Design, Prototyping, and Evaluation of a Directional Wi-Fi Antenna Using Simulation Models and Low-Cost Empirical Performance-Testing Techniques

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Abstract: This report documents the design, prototyping, and testing of a directional Wi-Fi antenna, as a part of the ELEN4001 High Frequency Techniques course at the University of the Witwatersrand. The design principles carried out were based on the methods described in *Antennas in Practice* by Clark and Fourie [1]. The antenna was designed using, tested, parameterized, theoretical models and thereafter was refined via the MATLAB (Antenna Toolbox) [2] simulation software. Lastly the Prototype antenna was physically constructed and tested yielding promising results.

Key words: Antenna, Low-Cost, Wi-Fi, Yagi-Uda, MATLAB, RSSI

1. Introduction

Wi-Fi routers are often designed to utilise 'omni-directional' antennas which *attempt* to radiate power isotropically within a building [3]. However this can be considered inefficient in cases such as in long buildings where a router can only be placed at an extreme end of the building. One solution to this problem is to increase the overall transmitted Wi-Fi power within the building, by either increasing the transmit power of the router, or by adding an additional router, making this solution cost ineffective. Considering that the inefficiency arises as power is radiated to areas where it is not needed (outside the building), instead of areas where it would be deemed useful, a more cost effective solution is to ensure that power is better 'directed'. Hence in this report a directional antenna is designed with the intent of increasing the range-of-use of a Wi-Fi Router within a building, under the constraint that it is affordable for home users. Additionally this report will focus only on the '2.4 GHz' Wi-Fi band, even though there also exists a '5 GHz' band [4]. It is assumed that by increasing the directivity of the transmitting antenna that an improvement in signal quality will be observed, despite despite the presence of obstacles. One could hypothesise that if power is better directed to an area initially receiving relatively low power, then the net power should increase as long the obstacles remain the same.

This report will first discuss the design process of the antenna by outlining its specifications to which antenna design theory can be applied to derive a base-line antenna model. Thereafter the base-line model is simulated, evaluated and then refined to ensure that the specifications are met. A physical prototype is subsequently constructed, and tested by gathering empirical measurements using inexpensive test equipment such as smart phones and consumer Wi-Fi routers. Lastly the results from the performance testing are evaluated to determine if the success criteria is met. The success criteria being that: the antenna is directional, matched correctly to the generator-transmission-line circuit (Wi-Fi router), and that it is efficient enough to outperform the stock omni-directional antenna regarding range-of-use.

2. Antenna Design

The design process of the antenna begins with defining: its operational specifications, and its type by considering potential construction material and Wi-Fi hardware; physical dimensions are then calculated based on the selected antenna type. Lastly a matching circuit is designed to ensure that the antenna operates efficiently.

2.1 Specifications

Wi-Fi Routers follow the IEEE 802.11 [4] Standard, which dictates antenna and connection media specifications, RF Frequency bands, and channel allocations on these bands (table 1). The specific band at which the antenna should operate is between 2.4 and 2.4835 GHz in most countries; however in other countries such as Japan it should operate between 2.471 and 2.497 GHz. Hence the designed antenna should have a bandwidth of 500 MHz and and should be centred at 2.45 GHz. The expected impedance at the connection terminals of the Wi-Fi router is 50Ω. It is important

Table 1: 2.4 GHz Wi-Fi Channel Allocations centred at Frequency f

Channel No.	1	2	3	4	5	6 ...
f (MHz)	2412	2417	2422	2427	2432	2437 ...

... 7	8	9	10	11	12	13	14
... 2442	2447	2452	2457	2462	2467	2472	2484

to note that indoor Wi-Fi antennas typically have a gain of between 0 to 6 dBi [3]. Gain is defined as the the product of *efficiency* and *directivity*. To recall: *efficiency* is the ratio of the power inputted to the power outputted of a system; *directivity* the measure of how much an antenna is able to 'focus' the power from one angular region to another. *Directivity* is presented as a logarithmic ratio relative to the directivity of an isotropic source (a source radiates perfectly in

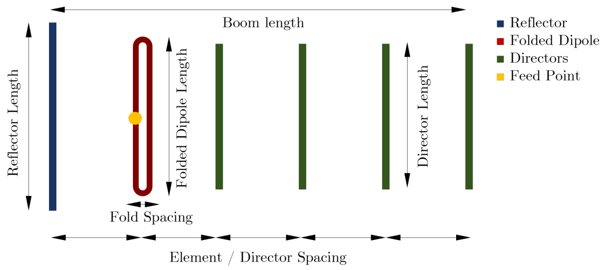


Figure 1: Diagram of the Parameterized Elements of a 4-director Yagi-Uda Antenna

all directions) using the units 'dBi' [1, p. 18-20].

Based on the above and the previously described project constraints the following specifications were derived and are listed in table 2.

Table 2: Specifications of Designed Antenna

Specification	Description
Frequency Range (MHz)	2400 - 2500
Design Frequency (MHz)	2450
Maximum VSWR	2:1
Input Impedance (Ω)	50
Cost (ZAR)	<100
Gain (dBi)	>6

The cost price of the antenna assumes that scavenged parts cost 0 ZAR (South African Rand), and that coaxial cable and corresponding connectors need to be purchased with a budget of 100 ZAR; also assumed to be "affordable for home users."

2.2 *Theory: Yagi-Uda Antenna*

The type of antenna chosen is the directional Yagi-Uda as it is simple to construct with material that is readily found within a house hold. It consists of an single *excited element* from which the antenna is fed, a *reflector* element, and a number of *director* elements. As literature [1, p. 67-68] explains the boom (total) length is proportional to the resulting directivity, however is inversely proportional the resulting operational bandwidth. Figure 1 shows a the core elements and length parameters of a 4-director Yagi-Uda antenna, from which an N-element antenna follows closely.

The design approach specified in [1, p. 69] mentions two sources: the NBS technical report published in 1976 [5], and the *Yagi-antenna Design* [6] text published ten years later. It is noted that the NBS report had computed optimal, varying, lengths for the director elements, however it was shown that using the average length of the directors also performed well [6], furthermore simplifying the antenna fabrication process as the director lengths are all the same.

Some of these elements lengths, specifically for: a 4-director, 10-director, and a 15-director Yagi-Uda configuration are presented in table 3 in units of wavelength (λ) and mm. It is important to note that element lengths presented in table 3 are designed for an element diameter of 0.008λ which equates to approximately 0.98mm, hence a correction factor is required if a different diameter is used. These configurations are are considered as they offer a range of design options from which either bandwidth or directivity can be maximised, with the 10-director configuration serving as a relatively neutral starting point.

The excited element commonly takes the form of a Folded Dipole antenna, however the overall length of this antenna differs from the case where there are no directors or reflectors [1, p. 69]. The recommended spacing between the the folded portion of the antenna is less than a twentieth of its length [7, p. 506].

Table 3: Recommended lengths for the elements of a 4-director, 10-director, and 15-director Yagi-Uda Antenna at 2.45 GHz [1, p. 69]

Element	4-director		10-director		15-director	
	(λ)	(mm)	(λ)	(mm)	(λ)	(mm)
Reflector	0.482	59.02	0.482	59.02	0.482	59.02
Spacing	0.200	24.49	0.200	24.50	0.200	24.50
Director	0.427	51.29	0.402	49.22	0.395	48.37
Exciter	0.378	46.29	0.382	46.72	0.396	48.49
R/D	1.289		1.199		1.22	
Suited for	Bandwidth		Neutral		Gain	

2.3 *Matching Circuit*

A matching circuit is often required to ensure that the antenna has the same impedance of the rest of the high frequency circuit. This is important because if an antenna is not properly matched to its driving circuit then power is reflected back to the driving electronics potentially causing damage. This would also mean that the antenna is less efficient as only a portion of the power is inputted to the antenna to be radiated, thus the antenna will also have a lower gain. Two methods are considered to match the antenna to the 50Ω Wi-Fi router port: a half-wave balun, and a stub matching circuit as posed in [1, p. 33,36].

It is expected that the impedance of a Folded Dipole-driven Yagi-Uda antenna is on the order of 200Ω, hence a 4:1 impedance transformer should match the antenna to a 50Ω line. Using a half-wave balun this is precisely what is achieved [1, p. 69].

In the event that the resulting antenna's impedance is not near 200Ω, the a stub matching circuit would have to be considered. Using such a circuit allows for a variable impedance transformation to occur, albeit for a narrow bandwidth. One favours the half wave balun as it is more simple to implement physically, as it only requires cutting a piece of coaxial cable to length, where as the stub matching circuit would re-

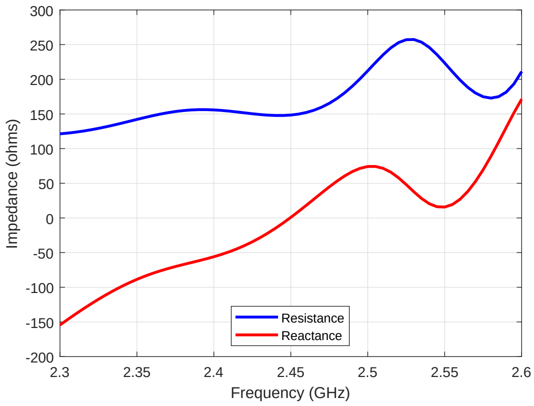


Figure 2: Antenna Input Impedance

quire multiple calculations, measurements, cuts and joins.

3. Simulation and Refinement

The recommended element lengths discussed in section 2.2 were inputted into a parametrised model of a Folded Dipole-driven Yagi-Uda antenna for the 10-director case using MATLAB's Antenna Toolbox [2]. Initial simulations showed that a maximum directivity of 11 dBi with a bandwidth of nearly 1 GHz (assuming matched conditions) was achievable. However the center frequency was not 2.45 GHz. According to [1, p. 69] the exciter element's length – the folded dipole – dictates resonance, hence it was tuned to ensure matching (zero reactance) at the center frequency using a binary search-based optimisation algorithm.

It was decided that the number of directors, and thus the boom length should be increased to 15 to make a trade-off between the larger than necessary bandwidth for a larger gain instead. Similar to the 10-director case, using the theoretical lengths yielded expected results, however the folded dipole length had to be tuned to meet the required center frequency.

The final dimensions for the refined antenna are the same as those listed in table 3 for the 15-element case as a 1mm element diameter was used (no correction factor). However the folded dipole dimension are as follows: the length is 53.1mm with a fold spacing of 1mm.

Figure 2 shows the input impedance for the refined antenna, it can be seen that the impedance is in the order of 200Ω for the 2450 to 2500 MHz range, hence a halve wave balun may be used. It can also be seen that the antenna is designed to have zero reactance at the center frequency.

The impedance bandwidth was determined using figure 3. The obtained bandwidth of antenna is under 300 MHz (2.3 to 2.6 GHz) assuming matched conditions (200Ω figure 3), whereas the antenna does not meet the 2:1 VSWR requirement if it were to be con-

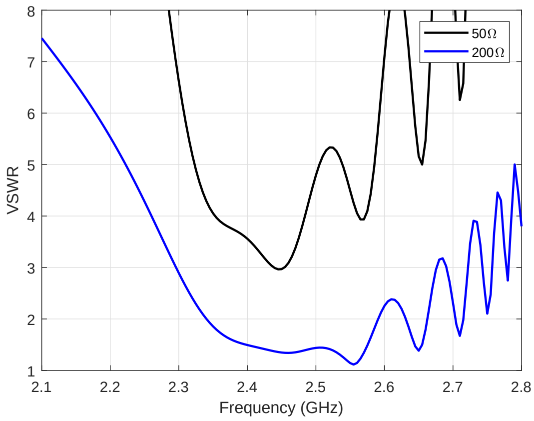


Figure 3: Impedance Bandwidth Relative to 50Ω and 200Ω

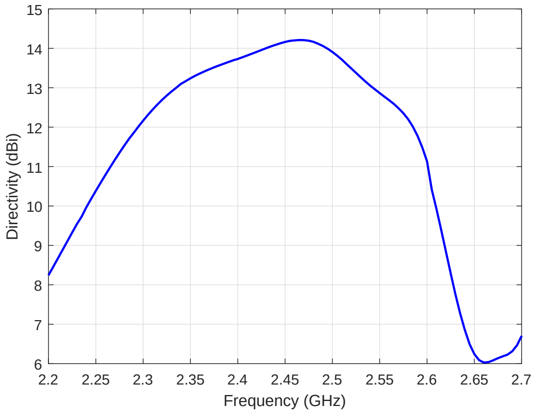


Figure 4: Gain Bandwidth at 90° Azimuth (dBi)

nected to a Wi-Fi router without a matching circuit (50Ω figure 3).

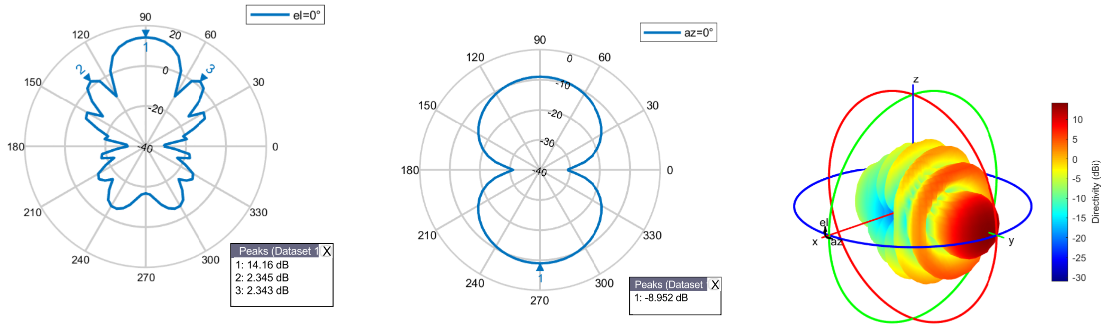
Figure 4 shows that there is a large gain bandwidth that meets the 6 dBi specification, but more importantly that the Gain of the antenna is maximised and consistent at the required frequency band. This figure was generated by performing a frequency sweep at maximum gain coordinate, which was obtained by the radiation pattern presented in figure 5. Figure 5 shows that a the antenna is indeed directional, and that maximum gain of 14.16 dBi is observed along the boom axis at away from last director element.

4. Prototyping

Based on the derived theoretical antenna model, and simulation results a physical antenna was constructed and then tested to verify that the intended design specifications were met.

4.1 Construction

A prototype antenna was constructed using 1mm steel rods, extracted from an old electric fly-swatter. fifteen director elements and a reflector element were cut to the values presented in table 3 (15-element). A metal file and calipers were used to shave the elements to



(a) Azimuth Pattern (dBi) (b) Elevation Pattern (dBi) (c) 3D Radiation Pattern

Figure 5: Antenna Radiation Pattern

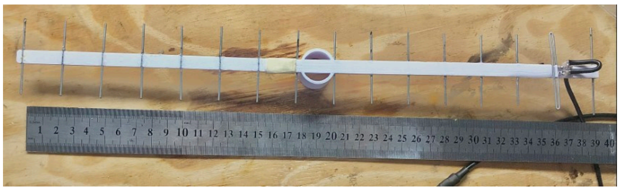


Figure 6: Constructed Prototype Antenna

0.5mm accuracy. The rod for the folded dipole was cut and then folded to the length determined in the *Simulation and Refinement* section. This was done to 0.8 mm accuracy, with the spacing between the fold being 0.2mm accurate. The finished elements are shown in Appendix, figure 9.

To connect the designed antenna to a Wi-Fi router, RG 174 A/U coaxial cable[8], and compatible Reverse-Polarity SMA connectors were procured for, a total cost of 45 ZAR.

To make the half wave balun transformer a piece of coaxial cable was cut to length, taking the velocity factor into account. Equation 1 was used to determine the length in mm. The using a velocity factor of 0.66 [8], the resulting length of coaxial cable is 40.4mm. A slightly longer piece of coaxial cable was cut so that the braid, and inner conductor could be exposed for soldering, however the length of the remaining sheath matched the calculated length. The balun is shown in Appendix, figure 10.

$$l_{mm} = \frac{300 \times VF}{2f_{MHz}} \times 10^3 \tag{1}$$

The next step of construction was to mount the elements to a plastic 3D printed boom which spaced the elements according to table3. And lastly the coaxial cable with crimped RP-SMA connector and balun was soldered to the feed point of the folded dipole (Appendix, figure 11). The constructed prototype is shown in figure 6.

4.2 Testing

To test the designed antenna a Wi-Fi router with external antenna-connection ports is used. The model of the Wi-Fi Router is a *Tenda 3G226R+*, which supports the IEEE 802.11 standard and has two 3 dBi antennas[9]. One stock antenna is used as a reference to determine the the directivity of the designed antenna.

4.2.1 Experimental Procedure

The experiment involves gathering data points that would allow for a pseudo-azimuth plot to be created for both antennas. The radiated power received from a smartphone – positioned at various angles and at fixed distance away from the antennas – is reported via its hardware's Received Signal Strength Indicator (RSSI). An Android application called *WiFi Analyzer* [10] is used to obtain an RSSI. The RSSI is expressed in dBm (power received relative to a milliwatt). Hence by gathering enough data points around the router a maximum signal intensity, and an approximation of the falfield radiation pattern can be determined.

One can conclude that the maximum RSSI obtained (dBm) for the stock antenna is proportional to its directivity (dBi); meaning the difference of the maximum RSSI values measured for the stock and the designed antennas should also be the difference of their Gains.

4.2.2 Results

The described experimental procedure was conducted by taking 12 measurements separated 30° apart at a constant radius of 5m. Figure 7 shows the prototype antenna on the marked experiment table which has a 5m length of rope nailed down to the centre. The transmitter power of the Wi-Fi Router was limited to 25 percent, and the router was configured to broadcast on Channel 6. The radius and transmitter power were set so as to ensure that all measurements would lie within the -20 dBm and -100 dBm scale of the

Figure 7: Experimental Setup – Prototype Antenna on 30°-interval marked table, with 5m Rope and Wi-Fi Router

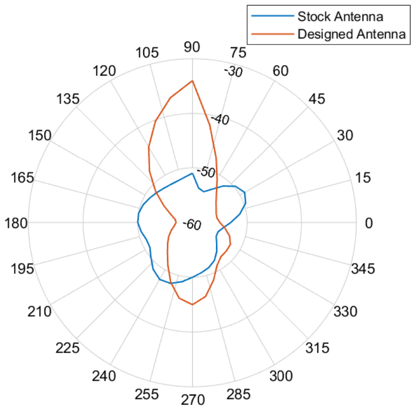


Figure 8: Measured RSSI (dBm) as observed from various angles for Stock and Designed Antennas at a distance of 5m with 25% transmit power (Channel 6)

hardware-reported RSSI. Figure 8 presents the empirical results that were gathered for the designed and stock antennas. It is important to note that the measured values often fluctuated by 3 dBm, and a measurement was only recorded once, the RSSI value settled for at least 5 seconds.

The maximum RSSI obtained for the stock antenna was -48 dBm at 240°, and -34 dBm at 90° for the designed antenna.

5. Discussion

As is seen in figure 8 the prototype antenna does appear to be significantly more directional than the stock antenna. This figure also hints that the efficiency of the designed antenna is of the same order of magnitude as the stock antenna since the stock antenna's maximum RSSI was surpassed; hence it can be assumed that the prototype antenna is sufficiently matched to the generator circuit. Assuming high efficiency (90%) an estimate of the prototype antenna's gain can be calculated as 17$\pm$2 dBi as described in *Experimental Proceedure*. This result does agree with the simulated result of 14.16 dBi considering the limited precision of the test equipment used.

Thus it can be said that the success criteria of the project has been met, however it must be noted that there has only been limited evidence that supports that the prototype produces similar results to the simulations. A significant limitation of the prototype is that thin coaxial cable was used, which at 2.45 GHz frequencies imposes significant attenuation[8].

There is much opportunity for future work, such as conducting the experiment using different Wi-Fi Channels to determine if the antenna operates efficiently for its full specified frequency range. Other work includes investigating, and researching whether the Android measurement application compensates for Automatic Gain Control, as this may explain the great amount of fluctuation at certain testing angles. Lastly it has only been assumed that the range of the Wi-Fi router is extended due to evidence of increased gain and directivity, this calls for another experiment to be conducted to measure this directly.

6. Conclusion

In this report a directional Yagi-Uda Wi-Fi antenna was successfully designed using theory, and simulation models. An affordable prototype antenna was then constructed, and tested using inexpensive test equipment. The results from the testing experiment showed that the prototype antenna had satisfied most design specifications, however future work must be conducted to verify consistency in performance for the rest of its specified frequency range.

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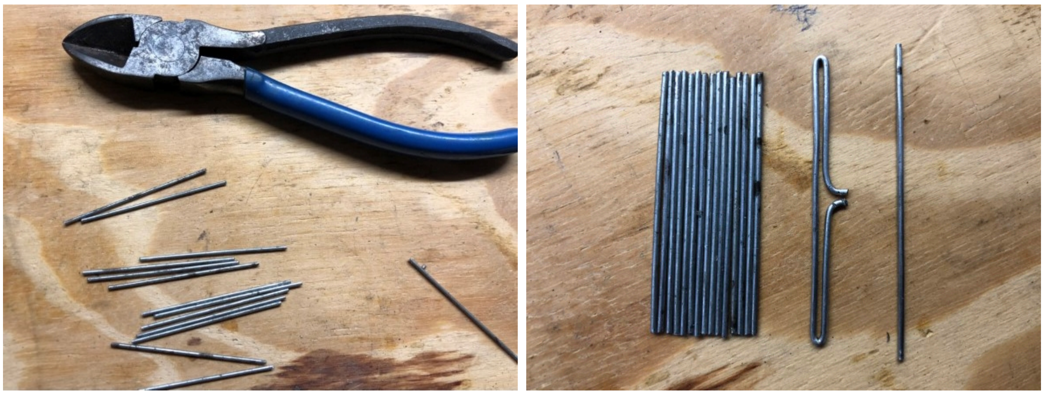
Appendix



(a) Steel Rod Cutting Tool

(b) Cut and Folded Elements

Figure 9: Yagi-Uda Element Fabrication

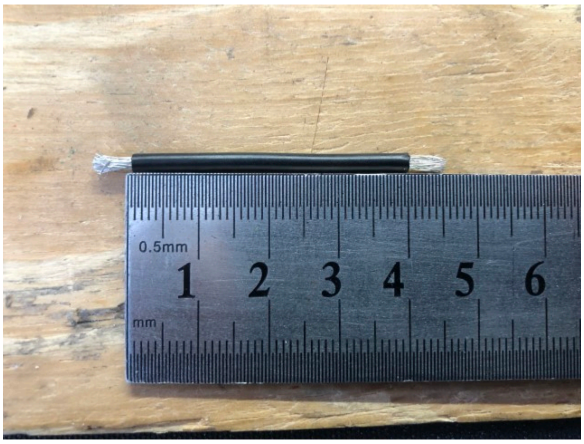


Figure 10: Coaxial Cable to form Half-wave Balun (40.4mm)

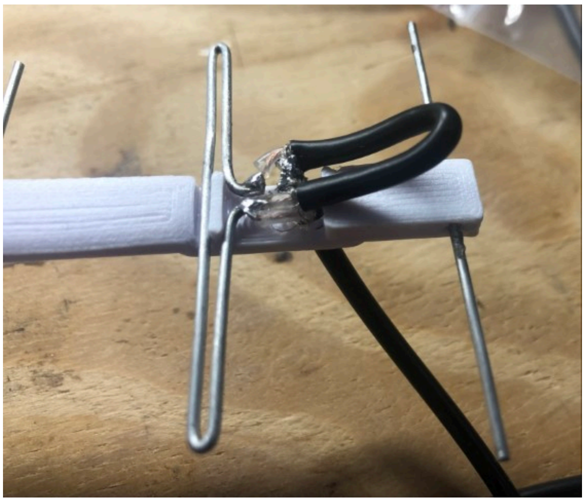


Figure 11: Prototype Antenna Feed-Point

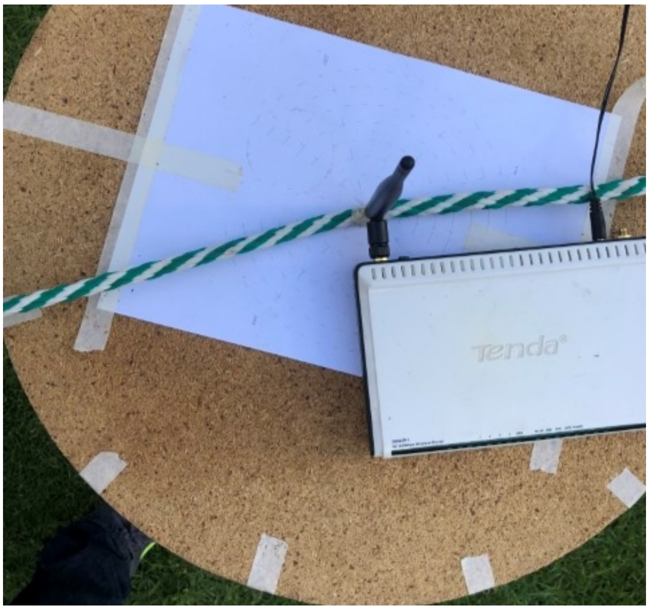


Figure 12: Experimental Setup for Stock Antenna