

ACDA6019 - Design and Analysis of RF Antennas

by Daniel Bridgewater

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DESIGN AND ANALYSIS OF RF ANTENNAS

ACDA6019

Abstract

This report aims to investigate performance relating to various types of radio-frequency antenna using simulations, designed with a mix of theoretical calculations and automatically generated using MATLAB. The types of antennae tested include patch, cylindrical dipole, folded dipole, horn, helical, and helical array. Discrepancies between theoretical calculations of resonant frequency and what was simulated were discovered, highlighting the need to test antenna designs in the real world. This report also evaluates the trade-offs between antenna complexity and directivity, as well as the wider impacts of antenna choices to society and the environment. Recommendations for selecting the appropriate antenna design are given, so that efficiency is maximised to reduce necessary power usage.

Daniel Bridgewater (2218703)

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Introduction

Different antenna shapes exhibit different behaviours, useful in different situations at different frequencies. This report aims to calculate then simulate some common antenna performances, evaluating their traits and suitable use-cases.

The antennas simulated include a patch antenna, cylindrical dipole, folded dipole, horn, helical, and helical array. Patch antennas are uniquely capable of being embedded directly into a circuit board, enabling low-cost production of high-frequency antennas which can fit directly inside the device. Dipoles are one of the most common types of antenna, being extremely simplistic. Both cylindrical and folded types of dipole will be tested so their differences may be compared. For microwave frequency communication, horn and helical antennas will be tested, along with a helical array so the benefits of adding extra elements can be compared against a single element antenna.

Finally, the impacts of the antenna types to human society and the environment will be considered, along with recommendations for reducing such impacts. This will include compliance with appropriate regulatory standards and long-term sustainability of the equipment.

Methodology

All operating frequencies were derived from  varying digits in the author's student ID.

The patch antenna was modelled in CST while all other antennas were created using MATLAB Antenna Designer. MATLAB is preferred where possible as it's capable of automatically determining the dimensions for common antenna types, given some operating frequency, reducing the chance for human error to influence the results.

Patch Antenna

CST Studio Suite 2024 (Learning Edition) was used to model the patch antenna, chosen for its granular control over the antenna's construction. MATLAB's Antenna Designer does not allow creating an antenna as if it were on a printed circuit board (PCB). The antenna will be designed for 2.2GHz, derived from the author's Student Number.

$$\text{Operating Frequency} = 2.2 \text{ GHz}$$

Equation 1: Patch antenna frequency

The ground plane and patch antenna element are modelled as perfect electrical conductors (PEC), while the dielectric is modelled as a lossy FR-4 material, commonly used in PCB. 1.6mm is a typical thickness for PCBs, and CST's dielectric constant for FR-4 is 4.3.

Given the antenna's target frequency ($f_o = 2.2 \times 10^9 \text{ Hz}$) along with the dielectric's thickness ($h = 1.6 \text{ mm}$) and permittivity ($\epsilon_r = 4.3$), it is possible to directly calculate the theoretically optimum size for the patch antenna, shown in Equation 2.

$$Width = \frac{c}{2f_0\sqrt{\frac{\epsilon_R+1}{2}}}; \quad \epsilon_{eff} = \frac{\epsilon_R+1}{2} + \frac{\epsilon_R-1}{2} \left[\frac{1}{\sqrt{1+12\left(\frac{h}{W}\right)}} \right]$$

$$Length = \frac{c}{2f_0\sqrt{\epsilon_{eff}}} - 0.824h \left(\frac{(\epsilon_{eff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\epsilon_{eff}-0.258)\left(\frac{W}{h}+0.8\right)} \right)$$

Equation 2: Equations for calculating theoretical patch antenna dimensions, provided by [1]

This yields a theoretical width of 41.85 mm and a length of 32.51 mm. However, when the patch antenna was built to these measurements in CST, the simulated resonant frequency was slightly low, at 2.1GHz instead of 2.2. To correct this, the length of the antenna was shortened to 31.3mm.

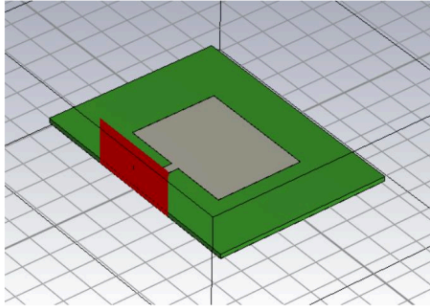


Figure 1: Patch antenna modelled in CST Studio

Cylindrical Dipole Antenna

Operating Frequency = 2 GHz

Equation 3: Cylindrical dipole frequency

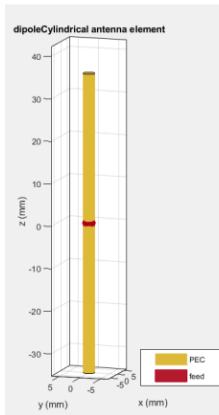


Figure 2: Cylindrical dipole

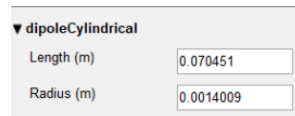


Figure 3: Cylindrical dipole calculated dimensions

Folded Dipole Antenna

$$\text{Operating Frequency} = \frac{221}{2} \text{ MHz}$$

$$= 110.5 \text{ MHz}$$

Equation 4: Folded dipole frequency

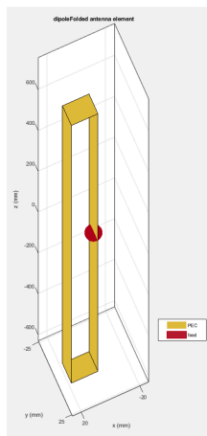


Figure 4: Folded Dipole



Figure 5: Folded dipole dimensions

Horn Antenna

$$\begin{aligned} \text{Operating Frequency} &= \frac{18}{2} \text{ GHz} \\ &= 9 \text{ GHz} \end{aligned}$$

Equation 5: Horn antenna frequency

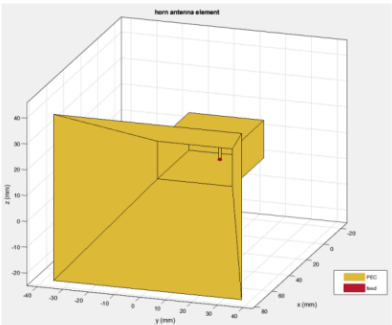


Figure 6: Horn antenna

▼ horn	
FlareLength (m)	0.054934
FlareWidth (m)	0.073026
FlareHeight (m)	0.064361
Length (m)	0.036439
Width (m)	0.029147
Height (m)	0.014572
FeedWidth (m)	0.00093329
FeedHeight (m)	0.0077724
FeedOffset (m)	[-0.010694 0]

Figure 7: Horn antenna dimensions

Helix Antenna

$$\text{Operating Frequency} = 21 \text{ GHz}$$

Equation 6: Helix antenna frequency

Helix Array Antenna

$$\text{Operating Frequency} = 21 \text{ GHz}$$

Equation 7: Helix antenna array frequency

When creating an antenna array, there is a variable which MATLAB cannot calculate automatically, that being the distance between each antenna element. This variable is important, as changing it can affect how the radio waves from each element interfere with each other, either constructively or destructively. To find the optimum spacing for constructive interference, the author simulated a wide range of distances and created a graph to show the impact on directivity (Figure 8). Distances shorter than 0.007 metres were not tested, as that would place the helical elements inside each other.

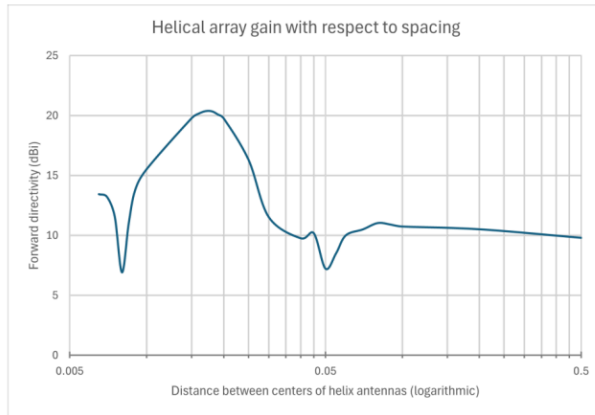


Figure 8: Graph of antenna element distances (in metres) and forward directivity

This revealed an optimum distance between 1 to 3 centimetres where the waves interfered constructively. Figure 9 was created to focus on this region, along with the thin band of destructive interference occurring when the elements were spaced at 80mm. This approximately coincides with $0.5\lambda = 73.5mm$, where the phase difference between elements would equal 180° .

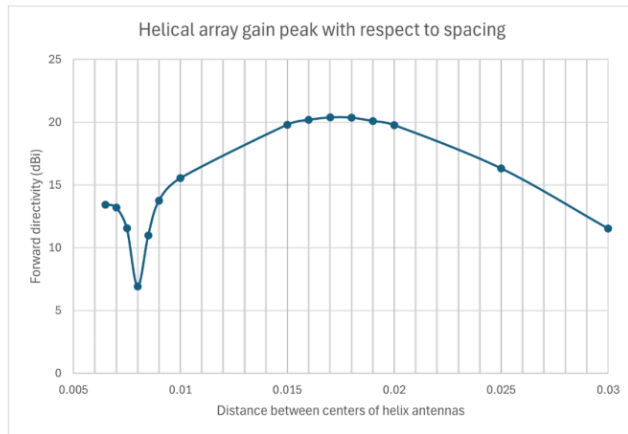


Figure 9: Zoomed graph of close antenna spacing impacting directivity, measuring distances between 70mm to 3cm.

Figure 9 shows forward directivity can be maximized when the centres of all elements are spaced 1.7cm apart (shown in Figure 10). This distance was used during all measurements of the helical antenna array, to fairly evaluate the performance of well-tuned arrays.

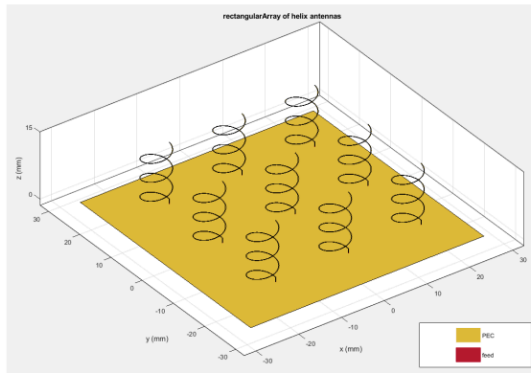


Figure 10: Helical antenna array with elements spaced 1.7cm apart

Results

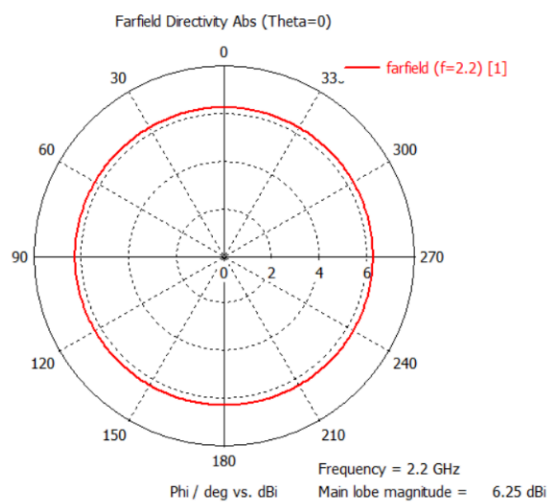


Figure 11: Patch Antenna directivity in dBi (azimuth cross-section, top-down)

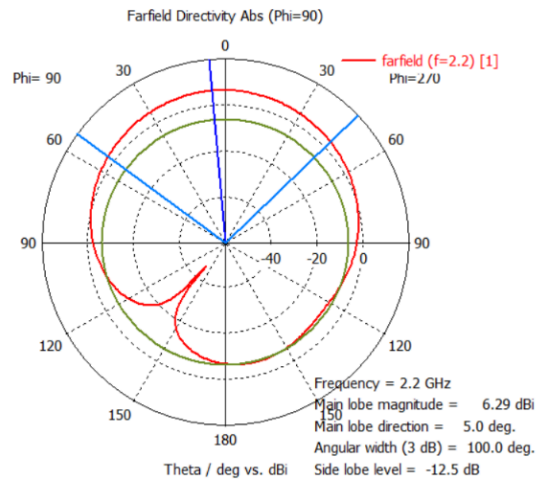


Figure 12: Patch Antenna directivity in dBi (elevation cross-section, side-on)

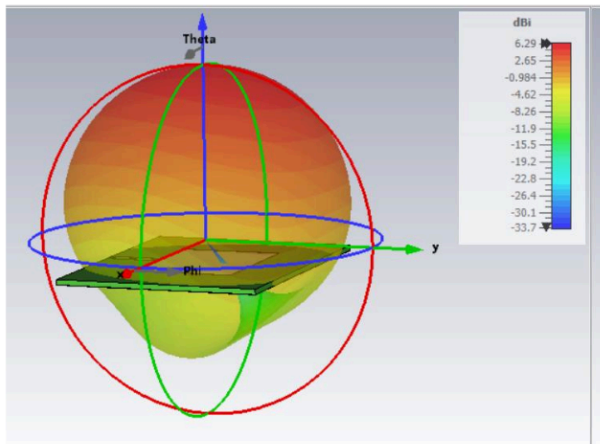


Figure 13: Patch Antenna directivity in dBi (3D view)

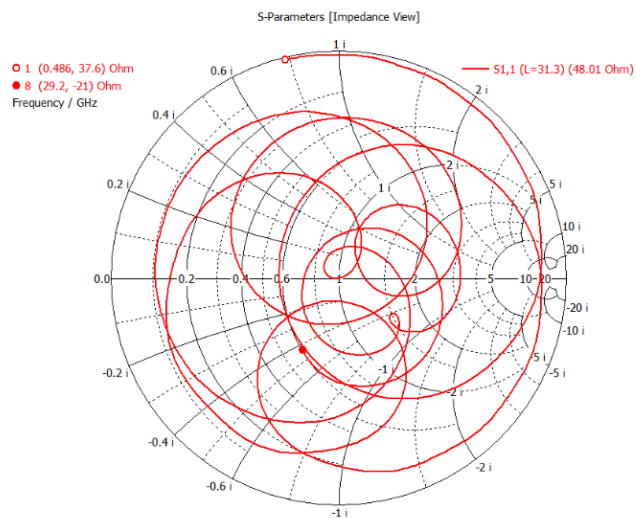


Figure 14: Patch antenna impedance Smith Chart

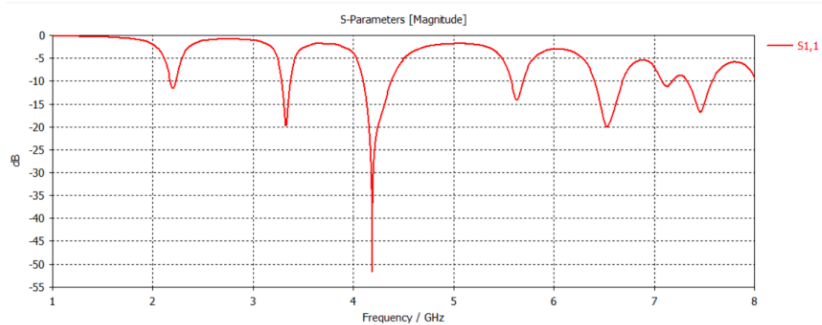


Figure 15: Patch antenna S Parameters, from 1 to 8GHz

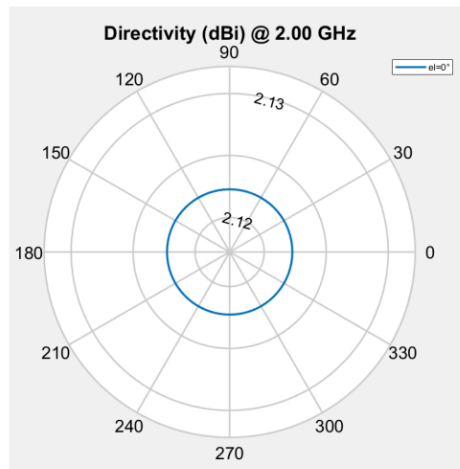


Figure 16: Cylindrical Dipole directivity in dBi (azimuth cross-section, top-down)

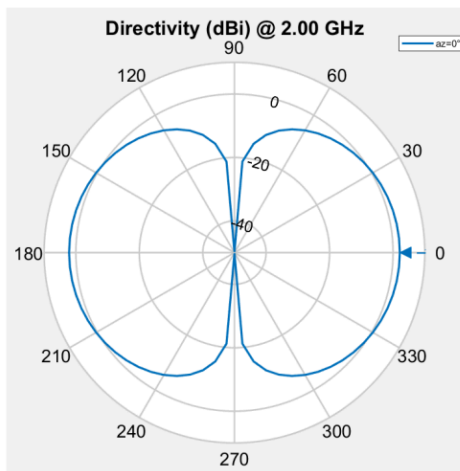


Figure 17: Cylindrical Dipole directivity in dBi (elevation cross-section, side-on)

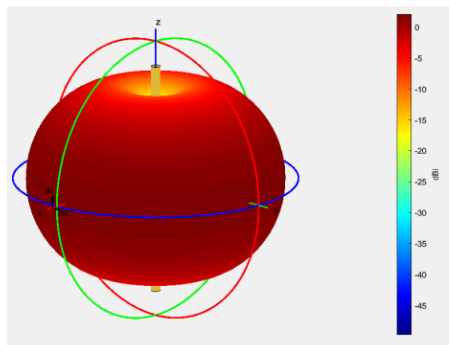


Figure 18: Cylindrical Dipole directivity in dBi (3D view)

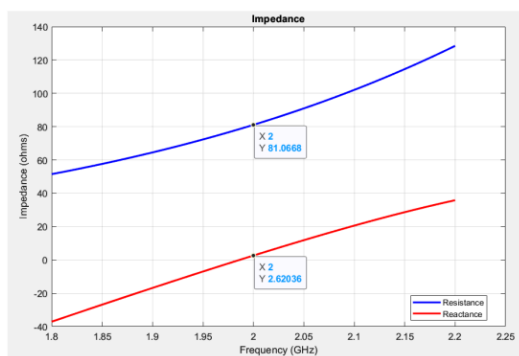


Figure 19: Cylindrical Dipole impedance graph

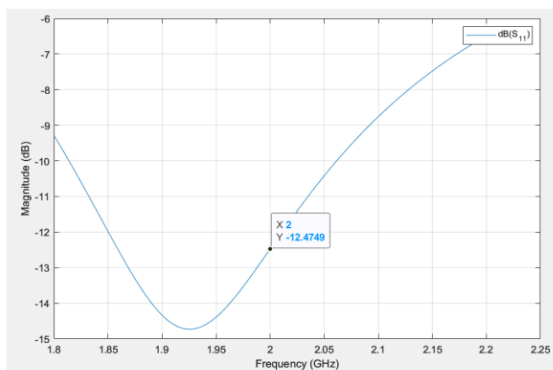


Figure 20: Cylindrical Dipole S Parameters at nominal 50-ohm matching

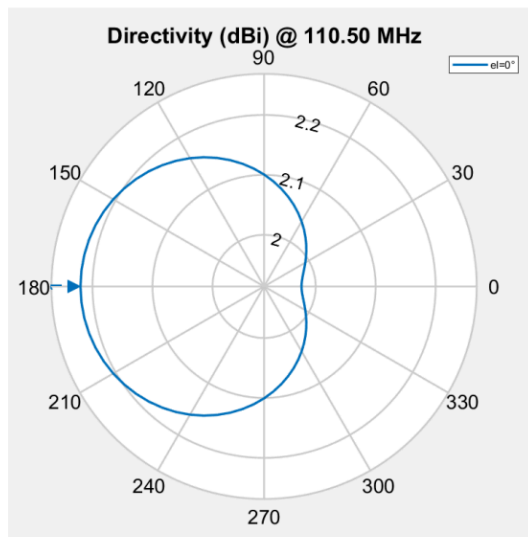


Figure 21: Folded Dipole directivity in dBi (azimuth cross-section, top-down)

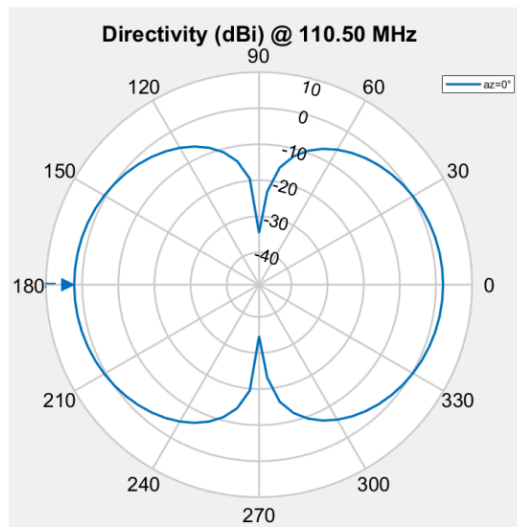


Figure 22: Folded Dipole directivity in dBi (elevation cross-section, side-on)

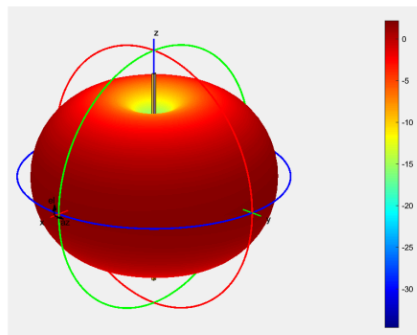


Figure 23: Folded Dipole directivity in dBi (3D view)

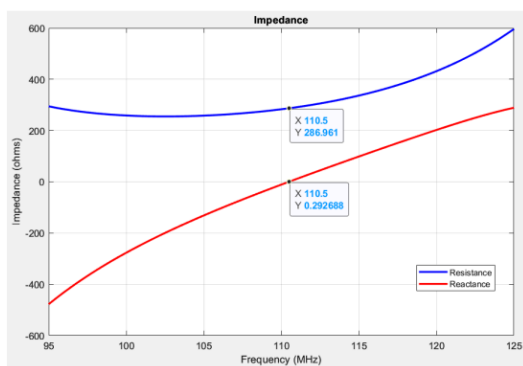


Figure 24: Folded Dipole impedance graph

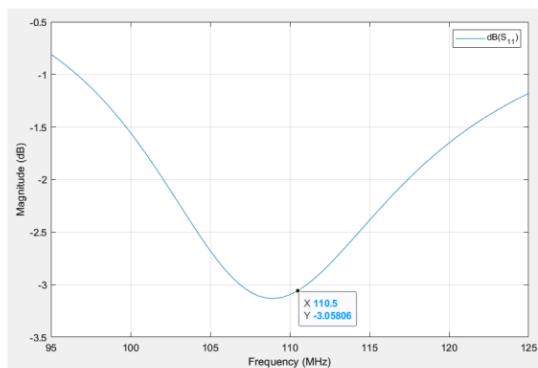


Figure 25: Folded Dipole S Parameters at nominal 50-ohm matching

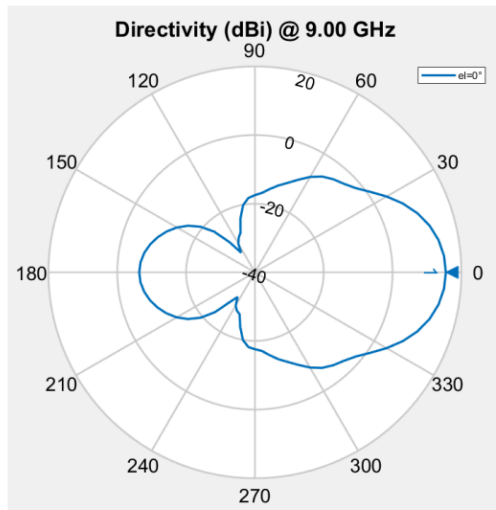


Figure 26: Horn antenna directivity in dBi (azimuth cross-section, top-down)

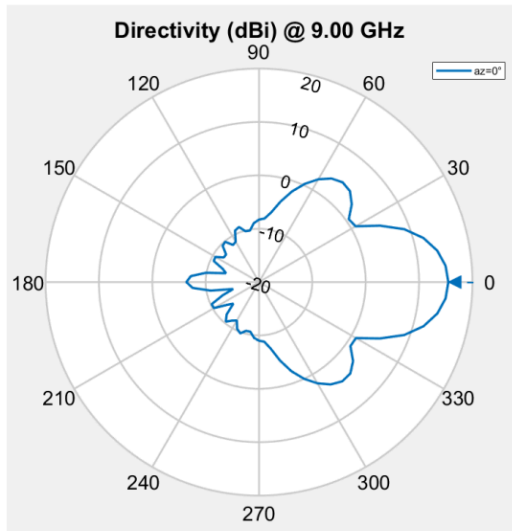


Figure 27: Horn antenna directivity in dBi (elevation cross-section, side-on)

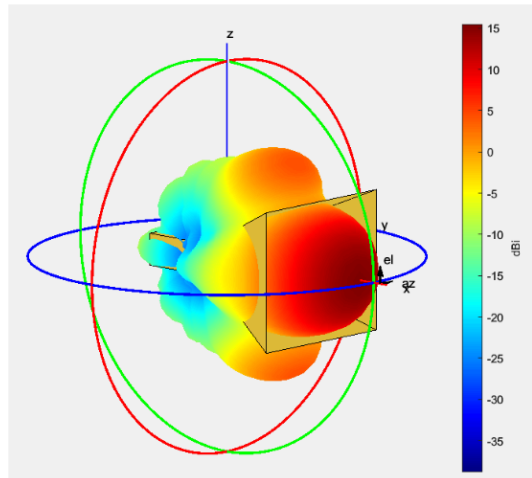


Figure 28: Horn antenna directivity in dBi (3D view)

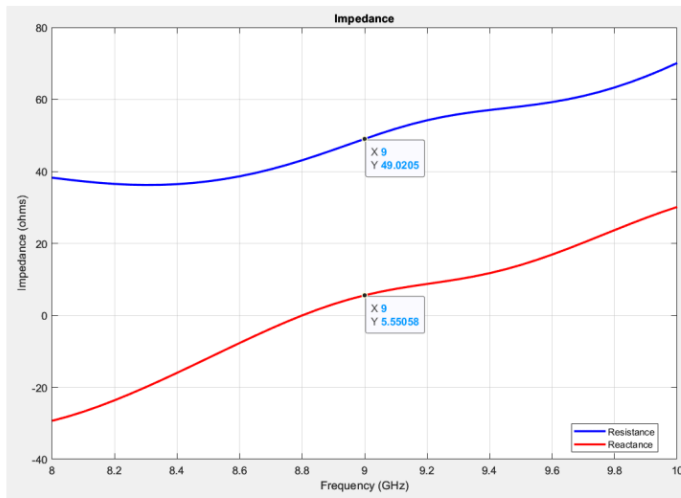


Figure 29: Horn antenna impedance graph

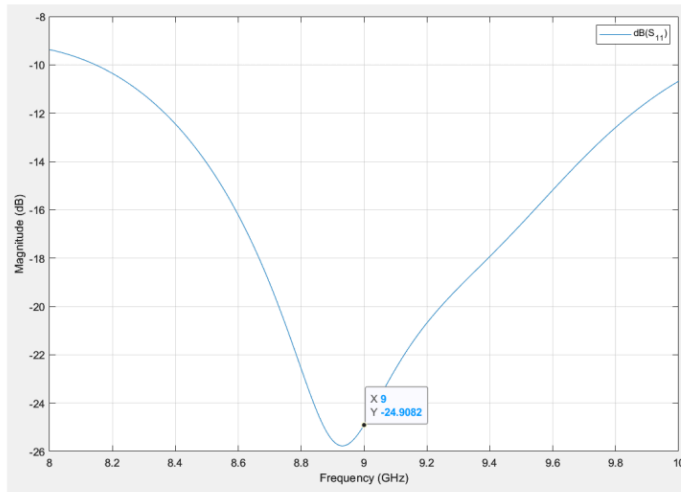


Figure 30: Horn antenna S Parameters at nominal 50-ohm matching

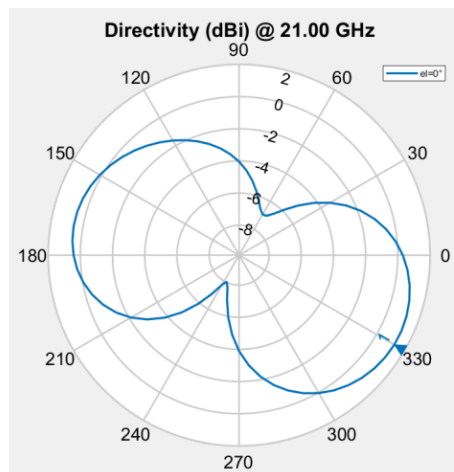


Figure 31: Helical antenna directivity in dBi (azimuth cross-section, top-down)

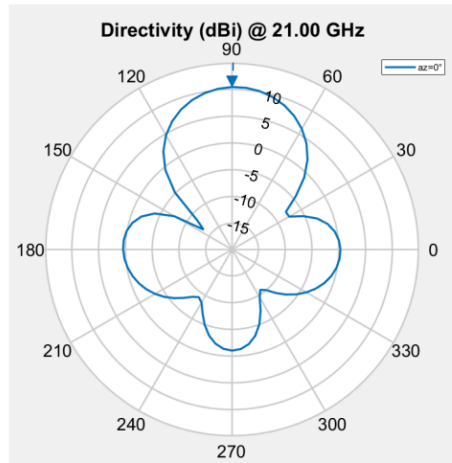


Figure 32: Helical antenna directivity in dBi (elevation cross-section, side-on)

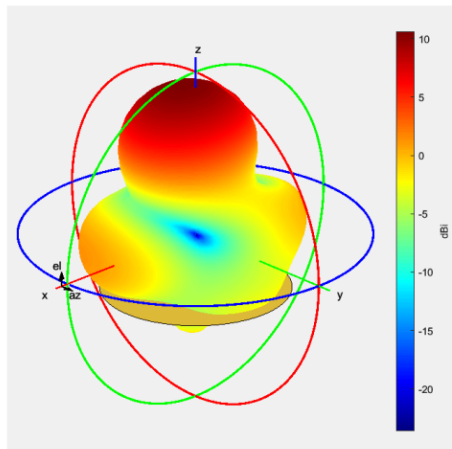


Figure 33: Helical antenna directivity in dBi (3D view)

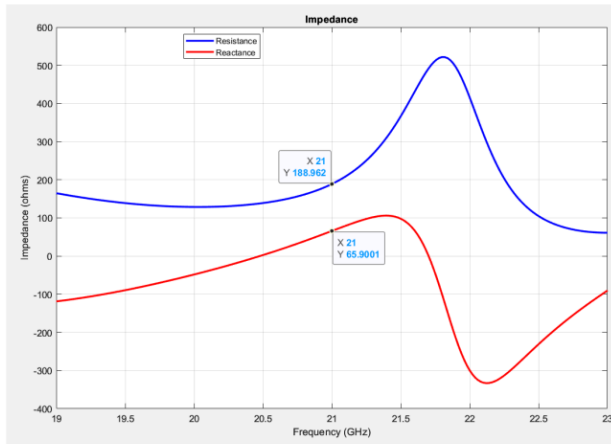


Figure 34: Helical antenna impedance graph

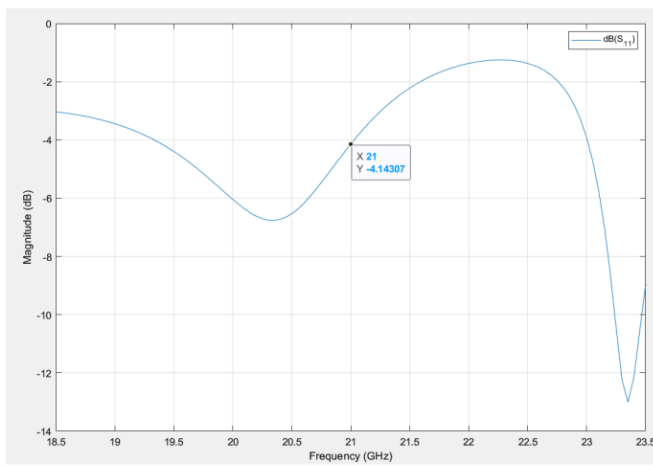


Figure 35: Helical antenna S Parameters at nominal 50-ohm matching

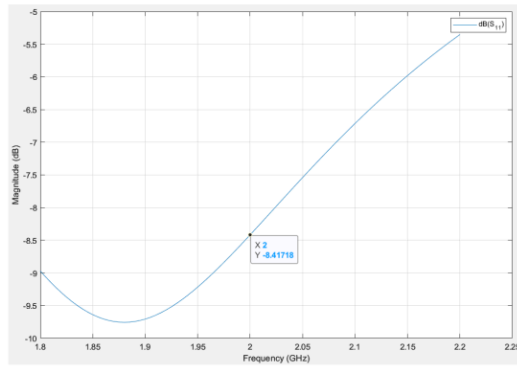


Figure 36: Cylindrical Dipole S Parameters mismatched at 30-ohms

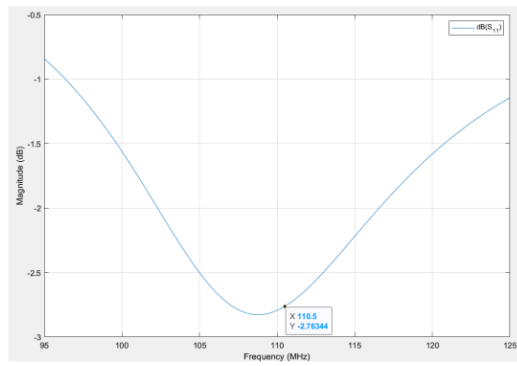


Figure 37: Folded Dipole S Parameters mismatched at 30-ohms

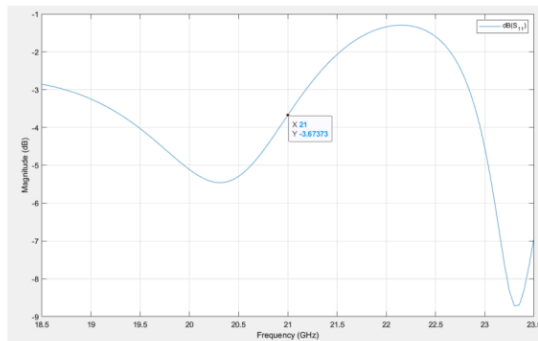


Figure 38: Helical antenna S Parameters mismatched at 30-ohms

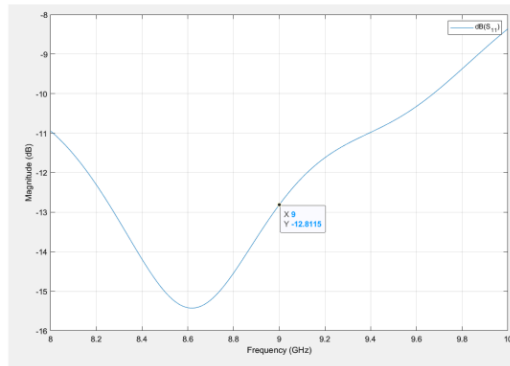


Figure 39: Horn antenna S Parameters mismatched at 30-ohms

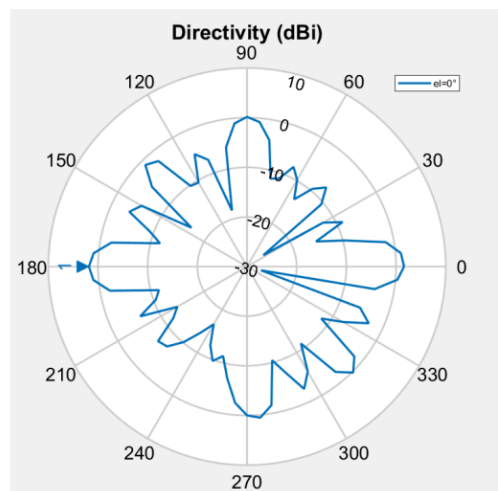


Figure 40: Helical antenna array directivity in dBi (azimuth cross-section, top-down)

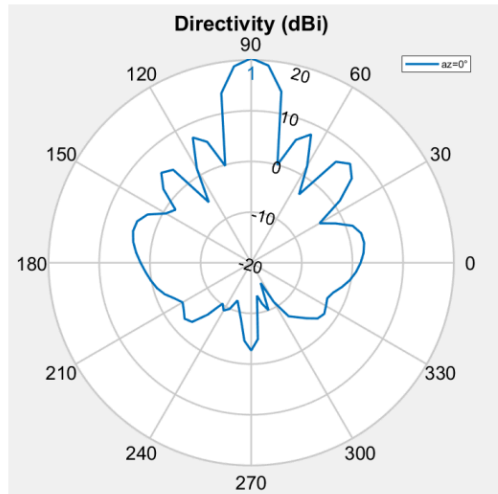


Figure 41: Helical antenna array directivity in dBi (elevation cross-section, side-on)

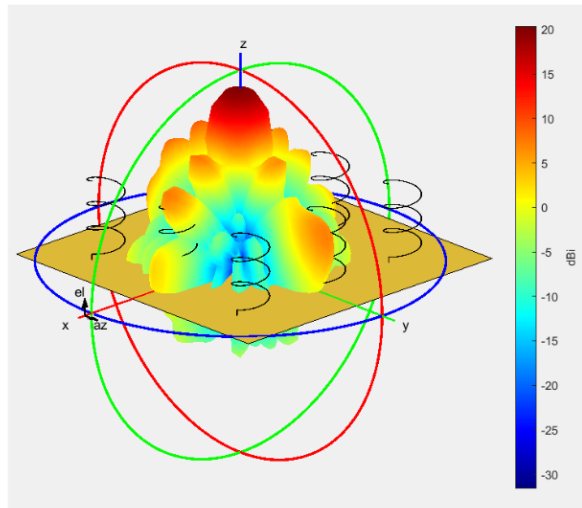


Figure 42: Helical antenna array directivity in dBi (3D view)

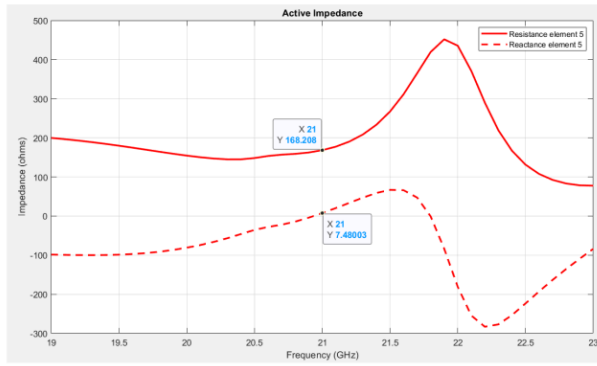


Figure 43: Helical antenna array centre element impedance graph

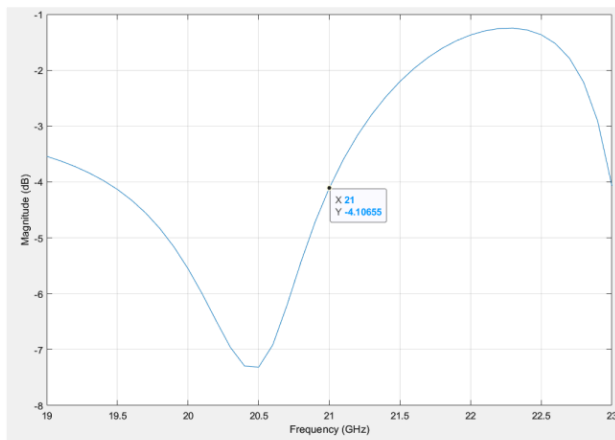


Figure 44: Helical antenna array S Parameters at nominal 50 ohm matching

Discussion

The patch antenna's size was calculated using Equation 2, given a frequency and information about the dielectric. However, creating the antenna using the calculated dimensions led to the resonant frequency being slightly lower than expected. Correcting this required adjusting the length in CST until the simulated antenna resonated at the desired frequency, shown in Figure 8. This highlights an important consideration when calculating theoretical antenna parameters; there are additional unknowable variables which impact antenna performance in the real world, so simple calculations can only find approximate values. Fine-tuning the antenna will require some degree of experimentation. This was only done for the patch antenna as CST permits directly altering the antenna's length. MATLAB only allows changing the target frequency, so all other antennas are unaltered.

Cylindrical and Folded Dipoles behave similarly, both being omnidirectional. However, there is a subtle difference in their radiation patterns, observable when comparing Figure 17 and Figure 22. The folded dipole has slightly higher emissions at the top and bottom compared to the cylindrical dipole, potentially allowing reception even when the antenna is not pointed in the correct direction.

Comparing the target frequency of each antenna modelled in MATLAB versus the actual resonance frequency shown in the S Parameter chart (see Table 1) reveals a peculiar pattern. Every time, MATLAB created an antenna which resonated below the target frequency, with discrepancies as high as 700MHz. The exact reason for this is unknown; only those who wrote MATLAB's Antenna Designer could explain the software's behaviour. However, the author speculates that the equations used by MATLAB are similarly imprecise to theoretical calculations, so both options must not be trusted blindly when creating an antenna where precision is required.

Antenna type	Target frequency	Resonant frequency	Difference MHz
Cylindrical Dipole	2 GHz (Equation 3)	1.93 GHz (Figure 20)	-70 MHz
Folded Dipole	110.5 MHz (Equation 4)	109 MHz (Figure 25)	-1.5 MHz
Horn	9 GHz (Equation 5)	8.93 GHz (Figure 30)	-70 MHz
Helix	21 GHz (Equation 6)	20.3 GHz (Figure 35)	-700 MHz
Helix array	21 GHz (Equation 7)	20.4 (Figure 44)	-600 MHz

Table 1: Comparison of antenna target resonance vs simulated resonance

Impedance matching is important, as properly matched antennas will perform better compared to incorrectly matched ones. This is because it minimises the power reflected back towards the RF hardware from the antenna, instead allowing it to be radiated usefully [2]. This is shown in Figure 36 through Figure 39, where mismatching the impedance to 30 ohms instead of the nominal 50 ohms causes the antenna's S Parameter to increase. Comparing Figure 20 and Figure 36, the Cylindrical Dipole S Parameter increased from -12.5dB to -8.4dB, representing a drop in performance by 32.8%. All antennas exhibited a noticeable drop in performance.

$$\frac{-8.4dB - -12.5dB}{-12.5dB} = -32.8\%$$

Equation 8: Calculation of mismatching impact on cylindrical antenna performance

There is an inherent trade-off between directivity and antenna complexity. Antennas with highest directivity (horn and helix, with relatively high directivities of 15dBi and 20dBi respectively, as shown in Figure 27 and Figure 32 respectively) will interfere less with surrounding electronics, thereby minimizing radio interference, as is required by UK law [3]. Cylindrical and Folded Dipole are the easiest to build, at the cost of being omnidirectional (shown in Figure 16 and Figure 21) and therefore less targeted. In some applications this is desirable, such as in consumer radios where the direction to the transmitter should not affect reception.

Antenna arrays provide an effective way to dramatically increase directivity by adding more elements. In testing, adding 8 elements positioned around the centre element (Figure 42) increased directivity substantially, approximately from 10 dBi (Figure 32) to 20 dBi (Figure 41), which is equal to 10 times greater.

Taking this into the context of societal and environmental factors, it is therefore important to choose an appropriate antenna for an RF system. If possible, it should be directed towards its receiver, so a minimum amount of power is required for the signal to be received. This also reduces emissions of stray RF into unwanted directions, helping to keep the electromagnetic spectrum free for other users. Furthermore, transmitting RF requires some amount of electricity to power the transmitter. If this usage can be reduced, it will be beneficial for the environment as less fossil fuels are required to power the equipment.

Conclusion

In conclusion, choosing the correct antenna type is crucial for optimal performance of the system, as choosing incorrectly can cause energy to be wasted if it is transmitted in the wrong direction. It is important to model the antenna in calculations and/or software so expectations of how it will perform can be verified. Furthermore, it is highly recommended for the system's impedance to be correctly matched, to avoid damaging the radio hardware with signal reflections and maximise antenna performance.

References

- [1] Pasternack, "Microstrip Patch Antenna Calculator," [Online]. Available: <https://www.pasternack.com/t-calculator-microstrip-ant.aspx>. [Accessed 12 05 2025].
- [2] D. A. Govind, "Antenna Impedance Matching – Simplified," [Online]. Available: <https://abracon.com/uploads/resources/Abracon-White-Paper-Antenna-Impedance-Matching.pdf>. [Accessed 19 05 2025].
- [3] *Wireless Telegraphy Act 2006*, Part 3 Regulation of Apparatus (54)(4)(a).

ACDA6019 - Design and Analysis of RF Antennas

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

71 /100

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Comment 1

Good work

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Comment 2

It would have been better, if the figures are included in appendix.

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GRADING FORM: ADV. RF SYSTEMS

DANIEL BRIDGEWATER

70.50

ENGAGEMENT WITH LITERATURE

The report should demonstrate the use of relevant, high-quality academic and professional sources. Comprehensive research incorporating recent journal articles, textbooks, and reliable sources should be evident. The credibility of each source should be evaluated, favouring peer-reviewed materials. All references must follow IEEE format, with consistent in-text citations.



Engages with a limited range of mostly relevant and credible sources. The report includes technical references. There is evidence of the ability to source and apply external technical materials. However, the use of peer-reviewed literature should be increased, and citation consistency improved using the IEEE format.

4

KNOWLEDGE AND UNDERSTANDING

The report must exhibit sound knowledge of RF principles, and antenna theories. Theoretical concepts such as impedance matching, array antenna, resonance frequency, and antenna applications should be clearly explained. Concepts should be related meaningfully to practical contexts. The report should demonstrate how this knowledge informed the design decision and the application of core knowledge in

mathematics, engineering, and natural sciences to solve broadly defined problems and analyse real-world RF systems.



Demonstrates excellent understanding of antenna theory, with accurate application of formulas and substrate properties. Design parameters are effectively linked to simulations, showing strong engineering principles. Applies fundamental electromagnetic concepts to explain radiation performance and impedance behaviour. Simulation data is well-supported by first-principle reasoning and wave propagation analysis. Shows awareness of real-world needs, including frequency tuning and application relevance. Further integration of regulatory standards and societal impact would enhance the design rationale.

19.5

COGNITIVE AND INTELLECTUAL

The report should present a critical analysis of simulation results and theoretical data. Findings must be discussed with evidence, leading to logical and valid conclusions. Comparisons between theoretical and simulation results should be presented. Discussions should include implications, limitations, and alternative solutions



The report demonstrates logical reasoning and critical thinking by analysing simulation results and identifying resonant frequency shifts, with attempts to explain these using fundamental antenna theory. Simulation discrepancies are thoughtfully examined, and the influence of constructive and destructive interference in array design is well recognised. Appropriate computational and analytical techniques are applied to model antenna behaviour, with some quantitative comparisons included (e.g., frequency deviation, gain). However, these metrics could be evaluated more systematically, and the discussion of design trade-offs or alternatives would benefit from deeper exploration. The limitations of the models are implied but not explicitly discussed, which would enhance the technical rigour of the analysis.

22

PRACTICAL SKILLS

Marks for practical skills will be provided based on the Practical application of engineering principles and skills in designing, simulating, or conducting experiments. Appropriate engineering software and methodologies should be applied to design antennas. The simulation process and parameters should be documented clearly, with justifications for methods used. Results should be presented with a neat plots and visuals. Problem-solving skills should be demonstrated through analysis and design refinements.. Proficiency with tools, and software to support your solutions.



Applies appropriate computational techniques using CST and MATLAB to model engineering problems, producing relevant results and visual outputs for each antenna. Demonstrates practical skills in design and simulation. Results include relevant data for each antenna, supported with visual outputs. Evidence of performance tuning is present. However, simulation setup details are not fully explained..

19

TRANSFERABLE SKILLS FOR LIFE

The report should be clear and well-structured for technical and non-technical readers. Complex ideas must be communicated effectively, with appropriate terminology and visual aids. A logical flow from introduction to conclusion should be maintained. Professional presentation elements such as clear headings, subheadings, and a well-organised reference list should be included.



Can communicate well, confidently and consistently in a suitable format. The report is well-formatted and demonstrates effective communication with technical and non-technical audiences. Regulatory and environmental considerations such as RF interference and UK frequency laws are addressed, showing awareness of real-world constraints. Visuals and structure further support clarity. It would have been better if the figures were included along with the

6

descriptions; otherwise, it may be difficult for the reader to follow.