ŌTAUTAHI CHRISTCHURCH AOTEAROA NEW ZEALAND
35TH AUSTRALASIAN ASSOCIATION FOR ENGINEERING EDUCATION ANNUAL CONFERENCE
8-11 DEC 2024
THE ENGINEER AND THE WORLD

Nurturing Tomorrow's Engineers Through Advanced Antenna Technologies for 6G Communications

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CONTEXT

With the rapid advancement of technology, particularly in the realm of 6G wireless communications, antenna engineering education requires a major re-evaluation. We propose to do this through Project-Based Learning (PBL) strategies with industry collaboration. This has shown to be successful through works of (Arboleya & Las-Heras, 2014; Rachchompoo et al., 2020; Sun et al., 2022; Yu et al., 2020). By immersing students in hands-on labs that involve fabrication, advanced simulations, and ongoing research, and through industry partnerships, we aim to cultivate engineers equipped to tackle real-world challenges and stay aligned with current industry demands.

PURPOSE OR GOAL

Last year's pilot study on simulation-based 6G antenna designs from real-world projects yielded promising results, with students reporting a deeper understanding of the material through practical application. Consolidating our achievements, this study targets the following research questions (RQ):
RQ1: How can laboratories involving antenna design be designed to better align with industry expectations?
RQ2: How much can an industry-aligned curriculum improve the skills and knowledge of the student in antenna engineering education?

APPROACH OR METHODOLOGY/METHODS

Our methodology prioritises industry collaboration, inviting guest lecturers to enrich an industry-focused curriculum. We also leverage existing research equipment to fabricate and validate the designed antennas. To gauge the effectiveness of the teaching strategies implemented, we plan to design both before, mid and after surveys. Additionally, we will leverage the past year's data to track changes over time.

ACTUAL OR ANTICIPATED OUTCOMES

Anticipated outcomes of this study include a transformative student experience enriched with hands-on opportunities for skill development in antenna design, fabrication, and testing. By seamlessly integrating theoretical knowledge with practical application and fostering collaborative learning, our innovative curriculum is tailored to meet the telecommunication industry demands.

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

Our study anticipates transformative outcomes in the student learning experience, characterised by hands-on opportunities in antenna design, fabrication, and testing. We also plan to develop a curriculum based on the proposed change of practice. This approach aligns with our commitment.

KEYWORDS

Project-based learning, Industry input, 6G communications and beyond.

1. Introduction

As the world shifts from 5G to 6G networks, innovative antenna designs are crucial for achieving ultra-fast data speeds and enhanced connectivity. University courses must adapt quickly to equip students with the skills needed to tackle these challenges. Antenna engineering builds on complex electromagnetics topics from undergraduate Electrical Engineering programs (Notaroš, 2019; Roussel & Hélier, 2012). While lecture-based methods are important for understanding theory, they must be enhanced to meet technological advancements and evolving academic needs (Boles & Whelan, 2017; Massa et al., 2020; Soliman, 2019; Uziak et al., 2016). Understanding antennas and propagation is vital for electrical engineers, as it connects the curriculum to practical applications in wireless telecommunications, as shown in Figure 1.

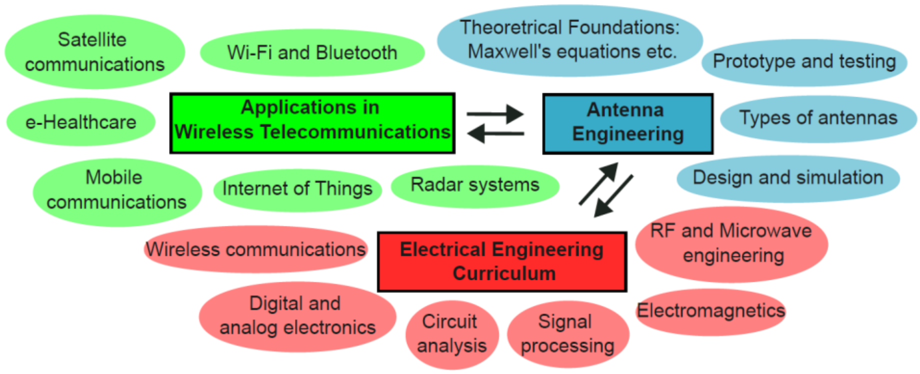

Figure 1: Flowchart showing the connection between antenna engineering, electrical engineering, and real-world applications, with circular boxes indicating sub-topics.

The complexity of these subjects has contributed to a decline in student interest (Johnson & Jones, 2006), exacerbated by a perceived lack of relevance to current technological advancements. To address this trend positively, suggestions include incorporating numerous hands-on activities (Holstermann et al., 2010), promoting active learning (Prince, 2004), and adopting flipped classroom approaches (Mohammed, 2019; Ravishankar et al., 2018). Integrating practical experiences with theoretical learning can effectively engage students and better prepare them for the evolving demands of the field.

Various teaching methods have emerged in recent years to cultivate self-guided learning and enhance student motivation. Among these, Project-Based Learning (PBL) methodologies have proven highly effective, particularly in advanced engineering courses aimed at preparing students for the job market (Mills, Treagust, et al., 2003). PBL promotes critical thinking, analytical skills, and improves social, negotiation, leadership, and teamwork abilities. Research conducted by (Arboleya & Las-Heras, 2014; Lopez-Salcedo & Seco-Granados, 2009) indicates that PBL enhances student motivation, deepens comprehension of the subject matter, and enables students to independently undertake practical projects, drawing on their prior knowledge.

1.1 Motivation

PBL and applied learning are increasingly recognised as effective educational strategies, enabling engineering students to gain hands-on experience and apply their skills to real-world challenges (Krajcik & Blumenfeld, 2006; Sanger & Ziyatdinova, 2014). Incorporating applied learning into the course, with input from industry partners in antenna design, has proven valuable in helping students understand and appreciate the link between theory and practice (Venkatarayalu et al., 2018). As a result, the course was upgraded last year with improved laboratory facilities and project exercises. The effectiveness of these enhancements and applied learning methods was evident during the initial rework of the two workshops/labs. Student feedback has been overwhelmingly positive, with selected responses provided below:

(a) Labs were useful in understanding the concepts, and new software was learned in the process.
(b) I learned how to design antennas and understood the theory behind it.
(c) The project problem was challenging and gave a taste of modern technologies.
(d) The lab is also fantastic. It provided a way to combine what I learned with practice, which gave me a deeper understanding of what I learned in this course.

To stay relevant, our project enhances the Antennas and Propagation course by upgrading laboratory exercises to reflect the latest industry advancements. This initiative equips students with practical skills to tackle real-world challenges in antenna engineering. Inspired by successful PBL applications in similar courses (Arboleya & Las-Heras, 2014; Rachchompoo et al., 2020; Sun et al., 2022; Yu et al., 2020), we will incorporate industry input and prototype fabrication. By integrating insights from industry professionals on antenna design challenges for 6G networks, we aim to bridge the gap between academic theory and industrial practice.

1.2 Objectives

The workshop aims to provide students with a comprehensive understanding of antenna engineering, covering design, simulation, optimisation, fabrication, and experimental validation as illustrated in Figure 2. Using advanced software like CST Studio Suite (2024), students design antennas and conduct simulations to assess performance and identify improvements. Optimization techniques refine these designs, which are then fabricated and prototyped, allowing students to gain hands-on experience with 3D printing and experimental validation.

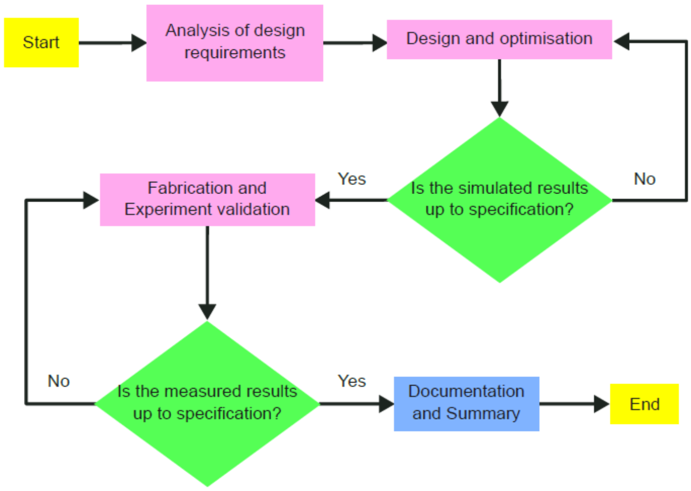

Figure 2: Flowchart depicting the conventional antenna design process.

To reinforce understanding of lecture material, our methodology includes workshop tasks that facilitate comprehension of electromagnetic wave behaviours. Research shows that 2D and 3D visualization is crucial (Dori & Belcher, 2005; Hennig & Mertsching, 2017; Maxworth, 2023; Ren, 2022). While animations and videos enhance understanding, specific exercises are essential for grasping antenna modeling and simulation techniques. Using commercial full-wave numerical simulation tools like CST Studio Suite (Soliman, 2019; Yu et al., 2020) and FEKO (Ren, 2022), students gain hands-on experience in antenna design and analysis. Incorporating software-driven activities has proven effective in improving student learning outcomes in antenna-related courses (Ren, 2022; Soliman, 2019; Yu et al., 2020, Salas-Natera et al. 2024).

The course uses PBL and applied learning through workshops and projects, involving students in all phases of antenna engineering. This bridges theoretical concepts with practical application, providing real-world experience and equipping students with industry-relevant skills and knowledge.

1.3 Organisation

The upcoming sections of this paper will detail the methodology and implementation of the enhanced Antennas and Propagation course. Section 2 will describe the course structure, focusing on industry integration and improved lab exercises, along with the use of applied learning and Project-Based Learning (PBL) methodologies. Section 3 will explore the antenna engineering process, particularly the leaky-wave antenna workshop. Section 4 will analyse student feedback results, demonstrating the impact of course enhancements on motivation, understanding, and skill development. Section 5 will discuss the broader implications of these pedagogical innovations for engineering education. Finally, Section 6 will summarize key findings and suggest future course improvements.

2. Course Structure and Methodology

The course is structured as outlined in Table 1. Lecture programs serve as the foundation, complemented by weekly quizzes and tutorials to reinforce understanding. Tutorials are tailored to enhance comprehension of lecture concepts. Concurrently, students participate in workshops to gain practical experience that complements their theoretical learning. The course integrates lectures, active learning, and project-based learning elements. The following subsection details the incorporation of PBL into the course.

Table 1: Course outline and syllabus.

Week	Topics	Workshops
Week 1	Fundamental Parameters of Antennas	No Workshop
Week 2	Linear Wire Antennas	Workshop 1 – Wire antenna
Week 3	Linear Array	Workshop 2 – Wire antenna array
Week 4	Metallic waveguides and Horn antennas	Workshop 3 – Horn antenna in D-band
Week 5	Mid-term exam, Guest Lecture from Industry	Catch-up session
Week 6	Loop antennas, dipole near or on a perfect conductor	Project Brief
Week 7	Intelligent reflective surfaces (metasurfaces)	Workshop 4 – Intelligent reflective surfaces
Week 8	Patch antennas	Workshop 5 – Patch antenna
Week 9	Traveling wave antenna and broadband antenna	Workshop 6 – Leaky-wave antenna

2.1 Project-Based Learning Framework

Project-Based Learning (PBL) is integrated from Week 1, with students engaging in workshops involving design, simulation, and experimental validation. Currently, only Workshops 3 and 6 include fabricated samples, with plans for all workshops to feature their own fabricated antenna designs. Key strategies supporting the PBL framework include:

The flipped classroom approach provides students with learning materials for antennas and workshops a week before each session. This effective method (Mohammed, 2019) shifts lecture focus to engaging activities that deepen understanding, enhance comprehension, encourage active participation, and foster critical thinking.

Weekly quizzes and tutorials assess students' understanding and provide opportunities to clarify doubts and ask questions, ensuring continuous feedback and support. This approach identifies areas where students may struggle, allowing for timely interventions and fostering a deeper grasp of the material.

Simulation tools like CST Studio Suite (2024), widely used by industry antenna designers, are integrated into the course. Students learn to use this tool through workshops in a semi-guided format. This structured approach ensures effective navigation and utilisation of the software, providing essential semi-guided experience until students achieve sufficient familiarity with complex antenna simulations and excitation mechanisms.

In Week 6, students begin a major group project to design a new antenna with specific performance requirements, introducing an antenna type not covered in lectures. This project fosters a challenging learning environment and culminates in an oral presentation for assessment in Week 10. By this point, students have gained significant knowledge and hands-on experience from earlier workshops, allowing for a smooth transition into the PBL component, where they apply their skills to real-world design challenges.

2.2 Methodology

The course content covers a spectrum from radio frequency to microwave frequency ranges. However, the workshop activities are specifically focused on translating these antenna designs into applications for 6G communication systems, with an emphasis on the D-band (110 GHz to 170 GHz). Workshops are carefully structured to include a fabrication component, detailed further in the following section. This hands-on approach allows students to engage fully in the entire process from initial design to experimental implementation.

For this study, workshops highlight the D-band, crucial for the upcoming 6G communications. Many communication companies are currently active in this frequency band. The theoretical framework for this research is based on constructivist learning theory (Briede et al., 2013), promoting hands-on, experiential learning and active learning through guided experiences. Additionally, the integration of real-world applications into academic learning is supported by industry-academia collaboration theories.

Methodologically, data collection includes pre-, mid-, and post-course surveys and questionnaires, as well as feedback from students and instructors, observations during lab sessions, and assessments of lab reports and projects. Quantitative methods will measure learning outcomes statistically, while qualitative approaches will extract insights from interviews and observations.

3. Workshop Design

This section discusses the "Leaky-wave antenna" workshop, where students design and optimize a D-band (110 to 170 GHz) uniform rectangular leaky-wave antenna. The antenna is a hollow-core rectangular waveguide with a longitudinal slot, based on a Waveguide Rectangular (WR) 6.5 waveguide with inner dimensions of 1.651 mm by 0.8255 mm. Students receive guidance primarily on using CST Studio Suite, supported by video tutorials for simulation setup. They apply knowledge from lectures and tutorials to meet specified design requirements, following the processes outlined in Figure 2. The order of tasks is as follows:

1. Create the simulation in CST Studio Suite.
2. Define a predetermined length of a WR 6.5 rectangular waveguide using specified tools.
3. Select the appropriate materials.
4. Define the waveguide ports as the antenna feed.
5. Set up electric-, magnetic- and far-field monitors at specific frequencies.
6. Set up the time-domain solver and run the simulation.
7. Analyse the simulation results.
8. Answer the questions in the workshop manual.

The calculations of the dimensions of the antenna involve optimisation and a certain number of iterations before arriving at a set of parameters that meet the design specifications. It is noteworthy that the waveguide ports in Step 4 also requires iterative calculations to achieve the best design. After going through all the design steps, the student would end up with a leaky-wave antenna model similar to the one shown in Figure 3. They would then examine the antenna parameters to ensure that the design specifications are met. These parameters would include S-parameters of the antenna, electric-field, and radiation efficiency.

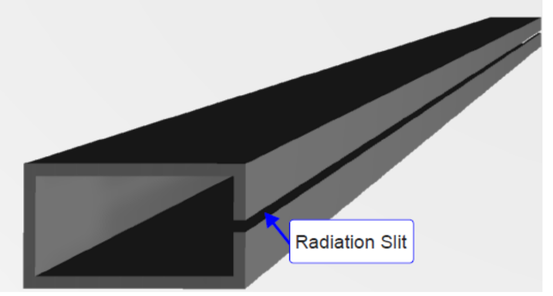

Figure 3: Leaky-wave antenna model from CST Studio Suite.

To clarify, S-parameters (scattering parameters) describe the behaviour of electrical signals within a network. S_{11}, referred to as the reflection coefficient, indicates the amount of signal that reflects back to the source, while S_{21}, known as the transmission coefficient, illustrates how much of the signal passes through the antenna. These parameters are essential for assessing antenna performance. An example solution of the S-parameters is shown in Figure 4(a). Students are also required to calculate the radiation efficiency of the leaky-wave antenna, which provides useful information as opposed to S-parameters, where an example is shown in Figure 4(b). Moreover, students analyse the distributions of electric fields to comprehend how the antenna radiates and interacts with its surroundings. The electric field illustrates the spread of electrical energy surrounding the antenna. Figure 5 provides an example solution for the electric field distribution. Through these analyses, students thoroughly understand their design's effectiveness and learn to justify their design decisions based on practical performance criteria.

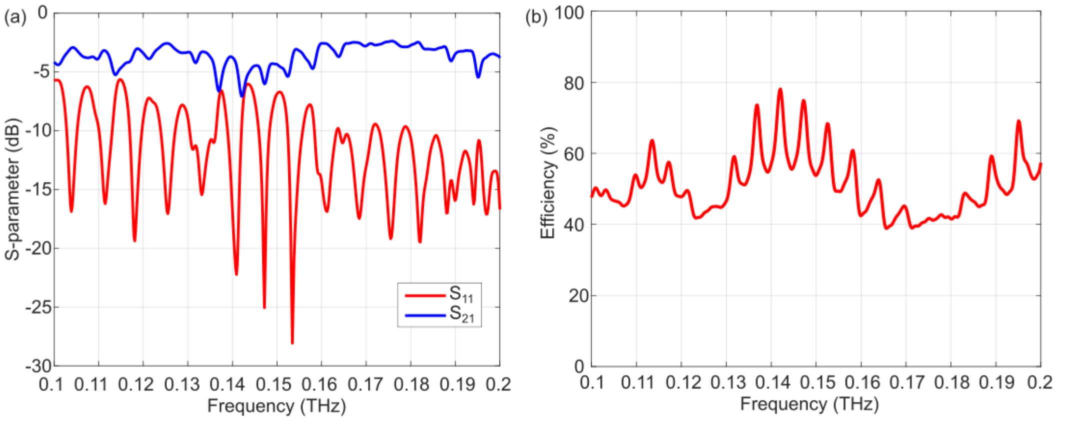

Figure 4: Example of simulated (a) S-parameters obtained and (b) calculated radiation efficiency of the leaky-wave antenna obtained from CST Studio Suite.

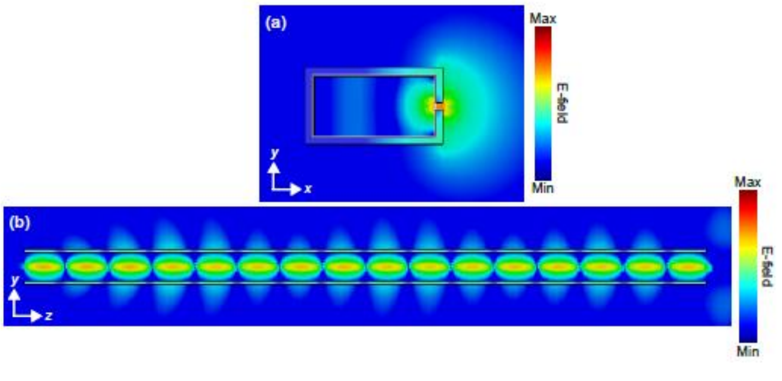

Figure 5: Example of simulated electric-field plots of the (a) side-view and (b) longitudinal slot view of the leaky-wave antenna at 0.12 THz.

The workshop's novelty lies in fabricating and experimentally validating designed antennas. Due to time constraints, leaky-wave antennas are prefabricated from 0.55 mm aluminum sheets using wire cutting methods as shown in Figure 6, instead of the initially designed 0.1 mm thickness. Key concepts are explained to ensure student comprehension. The antennas are integrated into the advanced D-band communication system developed by the Terahertz Innovation Group for experimental validation (Wang et al., 2024). This process aims to connect computer-simulated designs with prototyping and testing, reflecting the typical workflow of industry antenna engineers and enhancing students' understanding of theoretical concepts.

Regarding Gen AI vulnerabilities, they pose minimal concern to our workshops as they focus primarily on software to hardware experimentation. For the writing aspect, we can use tools like Turnitin to ensure originality and require proper citation for any AI-assisted content.

Figure 6: Fabricated samples of the leaky-wave antenna.

4. Analysis of Results

As the course progressed, feedback was collected from a previous cohort concerning the shift to the D-band frequency range for the workshop tasks. It's important to note that this year's cohort engaged in fabrication and experimental validation, while the selected feedback here comes from last year's cohort, who did not have these enhancements. The questions asked and summarised responses are detailed in the relevant subsections below.
1. Q: How valuable do you feel this workshop was in enhancing your understanding of antenna engineering?
2. Q: How did the shift from microwave to d-band frequencies affect your learning experience? Do you feel that it enhanced your understanding of the principles of antenna design and testing? Please elaborate on your experience.

Student satisfaction with the course reached 100% as shown in Figure 7, indicating successful adaptation of the curriculum to meet educational goals and expectations. The sample size for this study was 6, representing the total course enrolment at the time. Ethics approval was obtained to proceed with the research. Aligning content with industry standards and including hands-on D-band antenna design experiences improved learning outcomes and student engagement. Students appreciated the practical relevance and industry alignment of the D-band curriculum, which enhanced their understanding of advanced antenna design. Their positive feedback highlights the importance of integrating cutting-edge technologies into educational programs to prepare future engineers for industry challenges. Key takeaways from their feedback are outlined below.

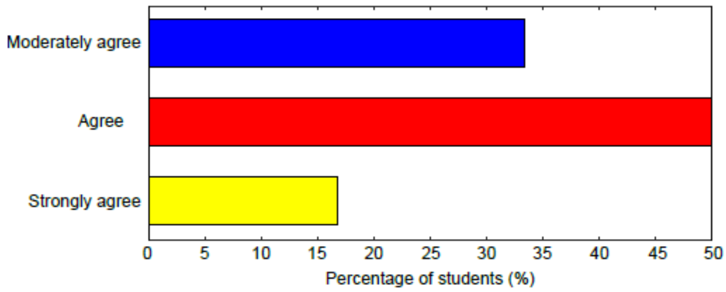

Figure 7: Percentage distribution of student satisfaction with the quality of the course.

The workshops enhanced students' focus on detailed design and reporting, aligning with industry standards. CST Studio Suite bridged theory with practical application. Transitioning to D-band frequencies gave valuable insights. Students appreciated the alignment between lab exercises and course content, benefiting from hands-on parameter variations and testing.

Students gained confidence in designing D-band antennas, including dipoles, horn antennas, and microstrip patch arrays. They expressed a need for more testing opportunities. The workshops and projects stimulated strong interest and enthusiasm in antenna engineering through practical applications.

The incorporation of industry-relevant tasks received high praise, suggesting a need for expanding real-world scenarios. Industry partnerships for lab tasks would expose students to current practices, advanced technologies, and mentorship opportunities, effectively bridging academic learning with practical industry applications.

5. Discussion

The analysis of student feedback has highlighted several key challenges and opportunities for enhancing the course in future iterations:

One recurring challenge identified was the limited time available for testing. Moving forward, an additional workshop session will be allocated specifically for the fabrication and experimental validation of designed antennas. The designed antennas are also prefabricated as most variations in design end up being quite similar. Integrating D-band frequencies and practical design tasks enhances the course, preparing students for modern engineering demands and next-generation communication systems. Replicating this model across other courses can enrich engineering education by fostering innovation and practical application. Gathering and acting on student feedback is crucial for refining workshops and projects. Incorporating student perspectives helps meet educational objectives, keeps the curriculum responsive to industry standards, and enhances engagement and learning outcomes. Integrating PBL, applied learning, and industry collaboration can greatly enhance engineering education. This approach provides hands-on experiences and industry partnerships, ensuring students gain both theoretical knowledge and practical skills for their careers.

6. Conclusion and Outlook

Integrating industry-relevant tasks and hands-on workshops has enhanced students' understanding of antenna engineering by connecting theory with practice. Insights from pilot studies show that lab-based fabrication and experimental validation in D-band communication systems allow students to align their designs with industry standards. However, challenges such as securing strong industry partnerships and accessing updated equipment due to high costs and rapid technological changes remain significant. Moving forward, expanding partnerships, improving workshop time management, and offering flexible project options will enhance the course. Continuous student feedback will ensure the course evolves to better prepare students for careers in antenna engineering with both theoretical and practical skills.

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Acknowledgment

This work was supported by the EFFECT 2024 program from the Faculty of Engineering, UNSW Sydney. The authors would like to thank Qigejian Alfred Wang for his assistance.

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