CHAPTER 1

Introduction to MODSIM

Today's technical challenges posed by system complexities require a range of multidisciplinary, physics-based, problem-matched analytical and computational skills [1]. In electrical engineering (EE), real-life systems (from nanoscale to kilometer-wide) are among the most complex ones and almost totally involved in electromagnetics (EMs). EM theory is well established with Maxwell's equations but teaching/lecturing is always a challenge. Experimentation and hands-on measurement are the fundamentals of EM engineering education; however, strong theoretical background and numerical simulations are also essential. An intelligent approach is to use physics-based modeling, hands-on training, numerical-based modeling, and computer simulations all together.

Computer simulations, either in-house prepared or commercially available, have been effectively used in EMs. Key issues are model validation, code verification, and calibration (VV&C) and physical interpretation of the numbers obtained. The four critical words are *mathematics*, *physics*, *experience*, and *practice* [1]. A good EM modeling and simulation (EM-MODSIM) course should cover them all. Note that despite a correctly presented physical model, numerical simulation of the model contains errors caused by the numerical method itself, simplification of the physical structure, assumptions made there,

Electromagnetic Modeling and Simulation, First Edition. Levent Sevgi.

machine computation limitations, and so forth. It is a challenge to establish a confidence in the results of numerical simulations.

Numerical models can be viewed differently from the developer's and the user's perspectives [2]. Developers, in addition to their concern about accuracy, cost/competition, and user friendly graphical user interface (GUI) design, deal primarily with the conceptual suitability and implementational steps of the code (verification), while the users are more involved in computation and application. Both are concerned with validation, although users are often tempted to apply code in a manner that it is not designed for, thus making validation an especially a sensitive topic. From the developer's perspective, the process of developing a numerical model involves conceptualization, formulation, numerical implementation, computation, and validation. On the other hand, the user's perspective involves the problem, that is, choosing a problem-matched approach and the application steps. A developer needs to know how the code works, but the user needs to know what it can do.

The fair metrics in characterization and comparison of numerical simulators are accuracy, reliability, efficiency, and, finally, applicability. Someone who deals with numerical simulation is in a quite similar position to that of an experimenter. They both need to understand requirements for their particular problem in terms of basic EM phenomena, but both also need to depend on complex tools that they did not design in order to accomplish their particular goals.

1.1 MODELS AND MODELING

When not measuring or soldering, engineers continuously deal with models when analyzing, designing, and implementing [1–3]. The two phases in modeling are *utilization* and *creation*. The utilization is common practice and does not necessitate further comment other than "make the right choice and use the model carefully." The creation phase requires delicate measurements, extreme perception, and/or excellent imagination.

Maxwell's well-known equations establish the physics of EE, well define the interaction of electromagnetic waves with matter, and form the basis for a real understanding of EE problems and their solutions. Moreover, circuit theory equations are also derived from Maxwell's

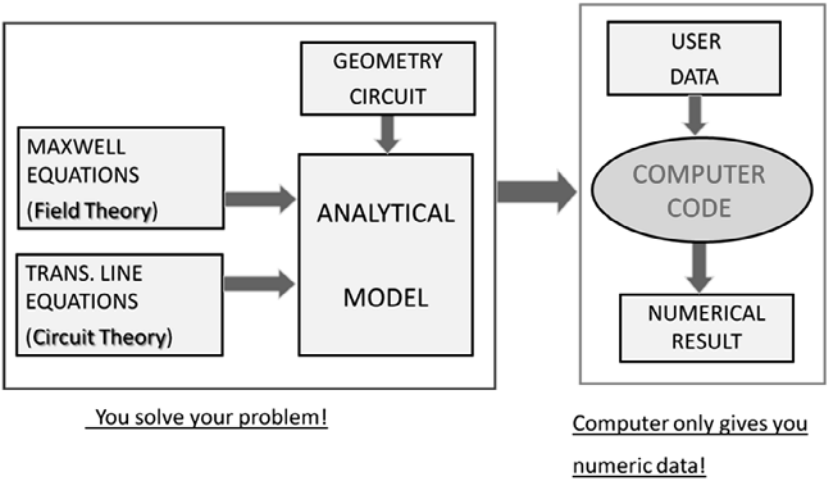

Figure 1.1. Analytical-based modeling.

equations. There are two different solution approaches: analytical formulations and direct numerical simulation methods. Analytical and numerical model-based approaches are schematized in Fig. 1.1 and Fig. 1.2, respectively. The key difference between these two is the placement of problem geometry (i.e., boundary conditions [BCs]). Analytical-based approaches are problem (geometry) dependent. Once geometry changes, the problem has to be resolved. On the other hand, numerical-based approaches are problem (geometry) independent.

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/cosine functions, Bessel/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*

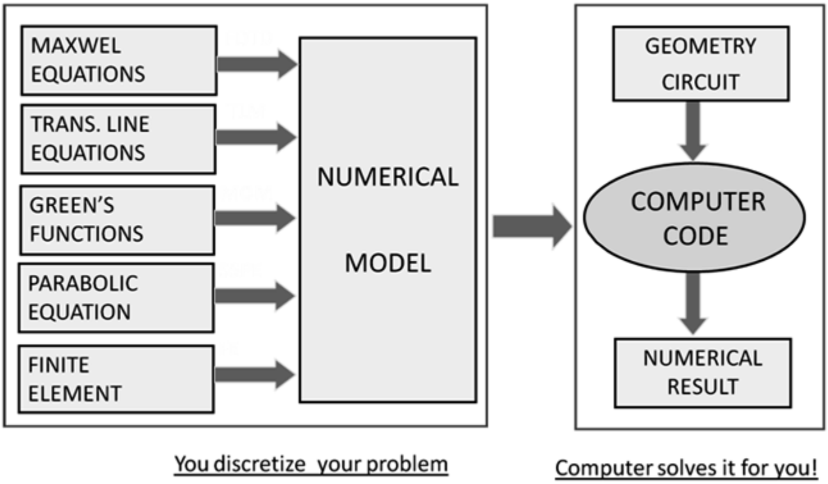

Figure 1.2. Numerical-based modeling.

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.

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.

So the challenging question for an engineer becomes "which model to use, when?" No easy answer exist other than "experience." One may wonder, "why not use the most sophisticated one?" The simple reply is that, to use a more complex model than needed may consume huge amount of computation time and, more importantly, obscure the insight to the problem.

1.2 VALIDATION, VERIFICATION, AND CALIBRATION

Engineers, when analyzing, designing, calculating, simulating, and so on, always use models. The crucial point here is to choose the right model for the physical problem under consideration. The same physical problem may be assigned different models, with increasing order of complexity, depending on the conditions.

EM-MODSIM requires high performance computing, applied mathematics and physics, intelligent systems, and information technologies. It is a relatively novel and cost-effective way of solving complex EM problems beyond the reach of analytical methods, and the outcome is powerful software packages and virtual tools for the students, lecturers, researchers, and scientists.

EM-MODSIM requires basic understanding of fundamental concepts such as modeling, analytical solution, numerical solution, analytical- and numerical-based modeling, simulation, model validation, code verification through canonical tests/comparisons, accreditation, and so on (see Fig. 1.3 for the fundamental building blocks and interrelations [4]).

EM MODSIM is extremely valuable in engineering if based on physics-based modeling and observable-based parameterization. It starts with the definition of a real-life problem. Its conceptual model is the basic theory behind the real-world problem. Maxwell's equations establish the mathematical model for field theory, define the interaction of EM waves with matter, and form the foundation for a real understanding of electrical problems and their solutions. All of the frequency and time-domain methods use either differential or integral form of Maxwell's equations.

A generic chart of EM-MODSIM is pictured in Fig. 1.4. A real-world engineering problem is first represented by a conceptual (mathematical or not) model and then is implemented in the discrete world with a computer code. The code may be augmented some numerical analysis methods, such as root search, numerical differentiation or

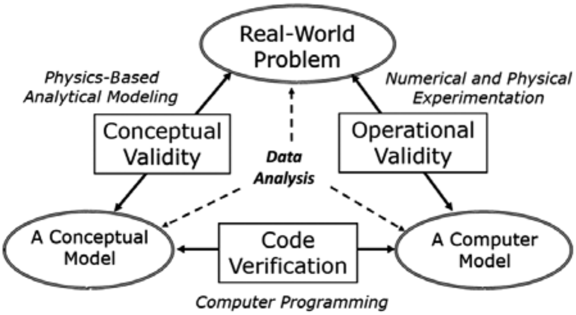

Figure 1.3. Fundamental blocks of numerical MODSIM.

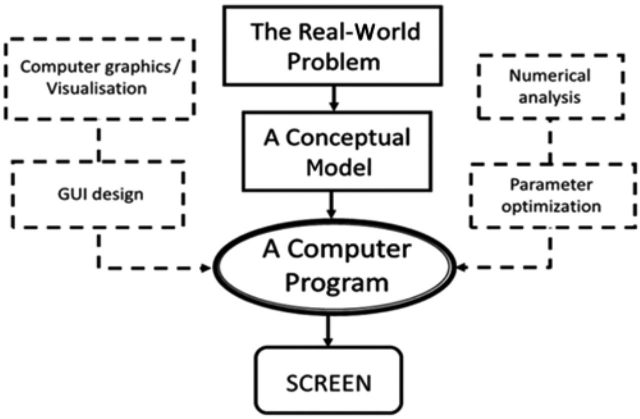

Figure 1.4. A generic chart of EM-MODSIM.

integration, solving systems of equations with a huge number of unknowns, etc., and some optimization algorithms. Visualization capabilities may also be inserted and a GUI can be designed.

EM scattering problems may be categorized under three groups: (1) antenna and radiation problems, (2) scattering and radar cross-section (RCS) problems, and (3) guided wave problems. All these are represented by Maxwell's equations with proper BCs. The solution then exists and is unique.

Antenna and radiation problems can better be handled via auxiliary vector potential functions since these functions perfectly matched with the excitation. In scattering and RCS problems, one needs to separate total EM fields into incident and scattered components. The word scattering includes reflections, refractions, and diffractions. The first two are primary effects and diffraction usually can be neglected in the presence of former two. In shadow regions, only diffracted fields contribute. Therefore, edges and/or tips necessitate special treatment. Finally, guided wave problems should be decomposed into transverse and longitudinal components prior to searching a solution. In this context, Sturm–Liouville equation and interrelations plotted in fig. 7.3 of Chapter 7 must be well understood.

Model calibration is performed through a VV&C procedure. This may be achieved via the following:

- tests and comparisons against analytical reference data
- tests and comparisons between numerical solution
- real-world measurements.

all of which are extremely challenging. Analytical exact solution does not necessarily mean analytic reference data; it necessitates accurate numerical computations. Comparisons among different numerical models may yield almost perfect agreement, but they may all be incorrect if used beyond their range of validity.

1.3 AVAILABLE CORE MODELS

Well-known and widely used EM-MODSIM models are FEM, MoM, PE, FDTD, and TLM. An EM-MODSIM course should touch upon all.

Finite element model (FEM) [5] is used for finding approximate numerical solutions mostly to partial differential equations (PDEs) and rarely integral equations. FEM discretizes the solution region of a problem into a finite number of subregions or elements, derive the governing equations for a typical element, assemble all elements in the solution region, and solve the system of equations obtained for a given BC. Its been widely used in electromagnetic, fluid dynamics, structural mechanics, civil engineering, and so on. FEM's capability in handling complicated geometries (and boundaries) is very high. The main difficulty encountered in FEM is element generation; therefore, special mesh generators have been developed for this purpose.

Method of moments (MoM) [6] is a numerical technique used to approximately solve linear operator equations such as differential equations or integral equations. The equation solved by MoM generally has the form of an *electric field integral equation* (EFIE) or a *magnetic field integral equation* (MFIE). The unknown function is approximated by a finite series of known expansion functions with unknown expansion coefficients. The approximate function is substituted into the original operator equation, and the resulting approximate equation is tested so that the weighted residual is zero. This results into a number of simultaneous algebraic equations for the unknown coefficients. These equations are then solved using matrix calculus. MoM can also be applied in time domain, but majority of MoM studies are in frequency domain. MoM has been used to solve vast number of electromagnetic problems during the last five decades.

Parabolic equation (PE) model, also known as the beam propagation method (BPM) in optics (see Refs. 7 and 8 and references therein), widely used in propagation scenarios, implements the solution of one-way parabolic-type wave equation with fast Fourier transform (FFT) or FEM. They are called split-step PE (SSPE) and FEMPE [8], respectively. The PE model neglects backscatter effects and is valid in regions close to near-axial propagation (two-way PE models have also been introduced lately [9–11]). It is an initial value problem and transverse and/or longitudinal characteristics (e.g., irregular terrain profiles as well as atmospheric refractivity variations) can be included, but boundary conditions must be satisfied artificially.

Finite-difference time-domain (FDTD) method [13] discretizes Maxwell's equations by replacing derivatives with their finite-difference (FD) approximations directly in the time domain. It is simple, easy to code, but has the open-form (iterative) solution, therefore, conditionally stable; one needs to satisfy stability condition. The FDTD volume is finite; therefore, it may model only closed regions. Free-space simulation is an important task in FDTD and various effective boundary terminations have been developed for the last two decades. Broadband (pulse) excitation is possible in FDTD but inherits numerical dispersion problem. Finally, only near fields can be simulated around the object under investigation; far fields can be extrapolated using equivalence principle (e.g., Stratton–Chu equations) [12].

Finally, transmission line matrix (TLM) method [14] uses Huygen's principle (i.e., is based on circuit theory) and three-dimensional (3D) fields are discretized in an array of 3D lumped elements. It is based on the analogy between the EM fields and a mesh of transmission lines (TLs), therefore discretizes the computational domain (volume in 3D, surface in 2D) in terms of a mesh of TLs, interconnected at nodes. TLM technique involves two basic steps: (1) replacing the field problem by the equivalent network and establishing the connection between the field and network quantities; (2) solving the equivalent network by iterative methods. TLM also inherits almost all FDTD problems, such as stability, numerical dispersion, incapability of far fields, and others.

1.4 MODEL SELECTION CRITERIA

Which of these models is going to be used, when, where, and why? It is also one of the aims of this book to answer these questions. Start with the user requirements: What kind of a problem are you interested in? Are you looking for narrowband or broadband response? How do you classify your problem; as a circuit model or an EM model? What kind of problem geometry do you have, is it simple or too complex in shape? Do you need to model specific details? What are the largest and smallest dimensions in terms of wavelength in your geometry? Which coordinate frame fits in better, rectangular, cylindrical, or spherical? Are you looking for something fast? How much computer memory do you need? What accuracy do you expect?

For example, time-domain simulations (e.g., with FDTD and/or TLM) are preferred because of their ability to handle complex EM environments and broadband responses obtained from a single simulation. Parameter selection, in this case, should be as follows (see Chapter 14 for the details of FDTD method):

- Specify frequency response (minimum, maximum frequencies $f_{\min}$, $f_{\max}$, and the frequency resolution Δf). For example, the radiation characteristics or input impedance of an antenna, RCS behavior of a chosen target, transmission and/or reflection characteristics of a microstrip network, propagation characteristics of a waveguide, resonance frequencies of a closed enclosure, shielding effectiveness of an aperture, and so on are among important problems.

- Choose the source waveform (pulse width) that contains maximum frequency of interest.
- In FFT, maximum frequency determines minimum time step, that is, $\Delta t_{FFT} = 1/(2 \times f_{max})$. This is the hard limit for frequency analysis.
- The frequency resolution Δf determines the observation time $T_{max} = 1/\Delta f$. Remember, time-domain simulations model transient effects; therefore, simulations should continue until all transients are over. If the structure has resonances (ringing in time domain), much longer observation time may be required.
- Watch out Courant stability criteria [11] and numerical dispersion. Spatial mesh sizes Δx, Δy, Δz are chosen according to numerical dispersion requirements. It is nothing but satisfying Nyquist sampling criteria in spatial domain. The minimum wavelength λ_{min} component must be sampled with at least two samples, that is, max of $\{\Delta x, \Delta y, \Delta z\} \leq \lambda_{min}/2$. In practice, at least $\lambda_{min}/10$ is required for acceptable results ($\lambda_{min}/20$ would be enough in many cases, but as much as $\lambda_{min}/100 - \lambda_{min}/120$ may be required in some problems).
- The time step Δt_{FDTD} may directly be chosen from the Courant stability criteria (choose $\Delta t = 1/\sqrt{3}c$ in 3D simulations, where c is the speed of light). Usually, Δt_{FDTD} is much less than Δt_{FFT}, therefore take Δt_{FDTD} into account.
- At the end, apply offline DFT/FFT on the FDTD data and get the frequency response.

Both FDTD and TLM suffer from long distances around the object under investigation since the whole computation volume needs to be discretized. Alternatively, near-to-near or near-to-far field transformations may be used for this purpose, but they are extremely time consuming. MoM, on the other hand, is very handy if the observer is quite far from the object under investigation, because the Green's function takes care of that.

Realistic problems have neither analytical exact nor approximate solutions; therefore, comparisons must be done against measurement or some other numerical model. It might be smart and fruitful to use two different numerical models and compare them with each other. It would be easy if both models are in time or frequency domains. If not, one needs to transform time data to frequency data or vice versa. For frequency-domain comparisons, time-domain data need to be converted via DFT/FFT procedure.

For example, in order to obtain input impedance of a microstrip circuit or an antenna versus frequency by using FDTD and MoM, one needs a single FDTD simulation and then an FFT procedure, but MoM simulations have to be repeated for a number of desired frequencies. If the field versus time inside a resonator is of interest, one needs only a single FDTD simulation. On the other hand, a three-step procedure is essential for MoM simulations. First, MoM simulations are repeated for a number of desired frequencies. These responses are normalized with the frequency response of the FDTD excitation source and then inverse DFT/FFT is applied. Field versus time of the MoM simulations is then obtained.

1.5 GRADUATE LEVEL EM MODSIM COURSE

Students who are willing to take this course are encouraged to have References 4, 12, and 14–18 as reference and to revisit fundamental EM theory. Although topics to be covered in this course are self-contained, an intermediate level EM theory knowledge is essential.

1.5.1 Course Description and Plan

EM-MODSIM course should be about giving fundamentals of the numerical models mentioned earlier and training on programming with canonical applications. It must establish a balance among EM theory (physics), analytical modeling (math), and computer implementation (numerical simulation). First, PDEs; elliptic, hyperbolic, and parabolic forms; Maxwell's equations and BCs; and one-dimensional (1D), two-dimensional (2D), and 3D decomposition should be discussed. Radiation, diffraction, and guided wave problems, coupled/uncoupled equations, and wave equation should also be given. Source-free (eigenvalue) and source-driven (Green's function) problem should be presented via the 1D Sturm–Liouville problem.

Propagation modeling inside a nonpenetrable, infinitely long parallel plate waveguide is an excellent structure in terms of simplicity and gaining physical insight. The Green's function representation, and analytical modeling in terms of exact mode and ray summations, should be reviewed before using the numerical models mentioned earlier. The steps of producing numerical reference data from analytical exact solutions should be discussed in this content. This necessitates time- and frequency-domain comparisons as well as VV&C procedure. A typical course plan may be as given in Table 1.1.

1.5.2 Available Virtual EM Tools

Several, simple, user-friendly, free EM virtual tools have been presented in this Magazine for nearly a decade. Some of them aimed only education, but many can also be used in research. Even source codes of many are available for further user improvements. These virtual tools that can be used in teaching EM-MODSIM with the content discussed earlier are listed in Table 1.2, Table 1.3, and Table 1.4.

1.6 EM-MODSIM LECTURE FLOW

Make a short introduction and talk about real world problems. Explain (1) why and when we need simulations, why analytical representations are not sufficient; (2) what mathematical models we are trying to solve with 1D Sturm–Liouville equation, what the Green's function and Eigenvalue problems are; (3) numerical simulation techniques FD, FDTD, MoM, PEM, TLM, FEM; (4) which problem domains are suitable for which technique, (e.g., TLM for patch antennas, MoM for radiation problems, etc.). Discuss current status of and future trends in parallel computing, cloud computing, and so on.

Start with fundamental issues in numerical analysis. Quickly review root search algorithms, N by N system of equations, numerical integration. Discuss Taylor expansion of an analytic function and use it in FD approximation of partial derivatives. Present simple MATLAB scripts and also use built-in MATLAB commands such as ***roots()***, ***diff***(), ***gradient***(), ***trapz()***, ***inv()***, and so on. Write a short MATLAB code which solves Poisson and Laplace equations in 1D and 2D with FD method. Then, write down coupled equations of a plane wave propagating along z-direction directly in time domain and introduce the FDTD in its simplest form (give students [25] and individual MATLAB projects).

Table 1.1.
A Typical EM MODSIM Course Plan

Week	Topics—Fundamentals
1	Engineers speak with numbers [18,47]
	Numerical analysis, Fourier transform, DFT, FFT, and Fourier series [19]
	Deterministic/stochastic modeling [20], hypothesis testing [21]
2	EM theory and Maxwell's equations [4]
	Elliptic, hyperbolic, and parabolic equations
	Radiation, diffraction, and guided wave problems
	Coupled/uncoupled and wave equation in 1D, 2D, and 3D
	2D TE and TM problems [22]
3	Source-free and source-driven problems
	1D Sturm–Liouville equation [23]
	Guided waves and eigenvalue extraction [24]
4	Laplace, Poisson, and wave equations [25]
	FD discretization
5	MODSIM [4]: Analytical and numerical modeling
	Validation, verification, and calibration (VV&C)
	Time-domain and frequency-domain comparisons
	Reference numerical data generation
6	Two-dimensional (2D) parallel plate waveguide [26,27]
	Ray and mode summation models
7	FDTD method [13], Yee cell, discretization, stability, numerical dispersion, open boundaries (PML), near- to far-field transformations
	1D plane wave propagator and time-domain reflectometer [29]
	MGL-2D package and cylindrical wave scattering [28]
	MTM-FDTD package [29]
8	General review and midterm exam
9	Method of moments (MoM) [6,31]
	MoM in resonating structures [32]
10	Antenna arrays and beam forming [4,33]
11	EM scattering (reflections, refractions, and diffractions)
	High frequency asymptotics (GO,PO,GTD,PTD,UTD) [34]
	High frequency models and FDTD [35]
12	PE and propagation modeling [36–40]
	Flat earth, knife-edge problem and terrain modeling
	Propagation through atmosphere
	MoM versus PE (GrMoMPE package) [39]
13	3D EM virtual tools
	FDTD-based microstrip design and analysis tool [41]
	FDTD-based RCS prediction tool [42]
14	Ground-wave propagation and mixed-path problem [43–45]

Table 1.2.
Basic Time-Domain EM Virtual Tools

VTool	Explanation
1DFDTD	A MATLAB-based FDTD simulation of plane wave propagation in time domain through single-, double-, or three-layer media. EM parameters are supplied by the user [25].
TDRMeter	A virtual time-domain reflectometer virtual tool. It is used to locate and identify faults in all types of metallic paired cable. Fourier and Laplace analyses are also possible [30].
MGL2D	A general purpose 2D FDTD package for both TE- and TM-type problems. Any 2D scenario may be created by the user by just using the mouse [28].
MTM-FDTD	Modified version of MGL-2D to simulate cylindrical wave propagation through metamaterials (MTMs) [29].
WedgeFDTD	A 2D MATLAB-based simulator for the modeling of EM diffraction from a semi-infinite nonpenetrable wedge using high frequency asymptotics and FDTD [35].

Table 1.3.
Basic Frequency-Domain EM Virtual Tools

VTool	Explanation
RAYMODE	Ray/mode representations inside a parallel plate nonpenetrable waveguide. RAY serves as a tool to compute and display eigenray trajectories between specified source/observer locations and to analyze their contributions to wave fields individually [27].
ARRAY	A MATLAB package designed to investigate wave propagation through a 2D dielectric waveguide. Both analytical formulations and the SSPE propagator are used for comparisons.
SNELL	A simple MATLAB package for the visualization of ray contributions between a source/receiver pair above a 2D ground using the ray shooting technique. A number of user-specified rays are shot through a propagation medium characterized by various linear vertical refractivity profiles [48].

Table 1.3.
(Continued)

VTool	Explanation
WedgeGUI	A 2D MATLAB-based simulator for the modeling of EM diffraction from a semi-infinite nonpenetrable wedge using GO, GTD/UTD, PO, and PTD [34].
WedgeGUIDE	A 2D MATLAB-based simulator for the modeling of Green's function in terms of NM, AM, and IM representations [46].

Table 1.4.
Advanced-Level EM Virtual Tools

VTool	Explanation
GrMoMPE	A MATLAB package which modifies MoM by the application of forward–backward spectral acceleration (FBSA) technique and integrate it with the SSPE method. SSPE versus MoM comparisons are possible [39].
MSTRIP	An FDTD-based EM simulator for the broadband investigation of microstrip circuits. The user only needs to picture the microstrip circuit via computer mouse on a rectangular grid to specify basic dimensions and operational needs such as the frequency band, simulation length [41].
MGL-RCS	An FDTD-based EM simulator for RCS prediction. The user only needs to locate a 3D image file of the target in 3DS graphics format, specify dimensions, and supply other user parameters. The simulator predicts RCS versus angle and/or RCS versus frequency [42].
DrMIX	A MATLAB-based Millington package prepared for the mixed-path, path loss predictions. The effects of the number of multimixed paths, path lengths, electrical parameters of each propagation section, and the frequency can be investigated [43].

Review fundamental engineering terms and discuss the meanings of the numbers obtained either by computation or by measurement. Go over the meanings of accuracy, precision, sensitivity, resolution, error, and uncertainty. Show how error propagates. Review stochastic modeling, randomness, statistics, and confidence level. In this context, discuss a stand-alone radar simulation problem. Then, use MATLAB and simulate complex radar signal environment including target, noise, clutter, and interference. Discuss radar/communication receiver unit and explain (as radar/communication engineers use) *decision making* or (as mathematicians use) *hypothesis testing* (give students [19,20] and individual MATLAB projects).

Spend extra time on Fourier transform, its implementation in a discrete environment (i.e., computer), and Fourier series expansion of a function. The former is important in obtaining frequency responses of the TD MODSIM models. The latter is especially important in teaching MoM. Discuss nonphysical effects introduced by discretization when using discrete/fast Fourier transformations (DFT/FFT) such as spectral leakage, aliasing, periodicity, and so on. Write together short MATLAB code; one for DFT and/or FFT which gives frequency spectrum, the other for Fourier series representation of any given function. Let students exercise and solve the problems alone.

Take 1D Sturm–Liouville equation into account and discuss it in details. Review source-free (eigenvalue) and source-driven (Green's function) EM wave problems and their relations via completeness and orthonormality properties. List 1D eigenvalue and Green's functions in finite and infinite domains and discuss alternative spectral representations.

Then, take propagation inside a 2D nonpenetrable parallel plate waveguide problem and discuss exact solutions in terms of mode summation and ray summation models. Mention important steps in generating numerical reference data from analytical exact solutions. Show the procedure of eigenvalue extraction from propagation characteristics of the problems. Optionally, discuss the wedge waveguide and review normal modes (NMs), adiabatic modes (AMs), and intrinsic modes (IMs) there. This concludes the first part.

Let us start the second part by discussing fundamental MODSIM terms and concepts such as model, analytical model, numerical model, simulation, validation, verification, calibration, and so on. Mention the importance of physics-based modeling and observable-based parameterization. Discuss open (iterative)- and closed (matrix)-form discrete representations of models and their advantages and disadvantages. Discuss stability and numerical dispersion. Pay attention to excitation and discuss point source, line source, beam, aperture antenna, and other excitations. Accurate source modeling is essential in VV&C. Give some examples from presented virtual tools starting from simple to extremely complex ones. Students now realize broad range of EM problems that can be handled with MODSIM.

Discuss major numeric models: FDTD, MoM, PE, TLM, FEM. State problems where, when, and how they are applicable or not. Give examples of EM problems which are solved by at least two of these methods and present some comparisons. Discuss VV&C. Discuss TD and FD comparisons. Show cases where these methods agree very well but still incorrect. Present some virtual tools. This concludes the second part.

Let us reserve the last part for a simple canonical problem where all analytical and numerical models are applicable. Revisit propagation inside a 2D parallel plate waveguide. Discuss mode and ray summation models, image method, PE, MoM, FDTD, and FEM altogether. Present short MATLAB code for each and then do tests and comparisons. Let the students choose a topic among microstrip circuit design, groundwave propagation, and RCS problems, and test with one of the sophisticated EM virtual tools (e.g., MSTRIP, DrMIX, MGL-RCS).

This will finalize the course. The progress and how far to go depend on students' individual interests and willingness.

1.7 TWO LEVEL EM GUIDED WAVE LECTURE

As will be discussed in detail throughout the book, guided wave problems are important in teaching EM. In most of these problems such as TLs, 2D parallel plate waveguides, and 3D rectangular and/or circular cross-section waveguides, analytical exact solutions are known. This is specifically important in (1) understanding the problem and gaining physical insight and (2) generating reference data for measurements and numerical simulations. A two-level guided wave theory can be taught as follows.

Level I (Undergraduate)

- Decompose Maxwell's equations into transverse and longitudinal components.
- Discuss Sturm–Liouville equation in 1D and establish characteristic relations between source-free (homogeneous) and source-driven (inhomogeneous) representations.
- Discuss *orthogonality* and *completeness*.

- Discuss Fourier series expansion of a function in a given interval at this point (use supplied F***Series.m*** script for various examples).
- Give mathematical details of 2D parallel plate waveguide with nonpenetrable boundaries (use ***PPlate.m*** script for various examples).
- Give mathematical details of 2D surface duct formation above flat Earth and discuss trapping effects of refractivity variations (use ***SDuct.m*** script for various examples).
- Briefly review 2D parabolic wave equation and give details of numerical SSPE propagator in terms of FFT.
- Discuss the formation of longitudinal correlation function and give steps of eigenvalue extraction procedure (use ***PPCorel.m*** script for various examples).
- Review 2D dielectric film waveguide and derive eigensolutions (use ***DiSlab.Fig*** and ***DiSlab.m*** scripts for various examples).

Level II (Graduate)

- Start with the Ray-mode representations inside the 2D parallel plate waveguide. Give details of alternative integral representations and derivations by contour deformations, residue series, and others on various complex planes.
- Discuss hybridization in terms of rays and modes partially.
- Use MATLAB-based virtual tools and visualize effects of rays, modes individually, and in hybrid form on various user-specified scenarios.
- Take propagation inside the 2D wedge waveguide into account and give mathematical details of NM, AM, and IM.
- Establish (exact) NMs in cylindrical coordinates.
- Establish (approximate) AMs in Cartesian coordinates.
- Give IM integral representation and its reduction to AM away from critical, for example, cutoff, transitions.
- Use MATLAB-based virtual tools and visualize the effects of different modal expansions on various user-specified scenarios.

1.8 CONCLUSIONS

A generic electromagnetic modeling and simulation (EM-MODSIM) course outline is introduced and a teaching flow is proposed. The course description/outline, a weekly course plan, and some virtual tools are presented. Wave propagation inside an infinitely long parallel plate waveguide with nonpenetrable boundaries is chosen as a canonical structure and fundamental analytical (ray-mode summation) and numerical models (FDTD, PE, MoM, TLM, and FEMs) are reviewed. The process of VV&C is also presented. Note that there are excellent books which describe different analytical and numerical models in details which serve as reference in EM-MODSIM studies; some of them are listed in Appendix B.

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