A Comparison of Theoretical and Empirical Reflection Coefficients for Typical Exterior Wall Surfaces in a Mobile Radio Environment

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Abstract—This paper presents microwave reflection coefficient measurements at 1.9 GHz and 4.0 GHz for a variety of typical smooth and rough exterior building surfaces. The measured test surfaces include walls composed of limestone blocks, glass, and brick. Reflection coefficients were measured by resolving individual reflected signal components temporally and spatially, using a spread-spectrum sliding correlation system with directional antennas. Measured reflection coefficients are compared to theoretical Fresnel reflection coefficients, applying Gaussian rough surface scattering corrections where applicable. Comparisons of theoretical calculations and measured test cases reveal that Fresnel reflection coefficients adequately predict the reflective properties of the glass and brick wall surfaces. The rough limestone block wall reflection measurements are shown to be bounded by the predictions using the Fresnel reflection coefficients for a smooth surface and the modified reflection coefficients using the Gaussian rough surface correction factors. A simple, but effective, reflection model for rough surfaces is proposed, which is in good agreement with propagation measurements at 1.9 GHz and 4 GHz for both vertical and horizontal antenna polarizations. These reflection coefficient models can be directly applied to the estimation of multipath signal strength in ray tracing algorithms for propagation prediction.

I. INTRODUCTION

WITH THE eminent arrival of commercial personal communication services (PCS), wireless service providers will need to rapidly deploy their networks to quickly gain marketshare. To install and maintain reliable PCS systems, a thorough understanding of the RF propagation channel is essential. Recent studies on ray tracing techniques for propagation prediction [1]-[12] have shown promising results in predicting channel parameters such as path loss and delay spread in complex environments. Ray-tracing approximates electromagnetic waves as discrete propagating rays that undergo attenuation, reflection, and diffuse scattering phenomena due to the presence of buildings, walls, and other obstructions. The total received electric field at a point is the summation of the electric fields of each multipath component (or ray path) that illuminates the receiver.

As with any radio propagation model, ray-tracing techniques need to be verified and enhanced with actual RF measurements which are representative of the possible installation scenarios. Propagation studies in microcellular environments have shown that significant multipath components arise from reflections off of building surfaces [13]-[16], [23]. Hence, ray-tracing techniques must reliably predict the influence of these buildings and other obstructions. For specularly reflected ray paths (i.e., reflection for which parallel incident rays remain parallel after reflection), the Fresnel reflection coefficients can be used to predict the reflection loss of a building surface, provided its dielectric properties are known. While there exists a classic body of literature for the electromagnetic properties of various materials [17]-[18], the actual reflective properties of typical external building structures at microwave frequency bands are just beginning to be explored [19]-[25].

To provide enhanced reflection coefficient models for buildings, measurements at 1.9 GHz and 4.0 GHz have been made for a variety of typical smooth and rough exterior building surfaces. The measured test surfaces include walls composed of limestone blocks, glass, and brick. Reflection coefficients were measured by resolving individual reflected signal components temporally and spatially, using a spread-spectrum sliding correlation system with directional antennas. The measured reflection coefficients are compared with theoretical Fresnel reflection coefficients using Gaussian rough surface scattering corrections when applicable. The measured reflection coefficients are compared with theoretical Fresnel reflection coefficients using Gaussian rough surface scattering corrections when applicable. The dielectric material properties of the tested building surfaces were taken from either published data [17], [18], or measurements [19]. These comparisons are used to develop simple, and empirically accurate, reflection models for building surfaces that can be directly applied to ray-tracing algorithms.

II. REFLECTION AND SCATTERING MODELS

The Fresnel reflection coefficients (\( \Gamma \)) relate the field reflected from an infinite dielectric slab to the incident field, and are described in [26], [27] as

\[
\begin{align*}
E^\perp &= \Gamma^\perp E^\perp \\
E^\parallel &= \Gamma^\parallel E^\parallel
\end{align*}
\]  

(1)

Manuscript received March 22, 1995. This work was supported by DARPA/ESTO and the MPRG Industrial Affiliates Program at Virginia Tech.

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Publisher Item Identifier S 0018-926X/96$05.00 © 1996 IEEE
where $\vec{E}'$ and $\vec{E}''$ are the incident and reflected fields, respectively. The parallel (perpendicular) subscript refers to the $E$-field component that is parallel (perpendicular) to the plane of incidence, as shown in Fig. 1. The reflection coefficients, determined by material properties, angle of incidence ($\theta_i$), and frequency, are given by

$$
\begin{align*}
\Gamma_\parallel &= \frac{\eta_2 \cos \theta_t - \eta_1 \cos \theta_i}{\eta_2 \cos \theta_t + \eta_1 \cos \theta_i} \\
\Gamma_\perp &= \frac{\eta_2 \cos \theta_t - \eta_1 \cos \theta_i}{\eta_2 \cos \theta_t + \eta_1 \cos \theta_i}
\end{align*}
$$

(2)

where the wave impedances ($\eta_m$) and the transmitted wave angle ($\theta_t$) are expressed as

$$
\eta_m = \sqrt{\frac{j\omega \mu_m}{\varepsilon_m + j\omega \varepsilon_m}} \quad (m = 1, 2)
$$

(3)

$$
\cos \theta_t = \sqrt{1 - \left( \frac{k_1}{k_2} \right)^2 \sin^2 \theta_i^2}
$$

where $\omega$ is the radian frequency and the wavenumbers ($k_m$) are

$$
k_m = \omega \sqrt{\mu_m \varepsilon_m - \frac{j\omega \mu_m \varepsilon_m}{\omega}}
$$

(4)

The properties of each of the dielectric materials at the interface are characterized by their permittivity ($\varepsilon_m$), magnetic permeability ($\mu_m$), and conductance ($\sigma_m$).

The Fresnel reflection coefficients in (2) account only for specular reflection, which occurs for smooth surfaces. When the surface is rough, impinging energy will be scattered in angles other than the specular angle of reflection (i.e., diffuse reflection), thereby reducing energy in the specularly reflected component [26]-[30]. The Rayleigh criterion is commonly used as a test for surface roughness, giving the critical height ($h_c$) of surface protuberances as

$$
h_c = \frac{\lambda}{8 \cos \theta_i}
$$

(5)

where $\lambda$ is the RF wavelength. The height ($h$) of a given rough surface is defined as the minimum to maximum surface protuberance, as shown in Fig. 2. A surface is considered smooth if $h < h_c$ and rough if $h > h_c$. Equation (5) shows that as the incident angle approaches grazing (i.e., $\theta_i \rightarrow 90^\circ$), the critical height becomes larger, effectively reducing the scattering effect of the surface protuberances. For the case of rough surfaces, a scattering loss factor ($\rho_S$) was derived in [28] to account for diminished energy in the specular direction of reflection, given by

$$
\rho_S = \exp \left[-8 \left( \frac{\pi \sigma_h \cos \theta_i}{\lambda} \right)^2 \right]
$$

(6)

where $\sigma_h$ is the standard deviation of the surface height about the mean surface height in the first Fresnel zone of the illuminating antenna. The assumption in (6) is that the surface heights are Gaussian distributed. In general, incident radiation on a surface will induce a current density ($J$) which is a function of both $x$ and $y$ directions shown in Fig. 2. Equation (6) assumes that this surface current density at height $y$ is always $J(y)$, regardless of whether the surface element at a particular $z$ is shadowed or illuminated by another part of the surface. This approximation was made to simplify the integral equations used to derive (6). When $\rho_S$ is used to modify the reflection coefficients, we refer to this model as the Gaussian rough surface scattering model, which is written as

$$
(\Gamma_\parallel)_{\text{rough}} = \rho_S \Gamma_\parallel \quad (\Gamma_\perp)_{\text{rough}} = \rho_S \Gamma_\perp.
$$

(7)

It was reported in [29] that the scattering loss factor of (6) gives better agreement with measured results when modified as

$$
\rho_S = \exp \left[-8 \left( \frac{\pi \sigma_h \cos \theta_i}{\lambda} \right)^2 \right] I_0 \left[8 \left( \frac{\pi \sigma_h \cos \theta_i}{\lambda} \right)^2 \right]
$$

(8)

where $I_0(z)$ is the modified Bessel function of zeroth order. When the Bessel function argument is small, (6) and (8) are approximately equal, since $I_0(z)$ approaches unity.

The Fresnel models presented here assume the dielectric slab is infinite in extent. Although this is not true for real buildings, the dimensions of the tested building reflecting surfaces are sufficiently large that they may be approximated as infinite, such that these models can be applied.

III. 1.9 GHz AND 4.0 GHz MEASUREMENT SYSTEMS

Various techniques for measuring UHF and microwave reflection coefficients of materials have been reported in the literature [20]-[25] and [31]-[33]. Of these, wideband measurement systems have the ability to temporally resolve desired reflections from spurious, unwanted signals. For this research, a wideband spread-spectrum sliding correlation system was...
The temporal resolution of these systems is determined by the transmitted RF bandwidth. The 1.9 GHz and 4 GHz measurement systems used slightly different hardware, but were conceptually the same. Fig. 3 shows the system block diagram of the 4 GHz measurement system. At the transmitter, a CW source was modulated by the maximal length pseudonoise (PN) sequence, giving the characteristic \((\sin(x)/x)^2\) power spectrum. This signal was then amplified up to a maximum of 10 W and transmitted via the high gain horn antenna. The transmitted power at the antenna terminal was monitored using the power meter and accounting for the RF coupler and cable loss.

At the receiver, the spread-spectrum signal was correlated to the identical PN sequence with a clock rate which was slightly offset from the transmitter. This causes the two sequences to slide past each other, giving maximal correlation when aligned. When multiple incoming signal paths arrive at the receiver with different time delays, each will correlate with the receiver PN sequence at the corresponding time. The correlation process effectively converts the wideband signal into the RF channel impulse response, where it was filtered, down-converted, and detected using a spectrum analyzer set to zero span. The baseband output was displayed in real time on the digital storage oscilloscope (DSO) and stored on a portable computer for later processing.

The temporal resolution of these systems allowed easy identification of desired reflected multipaths from other spurious signals. In particular, the 240-MHz PN sequence clock gave an RMS system resolution of approximately 4.2 ns. For spatial resolution, the 4.0-GHz measurement system used 18.6-dB standard gain horns (at the transmitter and receiver) with measured E-plane and H-plane half-power beamwidths of 17.2° and 14.3°, respectively. The 1.9-GHz system used trapezoidal log-periodic antennas with 60° half-power beamwidths. Further specifications of these systems are given in [20]. Due to the superior spatial resolution of the 4.0-GHz system, most of the measurements were performed at this band, where the surface roughness effects are more pronounced.

**IV. REFLECTION COEFFICIENT MEASUREMENT**

The reflection coefficients were measured using a two-step technique [20], [21] shown in Fig. 4. First, 10 line-of-sight (LOS) channel-impulse responses were measured with the two antennas facing each other. Then, the antennas were aimed at the reflection point on the test surface and 10 reflected channel-impulse responses were collected. The LOS measurements provided a reference for comparison with the received channel-impulse responses from the reflection measurements. Performing the LOS and reflected path measurements sequentially ensured that variances due to the measurement equipment (e.g., temperature variations, cable losses, connector losses, etc.) were minimized. This two-step method was repeated for each desired incident angle, as well as for different test surfaces.

Examples of measured LOS and reflected path impulse responses are shown in Fig. 5. In many instances, the reflected path impulse response contained both an LOS and reflected peak, where the LOS peak was attenuated by the directional antenna patterns. These multipath components were resolved temporally by comparing the measured differential delay (i.e., the difference in arrival times of the reflected path with respect to the LOS path) to the calculated differential delay using the geometry in Fig. 4. The result of this comparison is shown in Fig. 5(b).

The transmitter and receiver locations were constrained by a number of factors, including desired specular reflection angles, temporal resolution of the sliding correlator, far-field criteria, and environment topography. For example, the temporal resolution of the measurement system dictates the minimum resolvable differential delay, and hence, the allowable transmitter and receiver positions. In addition, the transmitter distance \(d_1\) in Fig. 4 was selected to ensure that incident waves striking the test surface could be approximated as plane waves. For these reasons, the dimensions shown in Fig. 4 varied over the following ranges: 3 m < \(d_1\) < 27 m, 3 m < \(d_2\) < 40 m, and 3 m < \(d_{LOS}\) < 65 m. For a particular incident angle, \(d_1\) remained fixed while the receiver distance \(d_2\), and hence, \(d_{LOS}\), was selectively varied.
Fig. 5. Examples of (a) LOS channel-impulse response and (b) reflected path channel impulse response at 4.0 GHz (time axis has arbitrary zero reference).

During the measurements, the antennas were kept stationary for two reasons. The first was that moving the directional antenna over a local area would induce artificial multipath fluctuations caused by directional antenna patterns, pointing errors, etc. The second was that it was observed in the field that the magnitudes of individual multipaths faded only slightly with small linear movements (i.e., a few wavelengths) of the receiving antenna. This observation agrees with the reasoning that signal fading in local neighborhoods is mainly due to the constructive and destructive interference of multipaths, rather than variations on the individual multipath amplitudes. This phenomena was also shown to be true for indoor factory channels containing an LOS path [35]. Individual multipath amplitudes should vary significantly within a small area only when a path is composed of a number of subpaths or when a path suddenly becomes shadowed by some obstacle in the environment. Since there were no obstacles in the test environments, the main cause of fades on any individual multipath is due to clusters of subpaths forming that multipath. Since the sliding correlation system can resolve individual multipath components 4.2 nanoseconds apart, the subpath clusters can possibly affect the wideband measurements in two ways. The first is in the LOS measurement where the ground reflection generally exceeds the system temporal resolution due to the physical geometry (discussed further in Section V). The second is in the reflected path measurements, where wall surface protuberances can induce interference effects that are also irresolvable by the wideband system. To observe this effect, the receiver distance ($d_2$ in Fig. 4) was selectively varied for most measured incident angles ($\theta_i$). These results are discussed in Section VII.

The post-processing task began with the conversion of the individual impulse responses into corresponding measured power delay profiles, using the calibration characteristics of the receiving system. Then for each transmitter and receiver location, the ensemble average of the 10 raw power delay profiles was calculated. The averaged LOS power from the averaged LOS delay profile was taken to be the free space value, i.e.,

$$(P_{R})_{LOS} = \frac{P_T G_T G_R \lambda^2}{(4\pi d_{LOS})^2}.$$  \tag{9}$$

The averaged power delay profile for the reflected path measurements was calculated in an identical manner. The averaged reflected power was taken to be the free space value for the unfolded path length multiplied by the square of the voltage reflection coefficient ($\Gamma$), or

$$(P_{R})_{refl} = \frac{P_T G_T G_R \lambda^2}{(4\pi)^2 (d_1 + d_2)^2} |\Gamma|^2.$$  \tag{10}$$

The use of the Fresnel reflection coefficient in (10) is an approximation since rigorous electromagnetic image theory requires perfect conductivity [36]. Equation (10) also assumes that the reflecting boundary is infinitely large, which is approximately true, when the wall dimensions are much larger than distances $d_1$ and $d_2$ in Fig. 4 and the wall surface area is much larger than the illuminated area. Assuming these conditions are satisfied, taking the ratio of (9) and (10) and solving for the reflection coefficient yields

$$|\Gamma| = \frac{d_1 + d_2}{d_{LOS}} \sqrt{\frac{(P_{R})_{refl}}{(P_{R})_{LOS}}}.$$  \tag{11}$$

Therefore, the empirical reflection coefficient is the square root of the ratio of the reflected and LOS power measurements, weighted by the difference in measurement distances (i.e., accounting for the path loss difference in the two measurements).

V. EFFECTS OF GROUND REFLECTION

In the LOS measurements, a ground-reflected multipath may interfere with the direct LOS path. These ground-reflected multipaths are irresolvable from the LOS path because they generally exceed the temporal and spatial resolution capabilities of the measurement system. The severity of this interference depends on the antenna patterns and the distance between the transmitter and receiver.

To determine whether ground reflection would have a significant effect on the reflection coefficient measurements, a series of LOS measurements were made. The transmitter and receiver separation was varied along a linear path while the wideband delay profiles were measured. These impulse responses were converted into their equivalent powers and plotted versus predictions with a two-ray model [20]. The two-ray model computes the received power as the magnitude squared of
the vector sum of the LOS and ground reflected electric field components, whose magnitudes and phases were computed theoretically. The ground reflected component was multiplied by the reflection coefficient of the ground and the elevation patterns of the antennas. The ground was modeled as either being moist soil or a perfect reflector. The moist soil reflection coefficients were calculated using (2) with tabulated dielectric parameters \( \epsilon_r = 30, \sigma = 0.02 \) S/m. The perfect reflector was simply modeled as having a unity reflection coefficient \( \Gamma = -1 \), regardless of incident angle. The elevation patterns of the directional antennas were modeled as \( \frac{\sin(z)}{z} \) functions. The two-ray model assumed antenna 3-dB beamwidths of 20° and two meter antenna heights (above ground). Figs. 6 and 7 show the results of the wideband LOS measurements and the various ground reflection models. The measurements show that there are minor variations around the free space LOS power, which loosely agrees with the predictions of the two-ray model. In general, the measurements agree well with the free space prediction, with the exception of one measurement point near 16 meters.

Let the LOS error \( E_{LOS} \) be defined as

\[
E_{LOS} = 10 \log \left( \frac{P_{R,LOS}}{P_{R,MEAS}} \right) \quad \text{(12)}
\]

where \( P_{R,LOS} \) is the ideal free space LOS power (in mW) and \( P_{R,MEAS} \) is the measured LOS power (in mW) including ground reflections. For each measurement point in Figs. 6 and 7, the LOS error was computed. From the ensemble of LOS errors, the mean error and standard deviation are less than 1.3 dB and 1.9 dB, respectively. The positive mean error of 1.3 dB could be easily caused by measurement system losses (such as cables, connectors, aperture efficiencies, etc.) which are not included in the free space model. Therefore, the significant parameter is the 1.9-dB standard deviation, which gives an indication of the variability of the measured LOS power. Assuming these errors are Gaussian distributed, 94% (i.e., two standard deviations) of the variations due to ground reflection are expected to be within 4 dB.

To quantify the effects of these LOS errors on the computed reflection coefficients, the reflection coefficient error \( E_{\Gamma} \) is expressed as

\[
E_{\Gamma} = \left| \frac{\Gamma \left( P_{R,MEAS} \right)}{\Gamma \left( P_{R,LOS} \right)} \right| - 1 \quad \text{(13)}
\]

For the measurements presented in this paper, the distance ratio in (13) is less than two for more than 85% of the transmitter and receiver positions used. Therefore, a conservative error estimate can be written as

\[
E_{\Gamma} \approx 2 \left( \frac{P_{R,LOS}}{P_{R,MEAS}} \right) \sqrt{E_{LOS} - 1} \quad \text{(14)}
\]

where \( E_{LOS} \) is now the linear power ratio (not in dB). As the reflected to LOS power ratio decreases, the effect of LOS errors decreases. Typical reflected to LOS power ratios for the measurements reported here were less than \(-15 \) dB, although occasionally were above \(-10 \) dB. Therefore, if 94% of the measured LOS variations were less than 4 dB, the typical reflection coefficient errors should be no worse than 0.2 (in magnitude of field ratio). In general, the errors will be much smaller than that, so these measurements should give adequate results for the reflection characteristics of the test surfaces.

### VI. Measurement Sites

Two buildings were carefully selected for the reflection coefficient measurements. These buildings had exterior walls made of rough limestone, smooth metallized glass, and brick. These walls were chosen since they were representative of typical building surfaces in a mobile radio environment. The chosen sites had homogenous surface characteristics (i.e., free of clutter, windows, doors, etc.) and were relatively isolated from objects which could induce additional reflection and scattering. The variation of surface roughness at these sites ranged from very rough stone to smooth glass.

The rough stone wall was located toward the rear of a six-story office building constructed of large rectangular limestone blocks. The sizes of the limestone blocks varied, with the average block being approximately 0.5 meters wide and 0.3 meters high. The outer surfaces of these blocks exhibited random roughness features, with a roughness height up to 12.7
cm. The metallized glass wall was located on the same building and separated an interior lounge area from a parking lot. The glass wall measurements were conducted at 4.0 GHz only, while both frequencies were measured at the limestone wall.

The brick wall was located in the rear of a multilevel recreational facility constructed of concrete and red masonry brick common in residential homes, as well as older urban buildings. Table I lists the estimated surface roughness parameters and the measured dielectric properties [19] of the limestone and brick surfaces at 4.0 GHz. The roughness parameters for these surfaces are the same for both frequencies, and the dielectric properties are approximately the same. The dielectric properties for the glass wall were not measured in [19].

<table>
<thead>
<tr>
<th>Wall</th>
<th>h (cm)</th>
<th>σh (cm)</th>
<th>εr</th>
<th>μr</th>
<th>σ (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>12.7</td>
<td>2.5</td>
<td>7.51</td>
<td>0.95</td>
<td>0.03</td>
</tr>
<tr>
<td>Brick</td>
<td>1.3</td>
<td>0.5</td>
<td>4.44</td>
<td>0.99</td>
<td>0.01</td>
</tr>
</tbody>
</table>

VII. MEASUREMENT RESULTS

Measurement and prediction comparisons were performed for perpendicular and parallel polarizations for each test wall surface. The predicted reflection coefficients are simply the Fresnel formulas of (2) versus incident angle, using the rough surface scattering corrections when appropriate. Each measured reflection coefficient was obtained by averaging 10 LOS and 10 reflected path power delay profiles, then using (11) with the corresponding transmitter and receiver distances. For most incident angles (θi), the receiver distance (d2 in Fig. 4) is selectively varied to observe overall measurement variations due to surface protuberances.

A. Limestone Wall Results at 1.9 GHz and 4.0 GHz

Figs. 8 and 9 show the 1.9 GHz comparison results for the rough limestone wall for perpendicular and parallel polarizations, respectively. The measurements are compared with the theoretical Fresnel reflection formulas for smooth surfaces and for rough surfaces using the scattering correction of (6) and (8). The Fresnel model using (6) is referred to as the Gaussian rough surface, while using (8) is referred to as the modified Gaussian rough surface. For this surface, the measured data shows significant variability as a function of the receiver distance (d2). This variability can be the result of a number of factors, including ground reflection effects and interference of the reflected multipath due to surface protuberances. Regardless, over 90% of the measured reflection coefficients are bounded by the Fresnel formulas for smooth and rough surfaces. In almost all cases, Figs. 8 and 9 show that using the Gaussian rough surface model alone gives pessimistic predictions to the measured reflection coefficient values. The comparison between the scattering loss factors in (6) and (8) shows that (8) gives better agreement with measured values.

Figs. 10 and 11 show the 4.0 GHz comparison results for the limestone wall for perpendicular and parallel polarizations, respectively. Again, the measurements are compared with the theoretical Fresnel reflection formulas for smooth surfaces and for rough surfaces using the scattering corrections of (6) and (8). The theoretical models show that the smooth surface reflection coefficients at 1.9 GHz and 4.0 GHz are nearly equivalent. This is an expected result since the reflection coefficients in (2) become frequency independent when σ → 0. However, the scattering corrections are a strong function of frequency.

From the 4.0-GHz results in Figs. 10 and 11, over 92% of the measured reflection coefficients are bounded by the Fresnel formulas for smooth and rough surfaces. Similar to the 1.9-GHz measurements, the 4.0-GHz measured data shows significant variability when varying the receiver distance (d2), although the variations tend to be more clustered. In addition, the Gaussian rough-surface model (with either scattering loss factor) tends to give pessimistic predictions of the measured reflection coefficient values, although (8) does provide some improvement over (6).

The observation that the scattering loss factor overestimates the scattering loss for many of the measurements may be attributed to a number of simplifying assumptions (e.g., Gaussian distribution of surface heights, sharp edge effects, etc.).
Regardless, Figs. 8–11 suggest that in the absence of measured data, an adequate model for rough building surfaces can be computed by averaging the Fresnel reflection coefficients for smooth and rough surfaces, as a function of incident angle, i.e.,

\[
\Gamma_{AVG} \equiv \frac{\Gamma_{\perp,\perp} + \rho_S \Gamma_{\perp,\parallel}}{2} = \frac{1 + \rho_S}{2} \Gamma_{\perp,\parallel} \tag{15}
\]

where \(\Gamma_{\perp,\parallel}\) is either the perpendicular or parallel polarization reflection coefficient given in (2) and \(\rho_S\) is the scattering loss factor given in (6). To assess the accuracy of the simple model in (15), \(\Gamma_{AVG}\) was compared to each measured reflection coefficient in Figs. 8–11. From the resulting ensemble of errors, the error statistics, including average error \(E_{avg}\), standard deviation \(s\), and the 90th percentile are given in Table II. From this table, \(\Gamma_{AVG}\) tends to underestimate the reflection coefficient at 1.9 GHz and overestimate the reflection coefficient at 4.0 GHz (on average). The overall fit of \(\Gamma_{AVG}\) to the measured reflection coefficients was slightly better for parallel polarization, as seen by the smaller standard deviations and 90th percentiles. Over the ensemble of measured results at both frequencies and polarizations, the model of (15) gives a 90th percentile of error of 0.19.

To quantify the improvement of \(\Gamma_{AVG}\) over using only \(\Gamma_{\perp,\parallel}\) for smooth surfaces, the error statistics comparing the measured data with the Fresnel formulas in (2) were computed. This was then repeated using the modified Fresnel formulas in (7), accounting for roughness effects. Table III details the error statistics comparing all of the 1.9 GHz and 4.0 GHz measured data with each of the three model combinations (i.e., \(\Gamma_{AVG}\), \(\Gamma_{\perp,\parallel}\), and \(\rho_S \Gamma_{\perp,\parallel}\)). This table shows that using the smooth surface Fresnel coefficient alone gives overly optimistic results, while the rough surface model gives overly pessimistic results. The average error improvement of \(\Gamma_{AVG}\) over the smooth and rough surface models is approximately 0.2 in both cases. The impact of this difference will be discussed in the next section.

B. Glass Wall Results at 4.0 GHz

Figs. 12 and 13 show the comparisons between the measured glass wall reflection coefficients and the Fresnel formulas for smooth surfaces for perpendicular and parallel polarizations, respectively. Since the glass wall was electromagnetically smooth, the rough surface scattering corrections were not applied. For this particular glass wall, the dielectric properties were unknown. The dielectric properties of clear, nondoped glass are typically quoted as: \(\varepsilon_r = 5\), \(\mu_r = 1\) and \(\sigma = 10^{-12}\) S/m [26]. Since the glass wall was metallized, the conductivity was higher than 10^{-12} S/m. Because the conductivity was unknown, several Fresnel reflection coefficient curves with various conductivities (10^{-12} to 10 S/m) are plotted in Figs. 12 and 13. A material having a conductivity of 10.0 S/m would be considered a semiconductor, similar to seawater or intrinsic germanium. A good conductor would typically exhibit \(\sigma > 10^{6}\) S/m.

Figs. 12 and 13 show that the measured reflection coefficients exhibit a dependence on incident angle similar to that predicted by the Fresnel formulas. In addition, these measurements exhibit significantly less variability than that seen in the rough limestone wall for a particular incident angle \(\theta_i\), indicating much less interference effects from surface protuberances.

The measured reflection coefficients of Fig. 12 closely agree with the theoretical Fresnel reflection coefficients using \(\sigma \approx 5\) S/m. For many of the measurements where \(\theta_i \geq 45^\circ\), the...
measured reflection coefficients are even greater than that predicted using \( \sigma = 10 \text{ S/m} \). In Fig. 13, the comparisons indicate that the measured reflection coefficients are well approximated by the Fresnel reflection coefficients using \( \sigma \approx 2.5 \text{ S/m} \). For modeling the glass wall, the conductivities of 5 S/m and 2.5 S/m were used for perpendicular and parallel polarizations, respectively. For each measured reflection coefficient, the modeling error was computed. From the resulting ensemble of errors, the error statistics, including average error \( (E_{\text{avg}}) \), standard deviation \( (\sigma) \), and the 90th percentile are given in Table IV. The overall fit of the Fresnel reflection formulas to the measured data shows excellent agreement when using the appropriate dielectric properties.

Over the ensemble of all measured results at the glass wall, the theoretical models give a 90th percentile of error of 0.13. These error calculations were then repeated using the tabulated conductivity for clear, nondoped glass \( (i.e., \sigma = 10^{-12} \text{ S/m}) \) for comparison purposes. Table IV clearly shows that modeling this glass wall using the clear glass conductivity was pessimistic (as seen by the large positive \( E_{\text{avg}} \)). The average error improvement of using a conductivity which fits the measured data over using the published value for clear glass is approximately 0.31 and 0.26 for perpendicular and parallel polarizations, respectively. The impact of these differences will be discussed further in the next section. These results demonstrate that metallization and other impurities can have significant effects on the reflectivity of glass surfaces commonly used in building construction.

C. Brick Wall Results at 4.0 GHz

Figs. 14 and 15 show the brick wall reflection coefficient results for perpendicular and parallel polarizations, respectively. For these comparisons, the Fresnel reflection formulas for smooth surfaces and rough surfaces were used. These formulas used the measured dielectric properties for brick [19] and the estimated roughness parameters from Table I. For this brick wall surface, there is little difference between the scattering loss factors of (6) and (8), because the small standard deviation of height \( (\sigma_h) \) causes the Bessel function in (8) to approach unity.

Similar to the glass wall measurements, the brick wall data points are clustered together for particular incident angles \( (\theta_i) \). This indicates little variability in the measured coefficients as the receiver distance \( (d_2) \) is varied and, therefore, are relatively insensitive to interference effects from surface protuberances. The differences between the theoretical models of the smooth versus rough surface for the brick wall are much smaller than in the rough limestone case. Hence, the measured reflection coefficients of the brick wall are not well bounded by the smooth and rough surface predictions, in general. The roughness of the brick surface is such that the critical heights \( (h_c) \) are greater than the maximum protuberances for many of the incident angles. Because of this, the Rayleigh criterion predicts that the surface appears smooth to the incident radiation and the reflection will be predominantly

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**Table IV**

<table>
<thead>
<tr>
<th>Surface</th>
<th>Polarization</th>
<th>( E_{\text{avg}} )</th>
<th>( \sigma )</th>
<th>90th %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass ((\sigma = 5 \text{ S/m}))</td>
<td>Perpendicular</td>
<td>+0.01</td>
<td>0.08</td>
<td>0.13</td>
</tr>
<tr>
<td>Glass ((\sigma = 2.5 \text{ S/m}))</td>
<td>Parallel</td>
<td>0.00</td>
<td>0.07</td>
<td>0.11</td>
</tr>
<tr>
<td>Glass ((\sigma = 10^{-12} \text{ S/m}))</td>
<td>Perpendicular</td>
<td>+0.32</td>
<td>0.06</td>
<td>0.38</td>
</tr>
<tr>
<td>Glass ((\sigma = 10^{-12} \text{ S/m}))</td>
<td>Parallel</td>
<td>+0.36</td>
<td>0.08</td>
<td>0.32</td>
</tr>
<tr>
<td>Brick</td>
<td>Perpendicular</td>
<td>-0.05</td>
<td>0.10</td>
<td>0.16</td>
</tr>
<tr>
<td>Brick</td>
<td>Parallel</td>
<td>+0.01</td>
<td>0.10</td>
<td>0.18</td>
</tr>
</tbody>
</table>
specular. To some degree, this is seen in Figs. 14 and 15 since the measurements are distributed about the predicted Fresnel reflection coefficients for smooth surfaces. To quantify the differences between the predicted reflection coefficients and the measured data, the modeling error is calculated for each measured data point. From the resulting ensemble of errors, the error statistics, including average error (E_{avg}), standard deviation (\sigma), and the 90th percentile are given in Table IV. The overall fit of the smooth surface reflection formulas to the measured data shows excellent agreement when using the known dielectric properties. Over the ensemble of all measured results at the brick wall, the theoretical models give a 90th percentile of error of 0.18.

In comparing the glass and brick wall measurements, both are accurately described using the smooth surface Fresnel formulas of (2). These formulas give slightly better agreement with the glass wall (using \sigma = 2.5 \sim 5 \text{ S/m}) than the brick wall. This is noted by the larger standard deviations and 90th percentiles in Table IV for the brick surface. Over the ensemble of measured results at both the glass and brick walls, the smooth surface model of (2) gives a 90th percentile of error of 0.14. These error statistics indicate that (2) gives an empirically accurate model for surfaces with roughness features smaller than the critical height of (5).

VIII. IMPLICATIONS FOR PROPAGATION PREDICTION

When discussing ray-tracing in urban environments and reflection properties of building surfaces, the following question typically arises, "How accurate must reflection coefficients be to obtain an accurate prediction?" While the question is straightforward, the answer is, unfortunately, that it depends on the situation. On one hand, there is potentially a large number of variables which can have a significant impact on accuracy, in which reflection properties are but one (e.g., LOS/OBS topography, reflection properties, diffraction modeling, terrain effects, accuracy of building database, local scattering effects, etc.). On the other hand, ray-tracing algorithms are fairly sensitive to the reflective properties of the environmental objects, and if not adequately modeled, can give large prediction errors.

As an example, let the true reflection coefficient of a building surface be represented by \Gamma. Now, assume the reflection coefficient was actually modeled as \Gamma' + E_{\Gamma}, where E_{\Gamma} is the reflection coefficient error. Using (10) to calculate the reflected ray powers using the true reflection coefficient versus the modeled coefficient, the power difference (\Delta) in dB of the two rays is

\[ \Delta = 20\log \left( \frac{\Gamma}{\Gamma + E_{\Gamma}} \right) \text{[dB]} . \] (16)

Fig. 16 shows the magnitudes of \Delta for various reflection coefficient values. A positive power difference (\Delta > 0) implies that the true reflected power is greater than the predicted power, and vice versa. As an example, the glass wall measurements in Section VII showed that average error improvement of the fitted reflection models over the predictions using published conductivities was approximately 0.31 for perpendicular polarization. Assuming the true reflection coefficient for this case was 0.75 for all incident angles, the predicted power error on a single reflected path would be approximately 4.6 dB.

IX. CONCLUSION

Microwave reflection coefficient measurements were presented at 1.9 GHz and 4.0 GHz for a variety of typical smooth and rough exterior building surfaces. The measurement test cases included walls made of limestone blocks, glass, and brick. The reflection coefficients were measured by resolving individual reflected signal multipath temporally and spatially, using a wideband spread spectrum system and directional antennas. The measurement results were compared to the theoretical Fresnel reflection coefficients using Gaussian rough surface scattering corrections when applicable.

The measured reflection coefficients at the limestone wall showed significant variability, which can be attributed to several factors, including ground reflection effects and interference of the reflected multipath due to surface protuberances. In any case, over 92% of the measured reflection coefficients at 1.9 GHz and 4.0 GHz were bounded by the Fresnel formulas for smooth and rough surfaces. An averaged reflection coefficient (\Gamma_{AVG}) was proposed to improve the prediction accuracy. Over the ensemble of measured results at both
frequencies and polarizations, $\Gamma_{\text{AVG}}$ was shown to give a 90th percentile of error of 0.19. This was an average error improvement of approximately 0.2 over the smooth and rough surface models alone.

The measured reflection coefficients at the metallized glass wall exhibited very little variability for particular incident angles ($\theta_i$). This indicated significantly less interference effects (from surface protuberances) as that seen in the limestone wall. The measurements were compared with smooth surface Fresnel reflection models with various conductivities. Over the ensemble of all measured results at the glass wall, the theoretical models give a 90th percentile of error of 0.13 when using $\sigma = 5$ S/m and 2.5 S/m for perpendicular and parallel polarizations, respectively. The average error improvement of using a conductivity which fits the measured data over using the published value for clear glass (i.e., $\sigma = 10^{-12}$ S/m) is approximately 0.31 and 0.26 for perpendicular and parallel polarizations, respectively.

Similar to the glass wall measurements, the measured reflection coefficients for the brick wall showed little variability as the receiver distance was varied and, therefore, were also insensitive to interference effects from surface protuberances. The differences between the theoretical models of the smooth versus rough surface for the brick wall were small due to the small standard deviation of surface protuberances ($\sigma_p$). Because of this, the measured reflection coefficients of the brick wall were not well bounded by the smooth and rough surface predictions, in general. Using the Fresnel reflection formulas for smooth surfaces, the comparison gave a 90th percentile of error of 0.18 over the ensemble of all measurements at the brick wall.

These comparisons show that the actual reflective properties of various external building surfaces can be adequately modeled using the Fresnel reflection coefficients and rough surface scattering corrections when applicable. These results can be directly applied to ray-tracing algorithms for the purpose of propagation prediction in microcellular environments. The simple models presented here are defined by physical roughness features and material dielectric properties of the reflecting wall surface in question.

ACKNOWLEDGMENT

The authors would like to thank J. Don Moore, Y. Ercog, A. Rustakoo, R. Valenzuela, M. Keitz, and D. Sweeney for many valuable discussions on this topic. For their help with the data collection and processing they would also like to thank C. K. Sou, A. M. Landron, H. Meng, B. Rele and P. Koushik.

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