator$ python3 antenna_calculator.py rectangular_patch --help
usage: antenna_calculator.py rectangular_patch [--help] [--verbose] [--type {microstrip,probe}] -f FREQUENCY -er RELATIVE_PERMITTIVITY -h HEIGHT
                                               [-u {meter,centimeter,millimeter,inch}] [-du {meter,centimeter,millimeter,inch}] [--dxfoutput DXFOUTPUT]
                                               [--pngoutput PNGOUTPUT]

optional arguments:
  --help                Show this help message and exit
  --verbose
  --type {microstrip,probe}
                        Type of patch
  -f FREQUENCY, --frequency FREQUENCY
                        Frequency in Hz
  -er RELATIVE_PERMITTIVITY, --relative_permittivity RELATIVE_PERMITTIVITY
                        Relative permittivity
  -h HEIGHT, --height HEIGHT
                        Substrate height in meters
  -u {meter,centimeter,millimeter,inch}, --unit {meter,centimeter,millimeter,inch}
                        Unit of measurement
  -du {meter,centimeter,millimeter,inch}, --dxfunit {meter,centimeter,millimeter,inch}
                        DXF Unit of measurement
  --dxfoutput DXFOUTPUT
                        Name of DXF file
  --pngoutput PNGOUTPUT
                        Name of PNG image for printing
```

Figure 2. The help menu for creating a patch antenna in the Antenna Calculator.

Manufacturing Patch Antenna Example

In this section, several antenna creation options are discussed. The first three methods focus on techniques that can be done with relatively common materials or tools, while the fourth discusses how to use the Antenna Calculator to generate Gerber files that can be sent off for professional manufacturing. The methods described here for manufacturing patch antennas at home all utilize FR-4, a fiberglass substrate used commonly because it is inexpensive and non-conductive, and 50 Ω impedance female SMA connectors designed to solder to PCB. SMA cables should be selected based on individual project needs and are not covered here. In all cases, exports from the Antenna Calculator tool are either used as printed templates, or imported for machining. Figs. 4 and 8 show examples of the exported files generated by the calculator tool, while Fig. 7 shows a chemical etching example for the rectangular patch manufacturing process.

A. COPPER TAPE

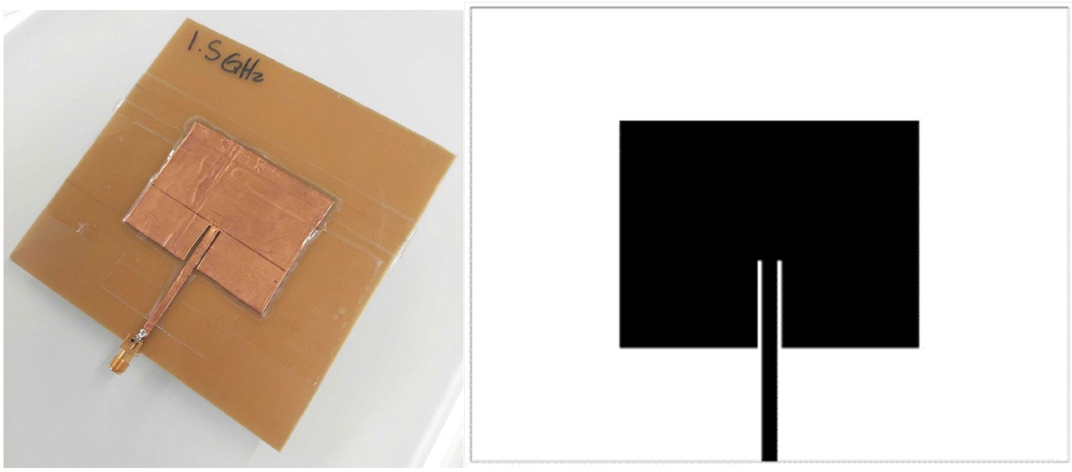

Figure 3. Left, a 1.5 GHz patch antenna created with copped tape. Right, the exported PNG used as a template.

The first method of manufacture is the simplest one, and the most accessible. The primary materials for this process are copper tape, single-sided FR-4 and an SMA connector. Using the Antenna Calculator with PNG output will provide a properly scaled image of the antenna silhouette that can be printed on common letter paper. This image can be adhered to the copper tape as a template to easily cut out the conductor for the antenna. In Fig. 3, a 1.5 GHz patch antenna was created using this method, and sticking the copper patch to the bare side of the FR-4. This method works well for frequencies at and below 2.4 GHz as the microstrip feed from the SMA connector to the antenna is large enough to cut by hand. The center pin of the SMA connector can be soldered directly to the copper tape without affecting the adhesive, likewise the heat from soldering the SMA pins onto the ground plane on the back does not cause the adhesive to noticeably degrade. When tuning, a sharp blade can be used to cut the copper tape directly on the FR-4 to remove excess, or copper tape with conductive adhesive can be added to the edges of the patch to lower the frequency.

B. CNC, Router, or Mill

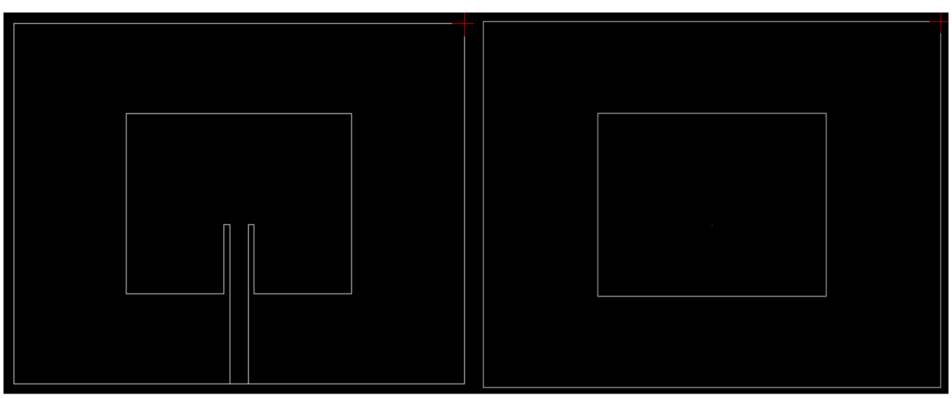

Figure 4. Left, the exported DXF for a microstrip-fed patch antenna. Right, the exported DXF for a probe-fed patch antenna.

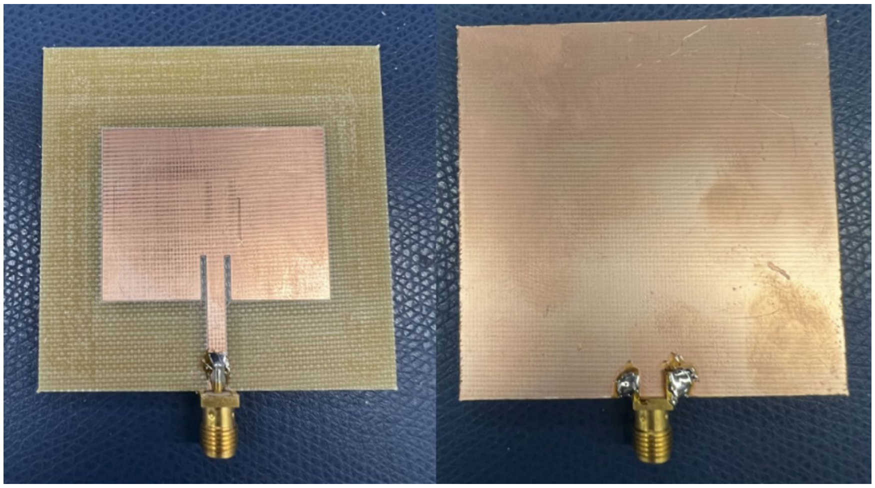

Figure 5. Front and back of the LPKF ProtoMat S103 milled patch antenna, including the soldered connector.

The second method of manufacture involves the use of a milling machine. In experiments, an LPKF ProtoMat S103 Prototyping Machine with LPKF CircuitPro software was used to mill the antenna from a sheet of double-sided FR-4. The open-source Inventables X-Carve CNC machine with Easel software has been used to create similar antennas. Using the Antenna Calculator with DXF output will provide a properly scaled image of the antenna that can be imported into most milling machines including LPKF ProtoMat S103 and Inventables X-Carve CNC machine. Fig. 8 shows an example of the exported DXF for the 2.4 GHz microstrip-fed patch antenna design which was imported into the software for both machines without compatibility issues. Fig. 5 shows an example of a milled antenna with the soldered center pin of the SMA connector as well as the ground plane on the back.

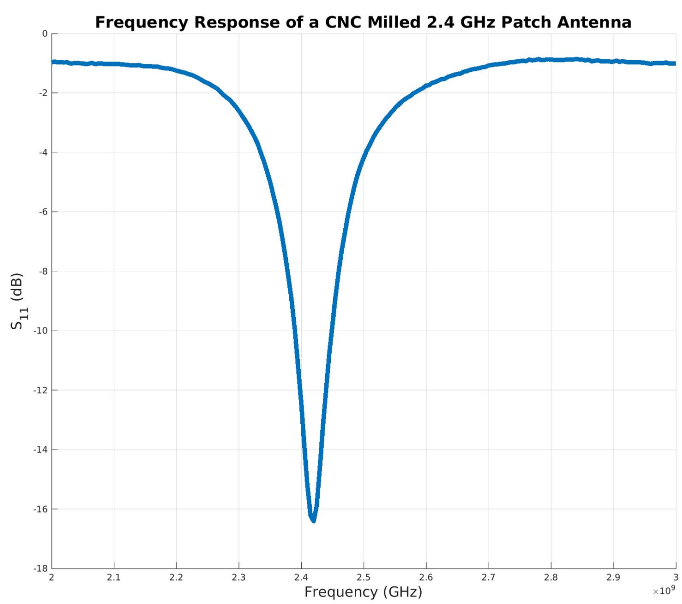

Figure 6. Measured data for a CNC milled 2.4 GHz patch antenna.

After the antenna is created, it should be measured and then evaluated on whether it is operable within the desired frequency band. Fig. 6 shows the S_{11} parameter, or the reflection coefficient, which indicates the antenna's resonant frequency. In general, the lower this number is, the better the antenna will perform at that frequency. The S_{11} parameter can be measured using commercially available tools such as a NanoVNA. While gain and directionality are also important factors in antenna design, finding hobbyist or entry-level devices to properly measure these aspects is difficult.

C. Chemical Etching

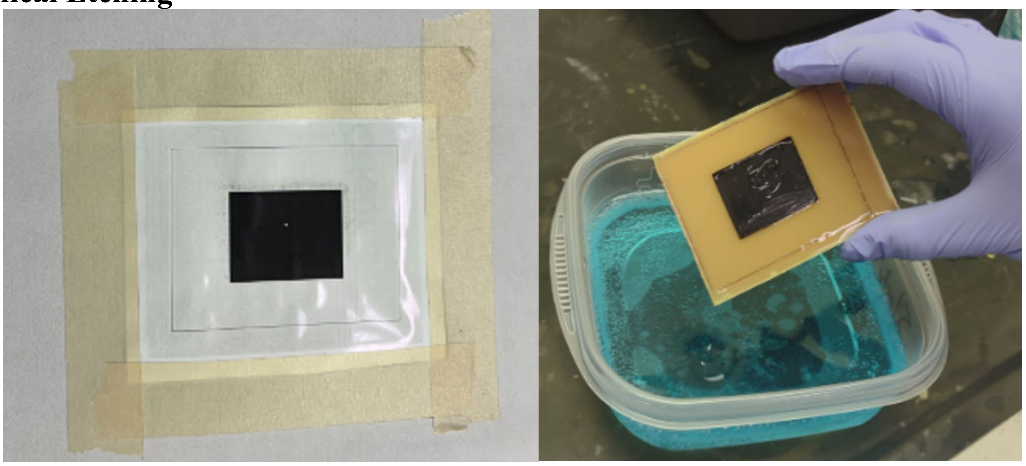

Figure 7. Left, a probe-fed patch design printed on vinyl backing using a laser jet printer. Right, the remaining ink transferred from the vinyl backing after chemical etching protecting the remaining copper below.

The third method of manufacture uses chemical etching to partially remove copper from one side of a double-sided piece of FR-4. Chemical etching is the most time-intensive process available for hobbyists to manufacture patch antennas, but the designs are more accurate than the copper tape method and some hobby-level CNC machines. This method can be hazardous and it is important to follow appropriate precautions when handling chemicals, including working in a well-ventilated area, wearing proper protective equipment, and following manufacturer recommendations for accidental exposure to chemicals. The materials needed for this process are as follows: double-sided FR-4, the female SMA to PCB connector, a laser jet printer, vinyl backing, an iron (such as one sold commercially for household use), muriatic acid, hydrogen peroxide, and if possible, a thermocouple or infrared thermometer. Optionally, acrylic-based nail enamel can be used to fill in areas on the FR-4 where toner transfer is thin.

Using the Antenna Calculator with PNG output will provide a properly scaled image of the antenna silhouette that can be printed using a laser jet printer directly onto the non-stick backing of a piece of self-adhering vinyl as shown in Fig. 7. In this method, only the non-stick backing is used, not the vinyl itself. The patch template printed on vinyl backing was attached to the FR-4 with masking tape and heated using the iron at 150°C. Even pressure was used for 2-3 minutes, which appropriately transferred the toner to the FR-4. Rather than printing a transfer for the ground plane, nail enamel was used to coat the other of the FR-4 in order to protect the copper.

After the toner and nail enamel were completely dry, a plastic container was used to create a mixture containing ⅓ Muriatic acid (HCl) and ⅔ Hydrogen Peroxide (H_2O_2). The double-sided FR-4 was placed into the mixture and gently agitated to remove the uncoated copper. This reaction can take 3-5 minutes, but must be attended to prevent over-etching the copper. When the copper has been removed and rinsed with water to halt the reaction, the toner and nail enamel can then be removed using acetone, which will expose the final version of the antenna. The last step is to solder the center pin of the SMA connector to the edge of the microstrip (or to the conductor if using a probe fed design), as well as the outer pins to the ground plane on the back as shown in Fig. 5.

D. Professional Manufacturing

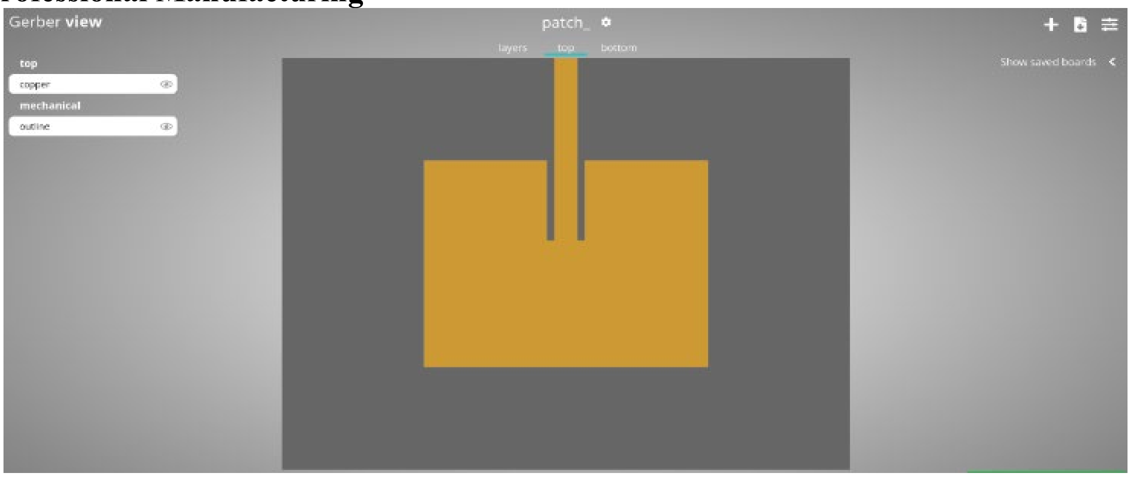

Figure 8. Generated Gerber file for 2.4 GHz patch antenna as viewed on pcbway.com [7]

The Gerber files exported from the Antenna Calculator tool can be uploaded to several PCB companies' platforms, such as Advanced Circuits or OSH Park, to have antennas manufactured professionally. This method is beneficial for high frequency antennas where high precision is necessary for proper function. Gerber files cannot be viewed on native applications, but websites such as pcbway.com [7] offer previews of uploaded Gerber files such as the 2.4 GHz design output in Fig, 8. Files can be generated and exported in a single step, as seen in Fig. 9, where the calculator takes design parameters and the DXF flag as input.

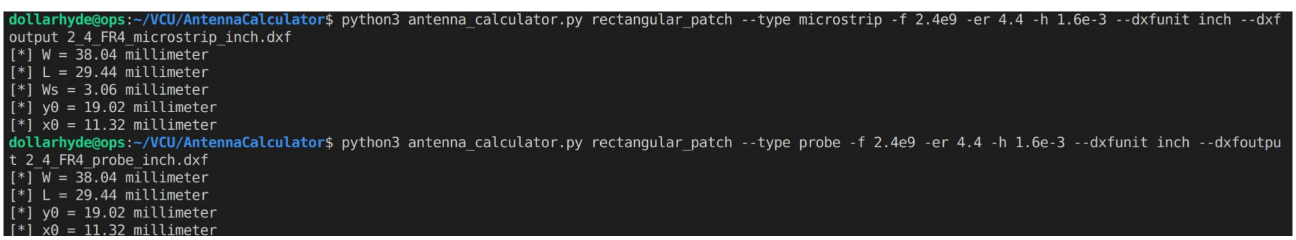

Figure 9. Exporting a DXF file for a 2.4 GHz microstrip-fed patch antenna (top), and a probe fed version of the same antenna (bottom).

Educational Applications and Implementation

Patch antennas are a vital element in multiple fields, such as in communication and cyber security. Incorporating patch antennas into education provides students with valuable hands-on experience, enhancing their understanding of core RF and electromagnetics (EM) fundamentals.

It is important to recognize that while learning RF design to build patch antennas can be beneficial, the primary focus of cyber security education incorporating patch antennas should be on the practical application of antennas rather than the intricacies of RF engineering and design. Using this as a focus, students can better understand how they can contribute to cyber security through wireless research, and how having a thorough understanding of how to select and use tools is going to be paramount in ensuring the success of the endeavor.

Hands-on manufacturing methods play a crucial role in developing a deeper understanding of simple antenna topologies, including patch antennas. High school students can be introduced to simple manufacturing tasks such as creating patch antennas with copper tape and use the antennas with low-cost microcontrollers such as Arduinos for basic demonstration of wireless communications. Although high school courses may be an early stage to introduce complex electromagnetics, the manufacturing and use of simple antenna topologies, especially patch antennas, can establish a strong foundation for future learning and encourage students to choose STEM (Science, Technology, Engineering, and Mathematics) careers.

At the post-secondary education level, the emphasis shifts to understanding either practical applications of antennas for a specific purpose such as cybersecurity-focused programs or deeper understanding of electromagnetics and other types of antennas. This educational approach offers several advantages. Learning to create custom antennas can be a cost-effective solution for students with limited budgets, enabling them to gain necessary hands-on experience without exorbitant costs. Through this process of hands-on experimentation, the students can gain holistic perspective that will allow them to develop a more profound understanding of the scope of their work and elements involved. Lastly, this encourages skill development that introduces complex devices that have practical applications which can then lead to a career path that aligns with their interests or goals. Some students may become interested in expanding on the applications of antennas, while others may be interested in the development, delving deeper into antenna design and engineering.

Advancements for Cyber Security Applications

One of the cyber security uses for the Antenna Calculator tool is for Internet of Things (IoT) security assessments. The most common SDR for hobbyists' use is the HackRF One by Great Scott Gadgets, which often includes monopole antennas, which work well for proof of concepts, but do not truly demonstrate the risks at higher distances.

It is important to note that patch antennas offer several advantages over monopole antennas in that they provide directional gain, which is necessary for long-range testing applications. When it comes to cyber security applications, the ability to isolate frequencies can be crucial for identifying threats and vulnerabilities in a network which can then be communicated with the manufacturer and in turn mitigate risks of IoT devices. Patch antennas can be used to create specialized equipment for this purpose further mitigating risks. From an educational perspective, the use of patch antennas can provide students experience in developing and testing specialized equipment for security assessments. This can help to enhance the importance of antenna design and practical applications of RF and EM knowledge in cyber security.

Discussion and Future Work

Presented here is the open-source Antenna Calculator and its applications in both the educational and professional fields, along with several methods of manufacturing of patch antennas. Unlike other patch antenna calculators available, this calculator provides crucial numeric values for physical parameters necessary for constructing the entire antenna accurately that other calculators overlook. This calculator also provides the ability to export templates for patch antennas that include a clear demarcation for the 50Ω point to assist in reducing power reflection issues.

The transmission line model used in the patch antenna example is the easiest to calculate, but these calculations are slightly less accurate when compared to more complex models such as those used in full-wave electromagnetic simulations. However, in practice, using the transmission line model with copper tape to manufacture patch antennas operating in the 2.4 GHz Wi-Fi band was accurate enough for transmitting data wirelessly. The milled antenna from Fig. 5 was tested using a Vector Network Analyzer, producing the results in Fig. 6, where the resonant frequency was in-band for 2.4 GHz Wi-Fi operation.

One of the key applications of the calculator is its role in education. Patch antennas were chosen as the primary example in this work because even though they have less gain compared to horn antennas, their ease of manufacture and cost-effectiveness makes them a more accessible option. This enables students to create antennas at low cost, helping them gain experience and develop a deeper understanding of their work. This educational approach paves the way for skill development in both cyber security and antenna design and may be an inspiration for a career in one of the related fields. Furthermore, the methods covered in this paper and covered in courses incorporating the Antenna Calculator tool can be directly applied in a professional setting. This calculator bridges the gap between introductory prerequisite learning and real-world use, demonstrating that the fundamentals taught are not simplified, but rather introduced in a way to form solid foundations for professional use. The calculator tool itself is located at the repository at [6], where future development updates including an expanded topology library will be available free for public use.