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A Concise Antennas Course based on a Single Semester of Electromagnetics Preparation

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Abstract

A new undergraduate elective course that develops a background in antennas for senior electrical engineering students is presented. The course is only three quarter-credits long, that is, two semester-credits. An innovative aspect of this course is the modest prerequisite of only a Junior-level, four semester-credits (four lecture hours per week) electromagnetics course or equivalent. In our quarter-based system, four semester-credit lecture hours translates into two courses of three quarter-credits (three lecture hours per week) each. The prerequisite courses, required in our undergraduate electrical engineering curriculum, are modulated in depth and breadth of topics, starting with vector algebra and coordinate systems and progressing through static fields, dynamic fields, transmission lines, plane waves, links, and electromagnetic interference principles. The integral forms of the fundamental electromagnetic relations are emphasized in these required courses. As a result, this antennas elective must incorporate pedagogically-selected background material such as differential operators and the differential forms of Maxwell's equations, skin depth, and reflection and transmission of plane waves at material interfaces. The course builds a solid foundation in antenna principles that serves students continuing into advanced studies in graduate school as well as those entering industry after graduation. This foundation is accomplished by strategically selecting and modulating the depth of topics in a pedagogic progression that focuses on developing insights into the fundamental concepts underlying antennas. Consequently, the course is not a survey course nor is it overstuffed. The course utilizes a thorough study of the dipole antenna as the vehicle for developing these fundamentals. The magnetic vector potential is used to derive the radiated dipole fields, which are then used to develop the concepts of radiation resistance, antenna efficiency, bandwidth, directivity, gain, and polarization. Image theory is used to develop the monopole antenna and analyze the effects of a ground plane on an antenna. These concepts are then extended to uniform linear arrays of antenna elements. Basic propagation and system link analysis are then used to examine the impact of antennas on the performance of practical systems. In this paper, the structure of the electromagnetics courses is examined initially to establish the prerequisite context. Details of the antennas course approach, structure, and implementation are presented, including the learning objectives, course topical and pedagogic flow, and a practical antenna simulation project utilizing the NEC2 computational electromagnetics software. The discussion section addresses results, lessons learned, and planned improvements for future offerings of the course.

I. Introduction

Today's engineering graduate is entering an increasingly connected, wireless world, with antennas at the heart of each of these wireless systems. In addition to communication links, antennas are integral components in medical imaging, radar, direction-finding, GPS, and electromagnetic interference (EMI) testing. Understanding the fundamentals of antennas allows an engineer working in diverse fields to make informed design decisions as well as to determine antenna placement in a device/platform for optimum performance.

Traditional antennas courses, represented in well-known textbooks,[1,2,3] are typically offered as semester-long senior level electives/graduate level courses that cover a large breadth of topics, including broad coverage of many different antenna types, and typically with an emphasis on design. These courses usually presume a student background consisting of a two-semester prerequisite sequence of electromagnetics courses. In contrast, at Milwaukee School of Engineering (MSOE) the junior-level electromagnetics sequence consists of two core, required electromagnetics courses, each a ten week quarter, that together form the equivalent of a single semester four-credit course. Under this limited time constraint, the breadth and depth of coverage is modulated in this sequence with a focus on the fundamental principles. The sequence begins with static electric and magnetic fields and then develops dynamic fields, transmission lines (T-lines), plane waves, and EMI. Topic coverage is limited to the core concepts necessary for the practicing electrical engineering graduate.

In order to understand and appreciate antenna theory, students need a broader and more advanced electromagnetics background than that acquired in the prerequisite fields sequence. Additionally, senior level electives at MSOE are normally limited to three quarter-credits (three lecture-hours per week). A concise, focused antennas course was needed that could achieve the desired learning outcomes within these stringent constraints. No literature was identified that addressed a time-constrained antennas course with limited electromagnetics prerequisites. Thus, a new antennas course was developed under the three quarter-credits constraint with an equivalent of a four semester-credit electromagnetics course as the only prerequisite. Topics were carefully selected and ordered to focus on the fundamental principles and follow a pedagogically sound conceptual roadmap. Although the course does not cover antenna design, it does develop a solid conceptual foundation in antennas that will serve both students entering industry and those who continue into graduate studies. Students can readily build on this foundation to specialize in antenna design.

This paper is organized in the following manner. Section II provides an overview of the prerequisite electromagnetics courses at MSOE in order to frame the electromagnetics background of students and to establish the context for the electromagnetics topics covered initially in the antennas elective. Section III outlines the focused approach of the antennas elective and provides details of the topical progression and pedagogy. Discussion of the course results, lessons learned, and future improvements are included in Section IV.

II. Electromagnetic Prerequisites Background

The prerequisite electromagnetics background to the antennas course addressed in this paper is examined in this section. This background sets the context for the antennas course pedagogy. This background is modest. It consists of two quarter-based courses that contain three lecture-hours per week at MSOE, which is equivalent to a single semester-based course of four lecture-hours per week. The second course also has a required weekly laboratory session. These courses are required of all students in the Electrical Engineering (EE) program at MSOE. Hence, the courses are not exhaustive and do not have a primary intent of preparing students for electromagnetics-related graduate studies. Instead, the courses have breadth and modulated depth with the primary intent to develop a set of baseline capabilities in electromagnetics and transmission lines for EE students regardless of the area of electrical engineering that they ultimately enter after graduation. An important secondary purpose is to prepare students for advanced studies in four electromagnetics-related electives at the undergraduate level, which are Radio Frequency Circuit Design, Advanced Electromagnetic Fields, Microwave Engineering, and Antennas. The details of the required courses are examined next.

The capabilities in electromagnetics for EE students that complete these core, required courses are documented in the learning outcomes for these courses, reported collectively:

1. Apply vector and calculus techniques to the solution of electromagnetic field problems in rectangular, cylindrical and spherical coordinate systems.
2. Apply Coulomb's law, Gauss's law, potential, and Biot-Savart law to determine the analytical expressions of the electric and magnetic fields produced under idealized geometrical conditions.
3. Describe capacitance in terms of electromagnetic field concepts and energy.
4. Describe electric and magnetic field behavior from analytic expressions and/or simulation results.
5. Apply Ampere's Circuital law to idealized current distributions, magnetomotive force principles for magnetic circuits, and inductance determination.
6. Explain the significance of each term in Maxwell's equations (integral form).
7. Explain wave propagation, characteristic/intrinsic impedance, reflections, and standing waves for T-lines and plane waves.
8. Determine DC step and pulse transients on a T-line from a traveling wave viewpoint.
9. Apply the wave equation results for the AC T-line to voltage, current, impedance, and traveling and standing waves on a T-line.
10. Measure and interpret displays and specifications of circuit/T-line reflection and transmission. [includes Smith charts and scattering (s) parameters]
11. Determine link loss per the Friis transmission equation.
12. Explain electromagnetic interference (EMI) and the other principles behind signal integrity and high-speed circuit effects.

These outcomes are now related to the pedagogy. The approach to the vector algebra (not calculus) and the Cartesian, cylindrical, and spherical coordinate systems aspects of outcome 1 form the initial primary focus and are described in detail because it is essential to the entire pedagogy of our approach to electromagnetics. It is commonly assumed that students enter electromagnetics courses with a good grasp of vector algebra and coordinate systems from their previous calculus and physics of electromagnetics courses. Our experience over numerous years disagrees with this conventional wisdom. We have conducted a prerequisite homework assessment for several years in the first electromagnetics course. Most students can decompose vectors into Cartesian components, such as in application of Coulomb's law for point charges, but this is mostly performed using trigonometry in a two-dimensional plane and labeling the vector components in the answer with unit vectors (**i**, **j**, **k**) as opposed to utilizing vector algebra in the solution process. Students are rarely capable of applying such vector concepts to anything beyond, such as determination of the electric field intensity at the origin due to a semicircle of uniform line charge density (8 out of 87 performed adequately on this assessment HW problem most recently). Vector analysis capabilities in cylindrical and spherical coordinate systems are absent. Integration in these coordinate systems is weak. For example, the assessment results have consistently shown that most students cannot develop the equations for the area of a rectangle, a triangle, and a circle *using multivariable calculus* (the crucial qualification; 32 out of 87 performed adequately most recently).

Given these prerequisite assessment results, a significant portion of the first course, on the order of 12 lecture hours, is dedicated to developing systematic vector algebra and coordinate systems capabilities (see Hayt and Buck[4], ch.1, for example). This study culminates in proficiency in developing the dot product results between unit vectors of different coordinate systems. We have found that this initial investment in the vector algebra and coordinate systems tools, and the consequent development of spatial visualization skills, has an enormous return throughout the remaining required and elective electromagnetics courses. These tools become an enabling asset as students progress through the concepts and mathematics of electromagnetics. In short, they are not "fighting the tools" at the same time they are learning new fundamental electromagnetics concepts and mathematics, namely outcomes 2 and 5. Instead, the tools become the vehicle through which they approach the new material both in mathematical analysis and, more importantly, in visualization of problem setup and results. We cannot overemphasize the importance of developing mastery of the vector algebra and coordinate systems tools in our one-semester equivalent approach to electromagnetics and transmission lines.

The vector calculus aspects of outcome 1 are developed in a just-in-time manner. As previously mentioned, integral vector calculus is mostly utilized in the required courses. The integration of non-Cartesian unit vectors, the mathematical incorporation of surface vectors into integrals, and path integrals are the primary analytic capabilities gained in outcome 2 and reinforced in outcome 5. The unit vector-dot product capabilities and insights that students gained previously serve to increase learning efficiency of these concepts. Only highly symmetrical charge distributions are analyzed mathematically, but bridging analytic results to insights (outcome 4) and into non-symmetrical cases becomes realizable, again because of the insights gained previously in the vector analysis tools. Although sparsely utilized in these required courses, the use of electromagnetic simulation for non-idealized/unsymmetrical cases is stated frequently.

Other fundamental electromagnetic topics (outcomes 2-5) are covered conceptually but analytically to a limited extent, namely the important special cases, to establish both the importance of these concepts and to build a sufficient yet not exhaustive basis for subsequent electromagnetic concepts and topics. The "modulation of depth and breadth" in these required prerequisite courses, the antennas elective, and other electromagnetics-related electives relative to a traditional two semester electromagnetics sequence is summarized in Table 1. For example, students are required to analytically develop the capacitances of only ideal parallel-plate, coax, and concentric spheres capacitors and the inductances of only the ideal solenoid and toroid, and of coax, but more importantly students are required to interpret numerous aspects of the developments and consequences from the results. An illustration of the latter is "*Why* is the inductance of coils generally proportional to cross-sectional area? To the square of the turns? To inverse length?" The students must answer with electromagnetic reasoning, not an equation.

The second course, which also includes a laboratory at MSOE, starts with Ampere's Circuital law (outcome 5) and then addresses time-dynamic electromagnetic fields and transmission lines (from Faradays' law to the end of Table 1, and outcomes 6-12). Fundamental wave concepts (outcomes 7-9) are developed for transmission lines, which is a strategic pedagogic step to the plane wave that is examined subsequently. Transmission lines and s-parameters establish the foundation for the vector network analyzer, one of the later experiments. In the last outcome, reflections and crosstalk, major signal integrity issues (outcome 12), are addressed in transmission lines. A very brief discussion of ground bounce and a concise examination of electromagnetic interference (EMI), the remaining signal integrity issues, concludes the course. A radiated and conducted EMI demonstration concludes the laboratory experiments.

Table 1. Comparison of Electromagnetics Courses at MSOE to a Traditional Treatment
(see abbreviations list following the table)

Traditional Treatment EM Topic	**Prerequisite EM courses**	**Antennas Elective**	**Other EM Electives**
Vector algebra	complete	utilized	utilized
Three coordinate systems	complete	utilized	utilized
Coulomb's law, point & integral forms	complete	none	none
Gauss's law, divergence	IF applied	DF discussed	applied
Potential, gradient	IF applied	none	applied
Laplace's equation	none	none	applied
Capacitance	special cases	none	applied
Current densities	IF applied	DF discussed	applied
Ohm's law, microscopic form	none	developed	applied
Biot-Savart law	for line currents	none	none
Ampere's circuital law, curl	IF applied	DF discussed	applied
Magnetic flux and density	IF applied	DF discussed	applied
Magnetic vector potential	none	applied	applied
Magnetic forces	Lorentz eqn.	none	motors course
Materials	μ & ε only	applied: μ, ε & σ	applied
Inductance	special cases	none	applied
Boundary conditions	cond./dielectric	complete	applied
Faraday's law	IF conceptual	DF applied	applied
Mutual inductance	applied	none	applied
Displacement current	IF conceptual	DF applied	applied
Maxwell's equations	IF conceptual	DF applied	applied
T-line concepts, transients	complete	utilized	utilized
AC T-lines, Smith charts	complete	utilized	utilized
s-parameters (usually not present)	related to specs	utilized	utilized
Plane waves, resultant equations	T-line analogy	applied	developed
Plane wave reflections, skin depth	mentioned	developed	applied
Antennas and links	gain&link eqns.	(see Table 2)	none
Signal integrity & EM interference	(see text)	mentioned	none

Abbreviations: cond. = conductor; DF = differential form; EM = electromagnetic(s); eqn. = equation; IF = integral form; specs = specifications; T-lines = transmission lines; ε = permittivity; μ = permeability

Overall, the discussion in this section has established that the investment in vector analysis at the outset of the first course establishes a sound basis to build electromagnetic concepts and select analyses that serves both the needs of our EE graduates at large and serves as a dependable basis upon which to advance into electromagnetics electives. The progression from this electromagnetic background in the antennas course will be related in the next section.

III. Antennas Elective

This section provides an overview of the antennas elective and details the learning outcomes and topics covered in the course. Focus is placed on the pedagogic progression of the topics. As described in Section I, this antennas course occupies a single ten lecture-week quarter with three lecture-hours per week. Additionally, the modest electromagnetics background discussed in Section II necessitates coverage of select advanced electromagnetics topics in the antennas elective. These constraints preclude the offering of a traditional, broadly scoped antenna course that includes significant design content. Instead, this course selectively focuses on fundamental antenna topics that form a solid conceptual foundation and avoids a survey of antennas. Specifically, dipole and monopole antennas are the *only* types of antennas *thoroughly* examined in the course, and serve as the vehicle through which the core concepts are developed. Careful modulation of topical breadth and depth is utilized to meet the time constraints of the course and to meet the learning outcomes:

1. Qualitatively describe how acceleration of charge produces electromagnetic radiation.
2. Develop the radiated fields and radiation resistance expressions of infinitesimal and half-wave dipole antennas from the magnetic vector potential using vector calculus.
3. Differentiate between the concepts of antenna gain, directivity, and efficiency.
4. Model basic dipole antennas using equivalent circuits.
5. Determine the effects of antenna impedance mismatch on antenna performance.
6. Design a basic reactive compensation impedance matching circuit.
7. Identify common balun configurations.
8. Perform link budget calculations for line-of-sight and multipath wireless links using the Friis transmission equation.
9. Analyze the performance of common wireless system links, such as cellular telephone, broadcast radio/television, satellite communication, and radar systems.
10. Select the appropriate antenna type for a given link (point-to-point, broadcast, etc.)
11. Determine the performance of dipole and Yagi antennas using computational electromagnetics software.
12. Describe radiation characteristics of more complex antennas in terms of dipole radiation characteristics.

These course outcomes can be met by following the time allocation by topic shown in Table 2, which shows how the 30 lectures are utilized during the quarter. The "modulation of breadth and depth" in this concise antennas elective relative to a traditional one-semester antennas elective is summarized in Table 3.

The course is organized into three distinct modules. The first module is comprised of the additional background electromagnetics concepts required for studying antennas. Foundational antenna concepts are covered in the second module within the context of the infinitesimal dipole. Finally, these fundamentals are extended in the third module to a few practical dipole applications and the effects of antennas in basic wireless links. The modules are examined next.

Table 2. Lecture Time Allocation by Topic in the Concise Antennas Elective

Topic	**Lectures**
Course Motivation	0.5
Electric and magnetic boundary conditions, normal incidence plane wave reflection and transmission	3
Lossy media, attenuation of plane waves, EM shielding, skin depth, Ohm's law	2
Differential operators, Maxwell's equations, magnetic vector potential	3
Basic radiation mechanism, radiated fields, near and far fields of infinitesimal dipole	2.5
Radiation resistance, rad. pattern, gain, directivity, efficiency, effective area, polarization	5
Half-wave dipole, simple reactive impedance matching, folded dipole	3
Dipole equivalent circuit, bandwidth and Q, baluns	3
Image theory and monopole antennas, ground effects	1
Two-antenna arrays, linear antenna arrays	2
Friis equation, practical system link analysis	2
Intro to computational electromagnetics, method of moments concept, simulation project	1
Examinations/review sessions	2

Table 3. Comparison of the Concise Antennas Elective to a Traditional Antennas Elective

Traditional Antennas Topic	**Concise Antennas Elective at MSOE**
Radiation from accelerating charge	Conceptual
Reciprocity	Conceptual
Radiation patterns, gain, directivity	Complete
Radiation resistance, input impedance, VSWR	Complete
Antenna polarization, polarization loss	Linear polarization only, circular conceptually
Infinitesimal and half-wave dipole analysis	Complete
Impedance matching	Reactive L & C, demo quarter-wave transformer
Radiation, Q and bandwidth	RLC equivalent dipole model
Baluns	Concept, common topologies
Image theory, quarter-wave monopoles	Electric currents only
Ground effects	Infinite, perfect conducting ground only
Loop antennas, duality	None
Line sources, traveling wave antennas	None
Linear antenna arrays	Uniform spacing, uniform excitation only
Yagi-Uda antenna array	Simulation project only
Multidimensional & phased arrays, aperture antennas	None
Computational electromagnetics for antennas	Conceptual method of moments (MOM)
Friis equation, basic link analysis	Developed, applied
Multipath propagation	Conceptual

Electromagnetics Background for Antennas Module
The antennas course begins with a development of the tangential and normal component boundary conditions for electric and magnetic fields at a material interface. Particular emphasis is placed on building intuition and enabling visualization of field behavior at conductor-dielectric and dielectric-dielectric interfaces. This discussion inherently reviews Gauss's and Ampere's laws, helping to form a strong conceptual bridge with the prerequisite courses. Boundary conditions are then applied to the reflection and transmission of plane waves at normal incidence to a material interface (oblique incidence is omitted). This analysis is coupled to corresponding transmission line concepts for mutual reinforcement.

The analysis of plane waves in lossless media is extended to lossy media via the complex propagation constant that was developed for lossy T-lines in the prerequisite courses. Attenuation of plane waves is examined for propagation through rain, foliage, and building walls. Particular attention is paid to the example of cell phone signals propagating through concrete walls, which helps many students relate their experience of signal drop-out or no service when inside certain buildings. These undesired attenuation effects are then contrasted with the concept of desired, *intentional* attenuation of plane waves via shielding. Practical applications are considered, such as Faraday cages, RF circuit board enclosures, and conventional microwave ovens. The example of holes in a microwave oven door that allow visibility yet shield the viewer from microwave power is particularly enlightening for many students, as this is one of the simplest frequency selective surfaces (FSS).[5] The thickness of a conducting shield required to provide a given level of attenuation is analyzed and is extended to develop the concept of skin depth. Emphasis is placed on distinguishing between the DC and AC resistances of a length of wire due to skin depth, which is central to the discussion of conductor losses in an antenna.

As noted in Section II, the integral form of Maxwell's equations are examined in the prerequisite courses. Differential operators (curl and divergence) and the differential forms of Maxwell's equations are developed next in the antennas elective. The operators are developed in Cartesian form and interpreted in cylindrical and spherical form. Maxwell's equations in integral form are converted into differential form. The magnetic vector potential is then introduced and interpreted (not rigorously derived). The general analysis procedure for determining radiated fields from a known current distribution is presented, which is utilized in the next module.

Antenna Principles Module
This section describes the development of the core concepts of the antennas discipline. Electromagnetic radiation from accelerated charges enables students to visualize the basic radiation mechanism. It is important to ground this concept in a physical picture for students because the magnetic vector potential analysis does not explicitly reveal this aspect. A qualitative, relativistic explanation of electromagnetic radiation from an accelerating charge is utilized, some of which is a review from the prerequisite courses. The Poynting vector is reviewed and is used to qualitatively interpret electromagnetic power flow away from the accelerated charge, including why the radiated power density is maximum in a plane perpendicular to the current direction.

Once the physical reasoning for electromagnetic radiation is established, the classic infinitesimal dipole is presented and is utilized as the vehicle to establish the concepts in this pedagogy. The magnetic vector potential is applied to rigorously derive the radiated electric and magnetic fields. The concept of near- and far-field regions for an antenna is introduced, and an examination of the electric and magnetic field components and their radial dependencies allows them to be sorted into each category. Furthermore, the far-field components are "discovered" to contain in-phase, orthogonal electric and magnetic fields which represent power flow away from the antenna. The plane wave and Poynting vector concepts are again reinforced. A similar approach is used to explain reactive fields in the near field. The shape of the far-field electric field pattern is plotted in three dimensional (3D) as well as two dimensional (2D) patterns, exposing the classic donut-shaped pattern. Linear antenna polarization is defined and related to the orientation of the antenna element.

The radiation resistance concept is then introduced with an analogy to the characteristic impedance of a T-line and is derived from radiated field expressions. The relationship between radiation resistance and antenna size is developed and interpreted. Additionally, EMI principles are reinforced by applying the radiation resistance concept to a printed circuit board trace.

Next, antenna directivity, gain, and effective area are developed in a customary manner. Several interpretations are examined to develop insight into these concepts. Antenna efficiency is established in terms of the conductor and dielectric losses, per the IEEE definition of antenna efficiency[6]. A distinction is made between the IEEE definition of Gain[6] (noted here as G_{IEEE}) and what is often termed "Realized Gain" (noted here as $G_{Realized}$), the latter of which treats mismatch reflections at the input to the antenna as part of the efficiency term. These two definitions are essential to interpreting antenna specifications and performance. The practicality of Realized Gain is demonstrated for the infinitesimal dipole which has a reasonable G_{IEEE} but an extremely low $G_{Realized}$ due to mismatch (assuming no external matching network). This foundation in antenna fundamentals is applied in the next module to practical antennas and system-level considerations.

Select Antenna Applications Module

The infinitesimal dipole is an excellent pedagogic and conceptual tool, but it is not practical by itself. The finite length of practical dipole antennas requires a modified treatment. Students often attempt to apply the infinitesimal radiation resistance equation to a half wavelength dipole and calculate resistances much higher than the typical 73 Ω (shown via simulation by the instructor). Student groups are formed to discuss the reason for the failure of this equation, arriving at the distinction between the cosine-shaped simulated current distribution of a practical dipole and the constant current distribution of the infinitesimal dipole. This result motivates the need for a new model: the cosine-weighted current distribution along a linear arrangement of infinitesimal dipoles. This concept is vital because 1) it provides insight into how the Method of Moments (MOM) Numerical Electromagnetics Code (NEC) computational software, which is used later in the course, discretizes a structure and solves for the total fields, 2) it reinforces distributed charge/current distributions previously used in Coulomb's and Biot-Savart laws, and 3) it previews the array factor concept discussed later in the course. Directivity and radiation resistance are examined numerically for various dipole lengths. The general dipole field expressions are then simplified to those of the half-wavelength dipole. The maximum directivity and the radiation patterns are analyzed. Integration of the Poynting vector to determine the total radiated power is used to confirm a radiation resistance of 73 Ω. The half-wave dipole reactance calculation is beyond the scope of the course, so the reactance is given (+*j*43.5 Ω, as used in the next topic) as a consequence of the reactive fields.

Impedance matching is not addressed in detail in this course, but the half-wave dipole offers an opportunity to introduce the matching concept via simple reactive impedance matching. An appropriately sized series capacitor is shown to cancel out the inductive reactance (+*j*43.5 Ω) at a given frequency, thus minimizing reflections. The impact of matching on realized gain and resonant frequency is determined. At this point, a simulation is used to demonstrate that a five-to-ten percent shorter dipole length shifts the actual antenna resonant frequency up to the desired center frequency. A quarter-wave transformer matching circuit is briefly analyzed (not designed) to illustrate a more sophisticated matching approach with the intent to promote awareness and motivation for matching techniques.

The frequency dependence of the input impedance of a dipole is examined next. A series RLC circuit is used to model dipole impedance in the vicinity of the first resonance. This circuit is analyzed by relating the students' circuit analysis background in filters to the frequency response of the antenna impedance. The circuit parameters of bandwidth, quality factor (Q), and voltage standing wave ratio (VSWR) are applied. In particular, the Q is used to relate the loss (efficiency) of the antenna to the bandwidth, emphasizing the trade-off between antenna gain and bandwidth for a fixed-size antenna. An analogy to the the gain-bandwidth product of an amplifier is made. The inverse relationship between antenna Q and the volume of the antenna is established and related to the achievable bandwidth and gain. A discussion follows on the implications for modern devices; for example, this tradeoff explains why antennas have not experienced the same miniaturization that has been achieved in electronic devices.

Finally, the feed to a dipole antenna is addressed. The inadequacy of a direct connection between coaxial cable and the dipole antenna is established by demonstrating that current also flows on the *outside* of the *outer* shield (a third current path!), producing radiation from the shield, as well as the resultant imbalance of dipole currents. The distinction is made between balanced and unbalanced electromagnetic structures, and baluns are introduced to interface them. A basic bazooka balun is analyzed to demonstrate one way in which current flow on the shield is mitigated. A few other common balun structures are surveyed to provide an awareness-level exposure.

The dipole antenna is next extended to the case of a monopole antenna. This common unbalanced structure is related to antennas on car hoods and telescoping whip antennas on walki-talkies and portable radios. Initially, basic image theory is developed and then applied to a single dipole arm (quarter wavelength) driven against the ground plane. The input impedance is shown to be half of that of a free space dipole. Practical implementations and trade-offs between dipoles and monopoles are discussed. The next logical question is posed: what happens to the pattern of a dipole when placed over a ground plane? Image theory is used to analyze this general case, and the resulting directivity pattern is shown to be a strong function of distance above the ground plane, especially the nulls and lobes. The interference between the actual and image currents elucidates the key concept that antennas are affected significantly by their environment and that proper antenna placement on a platform is critical to achieving the desired performance. Finally, the actual and image currents are recognized as forming a two-element antenna array, and thus the same directivity expression can be applied to two antennas arranged as a uniform array in free space. This result is generalized to an arbitrary number of antenna elements arranged in a linear array. The array factor for the generalized case is compared to the previous analysis of finite length dipoles. Radar and next generation WiFi antenna array examples are briefly discussed.

The course proceeds into how antennas are used in links. The Friis transmission equation is developed using the effective antenna area concept and modified to include polarization mismatch via the polarization loss factor (PLF). Examples of basic links, such as for broadcast FM radio, cell phone, and satellite communications, are analyzed. Emphasis is placed on how the gain pattern and the polarization alignment of the transmit and receive antennas affect link performance. The ground effect previously analyzed is used to show the impact of multipath and fading on a system. Practical examples are used to relate these concepts to the everyday experience of the students.

By the latter part of this course, students realize that modern antenna practice relies on the use of numerical simulations to design and predict the performance of antennas. One lecture near the end of the course is devoted to introducing a freely available antenna simulation software 4NEC2[7], based upon the NEC2 engine, an MOM solver. MOM is only discussed conceptually, without any rigorous math. Instead, insights into the setup and operation of MOM are emphasized. A dipole is partitioned into segments, that is, discretized, to show the antenna geometry format used in this software. An analogy is made to the sampling of signals in the time domain. The previous analysis of the finite length dipoles, that is, the summation of infinitesimal dipoles, is related to the overall operation of the software. Although this conceptualization does not consider the interaction/coupling between the segments, it still provides a context for the method and provides justification for careful discretization of the antenna. The class is guided through the construction of a simple half-wavelength dipole model and a simulation of radiation patterns, currents, and impedance and VSWR over a frequency band.

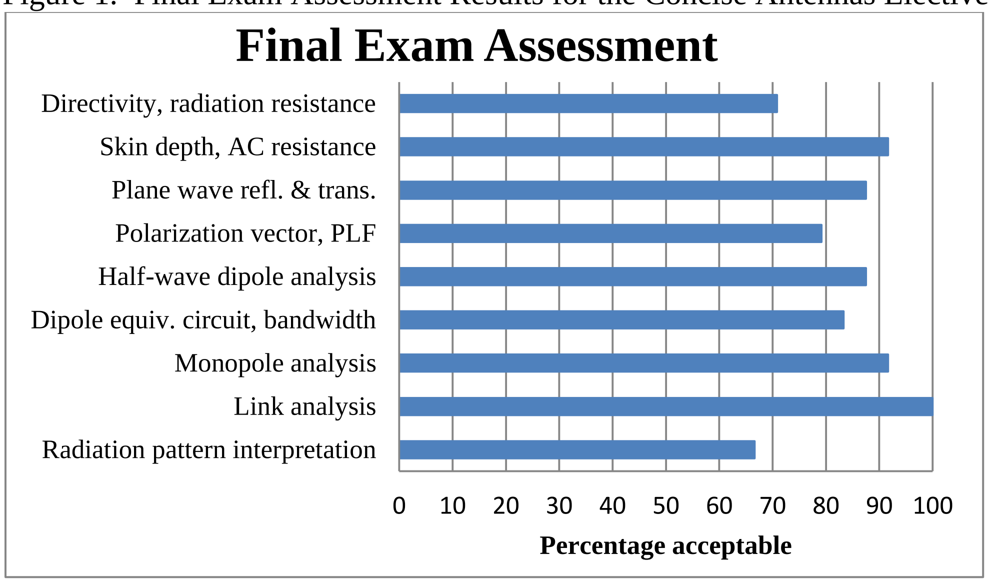
For the simulation project, students analyzed a five element Yagi-Uda array that resides in our laboratory at a center frequency of 300 MHz. This antenna was chosen for ease of simulation, because it is reasonably sized, and the students could physically inspect it. The project focuses on gaining experience using electromagnetic simulation tools and investigating the behavior of the Yagi array. Students initially simulate the Yagi element-by-element: start with a dipole, create a folded dipole, add a reflector, and then add each director one-by-one. The antenna is analyzed at each step so that students see the impact of each element and use physical reasoning to explain the evolution of the radiation pattern. The final antenna is analyzed to determine the gain pattern (full 3D as well as E- and H-plane cuts), beamwidths in each plane, the front-to-back (FBR) ratio, and impedance and VSWR versus frequency. Students were encouraged to experiment with the model parameters. For example, one student investigated the impact of random element misalignments due to fabrication tolerances.

The actual Yagi antenna performance was demonstrated to the class using a simple software-define-radio (SDR) as the transmit/receive test-set. First, the Yagi was pointed directly at the transmit whip antenna and oriented to align the polarizations of the two antennas. The peak signal was measured. The Yagi was then pointed away from the transmitter while maintaining polarization alignment, and the signal was shown to drop more than 25 dB, indicating a significant FBR. Secondly, the Yagi was pointed at the transmitter whip, only now the Yagi was slowly rotated around its axis until the Yagi polarization was orthogonal to the polarization of the transmit antenna. Students directly observed the drop in signal as the polarizations became increasingly misaligned.

IV. Discussion

This course was run for the first time during the 2014-15 academic year. Course demand exceeded the maximum enrollment capacity (limited to 24), indicating substantial student interest in the topic. Students were highly engaged throughout the course, actively asking questions and commenting on how the course material helped explain phenomena from their daily lives. Notably, many students went above and beyond the requirements of the simulation project with extra experimentation. This engagement was reflected in the final exam scores (average grade of AB), which demonstrated successful accomplishment of the course learning outcomes. Figure 1 shows the assessment results of the final exam, which consisted of nine questions in various key topical areas. Two-thirds or more of the answers were acceptable (minor errors at the most) on each question. Table 4 shows the results of a class survey (1 = lowest, 5 = highest). Clearly the vast majority valued this concise antennas elective and feel prepared for continued antenna studies in their careers.

Figure 1. Final Exam Assessment Results for the Concise Antennas Elective



Some aspects of this elective could be improved. A few of the theoretical developments, such as the derivation of fields using the magnetic vector potential, need to be streamlined. Making more use of derivation handouts with gaps and leaving some details as homework assignments would open time that could be spent on other topics and would further promote development of the mathematical capabilities of the students. Assigning a simple simulation project earlier in the term to familiarize students with the NEC2 software would enhance progress by the time of the Yagi simulation project. Finally, more demonstrations in lecture would also be beneficial to many of the students. One key demonstration planned for future offerings is to measure antenna impedance on a vector network analyzer in order to determine the bandwidth from the impedance response and to show how the antenna environment affects the impedance response.

Table 4. Class Survey Results for the Concise Antennas Elective
(Scoring: 1 = lowest, 5 = highest)

Survey Question	Avg.
1.) How well did this antennas elective reinforce the concepts from the required prerequisite electromagnetics courses?	4.67
2.) How well did this antennas elective increase your awareness of antenna applications in electrical engineering?	4.67
3.) Do you feel prepared for continued studies, either formally or informally, in antennas?	4.58
4.) Would you take a second antennas elective if offered and your schedule permitted?	4.75
5.) What educational value would you place on the simulation project in integrating the concepts from the antennas elective?	4.58

V. Conclusion

A concise antennas elective that builds a solid conceptual antennas foundation appropriate for students who enter industry as well as for students who pursue graduate studies was presented. This course is innovative in that it is achieved in three quarter-credits over a ten lecture-week quarter and with only a modest four semester-credit equivalent prerequisite electromagnetics background. Careful modulation of topical breadth and depth is essential to establishing the core antenna principles within the time constraint and with a sound pedagogical progression. The course is comprised of three modules: an electromagnetics module where advanced concepts not covered in the prerequisite courses are developed; an antennas principles module where gain, directivity, radiation resistance and so forth are developed; and an antenna applications module where the fundamental electromagnetic principles are extended to practical antennas such as half-wave dipoles, quarter-wave monopoles, and where the Friis transmission equation is applied to common system links. The elective ran for the first time in the 2014-15 academic year. Students were highly engaged throughout the course and were particularly interested in how course material helped explain phenomena from their daily experiences. Notably, many students exceeded the requirements of the simulation project with extra experimentation. The student engagement was apparent in the final exam scores, which clearly demonstrated meeting course learning outcomes. Encouragingly, a survey indicated that this elective was valued, that it enhanced student interest in electromagnetics, and that many students planned further study through other electromagnetic electives. Overall, this concise antennas elective met the course learning outcomes within the time and prerequisite constraints.

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