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Transferring PhD Research Outcome into Tertiary Teaching Laboratory in Electrical Engineering Education

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ABSTRACT

CONTEXT

Experiential learning is key to engineering education especially important for abstract disciplines. This paper presents the transfer of the research outcomes of advanced electromagnetism (AEM) to pedagogy in undergraduate teaching and learning. A very low-cost but innovative laboratory equipment is developed for teaching laboratories in AEM. The real-world demonstrations of wave propagation, polarisation of uniform plane waves and antenna design impart discipline knowledge to students. The students' satisfaction and lifelong learning have been achieved as a result of this innovative laboratory.

PURPOSE OR GOAL

The aim of the research is to develop transferable skills in PhD students through an extracurricular activity of designing an advanced electromagnetism (AEM) teaching laboratory to aid experiential learning approach by students under the supervision of the PhD Supervisor. The PhD students learn how to transfer their theoretical knowledge and design expertise in AEM into a teaching laboratory kit. As the demonstrators, the PhD students also develop technical competency in presentation, pedagogy on AEM and written communications skills drafting the laboratory manual for AEM laboratory.

Teaching AEM laboratory is a non-trivial task. The nature of the topic is highly abstract hence developing a laboratory for teaching is highly expensive and needs specific knowledge. The lab kit usually costs in the order of tens of thousands of dollars per unit. They are bulky and not easy to transfer from the laboratory. Therefore, the purpose or goal of the work is to bring innovation in the abstract discipline with a comprehensive but a very low-cost solution of less than $500 per unit. So that students in the field of electrical and electronic engineering learn basic skill sets on how to handle the equipment, and develop experiential learning. The tangible purpose is to deliver a flexible solution so that students can take the unit at home and learn flexibly the abstract concepts of AEM with the hands-on kits. Since the kit is very low cost it can be implemented in modern universities of both developing and developed countries. In the pedagogy aspect, the innovation develops experiential learning outcomes and makes the students employment ready. The experiments go well with the theories taught in the lectures and are verified with real-world scenarios. Students can plot antenna radiation patterns, learn the propagation of electromagnetic fields in different media and wave polarisations, and wireless communications.

The aim of the work was to transfer the outcome of an extracurricular activity of PhD research into a teaching laboratory with the two PhD students under the supervision of the PhD supervisor. The two microwave trainer boards with many important modules that augment the theories learned in classes were developed. A very low-cost vector network analyser (VNA) with the trade name miniVNA Tiny is used as the transceiver system. The VNA has a computer-controlled graphical user interface (GUI) and a calibration tool for accurate and efficient measurements. Students also learn the calibration technique for the VNA which is an advanced equipment. Such calibration skill is highly sought after in industry.

APPROACH

A portable low-cost, hands-on laboratory kit to augment AEM education was developed for senior students. The laboratory kit consists of a PC-based VNA, a jig, two microwave trainer boards, RF/MW cables, a set of calibration kit, aluminium and dielectric plates, and a Wheeler cap. All the laboratory components, except miniVNA Tiny, were designed from scratch. The laboratory equipment is designed in compact and lightweight so that it can fit in a small case (324 mm L × 265 mm W × 128 mm H). The overall weight of the case is only 2 kg. The laboratory kit is to illustrate the abstract concepts of plane wave propagation, wave polarisation, transmission and reflection of uniform plane wave theory, fundamental transmission line theory, terminated transmission lines, matching techniques, terminations, and antennas. To facilitate the experiment, a detailed list of the components and handling instruction are also inserted at the back cover of the cage. An independent laboratory manual was also developed from scratch so that students can learn the theory and experimental procedures and can do the experiment without any other external resource materials. By using the apparatus, students are able to measure microwave circuits and antenna parameters. The portability of the kit enables students to conduct experiments in a laboratory or at home. The flexibility of a lightweight low-cost experimental kit in a small and slim equipment box is another innovation. The experiment kit facilitates students' self-learning. Students can repeat the experiments until they get satisfactory results using this kit. Demonstrators were also available via zoom meeting and online chat for consulting if helps were needed. The laboratory kit provides students with exciting practical experience. Implementation of the laboratory kit in the curriculum has also contributed to increasing course enrolment and student evaluation teaching unit (SETU) scores. It has also promoted lifelong learning. After graduation, students came back to the lecturer with their satisfactory comments. In these comments they reflected how they implemented the learning outcomes in their current employments and responsibilities.

ACTUAL OUTCOMES

With the experiential pedagogy, both the learning experience and outcomes have been improved. This is evident with the SETU scores after the implementation of the laboratory since 2017 till date and the feedback after the students entered in jobs at industry.

Students develop lifelong learning experiences as the laboratory ingrains the learned theory through experiential learning. Many graduate students who took the AEM unit in their undergraduate course wrote back to the lecturer with appreciation. They stated that the experimental knowledge in wireless communications really helped them in other areas of emerging technologies. Such as global position system (GPS), microwave biomedical engineering, driverless cars, augmented reality and many other emerging fields are utilising the theory of AEM. Therefore, the laboratory teaching has equipped graduates with the appropriate skills and knowledge that industry is asking from modern universities in their pedagogy for employment readiness. The low-cost AEM laboratory can be used in developing countries for improving AEM teaching and learning methods.

SUMMARY

The transfer of the AEM research outcome from a doctoral research laboratory to a tertiary teaching laboratory is vital for innovation in pedagogy. The teaching tools can be utilised in highly abstract disciplines such as applied mathematics, physicals, astronomy, radio frequency electronics and microwave engineering, where the concepts of AEM are utilised. Due to its low cost it also can be used in universities in developing countries.

KEYWORDS

Experiential learning, practical experience, electrical and electronic engineering education, transferring PhD research outcome, transferrable skills, lifelong learning.

Introduction

Practice sessions are essential in engineering education (Litzinger et al., 2011). AEM deals with the abstract natures of the EM fields and waves and their interactions with matters. It is the most abstract discipline in the entire electrical and electronics engineering field. In an advanced electromagnetism (AEM) course, the benefits of experiential learning are more evident since the nature of the course is highly abstract and practical skills are needed for learning and the job market later. With the advent of modern wireless communications technologies AEM has been penetrating in every wake of human society. Therefore, the AEM becomes a core teaching unit in modern universities.

At Monash University, an AEM course is taught in one semester for senior students. The material is to encompass concepts related to the propagation of time-harmonic EM waves in wireless and guided media and antenna. Students are required to solve complex electromagnetic problems of wave propagation in vacuum/air and solid media, transmission line, waveguides, and antennas using vector analysis, physical laws and Maxwell's equations. Students have developed graduate skills through project-based approach and industry oriented problem based learning and extra-curricular activities (Karmakar & Forouzandeh, 2016). Due to the high degree of complexity of electromagnetic theory, software tools are utilised to enhance students' visualization and understanding of field distributions and wave propagation. However, hands-on experiences are most effective to deepen understanding and bridge gaps between theory and real-world applications. Moreover, RF and microwave equipment are often costly and bulky. Therefore, it is a challenging task to provide laboratory kits to a large number of students. Hence, the students' satisfaction score suffers.

In this paper, we present a lightweight, compact, portable, low-cost, innovative, hands-on laboratory kit for an AEM course. The laboratory kit consists of a jig, a miniVNA Tiny from mini Radio Solutions, RF/MW cables, a set of calibration kit, microwave (MW) trainer boards, an aluminium plate, a dielectric slab, and a Wheeler cap. The components are shown in Figure 1. All the mentioned components are accommodated into a small case (324 mm L × 265 mm W × 128 mm H). The kit was designed from scratch in Monash Microwave, Antenna, RFID and Sensor Laboratory (MMARS) at Monash University by two PhD students. The main goals are to reinforce concepts of wave propagation, transmission lines, antennas and to develop practical engineering skills for students' future careers.

Figure 1: Laboratory components.

Approach and Outcomes

Two PhD students who designed the laboratory kit and tested its efficacy in the research laboratory are demonstrators of the AEM teaching unit. As part of their PhD research in AEM, they are conversant in the subject matters of AEM as stated above. They also act as the tutors of the unit. Therefore, their comprehensive engagements as the demonstrators, tutors and designers of the laboratory kit aided the teaching process. The effectiveness of the pedagogy was reflected through the SETU scores.

Teaching implementation of AEM is deployed for senior students in electronic engineering. The unit focuses on the propagation of time-harmonic electromagnetic waves in wireless and guided media, and also explores different types of antennas that can be used to generate electromagnetic waves of linear, circular and elliptical polarisations. Also plane wave transmission and reflection theories are verified with propagation of electromagnetics wave through air, solid media such as foam, paper and metal. Also, electromagnetic compatibility and shielding effectiveness were taught through the propagation study. Frris transmission theory and Wheeler cap antenna efficiency measurement were also included in the experiment. The learning objectives and outcomes of the unit lead to the design project of a 2.45 GHz wireless fidelity (wifi) router antenna design for wireless communications. The design project is the final outcome of the learned theory and laboratory experiments using the kit.

In addition, students are taught the concepts of electromagnetic interference (EMI) and electromagnetic compatibility (EMC). During a teaching semester, students learn theory and real-world applications of AEM via the lab kit to enhance their experiential learning of the abstract AEM theory. The course has three main components: face-to-face and online lectures, laboratories & design project, and tutorials. The design project requires students to design, fabricate, and measure a 2×2 –element array antenna. The design project provides students with opportunities to work with real components, circuits, and devices.

The laboratory sessions starts with the learning of two state-of-the-art software tools called CST Microwave Studio® (*CST studio suite electromagnetic field simulation software*) and Advanced Design System (ADS) (*PathWave Advanced Design System*, 2022) follwed by the calibration of miniVNA Tiny and measuremnts of a few passive microwave components such as transmission lines, 2-way power dividers, lowpass and bandpass filters. The main advantage of using software was to assist students to visualise the abstract concepts such as field distributions of a coaxial cable and the radiation patterns of a patch antenna. However, using only software in laboratory teaching has no connection to real-world applications. To allow students to get benefits from hands-on activities, we have developed the portable laboratory kit.

While the main goal of designing the laboratory kit was to provide students with hands-on experience, The other goals were to illustrate, reinforce, and extend concepts taught in the course with experiments; to offer sustainable, portable, and low-cost experiments with real-world circuits applications and to bring an exciting experience of AEM to students. This highly innovative laboratory kit trains students to be competent engineers to take any real-world challenges in wireless communications.

The laboratory kit will be introduced as four main groups of components: jig, miniVNA Tiny and calibration kit, microwave trainer boards, and other components. Figure 2 illustrate the laboratory jig that supports the equipment.

Jig

When students perform the experiments, they need to set up the experiments with the use of VNA, the microwave training boards, and other components. To mount VNA and the boards, we designed the laboratory jig. The laboratory jig was built from wood so that no interreference of electromagnetic signal can occur. In many experiments with antennas, students are required to insert the antennas of the microwave trainer boards in the top slits of the rotary poles.

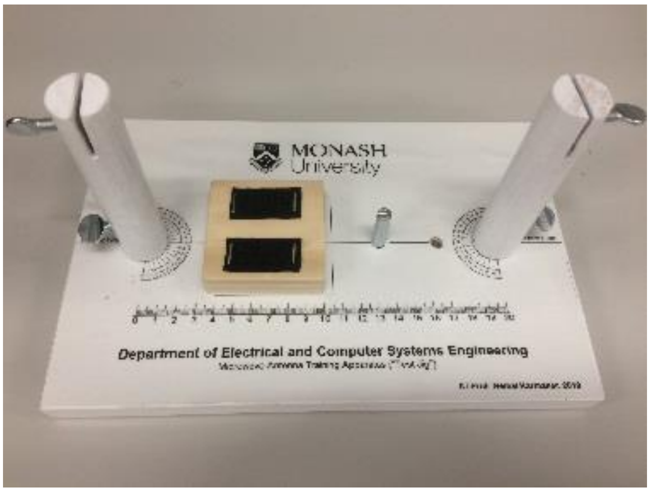


Figure 2: The laboratory jig.

To assist students to turn antennas facing each other with different angles, we designed the poles to be adjustable. The poles also can be arranged with different distances for the far and near field radiation measurements. The poles also can be removed from the base to store in the case after the experiment is completed. We placed a ruler printed on the board to assist students to align the space between the two poles to adjust the distance between two antennas for the far field and near field measurement. The distance is calculated based on the far field distance formula $R = \frac{2D^2}{\lambda}$, where R is the distance between the two antennas, D is the largest dimension of the antenna, for a rectangular patch antenna, D is the diagonal distance in meters, λ is the wavelength of the operating frequency in meters. For the patch antenna at 2.45 GHz, the far field distance is only 20 cm. We also designed two protractors on the bases of the poles so that students can rotate the poles at specific angles. The sticky pads are on top of the wooden bearing stand to mount a MiniVNA Tiny. The size of the jig is 300 mm x 240 mm. The antenna jig is highly useful for antenna radiation patterns, gain and efficiency measurement.

MiniVNA Tiny and calibration kit

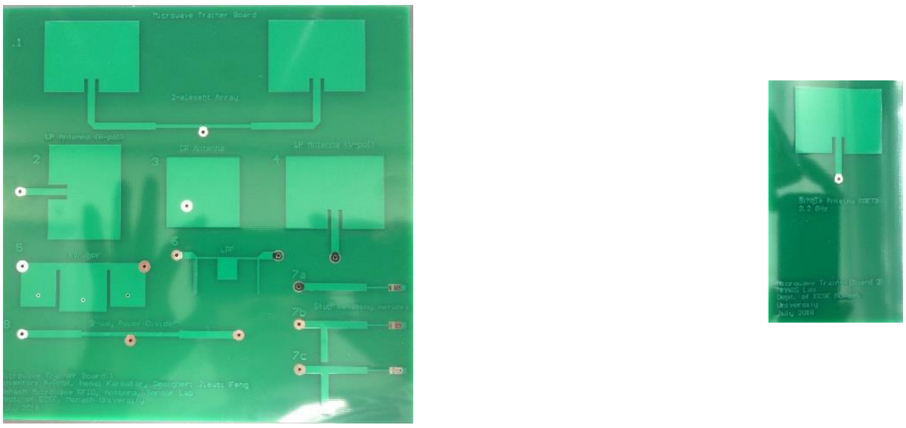
(a) (b)

Figure 3: (a) MiniVNA Tiny and (b) calibration kit.

The laboratory kit comprises a MiniVNA Tiny from mini Radio Solutions. It acts as the transceiver system for all experiments and also a microwave measuring equipment. Therefore, it is the heart of the experiment. For accurate measurement results, it needs calibration before the experiment starts. The photograph of the miniVNA Tiny and its calibration kit are shown in Figure 3. It is a PC-based, handheld VNA, with the frequency range from 1 MHz to 3 GHz. There are two ports scattering parameter (S-parameter), where S_{11} represents reflection coefficient and S_{21} represents transmission coefficient for the measurements. Both are in dB units. Students are given the theory of S-parameters in the laboratory manual and are taught to export the S-parameter data in several formats such as JPEG, EXCEL, S2P, and PDF. After data collection and analysis, they are asked to reflect their understandings of the measurement results in their lab reports. The VNA provides students with a friendly interface on a PC and/or a laptop. The calibration kit consists of an Open, a Short, a 50-Ohm Load, and an SMA female inline coupler for through calibration as shown in Figure 3(b). In the first laboratory session, students get familiarized with the VNA, the calibration procedures and other laboratory components as shown in Figure 1. In the first lab students learn to perform the calibration procedure, and to use the VNA for single (S_{11}) and two-port (S_{21}) S-parameter measurements for different passive components following detailed lab manuals. Most students have no experience using these kinds of equipment before. Therefore, we introduce and allow them to explore the equipment box first and check out components. The nature of these equipment is fragile and hard to replace; hence, we teach students to use equipment with proper cable and connector cares. Students also learn to connect cables to a VNA and a device under test (DUT) properly. As mentioned earlier, the calibration, measurement and connector care procedures are highly significant and demanded in microwave and wireless communications industries.

Microwave trainer boards

Our main innovation lies in designing the two microwave trainer boards as shown in Figure 4. We accommodated many components. As shown in Figure 4(a) from top to bottom there are a 2-element patch antenna array, three different polarised rectangular patch antennas, a passband and a lowpass filters, and three different loads - fully unmatched, and partially and perfect matched loads. The different components are fit into a single FR4 PCB so that students can use the same trainer board to perform numerous experiments. Figure 4(b) shows the photograph of the receiving rectangular patch antenna. The boards were designed, fabricated, and tested in our MMARS lab at Monash University. We used CST Studio Suite as a simulator to design the boards and fabricated them using FR4 laminate with thickness of 1.6 mm and substrate permittivity of 4.3. The microwave passive components on the boards operate at 2.2 GHz. Two PhD students, who have experience and expertise in microwave circuits and antennas, were in charge of designing and evaluation of the prototypes. By transferring research outcome to the teaching laboratory, not only the costs were reduced but also the technical innovations of the laboratory kit were facilitated. Further, the enrolled students have learned the measurements procedures of microwave circuits and antenna parameters in the laboratory sessions.



(a) (b)

Figure 4: Microwave trainer boards (a) # 1 (b) #2.

Ancillary components

The laboratory kit also has other components such as an aluminum plate, a dielectric slab, a Wheeler cap, a USB cable and two RF coaxial cables (as shown in Figure 1). The aluminum plate and dielectric foam slab are used for plane wave propagation and transmission studies and shield effectiveness for EMC. The Wheelers cap is used to measure the antenna radiation efficiency using Wheeler cap efficiency measurement theory.

In each laboratory session, students are assigned to get a laboratory kit. The kits must be returned at the end of each session. For a special case, students can borrow kits to conduct experiments themselves. Conventionally, microwave circuits and antenna measurements were conducted in a laboratory room with expensive and bulky devices. With this portable and compact innovative laboratory kit we have revolutionsed the AEM pedagogy and microwave measurement culture for the best outcome of learning experience of AEM. In this new approach, students have flexibility to conduct the experiments in the laboratories or other places.

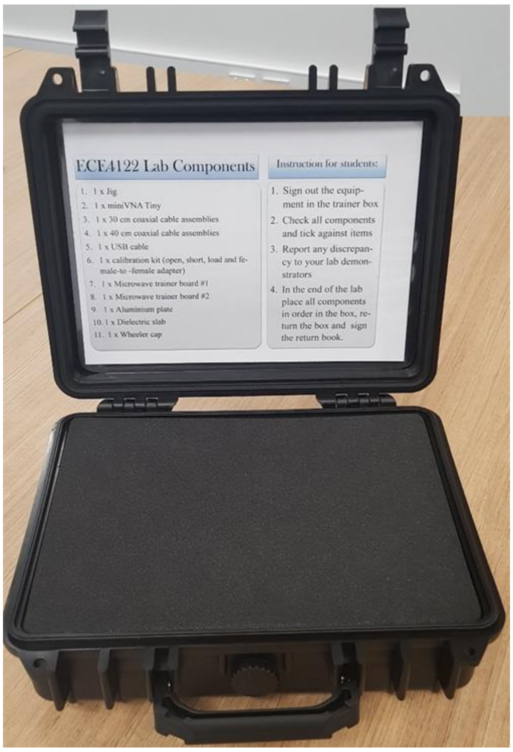


Figure 5: The laboratory case with component details.

Impact and evidence of AEM pedagogy

The new approach to using the new laboratory kit has been implemented since the second semester of 2018. The students studied teaching units ECE4122 and 5122 AEM stated that they enjoyed the laboratory activities. Many students said the magic boxes were “so cool” for them. For each year, unit surveys are conducted at the end of the teaching semester. Figure 6 illustrates the Monash University student evaluation of teaching unit (SETU) scores from 2017-2021. It reflects the positive outcomes of the implementation of the laboratory that augment the theory. With SETU score 1 being “strongly disagree”, and 5 being “strongly agree”. SETU scores show significant improvements in all aspects of pedagogy such as the learning outcomes, the resources, activities, the engagement in the unit, the laboratory assessments, the balance between the theory and practical applications. As for example in 2019, a 67 students sample reflect $\geq 85\%$ overall satisfaction score (median 4.5 out of 5).

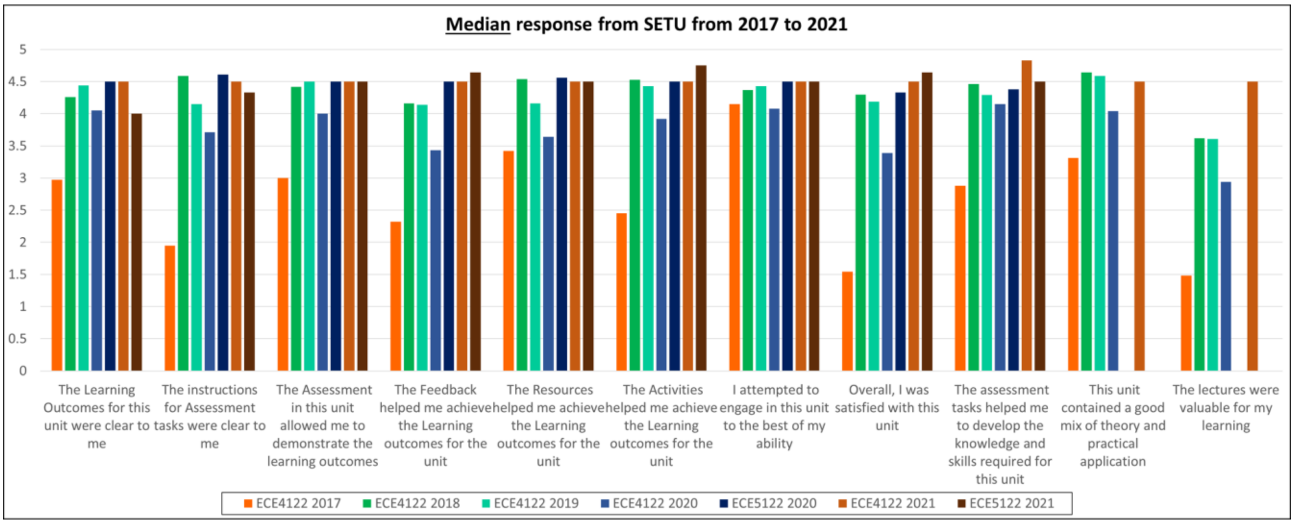


Figure 6: SETU scores from 2017 to 2021.

One student wrote "In this semester I learned Advanced Electromagnetics, Optical Communications, Wireless Communications and Smart Grids. I really appreciated that there are many practical labs and projects about antenna and RF in ECE4122, related to my previous work experience in radar area, and will be helpful to my future desirable direction in telecommunications."

Another student wrote, "I was a student of yours during ECE4122 last semester - I really enjoyed the unit and got a lot out of the practical work which was a core part of the curriculum. I am currently completing my final year project with a startup called in Biosciences. The startup is developing an ingestible gas sensing capsule which helps to diagnose gastrointestinal diseases.

I thought I would reach out to you to see if you / or your lab might be interested in collaborating or if you might know of any RF engineers or students who might be interested."

The above two communications from the past students are testimonials of their lifelong learning outcomes of the laboratory.

We also have been showcasing the laboratory kit to visitors at Monash University Open Days since 2018 till date. This showcase draws many visitors from many industry sectors such as law enforcement, wireless communications, biomedical engineering, logistics and supply chains. This Monash Open Day laboratory kits demonstration also has impacted enrollments in the unit and positive public sentiments for wireless communications in general.

Discussion

Within the EEE graduate course, conventionally, only the final year project (FYP) a full one-year unit component involved hands-on experience. We have introduced the design project in ECE4122/5122 unit. Students were required to design microwave circuits and antennas. The project-based approach allowed students to solve a real-world electrical engineering problem, gain knowledge, practical skills, and experience throughout the project. Since 2018, we have deployed a portable laboratory kit as a tool for students to conduct microwave and wireless experiments. The laboratory kit was a result of transferring the extra-curricular activity of PhD research work to university pedagogy under the leadership of a supervisor.

PhD research findings are generally too complex and incompatible with the EEE syllabus. We overcome the problem by selecting the appropriate and reliable research output to suit the EEE undergraduate pedagogy . Transferring the research work to build a laboratory kit brought many benefits. First, the PhD students, who had certain practical knowledge and research skills, contributed more to the improvement of the course. Also, they learnt the method of transferring knowledge and skills to solve specific requirements in engineering education. The transfer of know-how makes PhD students more motivated and triggers new insights into further research. On the other hand, the innovation of research work was integrated into the teaching laboratory, thus, the laboratory equipment standards were raised. The positive change was complying with the Monash University mission statement. Finally, implementing this approach reduces the cost of the laboratory equipment so that the kit could be provided to many students. Students ultimately are the ones who benefited from the transfer of knowledge and expertise to university pedagogy.

The laboratory kit is compact portable and lightweight. This allowed students to carry the kit with them and conduct experiments outside the laboratory rooms. Feedback from the students indicated that they enjoyed the kit and they felt like “playing with sophisticated toys” during the laboratory sessions. After four years of running the laboratory kits, only two out of thirty laboratory kits were out of operation due to only some loose connectors. That was also easily fixed. Before deployment of the laboratory kits, after fabricating their design project circuits, the students took turns to do measurements. Because there were not enough number of units for the students. Thanks to the implementation of the kits, students now have more freedom and save time in the laboratory experiments.

Conclusion

Usually, PhD research is meant for very high-level abstract outcomes. In this work, we transfer the PhD research in tertiary education through an innovation laboratory kit development. This developed kit creates real impact in teaching and learning and transferable skills development in EEE graduates. The lightweight low-cost and compact laboratory kits can be used flexibly in any setting to enhance the learning outcomes of AEM. Showcasing the laboratory kits in Monash University Open Days also draws interest from the public and many varied industry sectors where wireless technology is being used.

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