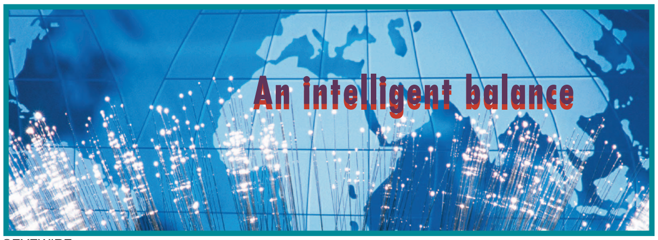

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and
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Today's technical challenges posed by system complexities require a range of multi-disciplinary, physics-based, problem-matched analytical and computational skills. Skills not adequately covered in conventional electronics and communication (EC) engineering curricula. Physics-based modeling, observation-based parameterization, computer-based simulations and code verification against canonical problems (i.e., exactness and numerically computable formulations) are the key issues of these challenges.

So "*what makes a modern engineer?*" As phrased by Einstein—*in the matter of physics, first lessons should contain nothing but what is experimental and interesting to see*—experimentation and hands-on training are essential at least at the undergraduate level. On the other hand, with new computer technologies, interactive multimedia programming languages (e.g. JAVA), and the World Wide Web, it is now possible to simulate engineering and science laboratory projects of all sorts on a computer all around the world. Experimental-oriented problems can be offered without incurring the overhead of maintaining a full laboratory.

Thus, the question arises: should an intelligent balance be established between real and virtual experimentations and how? Another similar problem is the balance between teaching essentials (theory) and cranking the gear (blind computer applications). The motto "*I did it, it works*" seems to be widespread among students, who, however, have not really grasped the general principles and boundaries of validity of the underlying phenomena. What is even worse is the accompanying false sense of satisfaction.

Engineering education

Engineering, as defined by the American Society for Engineering Education, is "*the art of applying scientific and mathematical principles, experience, judgment, and common sense to make things that benefit people.*" That is, it is the process of producing a technical product or system to meet a specific need in a society.

Engineering education is a university education, through which knowledge of *mathematics* and *natural sciences* are gained, followed up by a lifetime self-education where *experience* is piled up with *practice*. Therefore, the four key words *mathematics, physics, experience* and *practice* are the "untouchables" of engineering education.

Many applications in science and technology rely increasingly on Field Theory and Circuit Theory computations in either man-made or natural complex structures. Wireless communication systems, for example, pose challenging problems in regards to field propagation prediction, microwave hardware design, compatibility issues, biological hazards and so forth. Nanotechnologies, on the other hand, have challenges of locating multi-million circuit elements and sub-systems on a few square centimeter chips, with very low emissions and be immune to environmental interference.

Moreover, the need to and use of these theories is not limited to EC applications; they are exploited in a very wide spectrum ranging from biomedical to geophysical applications. Since different problems have their own combinations of geometrical features and scales, frequency ranges, material properties, etcetera, no single method or approach is best for handling all possible cases. Instead, a combination of methods or "hybridization" is needed to attain the greatest flexibility and efficiency in engineering. Relations between field theory and network theory play an important role in this respect.

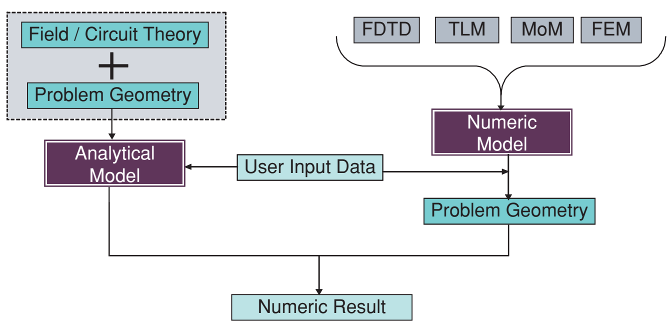

Fig. 1 Analytical- and numerical-based modeling (FDTD: Finite-difference time-domain, TLM: Transmission line matrix, MoM: Method of moments, FEM: Finite-element method) Distinguishing difference is the inclusion of a problem geometry at hand.

The observation that hybrid methods are needed is nothing new. For example, in scattering and antenna problems, techniques have been devised that combine the Method of Moments (MoM) and the geometrical theory of diffraction (GTD) or physical optics (PO). Similarly, numerical methods such as finite elements (FEM) or finite differences have been considered in conjunction with MoM, with integral equations, with boundary integrals, with modal techniques, with multipole methods, etc. Combinations of other methods, e.g. boundary-contour and mode-matching or hybrid electric field integral equations (EFIE) and magnetic field integral equations (MFIE) denoted as HEM, have also been proposed. This list of contributions, though necessarily incomplete, indicates that this topic is of considerable interest.

Physics-based modeling and observable-based (measurable) parameterization are very important in EC engineering and, hence, in EC education. The models that are established via well-known Maxwell equations (field theory) and transmission line equations (circuit theory) in both time and frequency domains parameterize a complex physical problem as a well-defined problem that guarantees existence, uniqueness of and convergence to solutions. Field and circuit theories are dual; that is, any field problem (e.g., antenna radiation) can be transformed into a circuit theory problem and solved there (or vice versa). Starting after World War II, circuit formulations of field problems have also been employed extensively in the design of microwave, optical and other closed and open *waveguiding* and *radiating* systems.

Also, as the count of active IC devices exceeds several tens of millions and the number of interconnects among these devices grows super-linearly with this count, efficient evaluation of time delays and signal integrity becomes more difficult and important. To give a flavor, devices with operating frequencies exceeding 100 GHz have been reported. Today, circuits contain millions of transistors per unit area (Intel

Pentium 42-55 Million) as opposed to the 1970s SPICE targeted software for circuits with a few hundreds transistors. Hence, the need arises for a new generation of simulators with improved numerical methods using, if possible, analytic solution techniques to handle very large circuits."

Engineering as defined previously is based on *practice*. A minimum amount of this practice should take place during the EC education. However, the cost to keep up in lab equipment, with the increasingly complex and rapidly developing high-technology devices, becomes unaffordable. Computers, other microprocessor-based devices (e.g., robots, telecom, telemedicine devices, automatic control/ command/ surveillance systems, etc.) and Programmable Systems on Chip (PSoC) make EC engineering education not only very complex and costly but interdisciplinary as well.

The cost of building undergraduate labs in EC may vary from 1 unit to 10^5 units; e.g. a spectrum or a network analyzer may cost a few 10^4 units whereas a simple software of 1 unit with or without the addition of specific cards costing 10^2 units may turn a regular personal computer (PC) into a virtual lab. Consequentially, EC engineering academia is constantly faced with the dilemma of establishing a balance between virtual and real labs, so as to optimize cost problems, while graduating sophisticated engineers with enough practice.

Doing numerical simulations in EC engineering has become as easy (as well as difficult) as doing measurements. It is easy because one can purchase commercial codes that do almost everything, like supplying computer-controlled devices for measurements. The simulation packages are user-friendly, have self-checking routines for control and all can be calibrated, like most of high-tech measurement devices. On the other hand, all the efforts of simulation can be in vain if one doesn't know how to interpret the resulting numbers. Moreover, important concepts such as *accuracy*, *precision* and *resolution*—in short, the *underlying theory*—should be well understood by engineers.

The Gibb's phenomenon that states (roughly) that "*a finite Fourier sum approximating a discontinuous function will not yield the function's value in a neighborhood of the discontinuity point*" is an example in case. Two researchers unaware of Gibb's phenomenon dismissed their well-developed simulator because of the mismatch around the discontinuity point.

Modeling, simulation vs. experimentation

Understanding EC engineering is important if we desire to manufacture less interfering, less susceptible and more compatible products. Therefore, physics-based modeling and observable-based parameterization are essential.

Maxwell's well-known equations establish the physics of EC engineering, well-define the interaction of electromagnetic waves with matter, and form the basis for a real understanding of EC problems and their solutions. Moreover, circuit theory equations are also derived from Maxwell equations. There are two different solution approaches: analytical formulations and numerical simulation methods. Analytical and numerical model-based approaches are schematized in Fig.1.

The model is derived from Maxwell's equations under a given problem geometry (i.e. for a given boundary conditions and medium parameters) for the analytical model-based approach. These models express solutions for independent variables, such as electric and magnetic field components or input-output voltages and currents, in terms of analytic functions (such as Sine or Cosine functions, Bessel and/or Hankel Series, etc.). A computer program is required only to calculate an output value for a given input supplied by the user.

On the other hand, the principal algorithm models the intrinsic behavior of fields/circuits without reference to specific boundary and material configurations. Some well-known and widely used numerical approaches are also listed in the figure. The generic *numerical model* is applied from the *very beginning* and is augmented by boundary simulators and/or other peripheral units, such as near-field far-field transformations. Different problems (with respect to geometry and medium parameters) can be accommodated using such models.

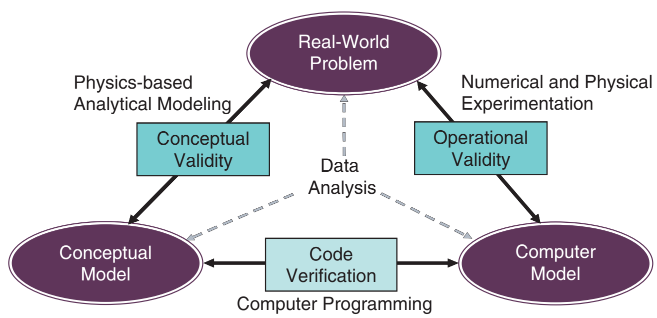

Fig. 2 Fundamental building blocks of a computer simulation

Whether analytical or numerical, models need to be coded for calculations on a computer. While the model used in analytical solutions is constructed according to the geometry of the problem (i.e., boundary conditions and medium parameters), the numerical model is general and the geometry of the problem (together with the input parameters) is supplied after the model is built. That is, the boundary and/or initial conditions are supplied externally to the numerical model together with the medium parameters, operating frequency, signal bandwidth and so forth. Once they are specified, simulations are run and sets of observable-based output parameters are computed for a given set of input parameters.

Modeling and simulation is the most effective, if not the only way to solve, complex electromagnetic problems whose analytical solutions cannot be obtained or are yet unavailable. With today's high-capacity, high-speed computers, powerful numerical simulation tools have been developed and successfully applied to a broad range of physical (practical) problems. EC engineering problems are among these problems.

The same holds true in modeling and simulating electronic integrated circuits. Here analytical solutions are impossible considering the millions of nonlinear devices embedded into a linear circuitry. Methods listed in Fig. 1, such as the FDTD, TLM, FEM, MoM or Model Order Reduction, Piecewise Linear and Spline approximations have become almost the most valuable tools in EC engineering.

Simulation in EC engineering usually refers to the process of representing the dynamical behavior of a "real" system in terms of the behavior of an idealized, more manageable, model system implemented through computation via a simulator. The fundamental building blocks of a simulation comprise the real-world problem entity being simulated, a conceptual model representation of that entity, and the computer model implementation of the conceptual model according to N. Ince (see Fig. 2). The suitability of

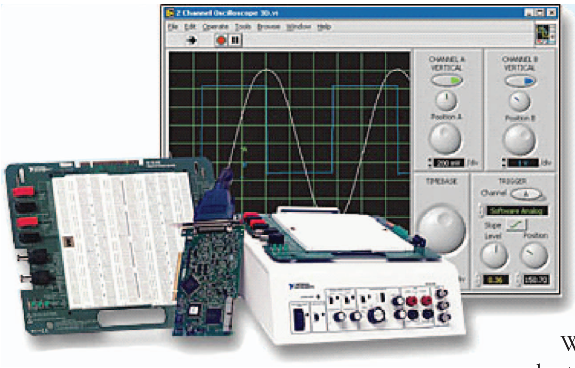

Fig. 3 A novel lab experimental setup NI-ELVIS (a DAC card for a PC)

the conceptual model, verification of the software and data validity must be addressed to make a model *credible*.

Credibility (accreditation) resides on two important checks that must be made in every simulation: *validation* and *verification*. Validation is the process of determining that *the right model is bu*ilt, whereas verification is designed to see if *the model is built right*.

Validation, verification and accreditation (VV&A) in EC simulations is important but so is the interpretation of the results. Analytical and numerical modeling can easily lead to non-physical results or to results beyond their range of validity of the chosen model, hence the issue of "*models being local*." Bluntly stated, "*no model is global*" in the sense that it represents the underlying physical phenomena for a certain observation period (locality in time), for a range of values of its variables (locality in operation), for certain atmospheric conditions (locality in space) etc. It is the primary duty of an EC engineer to choose the suitable local model.

It should be remembered that, every numerical simulation contains in addition to the solution of the correctly represented physical process, errors caused by: the numerical method itself, simplification of the physical structure, machine computation limitations and so forth. It is a challenge to establish a confidence in the results of numerical simulations. As a result, it is after this final step that solid *background knowledge, experience, judgment,* and *common sense* are needed the most in order to pass judgment on the results.

Novel approaches

EC—which lies in the foundation of many different scientific disciplines—occupies a special place in engineering. The interdisciplinary character of EC engineering requires new approaches to educate the *modern* engineer. As pointed out by L.B. Felsen:

"*to teach the necessary analytic underpinnings to a generation of students that has grown up with computers— commonly believing that computers, as such, solve complex problems, and that the printouts furnish physical insight— is a challenge to the academic community*."

With what and to what extent a student will be equipped "*to know and to do*" should be specified according to the rapid shifts in societal needs. EC engineering at Dogus University is a newly founded department that is establishing undergraduate as well as graduate level labs. It is an extremely hard optimization problem to establish low cost, highly effective labs that provide the rich spectrum of experimentation as required for EC students. The introductory level labs are standard and no serious problems were encountered in establishing them. On the other hand, for the higher level labs, after serious investigation, optimization resulted in favor of the newly developed National Instrument set, Educational Lab Virtual Instrumentation Suit (NI-ELVIS) which is shown in Fig. 3.

NI-ELVIS consists of LabVIEW-based virtual instruments, a multifunction data acquisition device and a custom-designed benchtop workstation and a prototyping board. This combination provides a ready-to-use suite of instruments found in regular educational laboratories. Because it is based on LabVIEW and provides complete data acquisition and prototyping capabilities, the system is "good" for simple experimentations, for hands-on training and academic courses from lower-division classes to advanced project-based ones. The major difficulty in using NI-ELVIS (or similar setups) is to prepare suitable experiments that balance analog parts for the benchtop workstation prototyping board against the digital operation in the connected computer.

An example is given with Fig. 4; a virtual instrument (*vi*) file showing the outcome of a Double Side Band (DSB) modulation experiment in analog communication; implementation of the DSB modulator is given with the block diagram in Fig. 5.

Obviously, this experiment can totally be done virtually without using the benchtop workstation prototyping board. If such is the aim, than NI-ELVIS sets are not a requirement since Matlab can do everything LabView does; it is sufficient to buy a student version of multi-user Matlab package and perform every experiment virtually on the computers. The superiority of LabView, coupled with NI-ELVIS, lies in the availability of high efficiency and high cost data acquisition cards. They make possible sophisticated research experimentation and advanced industrial developments and applications.

NI-ELVIS based labs included in the curricula also necessitates introductory lectures such as *Numerical Analysis*, *Engineering Statistics*, and *Stochastic Processes* in the first few semesters. These classes should be taught as complementary software courses. Matlab has become a very effective and student-friendly package for these purposes. Since LabView also recognizes Matlab scripts, the library of Matlab scripts that are developed by the students may serve as excellent tools in their future studies and/or research.

Prospective EC engineers should be taught to question their results at each step of either experimental or numerical studies. They should pose and answer questions such as:

- What am I going to do with the data collected in my experiment?
- What outcomes should I have expected before the experiment?
- What do the data mean?

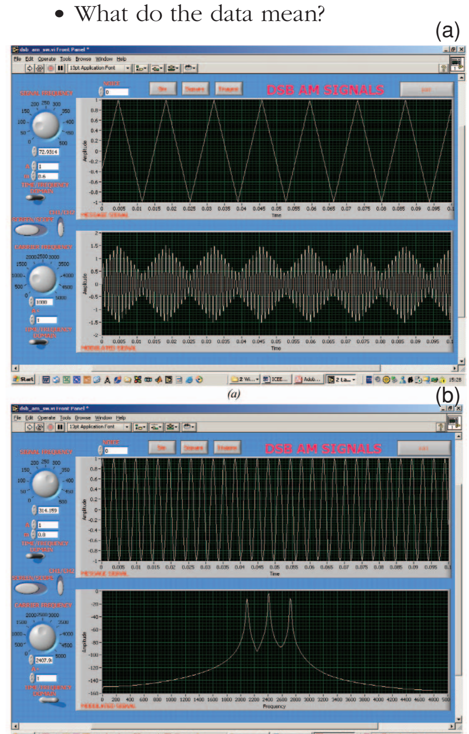

Fig. 4 Virtual instrument designed for DSB modulator (a) modulated signal in time domain, (b) modulated signal in frequency domain

- How do I check my results? Are they in the validity region of my model?
- What physical conclusions should I derive?

Final thoughts

The explosive growth of computer capabilities and the easy access to nano-miniature devices have revolutionized communication and the analysis of complex systems. The computer has made interdisciplinary exposure necessary in modern engineering. The EC engineer, either individually or as member of a team, can play an important role in this technically diverse mosaic. Rapid scientific advances, followed by fast changes in technologies, are here to stay. The engineering community must be prepared to adapt to frequent shifts in technical priorities. "*EC engineers must reeducate themselves at least to the equivalent of earning four B. Sc. degrees throughout their careers*" is the simplest and the only principle to adopt. Those who do not feel up to the challenge should seriously reconsider to opt for a new line of work.

EC engineers should also understand the physics of the problem, the fundamental theorems (which requires strong knowledge of mathematics) and the principles they are dealing with,

- Hands-on practice and training is a must in EC engineering education. Although, labs and test instruments have been simulated as virtual reality environments, which may be as good as the real environment, students still need hands-on training.
- Basic lectures, such as "measurement techniques" should be improved accordingly.
- Computer simulations are as necessary as hands-on training; therefore, modeling and simulation lectures should be included in EC programs.
- Practical EC problems usually do not agree with our expectations. The most dangerous case may occur when the results of the measurement or simulation agree with what is expected (i.e., what is deduced from incomplete knowledge). Therefore, an EC engineer should never be sure of the results until all critical tests are successfully passed.
- EC (especially biomedical) engineers become more publicized in parallel to the exponential growth in wireless communication. They may attend public meetings, regional activities and be confronted with questions related to safety, e.g. about mobile phones, base stations, etc. Therefore, lectures like "Science Technology and Society," or "Public Understanding of Science" should be included as part of the EC engineering curricula.

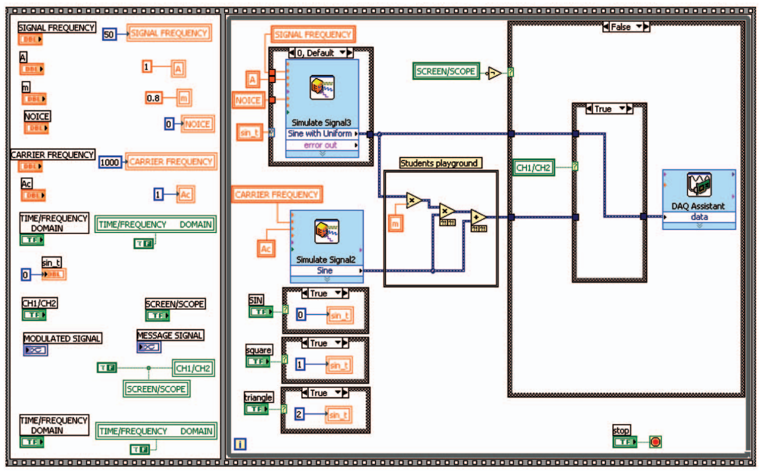

Fig. 5 Block Diagram implementation of a DSB Modulator

Read more about it

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