Interpolation of Perimeter Wireless Channel Measurements into the Measurement Region

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Introduction

From the uniqueness theorem of electromagnetics, it is known that for a source-free, homogeneous, and lossy medium, the electric fields within a volume are uniquely determined by the fields tangential to a bounding surface. For strictly 2-dimensional (2-D) fields, this surface collapses to a closed contour about a planar region. Thereby, a set of coherent channel measurements along the perimeter of a measurement region will enable an exact interpolation of the channel within the contour. To actually perform this interpolation, one may employ any number of techniques ranging from field expansions to finite-element methods to method of moments. Regardless of the specific technique, it is important to note that if only the electric field is measured, then two \( \lambda/4 \)-spaced contour measurements are required so as to suppress the resonant modes of the measurement region’s geometry [1].

The 2-D Interpolation of 3-D Wireless Channels

Strictly speaking, such contour-based 2-D interpolation techniques are only valid for 2-D wireless channels wherein contributing plane waves propagate along the horizon. Although wireless channels are inherently 3-dimensional, a given environment’s geometry oftentimes suggests a more simplified 2-D model. A very thorough measurement campaign by Kalliola et al. across a range of environments found that, for a pair of vertically polarized antennas, the mean and standard deviation of received power with respect to elevation angle-of-arrival (AoA) as measured from the horizon was 2.6° and 5°, respectively [2]. This small range of elevation AoAs tightly clustered about the horizon certainly lends weight to a 2-D channel model. However, it must be recognized that the methods used to interpolate perimeter measurement data require coherent measurement data. Plane waves with nonzero elevation AoA exhibit a smaller wavelength on the \( xy \)-plane that leads to phase deviations with respect to a comparable plane wave propagating along the horizon. Thus, when plane waves with seemingly small elevation AoA (\( \sim 10^\circ \)) are measured across regions on the order of several wavelengths, phase deviations become substantial and lead to an inaccurate interpolation of measurement data.

To account for the likelihood of waves incident at small, nonzero elevation angles, we have developed a modified cylindrical wave expansion (CWE) for so-called quasi 2-D channels [3]. This modified CWE effectively combines the basis sets of two cylindrical wave expansions at slightly different wavenumbers. Simulated and experimental data have demonstrated that the modified CWE produces a more accurate interpolation than the original CWE without requiring additional measurement data. Here, we note that for the modified CWE developed in [3], we used \( \Delta = 1 \) and \( D = \sqrt{2}L \).
for the wavenumber step size, $\Delta$, and region diameter, $D$, respectively, where $L$ is length of one side of the square measurement region.

**Measurement Setup**

A vector network analyzer (VNA) and uniaxial linear positioning system (LPS) were used to make track measurements of the wireless channel at the industrial, scientific, and medical (ISM) band centered at $f_0 = 2.45$ GHz. Transmit and receive antennas were mounted atop a pair of polyvinyl-chloride (PVC) masts at a height of 1.15 m. The receive antenna’s mast was attached to the LPS whereas the transmit antenna’s mast was affixed to a stationary stand. Both antennas were vertically polarized quarter-wavelength monopoles with circular ground planes. A 2-port calibration was performed at the ends of a pair of 12 ft coaxial cable connected to the VNA. These cables were then connected to the transmit and receive antennas. Using the LPS, complex $S_{21}$ measurements were taken along a linear path at $\lambda_0/4$ intervals, with $\lambda_0/4$ corresponding to the free-space wavelength of at 2.45 GHz. To ensure a static channel, measurements were carried out at night in evacuated areas, and the measurement data was temporally averaged to suppress receiver noise and minimize effects due to both time-varying scatters and in-band interferents.

**Diffraction Measurements**

To experimentally validate the modified CWE, channel measurements were taken within a 1.3 m by 1.3 m region near the intersection of two hallways at the top floor of an academic building. To attain the pair of closed contour measurements about a planar square region, two track measurements were made at each side of the square: one exactly along the boundary and one within the measurement region that was parallel to the boundary and spaced by $\lambda_0/4$. An additional pair of track measurements were made along two orthogonal paths corresponding to the square’s symmetry axes to assess the accuracy of the interpolated channel produced by the modified CWE. Figure 1(a) presents a to-scale diagram of the indoor channel measurement. “Tx” denotes the transmit antenna location; “Rx”, the receive antenna measurement area. The location of large, metallic objects within the environment is also marked. Figure 1(b) shows the interpolated channel’s frequency-averaged power angle spectrum. Observe that there is an excellent correlation between the interpolation-based power angle spectrum and the position of known scatterers within the measurement environment. Figures 1(c) and 1(d) present the interpolated channel’s magnitude and phase at 2.45 GHz. Note that the phase suggests a cylindrical wave originating at the diffracting corner, as is expected by the geometrical theory of diffraction (GTD) solution for a plane wave incident on a perfectly electrically conducting (PEC) 90° wedge.

Unfortunately, despite the agreement between the interpolated channel and our intuitive understanding of radio propagation, we found poor agreement between the measured and interpolated channel along the region’s symmetry axes. When normalized by the root-mean-square (RMS) of $|S_{21}|$ measurements from the symmetry axes, the RMS error in the interpolated $S_{21}$ at 2.45 GHz was 0.76. This indicated
that the interpolated channel’s error magnitude was approximately 76% of the actual channel’s magnitude. Across the ISM band, the mean and standard deviation of the normalized RMS error was 0.84 and 0.09, respectively. Although the large elevation AoA of floor and ceiling reflections (−27° and 32°, respectively) likely contributed to the large interpolation error, it was concluded that the dominant error source was the radiation pattern of the quarter-wavelength monopoles. With ground planes approximately one wavelength in diameter, simulated radiation patterns suggest that, in the elevation plane, the quarter-wavelength monopoles will have a −3 dB beamwidth of approximately 60° centered about 37° [4] (as measured from the horizon). Thus, the transmit antenna was launching the vast majority of its power at large elevation angles, and likewise, the receive antenna was amplifying power arriving from large elevation angles. This enhanced the 3-D nature of the wireless channel and severely degraded the accuracy of the 2-D interpolation.

To account for the transmitter and receiver antenna patterns, the diffraction measurement was moved outdoors. Measurements were taken within a 0.83 m by 0.83 m region on the gravel roof atop the 4th floor of an academic building. The diffracting edge was an exterior corner of the building’s 5th floor, the entirety of which comprises only a fraction of the building’s full footprint and allows access to the 4th floor’s roof. The exterior wall is composed of brick on the outside and cinder block on the inside. Figure 2(a) shows a diagram of the measurement region. Measurements were taken on a \(\lambda_0/4\) grid throughout the square region. This was done both to ensure the integrity of the data as well as to provide significantly more measurements for calculating the interpolation error. Only the outer pair of measurement contours were used for calculating the interpolated channel via the modified CWE; the remaining inner measurement points were used for calculating the normalized
RMS error. Figures 2(b) and 2(c) present the interpolated channel’s magnitude and phase at 2.45 GHz. Once more, the phase behavior suggests a cylindrical wave propagating away from the wall’s corner. For the outdoor measurement, the mean and standard deviation of the normalized RMS interpolation error was 0.33 and 0.01, respectively. This was a significant improvement over the RMS interpolation error from the indoor measurement and indicates that the interpolated channel is a good approximation to the actual channel.

Conclusion

The work presented here demonstrates the feasibility of interpolating perimeter wireless channel measurements throughout a planar region. The outdoor diffraction measurements have shown that, by applying the modified CWE to a pair of closed contour measurements, one may attain an accurate approximation to the true channel without having to tediously measure everywhere in the region. Thereby, this interpolation technique allows for an accurate acquisition of the wireless channel in a fraction of the time typically required. The interpolated channel may be used as additional measurements for developing stochastic channel models or as a 2-D electric field map for investigating the physical mechanisms underlying real-world radiowave propagation.

References


