Microcellular Radio-Channel Propagation Prediction

Kurt R. Schaubach
Southwestern Bell Technology Resources, Inc.
St. Louis, Missouri 63141

Nathaniel J. Davis IV
Bradley Department of Electrical Engineering
Virginia Polytechnic Institute and State University
Blacksburg, Virginia USA 24061

1. Abstract

Designers of wireless-communications networks require detailed understanding of radio-propagation in complicated, multipath channels. Unlike conventional cellular systems, emerging wireless personal-communication networks will most likely operate in confined, urban environments (microcells). The application of broad-band-digital modulation to these networks requires careful consideration of the dispersive nature of the urban radio channel. This paper presents a ray-tracing simulation technique which incorporates site-specific environmental data, such as the location, the orientation, and the electrical properties of buildings, to predict path loss and delay spread in urban microcells. Using simplified geometric-optics assumptions, rays are traced in three dimensions. This determines the paths by which direct, specularly reflected and transmitted, diffusely scattered, and diffracted rays arrive at a receiver. The received rays are combined incoherently as a function of delay, to estimate the channel power-delay profile. The power-delay profile is used for verification of model accuracy, via qualitative and statistical comparisons of measured and predicted data, for receiver locations on the Virginia Tech campus. The comparisons conclusively show the simulation's ability to accurately model urban microcellular propagation.

2. Introduction

The cellular-telephone industry has experienced a phenomenal growth rate over the past ten years. In the near future, economies of scale and new radio technology will allow mass personal communications to be provided by compact-radio systems. The implementation of a personal-communications network (PCN) will be accomplished, by constructing a microcellular structure of low-powered base stations. The cell size (less than 1 km in diameter) in this structure will be much less than current cellular systems (typically 10 km or more in diameter). The base stations of the microcells will be mounted, on, for example, lamp posts or building rooftops, and will be connected to the public-telephone network. As a result of the increased frequency re-use provided by the microcellular structure, it should be possible to accommodate more users in roughly the same amount of spectrum used in today's cellular systems. A current assessment of cellular and microcellular systems and their design can be found in Lee's text [16].

In microcellular systems, multipath propagation, induced by surrounding buildings and clutter, results in excessive power losses along the path, and in increased delay spread of the signals, themselves. Numerous experiments, conducted in a variety of different environments, have demonstrated the subtleties of multipath propagation and have illustrated the difficulties in accurately predicting channel characteristics [2, 3, 4, 19, 23, 25]. The results have further indicated that, depending on the physical surroundings of the communication paths, the path loss and the multipath-delay spread can vary dramatically. This is true for different paths with similar transmitter-receiver (T-R) separations, or for an identical path where the T-R separation changes by only several meters. Due to the variability in channel characteristics, systems designers have typically relied on statistical models [11, 27, 28] or empirical models [12, 17], when measured data were unavailable.

Research has shown that by using simplified descriptors for the physical propagation environment, it is possible to dramatically improve the modeling accuracy for conventional (i.e., tall-tower) cellular-system design [13, 29]. By incorporating a mathematical propagation model, and integrating statistical data on the average height and generalized location of building obstacles, median path loss can generally be predicted within 6-8 dB of measured data, based on shadow fading plus large-scale path-loss values. Due to the reduced base-station heights of microcellular systems, the propagation characteristics of these systems are dissimilar to conventional cellular systems [9, 10, 18]. As a result, the extension of statistical-design models to microcellular PCN systems is unclear. Furthermore, additional research has indicated that urban microcellular-channel parameters are highly dependent upon the specific location and orientation of building obstacles, rather than on statistical averages [21, 23]. Thus, more detail regarding the physical surroundings of the communications path is necessary for an accurate characterization of the channel.

Recently, geometrical-optics and ray-tracing techniques have been proposed, to predict channel characteristics in indoor and outdoor environments [5, 14, 15]. These techniques integrate site-specific information, pertaining to the physical environment, with simulation techniques adapted from computer-graphics algorithms for optical-ray tracing. Excellent agreement between measured and predicted path loss, and multipath time-delay profiles, has been observed. The ray-tracing methodology discussed in [14] is similar to the work presented here. However, Kurrner, Cichon, and Wiesebeck focus on the average propagation loss, associated with a receiver as it moves through an urban environment. We concentrate instead on the determination of power-delay profiles at fixed receiver locations. This permits us to estimate both the average power loss at the receiver, as well as the interactions of the various multipath components which arrive at a receiver. These techniques offer the potential to revolutionize the design methodologies used throughout the cellular-radio industry, and to thus remove a significant hurdle in the implementation of PCN systems.

This paper provides an overview of the key aspects of implementing a microcellular propagation-prediction tool which is based on the use of ray tracing. Section 3 provides an overview of the propagation mechanisms present in a radio channel, and discusses the impact of site-specific environmental considerations. Section 4
the propagation path. Figure 1 gives the magnitude of a typical channel impulse response (also known as the power-delay profile), for a multipath PCN channel, at a fixed receiver location. The envelope of the received signal varies with time. The times of arrival (or the signal’s delay) of different multipath components correspond to the peaks in the envelope. Thus, the area under the curve corresponds to the total received signal power, seen at the measurement location. The power-delay profiles of all potential receiver locations must be known, in order to predict the proper operation of the PCN system. At every site, the power level must be above a specified minimum-required level of performance, to insure correct reception, and the delay spread must be less than a specified maximum value, in order to avoid inter-symbol interference which can occur between transmitted bits of information.

When an obstacle is in a signal path, portions of the signal can be specularly reflected, transmitted, scattered, or absorbed by the obstacle itself (conservation of energy is maintained). Specular reflection, or simply reflection, is characterized by the incident and reflected rays making equal angles with the surface normal, as depicted by rays labeled $r_1$ and $r_2$ in Figure 2. Portions of the signal can also be transmitted through the surface, following Snell’s Laws of Refraction. Reflected and transmitted rays follow a $1/d^2$ power dependence, where $d$ is the total ray-path length. For example, the specularly reflected ray, shown in Figure 2, the path segments of which are labeled $r_1$ and $r_2$, has a power dependence which is proportional to $1/(r_1 + r_2)^2$.

Diffusely scattered rays, such as the one with segments $s_1$ and $s_2$ in Figure 2, have angles of incidence and reflection which are not equal. These ray paths exhibit a multiplicative power dependence, given by $1/(s_1 s_2)^2$. The multiplicative dependence is due to the additional spreading loss the ray experiences after scattering, and causes rapid attenuation of scattered signals. Many propagation models neglect the effects of diffuse scattering. In computing average path loss, this is a generally valid assumption: the specular components contain a greater portion of the total energy, and thus contribute more to an average taken over space in a local area. However, the diffuse component can be strong enough to influence the local average at locations that are physically close to the scattering surface (i.e., when $s_2$ in Figure 2 is small). On the basis of anticipated building geometries and their physical separations from receiver locations, scattering can not be neglected in microcellular PCN-propagation models.

When a receiver is heavily shadowed by surrounding obstacles, a significant portion of a received signal is due to energy diffracting over or around the building edges. A reasonable first approximation, to predicting coverage in shadowed topologies, is to predict the impact of diffraction along a “direct” path connecting the transmitter and the receiver, and to then let the reflection and the scattering portions of the model account for all other received-signal components. The diffraction model used in our simulator evaluates diffraction loss along the transmitter-receiver path using wedge-diffraction formulations [6]. The edges of a building, along the direct path, are modeled as perfectly absorbing, 90° wedges, which are infinite in length. Multiple-edge diffraction is included. However, for a specific T-R path, only one diffracting edge per building obstacle is considered. Only edges which are closest to the direct T-R path are evaluated. It is assumed that these edges are the most significant. A sample geometry for the diffraction model is shown in Figure 3.

Thus, the microcellular-propagation model includes direct, reflected, transmitted, and scattered fields, which are represented by
rays emanating from transmission sources. The impact of diffraction is also addressed. Each of these propagation mechanisms can be evaluated separately. The total field at a receiver is determined by the superposition of the individual contributions of each ray. As such, this approach is similar to the radiosity methods which are commonly used in optical-image rendering [7]. The field amplitude, $E_i$, of the $i$th ray arriving at the receiver, is given by

$$E_i = E_0 \cdot G_t \cdot G_r \cdot I_1(d) \cdot L_1(\phi_1) \cdot L_2(\phi_2) \cdot \prod_j \Gamma(\phi_j) \cdot \prod_k T(\theta_k).$$  \hspace{1cm} (1)

In Equation 1, $G_t$ and $G_r$ are the field-amplitude radiation patterns of the transmitting and the receiving antennas; $I_1(d)$ is the path loss for the $i$th component with path length $d$; and $L_1(\phi_1)$ represents the total diffraction loss for the $i$th ray, where $\phi$ is the angular dependence of the loss for each ray diffraction.

$L_1(\phi_1)$ is the loss applied to scattered rays. Diffusely scattered energy is computed using a simplified bistatic-radar-cross-section approach. Building surfaces are completely segmented into independent, electrically large, scattering panels, based on the number of rays intersecting the surface. Each scattering panel's area is proportional to its incident ray's wavefront area, and is thus related to the total number of rays which originated at the transmitter, as well as their angular separation. Hence, the total scattered energy at the receiver depends only on the total surface area of the scatterer, and not on the number of scattered rays traced from the surface. Scattered energy from each panel is computed using a flat-plate bistatic-RCS formula, where scattered energy is maximum in the specular direction. A cosine($\phi_1$) scattering pattern, where $\phi_1$ is the angle which the scattered ray makes with the specular direction, is assumed as an approximation to the true scattering pattern.

Reflection and transmission losses, $\Gamma(\theta_r)$ and $\Gamma(\theta_t)$, are shown as functions of the ray's angle of incidence to reflecting or transmitting surfaces. Such losses can be precisely determined through the application of Fresnel formulas. However, little published data exists concerning the dielectric properties of common building materials and building structures. As a result, a 12 dB reflection loss is used in the model, regardless of the angle of incidence or the type of building material used [1, 13]. Fresnel formu-

lations can be substituted for these constants, if dielectric properties can be accurately determined.

For a given receiver location, the mean field strength is the sum of the magnitudes of the individual multipath components, as given by

$$\bar{E}_R = \sqrt{\sum_i E_i^2}.$$ \hspace{1cm} (2)

Path loss is computed by referencing the result of Equation (2) to a one-meter free-space level. Wide-band channel parameters are computed by applying the methods of Rappaport, Seidel, and Singh [20].

4. Propagation prediction system

This section describes the general methodology required to develop an automated design tool, which can be used to predict the performance of a microcellular radio-based PCN. In particular, details are presented on the system used at Virginia Tech. Our simulation system is depicted in Figure 4. A building database is used to record the size, location, and electrical properties of buildings and other objects of interest, which fall within the microcellular-system's locality. Pertinent database information is used as input to the propagation-simulation model, and can be displayed on a computer workstation in the form of three-dimensional visualizations of the locality. Ultimately, the simulated performance data from the propagation model can be overlaid onto the graphical display of the cell's coverage area. This gives the designer an extremely effective visualization, depicting the likely performance of the overall cell site. More importantly, it gives the designer the ability to identify potential areas for poor coverage, and a means to compare alternative transmitter and/or receiver locations within the cell. The building database, graphical-user interface, and the propagation-prediction programs are described in more detail, below.

4.1 Building database

In order to incorporate site-specific information into a propagation-prediction tool, a database must be designed and maintained which contains relevant information pertaining to the area which is to be modeled. Data to be included in the database can be obtained from a variety of sources. The US Geological Service provides digitized-terrain information for much of the country and the world. Local governments, city planners, and architects typically maintain

![Figure 3. The wedge-diffraction model for shadowed transmitter-receiver paths.](image)

![Figure 4. The structure for the automated ray-tracing system.](image)
building and terrain database information for major urban areas, as well as smaller municipalities. Other resources, such as aerial photogrammetry and satellite imagery, can also be used as sources of database information.

We chose AutoCAD for use as the database manager and graphical interface for this propagation-prediction tool. AutoCAD is an industrial-standard CAD package, and one in which building data is readily available. It is used to construct a building database for a region or area in which a microcellular system is to be installed. The buildings in the database are modeled as convex polytopes, composed of individual planar panels. A planform environment is assumed (but not required), where terrain is flat and buildings have an effective height above the terrain level. Exact building heights are used when available; otherwise, the building is assigned a height of 42N (meters), where N is the number of floors in the building. Reflection and transmission losses, according to the building material or user specification, are designated for each object in the database, through the use of AutoCAD’s attribute-assignment capabilities.

A three-dimensional building database for the Crogill Plaza and the Upper Quad areas of the Virginia Tech campus has been developed, as a practical application of the modeling technique. The database is derived from a two-dimensional, AutoCAD-format, plan-view map of the campus. Figures 5 and 6 depict simplified AutoCAD displays of these portions of the campus. Exact building heights were used for the Crogill Plaza area, while approximate building heights were used for the Upper Quad area.

4.2 Propagation prediction using ray tracing

The key features of a ray-tracing simulation program, used to automate the propagation-prediction model, are presented in this section. The program uses geometrical optics to trace the propagation of direct, reflected, transmitted, scattered, and diffracted rays. The rays, which represent local plane waves of the total field radiated by the transmitting antenna, originate from point sources, and propagate in three-dimensional space. The methodology employed here is similar to computer-graphics ray tracing for image synthesis. The goal of graphical ray tracing is to provide a viewer with the realistic impression of looking through a camera “eye,” to acquire a view of a certain image. The resulting image is defined by the viewer’s observation point, the viewing direction, and the field of view. As such, graphical ray tracing typically traces rays from the observation point backwards, towards the source. This reduces the number of rays to be traced, since only those rays which propagate through the viewing space to the observation point need be considered. Since RF energy can arrive at the receiver from any direction, propagation prediction requires that rays be traced in three dimensions with respect to the receiver location, to guarantee that all possible propagation paths from the transmitter are considered. No real advantage exists in tracing rays by starting at the receiver, as opposed to starting at the transmitter. In the case of multiple receiver locations, starting from the transmitter clearly reduces the workload of the simulation, since only one set of rays must be evaluated (the “transmitter’s”), rather than one set from each receiver location. As a result, this system follows the more-intuitive process of tracing rays as they emanate from the transmitter. Data regarding the propagation of each ray (e.g., propagation-path length, signal amplitude, time delay, etc.) must be maintained for each ray that is traced. The similarities between ray tracing for visual rendering and the propagation-prediction simulation enable the visualization techniques to be directly incorporated into the propagation-model development. Computer-graphics ray-tracing techniques are detailed in, for example, [7, 8, 26].

The simulation program uses ray tracing to identify each ray path by which significant levels of energy, radiated from the transmitting location, reach the receiving point(s) specified in the building-information database. Multiple receiving locations can be defined, so the procedure described here can be applied to each receiving point. Initially, the program checks for the existence of a line-of-sight ray between the transmitter and the receiver. Next, the program generates and traces a ray from the transmitter in a predetermined direction, and detects if it intersects an object specified in the building database. If no intersection is found, the process stops.
and a new source ray is initiated. If an intersection occurs, the program determines if a scattered ray has an unobstructed path from the intersection point to the receiver. The specularly reflected and transmitted rays are then traced. Each ray is analyzed in a fashion similar to the source ray. This recursive generation and tracing of source rays continues until, for each ray, an intersection with a receiver occurs, a maximum number of tree levels is exceeded (corresponding to an excessive number of intersections with objects prior to reaching the receiver), the ray energy falls below a specified threshold level (e.g., transmitted rays), or no further intersection occurs. Note that scattered rays which do not intersect with the receiver are not traced recursively, since the amplitude of these rays decreases rapidly with distance.

In order to determine all possible rays which may leave the transmitter and arrive at the receiver, it is necessary to consider all possible angles of departure from the transmitter, and all angles of arrival at the receiver. It is therefore desirable that each ray generated at the transmitter be launched so that it maintains a constant angular separation from its neighboring rays, in the three-dimensional space. This constant angular separation ensures that each ray represents an equal, regularly shaped, and unique portion of the total spherical wavefront. One method of obtaining equal angular separation is to inscribe an icosahedron inside a unit sphere surrounding the transmitter [24]. An icosahedron is a twenty-sided polyhedron, with triangular faces, and twelve vertices. Rays can be launched through each vertex, achieving an angular separation of 63°. To decrease the angular separation between rays, and therefore increase the resolution of the process, each triangular face of the icosahedron can be further subdivided into smaller triangles, with rays launched through these new vertices. Decreasing the angular separation between rays causes a concomitant increase in the total number of rays which must be evaluated, and thus increases the simulation run time. We conducted a number of pilot studies to determine "reasonable" values for the angular separation. For typically sized microcells, an acceptable trade-off between adequate coverage of the cell's area and computation time was observed using approximately 40,000 rays, an angular separation between rays of less than 1°.

A minimum-distance test is used to determine if a reflected or transmitted ray reaches a receiving point. As shown in Figure 7, a perpendicular projection from the receiving location to the ray path (labeled as the test ray in the figure) is computed, and the total path length, d, which the ray travels from the transmitter to the projection point, is determined. A reception sphere [8], having a radius of \( \alpha d / \sqrt{3} \), where \( \alpha \) is the angular spacing between neighboring rays at the transmitter, is constructed about the receiving location. If the ray intersects the reception sphere, it is considered to be received, and thus contributes to the total received signal. If the ray path lies outside the reception sphere (such as the two adjacent rays in Figure 7), the ray is not considered to be received, and the recursive-tracing mechanism continues, as previously described.

The ability to vary the radius of the reception sphere, based on the receiver's distance from the transmitter, effectively accounts for the divergence of the rays from the transmitter, and ensures the uniqueness of all specular-reflection points. From simple geometry, it can be observed that at distance \( d \) from the transmitter, adjacent rays are separated by a linear distance of approximately \( 2\alpha d / \sqrt{3} \). Hence, if the radius of the reception sphere is set to one-half that distance (\( \alpha d / \sqrt{3} \)), then at most one ray of any group of adjacent rays (representing many specularly reflected rays) will intersect the sphere, and be received. For typically sized microcells and a sufficiently small \( \alpha \) (generally less than 1°), the reception-sphere's occurrence rate of rays will be on the order of 1 meter: the rays intercepting the sphere will be an accurate measure of rays which would pass directly through the receiving point.

The model and simulation program can accommodate relatively arbitrary T-R separations for microcellular systems. If the T-R separation is extended, the angular separation between generated rays must be decreased, to ensure that distant objects are not "missed." Decreasing the angular separation results in a significantly larger number of rays which must be traced. Additionally, any number of buildings, limited only by the maximum capacity of the database, can be included in the modeling effort. However, as the number of objects included in the database increases, the number of intersection tests which must be performed tends to increase exponentially. Adaptive-spatial partitioning is used to offset this increased workload. As the building database is constructed, each object or group of objects is associated with a larger "bounding" volume [22]. Intersection tests are first performed on bounding volumes, rather than subordinate objects. If a test fails (no intersection), then intersection tests on subordinate objects need not be performed. If an intersection with the bounding volume is detected, further tests are performed on the objects within the volume. By grouping objects and, by extension, grouping nearby bounding volumes into a hierarchy of bounding volumes, the number of intersection tests which must be performed can be significantly reduced.

5. Propagation measurements and predictions

This section describes a field study, undertaken to validate the use of the geometrical-ray-optics propagation simulator in a microcellular environment. The correct operation of the program itself is briefly discussed. The program is used to predict power-delay profiles, for a number of sites corresponding to locations on the Virginia Tech campus. These predictions are then compared to field measurements taken at those locations.

Verification of the modeling tool was done through the use of controlled simulations. The verification of the simulator's operation included diagnostic evaluation of the software itself, as well as the evaluation of simple, hypothetical building geometries, where the propagation results were known in advance or could be computed manually. These results provided verification of the automation process, and assurance that repeatable results could be generated.
All of the automation features, such as the ray-launching algorithm, the reception-sphere technique, and the bounding-volume procedure, were also verified. The use of bounding volumes reduced the number of intersection tests which were performed by an order of magnitude, when compared to the number of tests made without bounding volumes. The simulation was written in the C++ programming language, and was run on Sun SparcStation workstations.

5.1 Propagation measurements

Propagation measurements were made in two separate locations on the Virginia Tech campus, and compared to predicted results from the ray-tracing simulation system. The two sites were selected because they represented different, yet typical, microcellular environments.

The first cell site was the Cogwill Plaza, shown previously in Figure 5. This location was representative of a typical microcell topography, being very similar to a courtyard near a shopping mall, hotel, or office complex. The base station was located near one corner of the plaza, and had clear "views" down the streets and sidewalks between buildings. The four receiver locations were selected to provide sufficient channel characterization for validating the propagation model, since both line-of-sight (at Hancock Hall, Johnston Student Center, and Burroughs Hall) and shadowed (in front of Norris Hall) topographies were represented.

The buildings surrounding the courtyard were constructed of rough-hewn stone, and reinforced concrete with a stucco outer surface. Both Hancock Hall and the Johnston Student Center had complex features near the measurement sites. Both had several large, clearly visible, windows on their upper floors, and a covered walkway next to their ground floor. Cogwill Hall also had several complicated features, such as large glass panels inset between large concrete pillars, which were visible to both the transmitter and receiver. On the other hand, the discernible faces of Burroughs Hall and Norris Hall were less complicated, being composed mostly of stone with several small, regularly spaced windows. The courtyard and surrounding areas were relatively free of smaller scattering objects, such as street signs, lamp posts, etc. The only area with substantial foliage was along the north (back) face of Burroughs Hall. However, since these measurements were made in early spring, there was little leafage on these trees.

The Upper Quad, depicted in Figure 6, was used as a second representative cell site. This site was chosen because it had a courtyard topography similar to Cogwill Plaza, but the buildings which surrounded the courtyard were dissimilar to those of the first measurement site. This was done to examine the impact of any assumptions made for the predictions corresponding to Cogwill Plaza, such as the reflection and the scattering properties of the buildings, without having to attribute inconsistencies in prediction accuracy to extreme changes in topography. The base station was situated near Rasche Hall, so that measurable signal levels would be available at all five receiving locations (the area near Rasche Hall was the most "open" area in the courtyard). The buildings surrounding the courtyard were constructed mostly of brick and, except for Lane Hall, were only moderately complex. Most of the faces of these buildings were not contiguous. Rather, they were composed of several individual, planar panels, where each panel had a different horizontal offset from neighboring panels. This gave the entire building a unique, corrugated appearance. Windows were also a very discriminating feature, where each building had different window sizes and spacing. Lane Hall was the most complex building surrounding the courtyard. Some of the more remarkable features were a wooden veranda at the front of the building, and decorative copper flashing around the veranda roof, building roof, and rooftop flagpole. Unlike Cogwill Plaza, this microcell had several large trees near Brodie Hall and Rasche Hall. There were also four large trees in front of the east wing of Lane Hall (the side closest to Rasche Hall). The measurements at this microcell site were made in late spring, when the trees were most densely foliated, and could possibly impact on propagation measurements. This, however, did not prove to be a significant factor in the propagation study.

The measurement locations were tested when there was light pedestrian and automobile traffic, so that the channel could be considered to be wide-sense stationary. At both microcells, the transmitter antenna was elevated to a height of 7.6 meters (approximately 25 feet), which was considered typical for a lamp-post-mounted microcell base station. The transmitter EIRP was 30 dBm. At each receiver location, the antenna was mounted at 1.7 meters (5.6 feet), to simulate the signal which would be received by a user in the cell. At each measurement site, five profiles were recorded over a one-half meter track, and these profiles were averaged to generate a single power-delay profile. Spatial averaging was necessary, to ensure that individual multipath components were not fading over a local area (due to components arriving within the same pulse width), and to improve the dynamic display range of the measurement system. Both the transmitter and receivers employed omnidirectional discone antennas, so that multipath components arriving at a receiver could be detected regardless of the angle of arrival in azimuth.

A 1900 MHz continuous spread-spectrum channel sounder was used for the measurements. The main advantage of using the spread-spectrum measurement system was that wide-bandwidth impulse-response estimates could be measured, at a dynamic range comparable to narrow-band measurement systems. The improvement in dynamic range of the spread-spectrum channel sounder over direct-pulse systems was accomplished by de-spreading the sequence before detection. Narrow-band detection circuitry could then be used, and thus the dynamic range was improved by reducing the effective noise bandwidth of the measurement system. The spread-spectrum channel sounder used for these measurements operated at a chip rate of 230 MHz, which provided approximately nine nanoseconds of time resolution (base width of the probing pulse), and was capable of measuring up to 120 dB of path loss.

5.2 Comparison of measured and predicted results

This section discusses and compares predicted and measured results for the two microcell sites. A total of nine receiver locations in the two cell sites was used. Evaluation of the propagation-prediction results was performed in two ways. First, direct, graphical comparison of predicted and measured propagation data was done. This "visual" comparison gave a high degree of confidence that the predicted results were indeed a true estimate of measured data. To strengthen the confidence in these results, a second evaluation, using statistical-analysis techniques, was performed. In this evaluation, the hypothesis that there was no statistical difference between the measured and predicted values was tested. Each of these evaluation efforts is discussed in the subsections below. In the discussions which follow, a particular measurement site is referred to by the name of the building which is closest to the measurement location.

5.2.1 Line-of-sight (LOS) reflective environments. Three of the measurement sites (Burruss Hall, Rasche Hall, and Brodie
Hall) were grouped together, because each had a geometry which allowed for both direct-ray, and single and multiple specular reflections to be received. Specular reflections were the primary source of multipath-signal components. Because of these geometries, it was felt that impact on the power-delay profile from scattered energy would be minimized.

The results for the Burruss Hall location are shown in Figure 8, and are representative of the results for the other two locations. The prediction accurately determined both the amplitude of the LOS component (within 3 dB), as well as the spread in first-arriving energy (due to a ground reflection appearing immediately after the LOS component). Several scattered components, with relatively short delays, also appeared, and caused a spread in the pulse width. The predicted results indicated arrival of specularly reflected rays with excess delays of 68, 72, and 160 ns. These arrival times appeared to correspond to the measured energy near 60 ns and 130 ns. Although difficult to discern in the figure, the model also predicted the presence of energy at 225 ns and 440 ns. These components were predicted as being a summation of many scattered rays which were each just above threshold, and could thus account for the 10 dB discrepancy between measured and predicted results at these time delays.

5.2.2 LOS reflective environments with scattering.

Receiver sites at Hancock Hall, Johnston Hall, and Lane Hall were all situated close to complicated building surfaces, which had potential scatterers. In addition, other nearby buildings were believed to be good sources of reflected energy. Thus, at these three locations, it was possible to examine both the accuracy of the reflection model and of the scattering model.

Figure 9 is a power-delay profile of the measured and predicted data for the Hancock Hall site. Good agreement between measured and predicted results is seen in the figure. The prediction correctly identified the LOS component, and additional specular-reflection components arriving at excess delays near 15 ns, 110 ns, 250 ns, 290 ns, and 340 ns. In each of these cases, the amplitude of the predicted component was within 5 dB of its measured value. The impact of the scattering model on the prediction is shown by this figure. In the predicted result, the energy received with delays from 50 ns to 150 ns and from 200 ns to 275 ns was dispersive in nature. This spread in the received energy was indicative of diffuse scattering from Hancock Hall and Cowgill Hall. The delay spread of arriving energy was caused by the excess path length scattered rays traveled, relative to the specular path. Examination of the power-delay profiles for Johnson and Lanes Halls also showed agreement between the measured and predicted values.

5.2.3 Shadowed environments. The Norris Hall and Major Williams Hall sites were used to validate both the accuracy of the diffraction model, and the ability of the reflection and scattering models to predict coverage in shadowed topographies. The Norris Hall site had a clear propagation path from the transmitter to the (diffracting) building corner, and from this building corner to the receiver. In contrast, the Major Williams Hall measurement was more complicated, as several trees were interspersed along the transmitter-to-building path. At both receiver sites, though, the sur-
rounding buildings were potential sources of reflected or scattered energy.

Measured and predicted data for the Norris Hall measurement site is given in Figure 10. The first peak in the predicted result corresponded to the component diffracted by the corner of Norris Hall. The model predicted the remaining portion of energy to be a result of scattering. The multipath components, arriving immediately after the diffracted component, were due to ground scattering. The energy appearing at excess delays between 100 ns and 200 ns was a result of scattering from Burruss Hall (after a reflection from Norris Hall).

An interesting observation can be made by comparing the relative magnitudes of the signals for the unshadowed sites in Figures 8 and 9, with the shaded environment depicted in Figure 10. There is a 30-40 dB difference in the peak-power levels of these figures, which results from the reception (or lack thereof) of line-of-sight or reflected-signal components. Thus, the diffracted-energy level received at the Norris Hall site is approximately comparable to the scattered energy received from Burruss Hall—which was not deemed to be a significant energy level for the Burruss Hall measurements, discussed in Section 5.3.1.

5.2.4 Statistical analysis. The visual comparison of the measured and predicted power-delay profiles clearly indicated that the ray-tracing simulation system was producing realistic values. Peak-power levels, and delays in the time of arrival of the line-of-sight and major-reflected rays, for the nine receiver sites, were very nearly identical to measured values. The simulated data “looked good.” To quantify the agreement between the measured and predicted values, statistical analysis techniques were used to test the following hypothesis:

The mean value of the population of differences between the measured-power level and the predicted-power level was zero.

This hypothesis was tantamount to stating that there was no significant difference between the measured and predicted power-delay profiles.

To evaluate the hypothesis, a paired-difference Student’s t-test was performed, using data from all nine receiver locations. Power levels for every 25 ns increment of excess-delay time were extracted, from the collection of measured and predicted data, and used as inputs to the t-test. A total of 183 pairs of sampling points were used in the analysis. A standard significance level of $\alpha = 0.05$ (a 95% confidence level) was chosen for use in the test. Evaluating Student’s t-distribution with 182 degrees of freedom resulted in a critical two-tailed value of $t_{critical} = 1.973$, and a value of $t = 1.413$. Since the value of $t$ fell below the critical (or rejection) region of the t-distribution curve, the hypothesis was very clearly supported. The predictive power of the simulation tool was thus validated for all propagation means: line-of-sight, reflection, scattering, as well as diffraction.

5.3 Summary of comparisons

A set of wide-band measurements, taken in two different areas on the Virginia Tech campus, was used to examine the accuracy of a simulation model, in predicting propagation in several different topographies. Visual comparison and statistical analysis of measured and predicted data was conducted, and the results indicated that excellent agreement was possible for a variety of channel topographies. The following specific items can be inferred:

- Simulation models, derived from the combination geometrical-optics, ray-tracing, and electromagnetic-transmission theory, can be used to predict microcellular channel-propagation characteristics. The observed level of accuracy exceeds the results typical of commercially available planning and prediction tools.

- By approximating a building with simple geometric shapes, it is possible to identify the major component of energy reflected from the building’s surface. However, for complicated building surfaces, small-scale building features can have an impact on the fine structure of the power-delay profile.

- A 12 dB reflection loss, regardless of incidence angle or polarization, appears to be a practical first-order approximation to the reflective properties of most buildings. Since the quantity of data collected was limited, it is not possible to make any specific comments regarding the reflective properties all of common building materials. However, a 12 dB loss per reflection is a reasonable value, until exact data become available.

- Secondary scatterers, which are in close proximity to the propagation path, may impact the received power-delay profile. Measurement locations used in this study were specifically chosen to minimize the impact of secondary scatterers. To enhance the accuracy of a prediction, it may be necessary to include these scatterers in the site-specific environmental database. This is especially true in shadowed topographies, where weak, scattered components can have a more significant effect on the power-delay profile.

6. Conclusions

This paper presented an innovative approach to site-specific propagation prediction, for microcellular-radio systems. Geographic and building information was integrated into an automated ray-tracing simulator, to predict radio-channel characteristics and signal-reception statistics, for receivers at specified locations within a microcell’s coverage area. The propagation model included the effects of direct, reflected, transmitted, and scattered, and diffracted radio waves. The waves were represented as rays, generated and launched in three-dimensional space, from the transmitter location. Using two areas on the Virginia Tech campus as representative cell sites, predicted signal levels were compared to field measurements. Excellent agreement was observed. Key predicted and measured levels were within 5 dB of each other. Statistically, the simulation values for channel-propagation characteristics were shown to be highly accurate predictions of measured results. Thus, simulation techniques, based on geometrical-optics ray tracing, have proven to be an effective means of incorporating critical, site-specific knowledge into the design of microcellular-radio designs, enabling the rapid implementation of PCN systems.

6. References


Introducing Feature Article Authors

Kurt R. Schaubach is an engineer with Southwestern Bell Technology Resources Inc., in Saint Louis, MO. He received his BSEE in 1990, and his MSVE in 1992, both from Virginia Polytechnic Institute and State University. While completing his degree requirements, he worked as an engineering intern at AT&T Quality
Management and Engineering, and at Kearfott Guidance and Navigation. His research interests are centered on the characterization of RF propagation for wireless communications-systems design. He is a member of the IEEE and the Eta Kappa Nu honorary society.

Nathaniel J. Davis IV is an Associate Professor of Electrical Engineering at Virginia Polytechnic Institute and State University. Prior to joining Virginia Tech, he spent 12 years on active duty with the United States Army Signal Corps, rising to the rank of Major. His research interests include parallel-processing systems, fault-tolerant and reconfigurable-computing structures, and computer-communication networks. Dr. Davis received the BSEE in 1976, and the MSEE in 1977, both from Virginia Tech. He received his PhD degree in electrical engineering, in 1985, from Purdue University. He is a senior member of the IEEE, and a member of the Armed Forces Communications Electronics Association and of Sigma Xi, Eta Kappa Nu, and Tau Beta Pi.

Kurt R. Schaubach
Nathaniel J. Davis IV

Feature Article Correction

Correction to ‘A Deformable Subreflector for the Haystack Radio Telescope’

An undetected font substitution occurred in the editing of the article, “A Deformable Subreflector for the Haystack Radio Telescope,” by Joseph Atebi, Melodi S. Zarghamieh, Frank W. Kan, Haywood Hartwell, Joseph E. Salah, and Steve M. Milner (IEEE Antennas and Propagation Magazine, 36, 3, June 1994, pp. 19–28). As a result, with the following exceptions, all units which should have appeared as “μm” (micrometers) appeared as “mm” (millimeters). With the following exceptions, all occurrences of the units, “mm,” should be replaced by “μm” (i.e., the units are correct in the following):

pg. 20, left column, first full paragraph, line three: 25.4 mm
pg. 21, left column, fourth paragraph, lines four, six, and seven: 6 mm; 12 mm; 38 mm; 64 mm
pg. 22, right column, first full paragraph, line two: 2.54 mm
pg. 24, left column, paragraph 7.3.1, line two: 2.565 mm

Figure 7 should also be rotated 180°.

The Magazine regrets these errors. A corrected reprint of the article may be obtained from Joseph Atebi, Simpson Gumpertz & Heger Inc., 297 Broadway, Arlington, MA 02174. WRS

Correction

Errors occurred in two figures in the article, “Graphics for Visualizing RCS as a Function of Frequency and Angle,” by C. L. Laroche, S. R. Mishra, and C. W. Truemane (IEEE Antennas and Propagation Magazine, 36, 3, June 1994, pp. 7–13). Although the figure captions were correct, the prints in Figures 5a and 11 were interchanged. The identifications of polarization which appeared on the prints themselves were correct. The Magazine regrets the error.

WRS