An Innovative Approach to Teaching An Undergraduate Electromagnetics, Antennas and Propagation Course

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Abstract – In this paper an innovative approach is taken to teach electromagnetics (EM), antenna theory and signal propagation to undergraduate students. The method relies on hardware design and implementation projects that reinforce the underlying theory, enable the student to gain practical insight into the various EM topics, and ultimately provide the student with a working knowledge to analyze, problem solve and engineer EM systems. Topics include the basic EM theory, electromagnetic compatibility (EMC) and interference (EMI), transmission lines, antennas, phased arrays, and wireless propagation. Projects range the prosaic EM experiments to more open ended design with multiple possible solutions.

Index Terms – experiential learning, laboratory development, electromagnetics education, antenna and propagation education

I. Introduction

A previous paper [1] discussed the increasing necessity of having electromagnetics (EM) and antennas coverage in the undergraduate electrical and computer engineering (ECE) curriculums despite the fact that most ECE curriculums are increasingly crowded with much of the usual and/or currently "hot" topics. However, like circuits, EM is fundamental to electrical engineering (EE) and needs to be covered. For example, electromagnetic compatibility and interference (EMC/EMI) is often the critical element for successful product design. Furthermore, in today's world of wireless communication and high speed digital circuits, it is imperative that the ECE graduate have a good working knowledge of EM systems, antennas, and signal propagation. *Many times the most challenging problems facing the designer are EM issues and not software.* At the same time however, EM theory is perceived to be too theoretical, arcane and mathematical for today's generation of undergraduates. Some of these perceptions have merit. For example, what good is it for a student to do calculations using the curl operator, when they cannot engineer a solution reducing undesired EM radiation or understand why undesired pulses occur on board traces that happen to run parallel to other traces carrying large switching currents? EEs should know why HF, and not VHF signals propagate across oceans, why only local broadcast AM signals are heard during the day, and the technical versus regulatory considerations that dictate why UHF and not HF signals are used for the wireless cellular phone system.

There is a great deal of interest and work being done to create a more student friendly EM instructional experience. Selvan [2] addresses student centered EM instruction; Mukhopadhyay and Pinder [3] addresses the inherent difficulty of teaching EM, and Crilly[1], Xie, Liang and Wang [4] present laboratory based EM instruction methods. Rao [5], Iskander [6], and Raida [7] addresses EM instruction using technology; Zhou [8] uses the seminar approach to EM education.

This paper will present a project oriented approach to teaching EM, antennas and radio frequency propagation that is currently being done for the EE program at the United States Coast Guard Academy (USCGA). The current course at the USCGA covers, but hopefully *uncovers* basic EM theory, antennas and propagation. The main points are as follows: (a) Coverage starts with the operation of the half-wave dipole to illustrate how an accelerating electron causes a radiated EM field. This is reinforced by a demonstration to quickly dispel the notion that ordinary circuit theory can adequately explain the behavior of distributed parameter systems. (b) This is then followed by transmission lines and then classical EM theory, antennas and propagation. (c) The lecture material is augmented by eight labs. (d) Increased emphasis on how EM theory can be used to solve modern electrical engineering problems such as multipath interference, EMC/EMI, and wave travel through lossy media. (e) The design, construction and testing of dipole and Yagi antennas, and (f) the design, analysis and implementing of phased arrays. Much of the traditional mathematical content and theory of the course is retained but the focus is on the *understanding* of Maxwell's equations and how they can be used to solve practical engineering problems. In other words, what can you do with all this arcane physics and mathematical theory?

A strong aspect of our course includes real world situations that include the following: (a) what are the challenges with underwater communications, (b) why is a Yagi antenna

directional, (c) why isn't polarization critical for short wave broadcasts versus VHF-FM broadcasts, (d) in addition to its directivity, why is the physical size of an antenna important, (e) for a given application, what frequency band is appropriate, (f) what are the advantages and disadvantages of coaxial cable as compared to other types of transmission lines and media, (g) what factors affect antenna efficiency, and (h) what are the sources of noise, and what are feasible means to maximize signal-to-noise ratio?

What has often been forgotten in many of today's research intense engineering programs is that engineers engineer, build and then re-engineer to improve their design! Most engineering students go into the field because they want to use their creativity to build, test and then make things work. And if their design doesn't work as intended, then go back and do what it takes to make it work. Hence the strong interest of EE students in such areas as mechatronics, embedded systems, and software design. EM and antenna systems should not be the exception.

II. Lectures and class demonstrations

A. Lectures

The lecture material pertinent to EM theory, transmission lines and to some degree antennas is primarily based on the textbook by Ulaby, Michielssen and Ravioli [9]. To help with some of the fundamental concepts or provide a different perspective of vector calculus, we use a monograph book by Fleisch [10]. To augment the text for antenna theory, we use Krauss [11], and the Silver [12]. For propagation theory we use Jordan and Balmain [13], Silver [12] and Nichols [14]. Ulaby, Michielssen, and Ravaioli [9] cover the necessary theory to prepare students for more advanced courses on EM, and yet in a user friendly manner. The textbook has good end of chapter problems. Fleisch [10] provides down to earth treatment of Maxwell's equations, and their associated math and has good end of chapter problems. The solutions are posted on a web site. Student response to the Ulaby textbook is largely favorable. Students who take this course have already had physics and vector calculus and therefore, we emphasize engineering problem solving rather than physics.

B. Class Demonstrations

Dipole current profile - On the first day of class, we demonstrate that dipole antennas do in fact carry an RF current sufficient to power a set of light bulbs. Figure 1 shows a half wave dipole with incandescent light bulbs (resistors) that are placed periodically along its length. When the transmitter outputs power to the dipole, the bulbs closest to the feed point are brightest and as you get further from the feed point, the current decreases causing a similar decrease in bulb brightness. This brightness profile matches the theoretical

current profile of a half wave dipole.[*] Even more profound however is that students see light bulbs turning on when there is no return path for the current. This goes against what they've learned in circuit theory and therefore, they get a better appreciation of EM and distributed parameter systems.
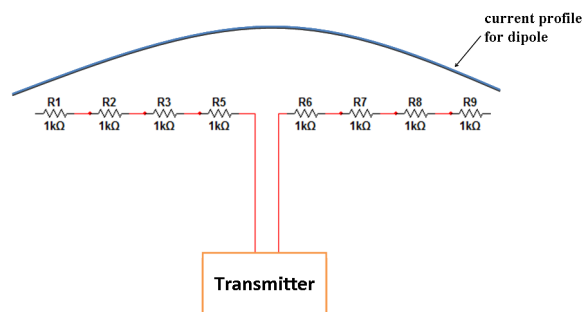

Figure 1. Current profile for a half wave dipole.

Standing wave ratio (SWR) - To illustrate standing waves and how we can measure SWR and wavelength, we do a slotted line demonstration. This consists of a 1 meter long slotted line, moving sensor and voltmeter. The slotted line mimics a coaxial transmission line. The sensor consists of a wire probe that runs slightly above, but does not touch the center conductor. The wire probe is fed to an envelope detector circuit that converts the RF voltage to a DC level where it is observed on a DC voltmeter. As we slide the sensor along the slotted line, we readily observe how the voltage magnitude varies as a function of distance from the feed point. The variation in voltage levels is indicative of the SWR; the physical distance between peaks and/or valleys is a function of the wavelength and then from wavelength, we calculate frequency. By varying the load types, it is relatively easy to demonstrate that a terminated line will have less voltage variation, hence lower SWR than an open or short circuited line. A one meter slotted line was chosen since most laboratories have signal generators that can reach 400 MHz and thus at least one peak and valley can be observed.

Noise sources - Another demonstration seeks to illustrate noise sources of HF and VHF communication. With a HF receiver it is readily observed how the background noise goes away when the antenna is disconnected, thus demonstrating that the channel, not the internal electronics, is the main noise source. On the other hand, doing the same experiment with a VHF or UHF receiver, there is no change to the background noise, and thus the noise source is in the receiver electronics, not in the channel.

Ionospheric propagation - To illustrate the effects of ionosphere propagation, we use a short wave receiver to pick up AM broadcast and short wave signals. The effects of the D-layer absorbing signals below 5 MHz are readily observed

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[*] When a coaxial line is used, only lights connected to the center conductor are illuminated.

such that during the day only local AM stations are heard whereas at night, stations from across the continent are heard via ionosphere refraction. Furthermore during the day if we listen to signals in the 14 MHz range, well above frequencies where the D-layer absorbs signals, overseas stations are readily heard. Finally, to illustrate the maximum useable frequency (MUF) we demonstrate how NIST (WWV) broadcast signals are readily heard at 10 MHz, but not necessarily at 20 MHz.

Parasitic elements - To demonstrate parasitic capacitances and inductances in circuit elements we first take a coil of wire and determine its resonant frequency. For example, a 36 turn coil at 2 inches in diameter has a resonant frequency of approximately 1.5 MHz. This shows that the parasitic wire capacitance due to the spacing between turns enables the supposedly pure inductor to actually be a parallel LC circuit. A second demonstration is terminate a 50 ohm transmission line with a 50 ohm resistor where at 1 MHz acts as a pure resistive load (ie. an $SWR \cong 1:1$), but as the frequency is increased, say to 50 MHz, the non-zero length of the resistor starts to act like a series RL circuit resulting in a SWR significantly greater than 1:1.

Phased arrays – We first derive the mathematical expression for the sinc(x) far field radiation pattern for an 8 element phased array system. The end result of the derivation is a large peak or main lobe at the horizontal center of the array (i.e. an arrival angle of 90 degrees or $x = 0$) and smaller peaks and nulls at each side of the center (i.e. other arrival angles and thus positive and negative values of x). The demonstration apparatus consists of an array of 8 speakers spaced $n\lambda/4$ apart and driven by an audio signal. When all the speakers are driven simultaneously, the audience readily observes the main lobe at $x = 0$ but even more profound is they observe the nulls (i.e. no sound) as they move back and forth along the horizontal distance in front of the speaker array.

III. Labs and Design Projects

The laboratory component of the course initially consists of short experiments and then progresses to an antenna capstone project whereby the student has to design, build, and test an antenna that meets a specified set of requirements. The equipment we use consists of the following: (a) Agilent 9912A Field Fox analyzer, (b) a 0-20 MHz waveform generator, (c) 300 MHz oscilloscope, and (d) MJE-259 SWR Analyzer/RF source and (e) Byonics Microfox, a 144 MHz intermittent signal source). The 9912A serves as a spectrum analyzer, signal source, SWR analyzer, and time domain reflectometer.

A. Lab experiments to augment lecture material

Resonant circuits and direction finding – The goal is to locate a local AM station using the relatively sharp null point of a resonant loop antenna. Later on, they will do direction

using the sharp lobe of a Yagi antenna. First the student constructs an LC circuit using a multi-turn coil of approximately 8 inches in diameter mounted on a piece of wood 5" X 5" The resonant frequency is set to the desired AM station's carrier frequency. Another set of turns is overlaid on the coil (i.e. to make a transformer) which then connects to a portable spectrum analyzer. At one location, the student rotates the loop to look for the null in the station's carrier impulse. The null bearing is then plotted on a map using a compass and ruler. The students can use a portable GPS to determine the loop's location. Note most students use their smart phones with built in GPS and map apps for the bearings. The student then repeats this process but at some distance away. The AM station is located where the two bearings intersect. Because the AM station's location is published in the FCC data base, the students have a basis of comparison for their measurements.

Electromagnetic compatibility – This relatively simple experiment illustrates how radio frequency interference can corrupt logic signals. As illustrated in Figure 2, we connect a of 24 inch length of RG-58 coax from the 0-3 volt, 1 kHz square wave obtained from an oscilloscope test output to a scope input. We then take an 8 inch length of RG-8 coax cable shield, slip it over the RG-58 cable and then connect the RG-8 shield to a 10-20 MHz sinusoidal source. The 10-20 MHz interference is readily observed on the 1 kHz square wave. If we then clip on ferrite chokes over the RG-58's inner conductor, the RF interference is sharply attenuated. As an alternative to this non-invasive approach to interference reduction, we have the student connect a 1 µH inductor in series with the RG-58 inner conductor and observe the attenuation of interference.
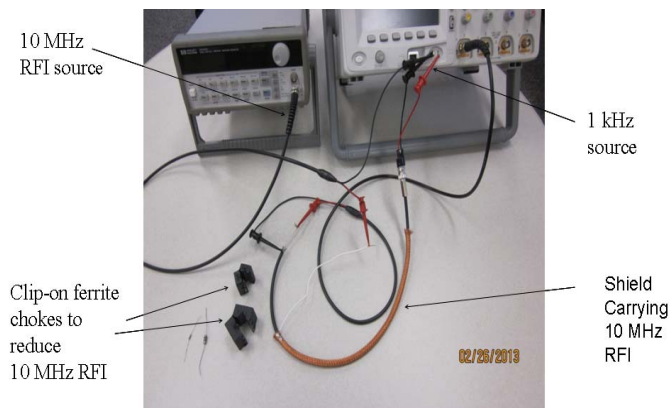

Figure 2. Equipment and setup for the EMC experiment.

Transmission line faults and losses – The Agilent 9912A Field Fox has a time reflectometry mode that can be used to determine the length of a cable and where any faults are located. We can also use the 9912A to measure cable attenuation. In this lab, we provide the students with several lengths of RG-58 and RG-213 cables and have them measure their lengths, losses, and locate any faults, if any, in the cable.

This lab also provides the student a better appreciation of what is meant by velocity factor. Given the various cables, the student then calculates the loss per kilometer and the determines how much power is lost for a 100 meter cable, and an input power of 100 watts.

Cross-talk due to adjacent electric fields – In this lab we first show how cross-talk can occur between densely packed circuits carrying high frequencies signals, and how it can be remedied by a grounded shield between the "aggressor" and "victim" circuits. Using standoffs we mount four parallel wirest on a board. The first two wires will be the aggressor, and the second two the victim. Their length is 2 meters. The two inner wires will be carrying the aggressor and victim signals and the two outer wires are the return paths to ground. The aggressor circuit is terminated with a 100 kΩ resistor and both ends of the victim lines will be connected to 100 kΩ resistors. The spacing between the aggressor and victim line pairs is adjusted to vary between 0.5 and 14 cm. A function generator whose frequency will vary between 1 kHz to 20 kHz is connected to non-terminated end of the aggressor circuit and then a scope is used to measure the signal on the victim lines at various generator frequencies. For a fixed aggressor versus victim spacing, the student then plots the victim's voltage versus frequency. Next, we fix the frequency, and then repeat the experiment except we vary the spacing and plot the victim's voltage versus spacing. Because the cross-talk is due to capacitive coupling, the voltage level of the victim should increase with increasing frequency and decreasing spacing between the aggressor and victim circuits. Finally, to emulate the effect of coaxial cable shielding in reducing cross-talk, we repeat the above four experiments except with a grounded metal shield between the 2 signal wires. The level of cross-talk should be significantly reduced thus making the point that shielding reduces cross-talk.

Impedance matching with stubs – In this experiment we seek to show how a length of open or short circuited coax can be used to create an inductor or capacitor and then to use these reactors to cancel out load reactances. Hence, stub matching. We have the MFJ-259 SWR analyzer/signal source feed a transmission line that is terminated with a reactive dummy load. At some point before the load, there is a T connector to enable a connection to a parallel stub. The SWR is then measured and recorded. Note MFJ-259 will also indicate the type of the reactance at the load. The student then designs a shorted or open circuit stub that will cancel out the reactance. Again velocity factor has to be taken into account. The stub is then trimmed to the point where the SWR and overall reactance is then minimized.

Vertical antennas – The first antenna project is to simulate, construct and then test a λ/4 wave vertical antenna. Simulation software can be the Numerical Electromagnetic Code (NEC) supplied by the ARRL antenna handbook [12], other NEC simulation programs available online, or some commercially available finite element simulation programs. Using the MJE-

259 SWR analyzer and/or the 9912A, the student can readily see how the absence or oversupply of radials affects the SWR. Figure 3 shows one way to measure the radiation pattern. Note, in order for measurements to match simulated results, they should be done on an open field.
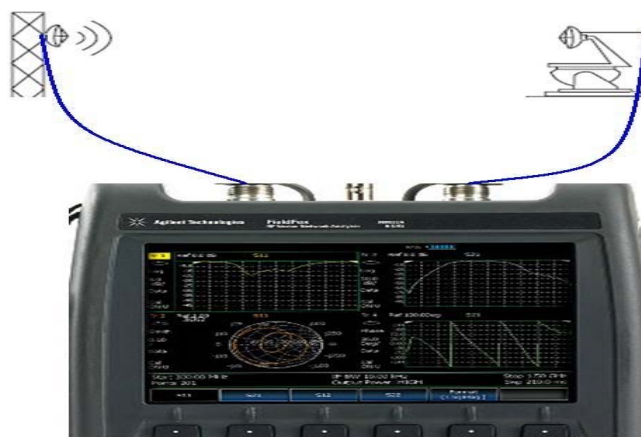

Figure 3. Antenna radiation pattern measurement setup using the Agilent 9912A.

B. Capstone Design Antenna Project

Yagi simulation and design – The mini capstone experience is for each pair of students to design a directional antenna subject to some constraints. They first have to simulate their design and then when constructed, they can use the scheme of Figure 3 to measure its radiation pattern. Typically students implement a Yagi, using readily available PVC pipe and copper or brass wielding rod. If their antenna is constructed using the popular gamma match and is coax fed, they also learn that the measured radiation pattern may not be symmetrical.

Yagi antenna, direction finding and the fox hunt – One of the fun parts of the course is to use their newly constructed directional antenna to locate a "fox." The "fox" is a Byonics Microfox which puts out a low power 144 MHz intermittent signal. As already stated, direction finding is based on the relatively sharp lobe of their Yagi. As an alternative to finding the hidden fox, the students could design a directional antenna for a local FM broadcast station and then locate it using their Yagi in a similar manner to what was done for the AM station, except that the bearing is based on the signal peak, not the null.

IV. Conclusions

A project oriented and comprehensive antennas and propagation course has been taught for the past two years at the USCGA. Student response has been positive and the course content and laboratory projects continue to be updated.

Acknowledgements

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