

EM Simulation Numerical Methods for Comprehensive Design

This booklet explores the core numerical methods utilized in Remcom’s software products. Remcom’s EM analysis products are used for a wide range of applications, requiring a variety of numerical methods to cover all of your EM challenges, from the simple to the technically complex.



Several EM solvers and ray-tracing techniques work together to ensure a comprehensive design and analysis process, from device design and antenna placement to EM propagation and wireless communication system analysis.

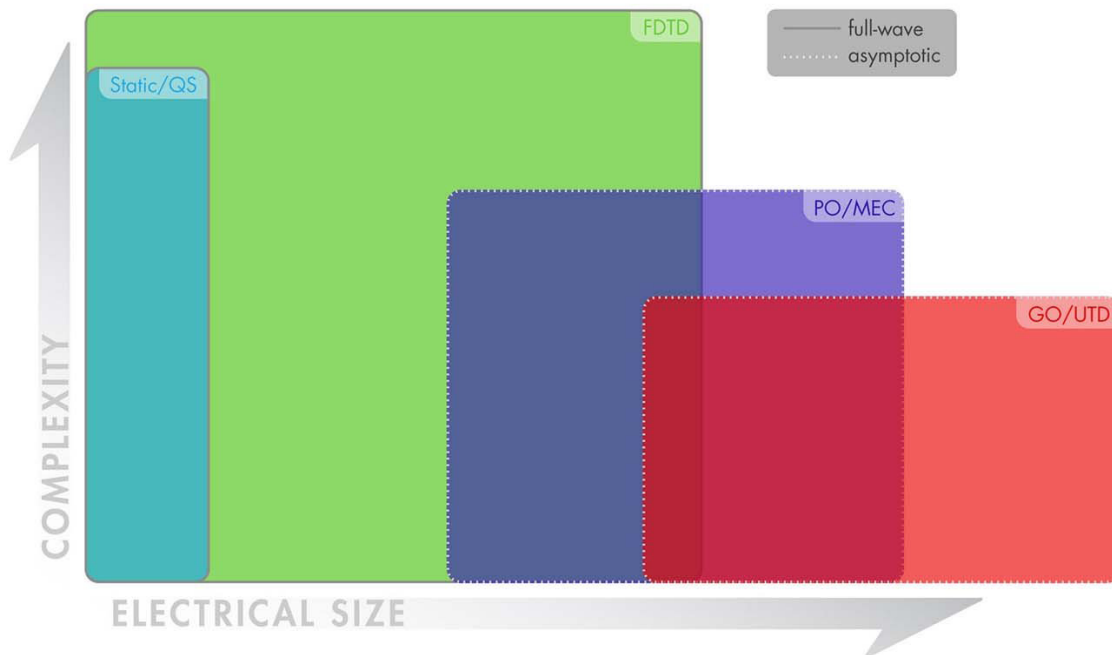
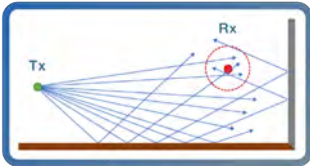


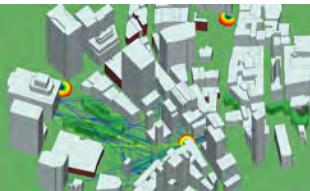
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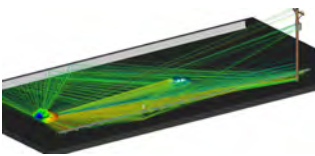
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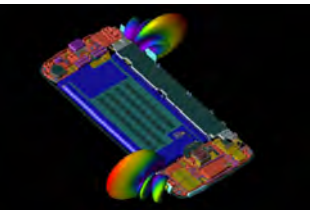
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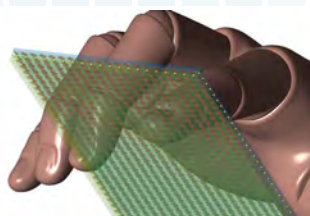
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EM Simulation Numerical Methods: Introduction

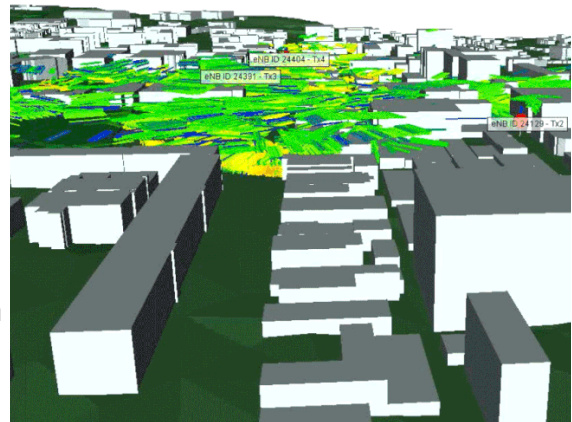
Ray-Tracing Methods

Ray-tracing methods use discrete rays to represent advancing wavefronts as they propagate from a transmitter through a scene. Rays interact with geometry in the scene through reflections, diffractions, and transmissions. The two dominant ray-tracing methods are Shooting-and-Bouncing Rays and Image Theory. Remcom's software combines these two methods to leverage the advantages of each.

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Ray-Tracing with Geometric Optics and UTD

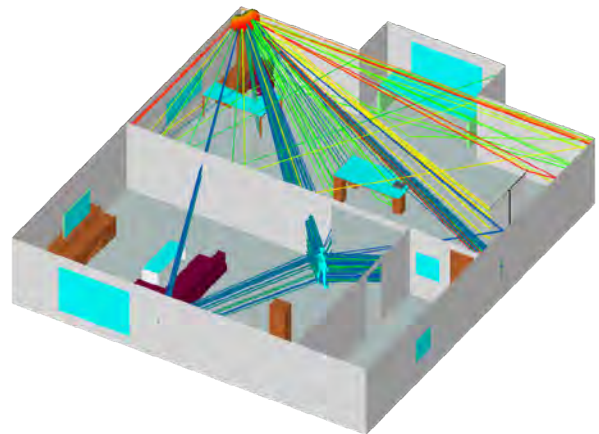
[Wireless InSite's](#) ray-based solvers use Geometric Optics (GO) and the Uniform Theory of Diffraction (UTD) to evaluate a ray path's electric field. These methods provide accurate results when the scenario geometry is large compared to the wavelength of the propagating wave. For typical applications, the GO/UTD-based models provide accurate predictions from approximately 100 MHz to approximately 100 GHz.



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Ray-Tracing with Physical Optics and MEC

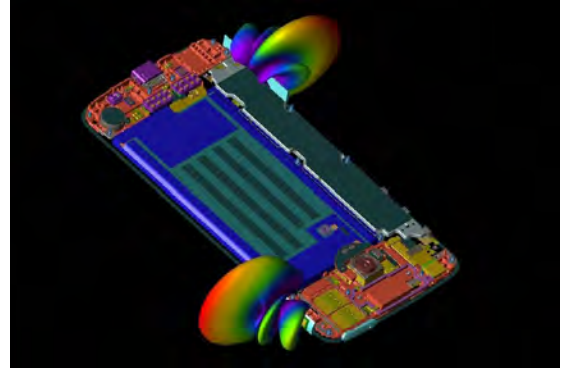
The Physical Optics (PO) ray-tracing method involves a full surface integration over faceted structures and is typically used for complex scattering analysis. Effects can be further improved through edge corrections based on techniques such as the Method of Equivalent Currents (MEC). Remcom's [WaveFarer](#) radar simulation software uses these techniques with specialized ray-tracing that ensures full target illumination; additional enhancements account for near-field effects and multipath in order to simulate interactions between a radar and its immediate environment.



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Finite-Difference Time-Domain Method (FDTD)

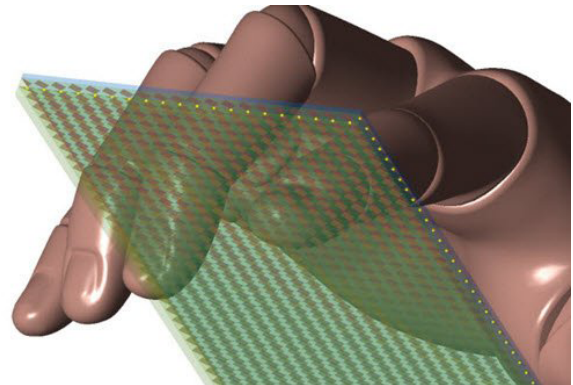
While many electromagnetic simulation techniques are applied in the frequency-domain, FDTD solves Maxwell's equations in the time domain. This means that the calculation of the electromagnetic field values progresses at discrete steps in time. One benefit of the time domain approach is that it gives broadband output from a single execution of the program; however, the main reason for using the FDTD approach is the excellent scaling performance of the method as the problem size grows. As the number of unknowns increases, the FDTD approach quickly outpaces other methods in efficiency.



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XFDTD's Electrostatic Solver

Remcom's static solver module is a second-order solver which works with the same geometry and grid used for time-domain computations and is compatible with the time-domain solver. In addition to fully static problems, the solver may be used to compute initial conditions for a time-domain simulation, such as those involving time-varying switches or nonlinear electric or magnetic materials.



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Ray-Tracing Methods Overview

Ray-tracing methods use discrete rays to represent advancing wavefronts as they propagate from a transmitter through a scene. Rays interact with geometry in the scene through reflections, diffractions, and transmissions. Rays that reach a receiver represent the paths that waves may travel from the transmitter to the receiver. The electric field, received power, and other electromagnetic quantities can be calculated through the superposition of the contributions from all of the propagating waves that reach that receiver point.

There are two dominant methods used in ray-tracing, explained below.

Shooting-and-Bouncing Rays (SBR):

This approach shoots rays in all directions, usually with a fixed angular spacing, and follows them as they interact and split further into additional paths, reflecting from surfaces, transmitting through them, or diffracting from wedges.

Image Theory:

From a predefined pair of end points (e.g., a transmitter and receiver), this approach finds all of the paths between the points, using the method of images to determine where ray-tracing interactions will occur. The approach is then repeated for each subsequent pair of points in a calculation.

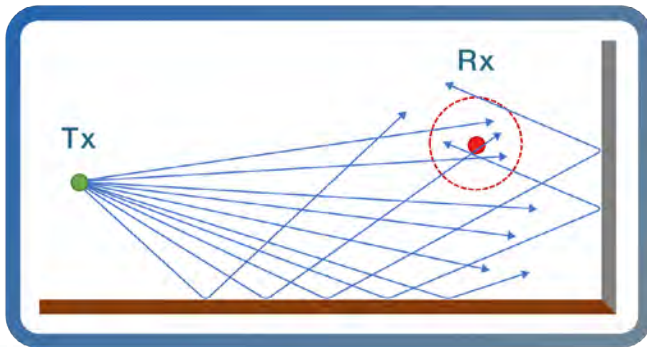


Figure 1: Shooting and Bouncing Rays

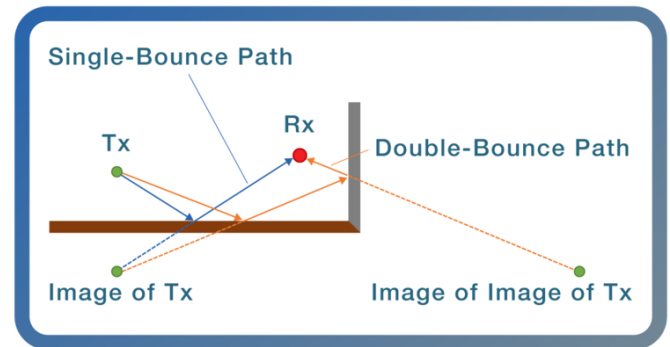


Figure 2: Image Theory

SBR is a relatively efficient approach for finding ray-tracing paths through a complex scene, but as rays propagate, they continuously spread, and they risk missing interactions with smaller objects while also incurring increasing error in the calculation of path length and phase. Image theory, on the other hand, is a more precise approach, but because it must be repeated for each pair of Tx and Rx points, it can be very computationally intensive in a scene with large numbers of facets and large numbers of transmit and receive pairs.

Ray-Tracing Methods Overview

For these reasons, Remcom's most advanced ray-tracing models in [Wireless InSite](#) and [WaveFarer](#), which are based on the [X3D ray-tracer](#), combine the two techniques. SBR is used to find the initial chains of interactions, using GPU-accelerated ray-tracing. Image theory is then used to perform an exact path correction (EPC), finding the precise paths between each point pair. The result is the capability to efficiently find propagation paths, while providing precise calculations of time of arrival, phase, and polarization. Precise estimates of these quantities have become increasingly important, if not required, for many current problems of interest, including MIMO analysis, fading due to mobility, and Doppler.

The way in which rays are traced and the propagation paths used depends significantly on the physics techniques that will be used to calculate the electromagnetic fields and power at receiver antennas. Two broad categories of techniques include (1) Geometric Optics and the Uniform Theory of Diffraction, and (2) Physical Optics augmented by the Method of Equivalent Currents or other similar techniques to adjust for edge effects.



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Ray-Tracing with Geometric Optics and UTD

Geometric optics and the uniform theory of diffraction (GO/UTD) provide one of the dominant combined sets of methods used for calculating electromagnetic fields using ray-tracing. This method is very effective for calculating fields from waves propagating through a complex environment, such as an indoor office environment, or a dense urban scene such as that shown in Figure 1. It is the dominant set of techniques used in Remcom's [Wireless InSite](#).

Why Geometric Optics and UTD?

With GO/UTD, as rays propagate, they interact with geometric structures in the environment, reflecting from surfaces, diffracting from edges, and transmitting through obstructions. Effects from these interactions are calculated using reflection, diffraction, and transmission coefficients calculated based on the material properties of each object, usually specified in terms of the dielectric properties (relative permittivity and conductivity) of one or more material layers. Scattering effects can also be accounted for in terms of additional paths that scatter from surfaces that are rough compared to a wavelength.

A base assumption is that object surfaces are multiple wavelengths in size, though the edge corrections in the UTD method allow for one dimension to be fairly narrow relative to a wavelength. These basic size assumptions allow calculations to be performed based on interaction points rather than surface integrations, required for techniques such as Physical Optics (PO). This allows the methods to efficiently calculate propagation through large-scale indoor and outdoor scenarios, where interactions with many structures and walls can lead to dense multipath.

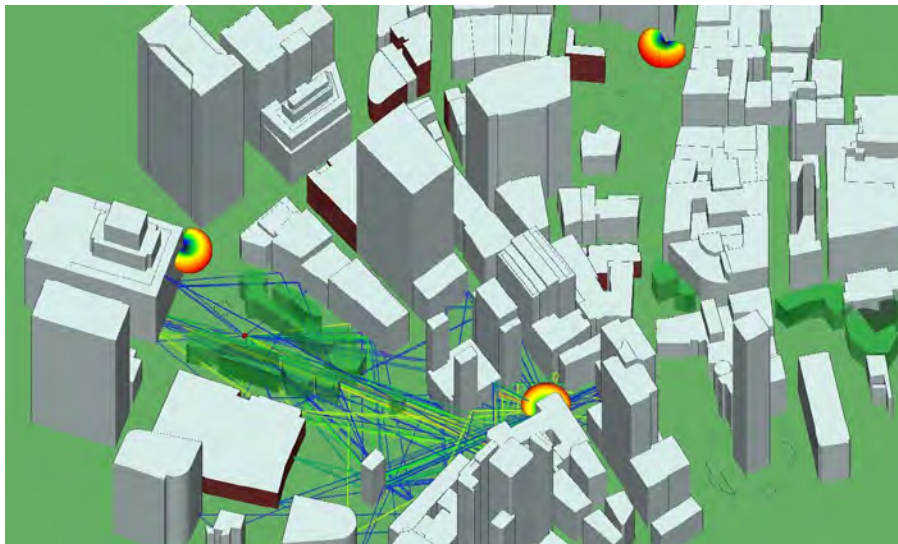


Figure 1: Dominant propagation paths from a base station to a point within an urban setting

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Ray-Tracing with Physical Optics and MEC

Physical Optics (PO) is a ray-based physics technique that is very effective for radar scattering and other applications that require calculation of backscatter from detailed faceted objects. Unlike methods based on the GO/UTD approach, PO involves a full surface integration over faceted structures. This requires denser ray tracing and is more computationally intensive than geometric optics and UTD; however, the additional computation can provide much more accuracy for calculations that require analysis of scattering from faceted structures that are highly detailed, such as the calculation of radar backscatter from a finely-faceted model of a vehicle, aircraft, or naval vessel, or reflections from other high-resolution surfaces. Traditional approaches often make far-field assumptions and are applied to problems such as the calculation of far-field RCS. In Remcom's [WaveFarer radar analysis software](#), however, the technique has been specifically enhanced to account for near-field effects, allowing the method to be applied to closer-range applications such as automotive radar or indoor sensing.

In PO, a scattering object is composed of a set of facets that define a closed surface. Ray-tracing is used to find paths to every facet on this closed surface, potentially incurring multipath interactions with other surfaces along the way. It can be combined with GO/UTD methods to incorporate the effects of multipath interactions with other structures in the environment into its calculation of the electromagnetic fields incident on each facet of the surface. The surface integration requires very dense paths, which Remcom's solutions achieve by targeting facets and incorporating extensions to multipath rays that intersect a target's geometry. Figure 1 shows an example of the top 50,000 paths for an automotive radar scenario. Once paths are found, the received voltages for each path to each facet are calculated using a generalized Green's function. The total received voltage at an antenna is then calculated from the sum of the contributions from all combinations of paths and the facets with which they interact.

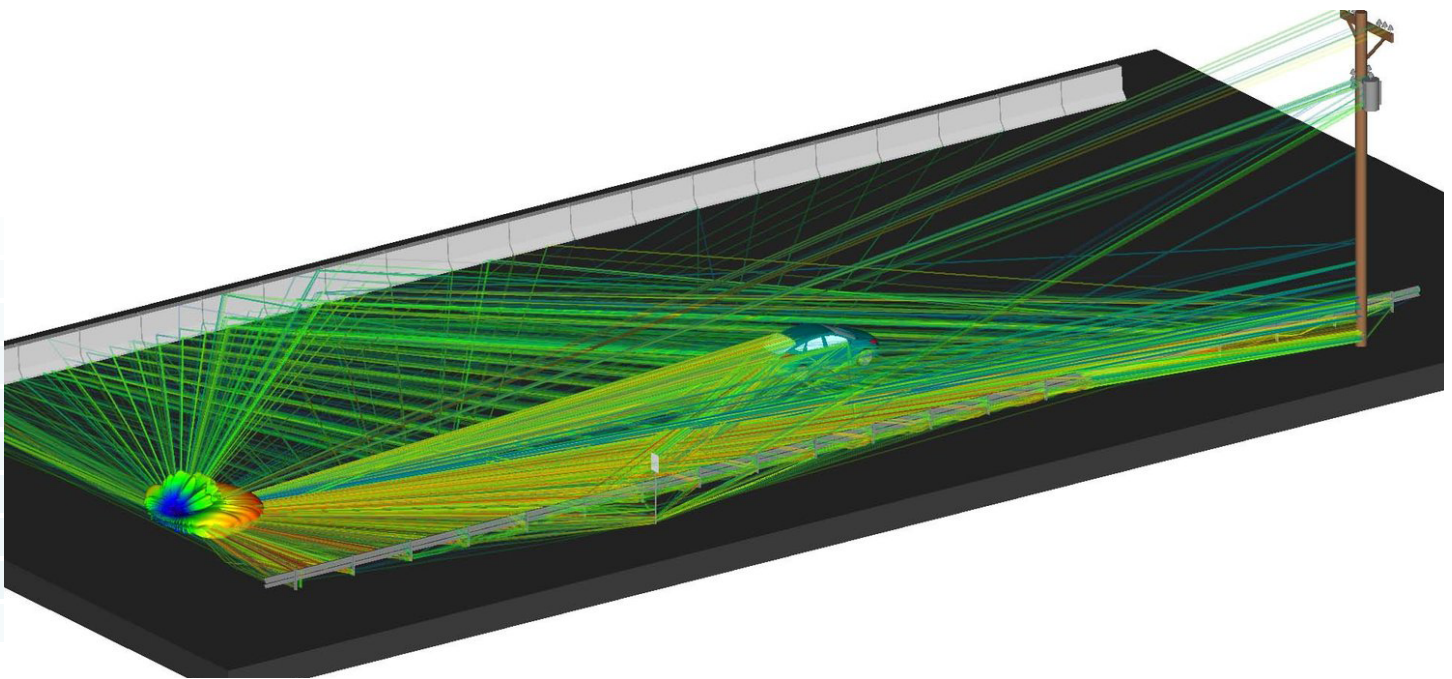
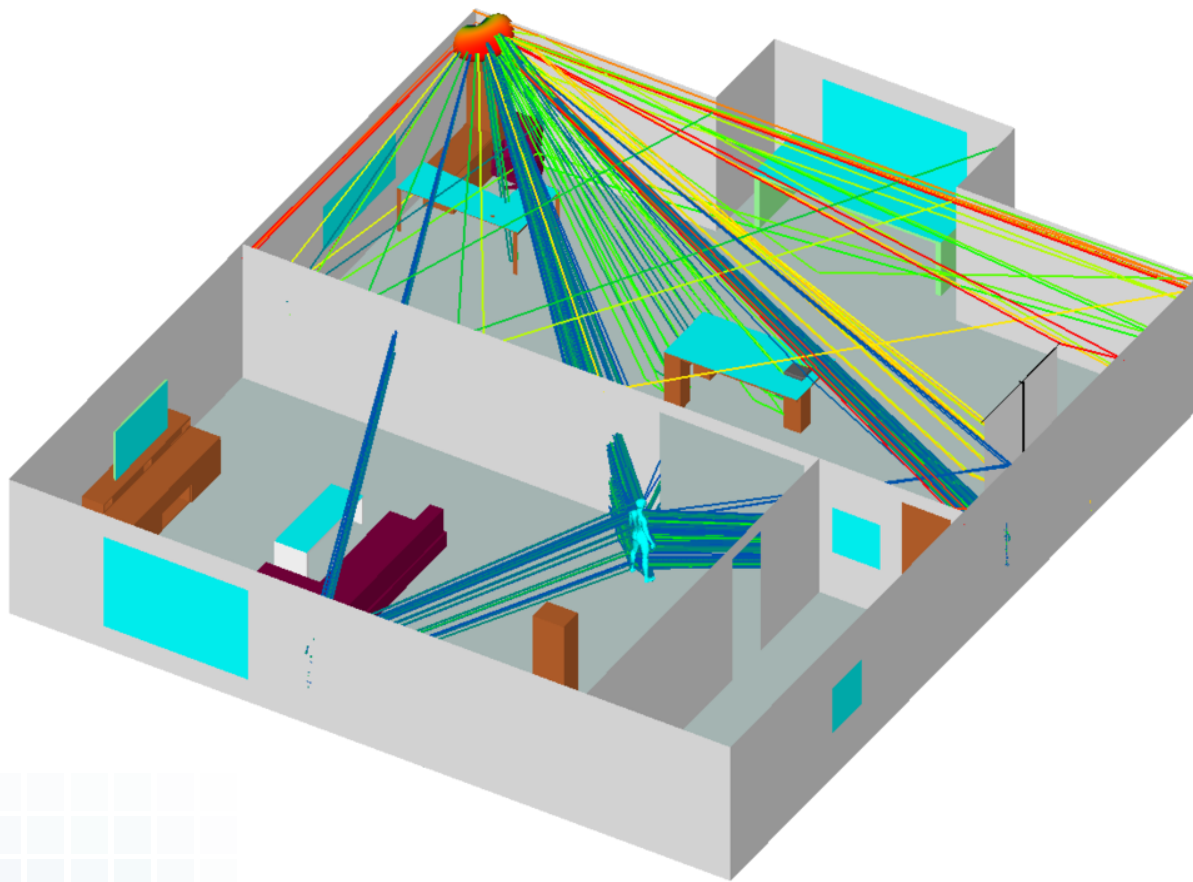


Figure 1: Top 50,000 paths between radar, environment and vehicle in auto-radar scenario

Ray-Tracing with Physical Optics and MEC

Method of Equivalent Currents (MEC)

While physical optics does include the effects of edges in its scattering calculations, these effects can be further improved through corrections based on techniques such as the Method of Equivalent Currents (MEC). Remcom's solutions have applied MEC to find equivalent electric and magnetic currents associated with each edge, which are then included in line integrals to supplement the PO surface integral. The result produces a better numerical approximation for near-zone or far-zone scattered fields than surface PO alone.

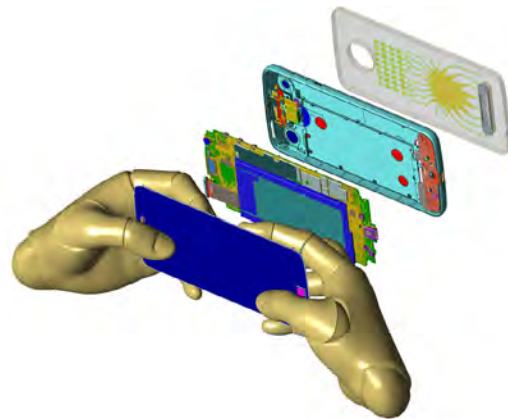


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The FDTD Method for Electromagnetic Simulation

Why Use FDTD Simulation Software?

While many electromagnetic simulation techniques are applied in the frequency-domain, FDTD solves Maxwell's equations in the time domain. This means that the calculation of the electromagnetic field values progresses at discrete steps in time. One benefit of the time domain approach is that it gives broadband output from a single execution of the program; however, the main reason for using the FDTD approach is the excellent scaling performance of the method as the problem size grows. As the number of unknowns increases, the FDTD approach quickly outpaces other methods in efficiency. FDTD has also been identified as the preferred method for performing electromagnetic simulations for biological effects from wireless devices [1]. The FDTD method has been shown to be the most efficient approach and provides accurate results of the field penetration into biological tissues.



Mobile phone model provided courtesy of Motorola Mobility, LLC/Lenovo.

A Brief Summary - FDTD Simulation Basics

In the FDTD approach, both space and time are divided into discrete segments. Space is segmented into box-shaped cells, which are small compared to the wavelength. The electric fields are located on the edges of the box and the magnetic fields are positioned on the faces as shown in Figure 1. This orientation of the fields is known as the Yee cell [2, p. 37] and is the basis for FDTD. Time is quantized into small steps where each step represents the time required for the field to travel from one cell to the next. Given the offset in space of the magnetic fields from the electric fields, the values of the field with respect to time are also offset. The electric and magnetic fields are updated using a leapfrog scheme where first the electric fields, then the magnetic, are computed at each step in time.

When many FDTD cells are combined together to form a three-dimensional volume, the result is an FDTD grid or mesh. Each FDTD cell will overlap edges and faces with its neighbors, so by convention each cell will have three electric fields that begin at a common node associated with it. The electric fields at the other nine edges of the FDTD cell will belong to other, adjacent cells. Each cell will also have three magnetic fields originating on the faces of the cell adjacent to the common node of the electric fields as shown in Figure 1.

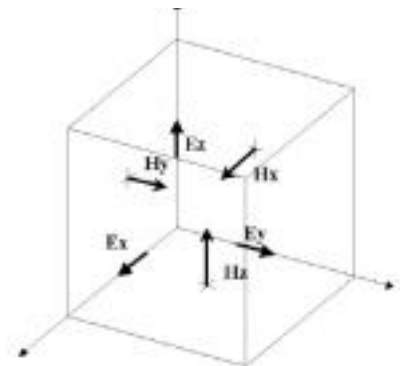


Figure 1: The Yee cell with labeled field components

The FDTD Method for Electromagnetic Simulation

Within the mesh, materials such as conductors or dielectrics can be added by changing the equations for computing the fields at given locations. For example, to add a perfectly conducting wire segment to a cell edge, the equation for computing the electric field can be replaced by simply setting the field to zero since the electric field in a perfect conductor is identically zero. By joining numerous end-to-end cell edges defined as perfectly conducting material, a wire can be formed. Introducing other materials or other configurations is handled in a similar manner and each may be applied to either the electric or magnetic fields depending on the characteristics of the material. By associating many cell edges with materials, a geometrical structure can be formed within the FDTD grid such as the dielectric sphere shown in Figure 2. Each small box shown in the figure represents one FDTD cell.

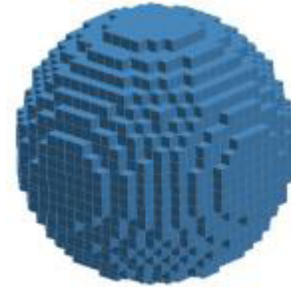


Figure 2: A dielectric sphere as meshed in a traditional FDTD grid with staircasing. The individual cell edges (electric field locations) are displayed as overlapping grid lines.

The cell size, the dimensions of the small box, is the most important constraint in any FDTD simulation since it determines not only the step size in time, but also the upper frequency limit for the calculation. A general rule of thumb sets the minimum resolution, and thus the upper frequency limit, at ten cells per wavelength. In practice the cell size will often be smaller than this in order to resolve dimensions and features of the structure to be simulated such as the thickness of a substrate or the length of a wire.

An excitation may be applied to an FDTD simulation in many different ways. One method emulates exciting a geometry at discrete locations by applying a sampled waveform to the field update equation at one or more locations. At each step in time, the value of the waveform over that time period is added into the field value. The surrounding fields will propagate the introduced waveform throughout the FDTD grid appropriately, depending on the characteristics of each cell. A calculation must continue until a state of convergence has been reached. This typically means that all field values have decayed to essentially zero (at least 60dB down from the peak) or a steady-state condition has been reached.

Cell Staircasing Advancements

Traditionally, staircased FDTD cells are considered cumbersome and inefficient at resolving curved surfaces or highly varying fields. [Advancements in FDTD](#) allow for conformal meshes and singularity correction.

The cubicle Yee cell of Figure 1 can in general be rectangular. The spacings between cells in the x, y, and z-directions can vary throughout the problem space. This allows more cell edges to be placed in regions of strong fields, such as around small features of highly conductive material.

The FDTD Method for Electromagnetic Simulation

Within a cell, the standard update equations of FDTD may be refined in many ways, for example to allow for wires that are thinner than a cell size or to calculate the strong fields on the edges of conductors such as microstrip lines. Another refinement can allow for objects whose surface intersects the cell at arbitrary angles with respect to the principle axes. These “conformal” cells can be further refined to account for curvature of the object surface within the volume of the cell.

Figure 3 shows the geometry of a portion of a mobile phone. For clarity, the visibility of many of the parts, including the outer case, has been turned off to show the region near the antenna. A small portion of the FDTD mesh of the phone is shown in Figure 4a using simple rectangular cells. In Figure 4b the same part of the phone mesh is shown, this time using a type of conformal treatment for cells which contain portions of the surface of an object. Figure 5 shows a larger view of the surfaces of the conformal mesh.

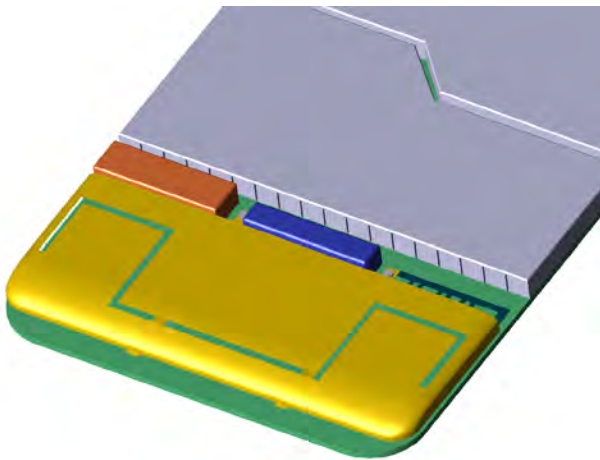


Figure 3: Antenna section of mobile phone.

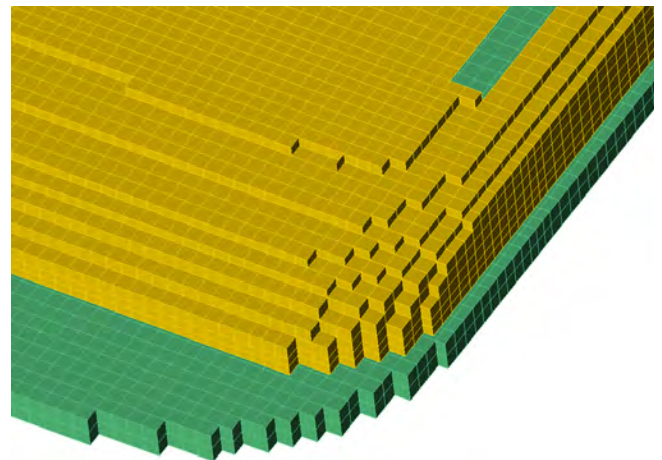


Figure 4a: Mesh view of corner of antenna using simple rectangular mesh.

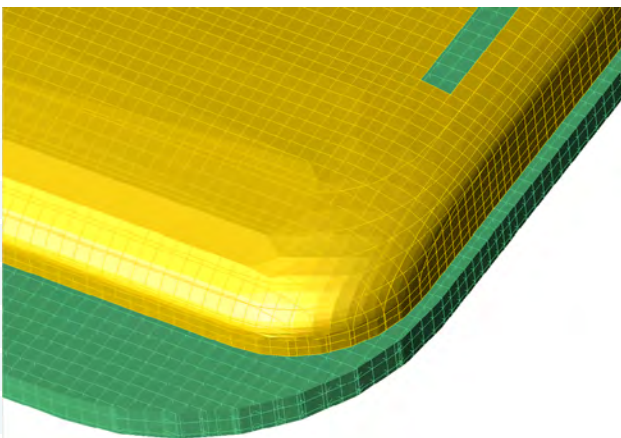


Figure 4b: Mesh view of corner of antenna with conformal mesh.

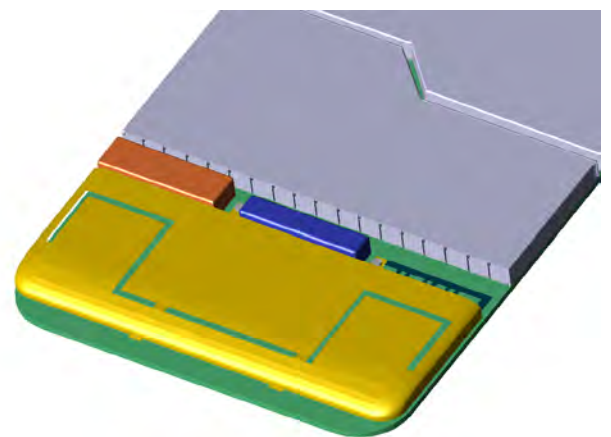


Figure 5: Conformal mesh of mobile phone antenna.

The FDTD Method for Electromagnetic Simulation

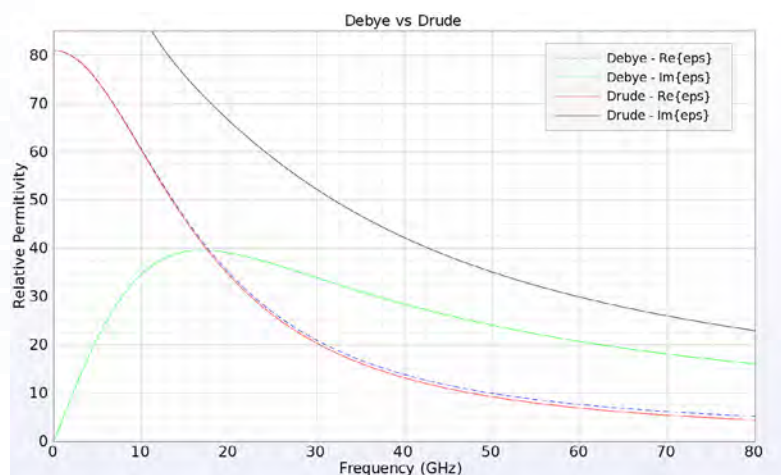
Materials

FDTD simulation software is capable of simulating a wide variety of electric and magnetic materials. The most basic material of course is free space. All FDTD cells are initialized as free space and the fields at all cell edges are updated using the free space equations unless another material is added to replace the free space.

Perfectly conducting electric and magnetic materials are simulated by setting the electric or magnetic field to zero for any cell edges located within these materials. Because of the simplicity of the calculation for these materials, it is better to use a perfect conductor rather than a real conductor whenever feasible. Conductors such as copper can be simulated in FDTD, but since the equations for computing the fields in copper material are more complicated than those for a perfect conductor, the calculation will take longer. Of course for cases where only a small percentage of the FDTD cells are defined as a conductor, the difference in execution time will hardly be noticeable.

Frequency independent dielectric and magnetic materials are defined by their constitutive parameters of relative permittivity and conductivity or loss tangent for the electrical material, or relative permeability and magnetic conductivity for the magnetic material. In many cases, even when performing a broadband calculation, these materials are appropriate since the parameters do not vary significantly over the frequency range.

In some cases a frequency independent material is not appropriate and instead a frequency dependent, or dispersive, material should be substituted. Some common examples of frequency dependent materials are high water content materials such as human tissues, metals when excited at optical frequencies, and dielectrics over wide bandwidths. Included in [XFDTD](#) is the capability to simulate electric and magnetic Debye and Drude materials such as plasmas, Lorentz materials, and anisotropic magnetic ferrites, as well as frequency independent anisotropic dielectrics. These materials may have permittivities or permeabilities that are negative at some frequencies, making them effective for simulating metamaterials macroscopically. FDTD is also particularly effective at simulating nonlinear materials, several of which are included in [XFDTD](#).



The FDTD Method for Electromagnetic Simulation

Near-Zone Versus Far-Zone

For any given calculation the geometry of the structure being simulated is defined by setting the cell edges at specific locations to certain materials. The entire FDTD geometry space, commonly called the grid or the mesh, is composed of a three dimensional block of these cells. This three dimensional volume is considered to be the near-zone region in FDTD in terms of the data storage. The field value at any edge in the FDTD grid may be observed as a function of time by saving a “near-zone” point in [XFDTD](#). Other types of data such as steady-state field magnitudes, specific absorption rates, S-parameters, or impedance may be stored as well for appropriate points, surfaces, and volumes within the grid.

It is possible to make an FDTD grid that is large enough to allow sampling of points in the far field of a geometry. In general this will be extremely costly in terms of computer memory and calculation time since the number of unknowns (cells) will most likely be large. Note that each FDTD cell has a maximum size of one-tenth of a wavelength, so moving many wavelengths away from a structure will require a large number of cells. In most cases this is not an appropriate method of monitoring far field results.

A more practical method for transforming field values to the far-zone and for calculations of radiation gain or radar scattering patterns is to use a transformation to convert the near-zone values in the FDTD grid into a far field value at some location away from the grid. This is done by enclosing the geometry in a box and storing the fields on the outer faces of this box for general far-zone problems. The faces of the box are located five FDTD cells from each outer edge of the FDTD grid. For the transformation to be valid, all parts of the FDTD geometry must be contained within the box.

The polar coordinate system used in [XFDTD](#) is defined with the azimuthal (ϕ) angle referenced from the x-axis and the elevation (θ) angle referenced from the z-axis, as shown in Figure 6. This coordinate system is used for locating far-zone positions and for defining the incident plane wave direction.

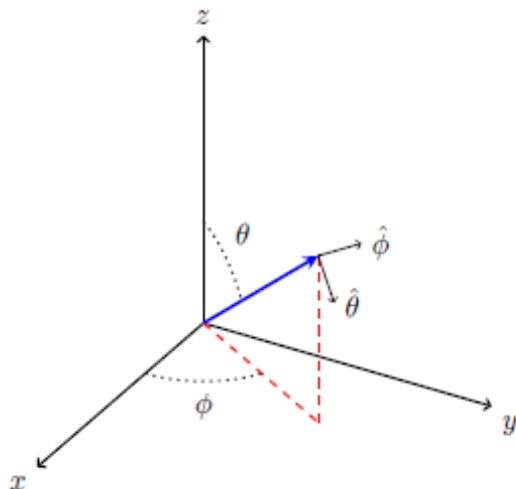


Figure 6: Polar coordinate system used for far-zone and incident plane wave directions.

The FDTD Method for Electromagnetic Simulation

Broadband And Steady-State Calculations

Generally a broadband calculation is performed with FDTD since a single calculation can yield results for a wide range of frequencies without requiring extra computer resources. When data at particular frequencies are required, steady-state data may be computed from the broadband calculation by means of a Fourier transform.

Common examples of data vs frequency include antenna patterns at specific frequencies, biological applications such as the Specific Absorption Rate (SAR), electric and magnetic field magnitudes, magnetic flux magnitudes, conduction currents, and “circuit” type information such as S-Parameters, group delay, impedance, power, efficiency, etc.

Sinusoidal excitation may be desired in certain occasional cases, such as when avoiding a strong resonance near, but outside of, the frequency range of interest.

Outer Radiation Boundaries

A three-dimensional grid of cells forms the FDTD geometry and the fields updated at every cell location are dependent on the neighboring fields. However, due to memory limitations the grid must end at some point and because of this, the fields on the outer edges of the grid cannot be updated correctly. To correct this situation, outer radiation boundary conditions are applied at the edges of the FDTD grid.

The outer radiation boundary is a method for absorbing fields propagating from the FDTD grid toward the boundary. By absorbing these fields, the grid appears to extend forever. The performance of the outer boundaries is an important factor in the accuracy of an FDTD calculation and care should be taken to correctly use them.

In some cases a reflecting boundary rather than an absorbing one is preferred. A perfectly conducting boundary (either electric or magnetic) may be used to image the fields in an FDTD calculation to take advantage of problem symmetries. A periodic boundary condition is useful for simulating a single unit cell of a large symmetrical geometry.

Computer Resources

FDTD is a computationally intensive method and most reasonable calculations will need a fast computer and at least a few Gigabytes of computer memory. For most applications it is fairly simple to estimate the amount of computer memory required for a calculation. The most important factor for the memory usage, and in large part the run time, is the number of FDTD cells used to represent the structure under test. Each FDTD cell has six field values associated with it: three electric fields and three magnetic fields. Additionally each cell has six flags associated with it to indicate the material type present at each of the six field locations.

The FDTD Method for Electromagnetic Simulation

The field values are real numbers, each four bytes in length, while the flags may each be one byte. This gives a memory usage per FDTD cell of 24 bytes for fields and 6 bytes for flags for a total of 30 bytes. To estimate the total memory required, in bytes, simply multiply the number of FDTD cells by the 30 bytes per cell value. There is some overhead in the calculation, but it is generally quite small. One notable exception is the broadband far-zone angles that allocate six one dimensional real value arrays per direction.

Estimating the execution time of an FDTD calculation is more complicated since performance of computer processors varies. One method of estimating is to compute the total number of operations to be performed. There are about 80 operations per cell, per time step during the FDTD calculations. The total number of operations is found from the product of the number of cells, the number of time steps, and the factor of 80 operations per cell, per time step. If a value of the floating-point performance of the processor is known, a value for execution time can be computed. In general though, a better estimating method is to determine the execution time of a simple problem on a given computer and then scale the time by the ratio of the number of operations between the desired calculation and the simple one.

There are many ways to increase computation speed of FDTD, though some will require considerable effort to program. Some of the most effective are to use multiple CPUs of a computer in parallel, use multiple computers in parallel, optimize computation loops for cache, or take advantage of parallel methods on CPUs such as SSE and AVX. FDTD software is especially well suited to computation on GPU processors as the notion of many cells performing a relatively small number of update algorithms in parallel fits well with the methods developed for updating video displays.

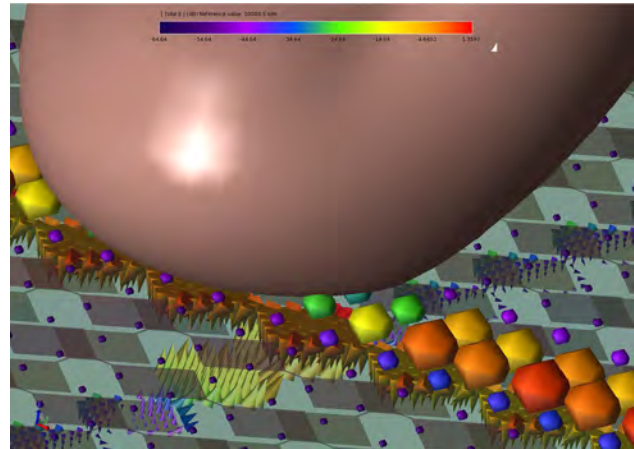
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1. C95.3.2002, "Recommended Practice for Measurements and Computations with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 100kHz to 300GHz," IEEE Standards and Coordinating Committee 28 on Non-Ionizing Radiation Hazards, April 2002
2. K. S. Kunz and R. J. Luebbers, "The Finite Difference Time Domain Method for Electromagnetics," Boca Raton, FL: CRC Press, 1993.

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XFDTD's Electrostatic Solver

XFDTD's static E solver module computes the static and (in some cases) quasi-static E-field given a geometry with one or more boundary conditions. The boundary conditions include fixed or floating potential on objects and outer boundary conditions. Supported material types include PEC, good conductors, lossy and lossless dielectrics.



The static solver module is a second-order solver which works with the same geometry and grid used for time-domain computations and is compatible with the time-domain solver. In addition to fully static problems, the solver may be used to compute initial conditions for a time-domain simulation, such as those involving time-varying switches or nonlinear electric or magnetic materials. Examples of the various use cases include studies of the effects of transient fields in RF circuits induced by electronic switches and soliton simulations induced in nonlinear materials for particle accelerators.

	Driving 1	Driving 2	Driving 3	Sensing 1	Sensing 2	Sensing 3	Sensing 4
Driving 1	19.5	(9.1)	(7.1)	(14.0)	(12.0)	(9.0)	(13.0)
Driving 2	(10.4)	(49.6)	(10.4)	(14.0)	(10.0)	28.0	(11.0)
Driving 3	(7.1)	(9.1)	19.5	(14.0)	(12.0)	(9.0)	(13.0)
Sensing 1	(15.0)	(14.0)	(15.0)	22.8	(15.5)	(7.6)	(4.6)
Sensing 2	(14.0)	(11.0)	(14.0)	(16.0)	12.6	(10.4)	(7.8)
Sensing 3	(10.0)	28.0	(10.0)	(7.7)	(9.7)	(130.4)	(10.2)
Sensing 4	(13.0)	(10.0)	(13.0)	(4.4)	(6.7)	(9.5)	8.7

Table 1: Change in mutual-capacitance between loaded and unloaded case (fF)

	Driving 1	Driving 2	Driving 3	Sensing 1	Sensing 2	Sensing 3	Sensing 4
Driving 1	19.5	(9.1)	(7.1)	(14.0)	(12.0)	(9.0)	(13.0)
Driving 2	(10.4)	(49.6)	(10.4)	(14.0)	(10.0)	28.0	(11.0)
Driving 3	(7.1)	(9.1)	19.5	(14.0)	(12.0)	(9.0)	(13.0)
Sensing 1	(15.0)	(14.0)	(15.0)	22.8	(15.5)	(7.6)	(4.6)
Sensing 2	(14.0)	(11.0)	(14.0)	(16.0)	12.6	(10.4)	(7.8)
Sensing 3	(10.0)	28.0	(10.0)	(7.7)	(9.7)	(130.4)	(10.2)
Sensing 4	(13.0)	(10.0)	(13.0)	(4.4)	(6.7)	(9.5)	8.7

Table 2: Change in self-capacitance between loaded and unloaded case (fF).

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