Ray Tracing as a Design Tool for Radio Networks

John W. McKown
R. Lee Hamilton, Jr.

Designers of indoor and urban radio networks require detailed understanding of radio propagation in these reflector-rich environments. Digital radio networks convey information as a sequence of symbols chosen from a known set, whose identity must be decided by the receivers. These decisions are typically made in the presence of noise and, within or near building walls or other reflectors, multiple echoes of the transmitted signal. The echoes arrive at various delays: echoes at short delays may cancel the received signal; echoes at longer delays distort the signal by causing different symbols to overlap. These effects are called the multipath problem. There are strong incentives to characterize the multipath problem on a site-by-site basis and thus, to map the service quality (coverage) to be expected from a candidate design. In this way, it may be estimated how many sites the proposed system can serve. Coverage maps are usually determined by maps of site-dependent parameters like received signal power and Root-Mean-Square (RMS) delay spread [1] along with system performance parameters like receiver sensitivity and required carrier-to-interference power ratio.

The ultimate details of multipath propagation may be obtained, in principle, by solving Maxwell's equations with boundary conditions that express the physical properties of the walls and other structures that scatter the radio waves. Unfortunately, this is the mathematical essence of the problem of calculating Radar Cross Sections (RCSs) of (very) large, complex structures. Calculation of RCSs is a highly developed and evolving field [2] [3], but at present it does not permit economical treatment of large buildings at high frequencies, even though the boundary conditions for RCS problems are generally much simpler and advantageous than those for indoor propagation.

Since field trips and physical measurements are expensive, approximate numerical methods are of interest. Coherent ray tracing is an intuitively appealing method for calculating radio signal strength and related parameters [4] [5]. Ray tracing approximates the scattering of electromagnetic waves by simple reflection and refraction. Ray tracing can be much less demanding of computation than methods based on Maxwell's equations and can provide much more detail than common statistical measures such as "propagation power laws" that describe the spatially averaged dependence of received power on receiver-transmitter separation. This article describes efficient radio ray tracing programs developed at Motorola, discusses uses and limitations, and presents examples.

Ray Tracing Approximates Wave Propagation

A ray is the path of an ideal bullet that travels in a straight line except for instantaneous ricochets, i.e., reflections and refractions. Ray tracing is a brute force method for calculating the progress of wave fronts—the ideal bullets are interpreted as points on the traveling wave front. When applied to radio propagation problems, ray tracing is an approximation: Maxwell's coupled differential equations provide scattering effects not possible with simple particles. The accuracy of the ray tracing approximation depends mainly on the ratio of the wavelength to the dimensions of the scatterers and the volume of interest. Some comparisons of ray tracing calculations with (spatially averaged) measured data are presented in [1].

Ray tracing is most accurate when the point of observation is many wavelengths from the nearest scatterers, all scatterers are large, compared to a wavelength, and smooth, i.e., have surface features that are small compared to a wavelength. These conditions are well met in mirrored rooms illuminated by visible light.

Our ray tracing functions in a world of flat, infinitely thin, partially silvered mirrors. Upon striking such a mirror, an inci-
A simple building. Overall dimensions are 14.63 m × 9.14 m × 3.05 m; the small rooms are each 3.05 m × 3.66 m. A small dot marks the location of a transmitter 2.44 m above the center of the floor.

...d ray gives birth to two daughters, the reflected ray and the transmitted ray. The transmitted ray proceeds along an extension of the incident ray; the reflected ray proceeds in a new direction determined by the orientation of the mirror; the incident ray dies. The mirror may absorb some power, but total power is conserved. Thus, rays have the properties initial power (amplitude), direction, and distance of propagation.

The radio source is considered coherent and the phases of the rays are computed prior to addition at the receiver. The programs trace fictitious, scalar rays, but polarization could be included with little additional complexity.

Antennas are assumed to be infinitely small. There is no limit to field strength as the point of observation approaches a small source, but it is easily shown that if the source would produce unit received amplitude at unit distance in free space and all mirrors are flat, then field strength is not greater than the number of mirrors divided by the distance between the receiver and source. Maps of received power are thus easily normalized.

The ray tracing programs developed by the Motorola Radio Telephone Systems Group generate maps of continuous wave signal strength and RMS delay spread in indoor and simple (planiform) outdoor environments. They also generate what may be called specular approximations to the power delay profile, i.e., lists of the strengths and delays of discrete echoes. Since our programs involve some unrealistic approximations, we do not seek, or expect, quantitative agreement with physical measurements made in or near typical buildings. We interpret the images qualitatively as in Examples, below.

Efficient Algorithms

Our major requirement was that our code execute fast enough to be useful for generating two-dimensional maps. This ruled out the most simple approach to ray tracing, which is to spew out a cone or pin cushion of rays from the transmitter, trace them until they either hit the receiver or become attenuated beyond some threshold, add together the fraction that reach the receiver, and increment the receiver position and repeat the process to build up the desired map.

Other goals were to account for antenna patterns, the dependence of reflection coefficients on angle, multiple reflections, and multiple wall types. The programs operate in 3-space, but the present versions only treat rectangular walls (and ceilings and floors, collectively referred to as panels below) that are perpendicular to the Cartesian coordinate axes.

We use images to order rays by number of reflections. This ensures that all rays that undergo a given number of reflections (or fewer) on their way from transmitter to receiver are tracked. For example, the programs can be instructed to process just the Line Of Sight (LOS) ray, or the LOS and all rays that reach the receiver after one reflection, or the LOS and all one- and two-reflection rays, etc., up to six reflections. Processing time varies roughly as the number of panels taken to the power of the maximum number of reflections. Complicated buildings thus compete with high-order reflections.

The basic idea can be understood with the aid of Figure 1, which shows a source $S$, a destination $D$, two planes $A$ and $B$ (seen edge on), and various images labeled by appending the sequence of reflecting panels that generated them. The straight line distance from an image to the destination is equal in length to the corresponding actual reflected ray path. For example, the line $Sxyd$ has the same length as the straight line from...

b. Calculated 18 GHz standing wave pattern of signal power attenuation, in dB, within the leftmost area of the small rooms in Fig. 2.

b. Map of RMS delay spread in nanoseconds.

Fig. 3. A calculated 18 GHz standing wave pattern and map of RMS delay spread in nanoseconds. The mapped plane is 61 cm above the floor. Both receiver and transmitter are equipped with omnidirectional antennas.
image $S_{AB}$ to $d$. It is easy to generate the images of a source object in all the planes. These images then serve as objects for a second round of reflections, and so forth. If there are $N$ reflecting planes then there are $N$ first-order, i.e., one-reflection, images of a source, $N(N-1)$ two-reflection images, $N(N-1)(N-1)$ three-reflection image, etc. The images can thus be arranged as a tree graph. The first branching is $N$-fold; all the later ones are $(N-1)$-fold. With squared-off reflecting planes it can happen that some of these images will coincide in space, but the program treats them separately because they have different positions in the tree. The one-to-one correspondence between images and rays is thus a useful way to avoid treating rays that leave the source, but do not reach the destination of interest. Algorithms based on images naturally avoid processing these irrelevant rays.

This is not to say all images of the source are visible at the destination. The operation of generating images discussed above assumes, in effect, all the reflectors are infinite planes. The real walls are finite-size panels on these planes and many rays will miss them. Thus, many locations on the image tree may represent images invisible from some particular destination point. To determine whether an image of the source is visible at the destination is to determine whether the corresponding reflected ray intersects all the necessary panels and thus reaches the destination and contributes to the received power.

It would be nice if the fact that a particular image cannot be seen at the destination meant all higher order images of that image were also invisible, but this is not the case. However, if we ignore rays weaker than some threshold then we can prune the tree because dim images give rise to still dimmer images.

Our programs determine image visibility by proceeding backwards from the destination toward the (highest order) image involved with the ray of interest, for example from $d$ toward $S_{AB}$ in Figure 1. We solve for point $x$ at which the line $dS_{d,x}$ intersects the last generating plane (plane B). If point $x$ lies on the finite panel associated with the infinite plane, then the required reflection is possible and processing continues; otherwise the ray is discarded because (at least) one of the required reflections missed its panel. If $x$ lies on panel B, then back tracing proceeds toward the next lower order image, $S_y$. If point $y$, where the line $xS_y$ intersects plane $A$, lies on panel $A$ then that required reflection also occurs. In this fashion, we work backwards through the image subscripts, i.e., the generating planes, to see if all reflection points are on the appropriate panels.

Once a ray has been traced through all its reflections to the source, the reflection attenuations are calculated. The question then arises "did any of the ray segments pierce any panels as transmitted daughters?" That is, the position of an image on the image tree specifies the panels that contributed as reflectors, but not the panels that contributed as transmitters. These latter panels must be identified, again by checking whether intersections of lines with infinite planes fall within given panels.

To reduce processing time, it is important to discard candidate rays as early as possible, e.g., when some particular two-reflection ray missed one of its reflecting panels.

It is even more important to exploit knowledge about smoothness. If an image is visible at one point, then it is likely still visible at a neighboring point. If it is visible at two points on a short line, then it is likely visible at all the intervening points. If it is (in)visible at the four corners of a small square, then it is likely (in)visible everywhere within the square and we can avoid the laborious searches in the interior. We thus use

**Fig. 4.** Both receiver and transmitter are equipped with 120-degree aperture (conical) antenna patterns.

**Fig. 5.** Signal power attenuation, in dBi, for the same conditions as Fig. 4, except the frequency is 1.8 GHz.
two grids on the map being generated: a coarse one with panel searches and a finer one without. If the visibility of any image is different at any two corners of a square of the coarse grid, we do full searches for all the interior points. If the image is visible at all corners, we use the panel sequence of one of the corners everywhere within the square. If the image cannot be seen from any of the corners, we assume it cannot be seen anywhere within the coarse grid square.

To be sure, it is just possible that an image cannot be seen from the corners of a small square that includes a still smaller area in which the image is visible, but this rare event can be made rarer still by using a finer coarse grid. It is possible to specify a grid size that guarantees no images will be missed. Similar statements can be made with respect to pierced panels: it is possible that an image will change brightness within a coarse grid cell because the ray passes the edge of a pierced panel. This dual-grid technique dramatically speeds processing.

**Examples**

Figure 2 shows a simple example building (the ceiling and two exterior walls are removed in the figure). There are 23 panels in all, including the desk. Figure 3a is a map of signal strength attenuation in decibels, calculated at a height of 61 cm i.e., 15 cm below the desk top, within the room (the one with the desk). It accounts for all rays that experience up to and including two reflection on their way to the receiver. The transmitter is located 2.44 m above the floor in the large open area, at the center of the building. Both transmitter and receiver employ omnidirectional antennas. The walls in this example transmit 50% of the incident amplitude and reflect 50%. The desk transmits nothing and reflects 95%. These values were chosen arbitrarily, as were the phase changes of reflection and transmission (zero degrees). The carrier frequency is 18 GHz. Figure 3b shows the corresponding RMS delay spread. There are two pixels per wavelength in the data sets for both pictures. Each picture required a few hours of computation on a Sun 3/80 workstation.

A beam may be seen entering from the open doorway and reflecting off the West wall. Close inspection of the West edge of the doorway shows a blunted vertex where the beam enters the room. This is an artifact of the included-image type. The blunting can be reduced with a finer coarse grid. In the building of Figure 2, three-reflection rays are not important contributors to signal strength: processing three-reflection rays produces a map virtually indistinguishable from Figure 3a, because the walls are not highly reflective. The large arcs centered on the transmitter’s off-screen location which dominate the attenuation maps are due to interference between the direct ray and the ray reflected once by the floor. Signal strength vanishes inside the reflective drawer cabinets, of course.

Figure 4 shows the effect of a 120-degree-sector (more precisely, cone) antennas on both transmitter and receiver. The boresight directions are fixed and oriented such that they are face-to-face and colinear when the receiver is in the center of the mapped area. Comparing Figure 3 and Figure 4, we see the general simplifying effect of sector antennas. The beam seen reflected from the West wall in Figure 3a is not received by the sector antenna and thus, is missing from Figure 4a.

Figure 3b and Figure 4b are maps of RMS delay spread rounded to integer nanoseconds. Such figures generally consist of a number of polygons that are two-dimensional slices of three-dimensional domains. The domains are determined by the images as follows: imagine you are in a building whose walls and floors are partially silvered mirrors. Somewhere else in the building is a light source. You see many reflections of it. The number of images you see above some threshold brightness is finite and remains constant as you move your head through small motions. If you move your head far enough you will either see a new image appear at an edge of one of the mirrors, or see one of the old images disappear beyond an edge, or both. In this way, you can probe the boundaries of your current image-set domain. If the source and mirrors are reasonably far away, the intensities and delays of the images (echoes) will not change much anywhere within a domain and a phase-independent quantity, like RMS delay spread, will be nearly constant—this is why the map of rounded RMS delay-spread closely corresponds to slices through the image-set domains. Figure 5 is identical to Figure 4a except the frequency has been lowered to 1.8 GHz. The ten-fold increase in wavelength dictates larger features for the standing wave pattern, including dead spots.

**Summary and Discussion**

The image-based, dual-grid, scalar, coherent, ray tracing programs described in this article generate maps (two-dimensional slices) of three-dimensional standing wave patterns for continuous wave illumination. We use our calculated maps to estimate system coverage quality in a macroscopic sense and investigate design alternatives regarding antenna beamwidths, boresight orientations, spatially averaged signal strengths, and so forth.

Our programs run fast enough on engineering workstations to support indoor radio system design, but not fast enough for interactive use. Faster algorithms and codes may therefore be necessary if ray tracing is to be interactively applied to optimize microcell (base station) placement.

**Acknowledgment**

We are pleased to acknowledge our use of the XIImage data visualization software (available free) from the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign.

**References**


**Biography**

John W. McKeown received his B.S. degree in physics and his Ph.D. degree in biophysics in 1971 and 1981, respectively, from the University of Illinois at Urbana-Champaign. From 1981 to 1989, he was employed by E-Systems in Garland, Texas, where he worked on demodulation and interference cancellation techniques. Since 1989, he has been with Motorola’s General Systems Sector in Arlington Heights, Illinois, working on multipath problems associated with indoor radio systems. His e-mail address is mcownm@whistle.rsg.mot.com.

R. Lee Hamilton, Jr. received his B.S. degree in electrical engineering from Virginia Polytechnic Institute and State University in 1992 and received his Ph.D. degree in electrical engineering from Purdue University in 1986. From 1986 to 1990, he was on the faculty of the Department of Electrical Engineering at the Ohio State University. Since 1990, he has been with Motorola’s General Systems Sector in Arlington Heights, Illinois working on building radio systems.