Modeling the Impact of Human Blockers in Millimeter Wave Radio Links

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Abstract

The loss from multiple human blockers is investigated at millimeter wave frequencies. We model the blocking as absorbing screens of infinite height with two knife-edges, and use a physical optics approach, as opposed to a geometric optics approach used in literature, to compute the diffraction around the absorbing screens. The blocking model is validated with blocking gain measurements of multiple human blocking configurations on an indoor link. The blocking gains predicted using Piazzi’s physical optics numerical integration method have good agreement with the measurements in the range of approximately 2.7 dB to -50 dB, making this model suitable for real human blockers. The mean prediction error for the method is approximately -1.2 dB and standard deviation is approximately 5 dB.

Keywords: 60 GHz, Diffraction, Human Blocking Loss, Human Shadowing, Indoor Environment, Millimeter Wave Propagation, Physical Optics
I. Introduction

To successfully perform simulations of systems using millimeter wave transmissions, the effects of common obstructions in the radio environment must be investigated and accounted for. In millimeter wave systems with access links to mobile users, humans are likely blockers of the radio links, for example, in shopping malls, store fronts, and airports. From past works [1], [2], humans can cause severe fades (loss of >20dB). Therefore, it is critical to include the effects of human blockers in simulations. In this work, we focus on the modeling and computation of human blocking/shadowing for a millimeter wave radio link.

Because the transmission loss through human blockers is very high at millimeter wave frequencies (virtually opaque), it is the diffraction around the human blockers, and reflection and scattering from nearby objects or structures that contribute significantly to the received power. Millimeter wave systems that include link distances greater than a few meters typically use highly directional antennas or arrays in order to overcome the path loss incurred at high frequencies. Thus, the reflection and scattering contributions from surrounding objects away from the direct line between the transmitter and receiver are greatly attenuated by the antenna patterns or array beamforming patterns. Therefore, we focus on investigating and modeling the diffraction around the human blockers.

The exact electromagnetic characteristics of human bodies are not found in the literature. Instead, previous works proposed approximate human body models which attempted to embody the electromagnetic properties of humans at millimeter wave frequencies. For examples, human bodies have been modeled as absorbing screens [3], [4], water phantoms [5], cylinders [6], [7], and rectangular prisms [8]. Validations of these models were performed only with measurements from a single human blocker, but to the best of our knowledge, validations with multiple human blockers have not been performed. Furthermore, in the simulations found in previous works, the impact of multiple human blocking on the radio environment is found through geometric optics (e.g., ray-tracing). However, the use of geometric optics with the Geometric Theory of Diffraction (GTD), and/or Uniform Theory of Diffraction (UTD) without higher order diffraction terms [9] is not valid for multiple blockers located in each other’s transition regions. Therefore, other approaches, such as physical optics, are recommended. It should however be noted that both geometric and physical optics are approximate techniques. Full wave solutions by numerical techniques (e.g. Finite Difference Time Domain, Finite-Element, and Method of Moments) are computationally infeasible due to the small wavelength at millimeter wave frequencies.

![Figure 1](image-url) Multiple human blocking scenario with blockers modeled as absorbing screens of infinite height
In some millimeter wave radio scenarios, the transmitting and receiving antennas are low relative to the human blocker heights so that the dominant diffraction contributions travel around the human blockers rather than over and this scenario is the focus for this work. We propose to use physical optics, which states that points in space where there are wave fields may be considered as elementary sources of radiation whose amplitudes are proportional to the amplitudes of the fields at those points, to compute the received field around the human blockers. Here, human blockers are modeled as absorbing screens of infinite height with two knife edges similar to [10] as seen in Fig. 1. This model is computationally favorable, so if it has sufficient accuracy, it is preferable to use it over more complex models for rapid simulations of the radio channel. From physical optics, the received field can be expressed in the form of multiple integrals which we numerically evaluate using Piazzi’s numerical integration method [11]-[13]. The predicted blocking gain from the diffracted fields is then computed using two approaches: (1) coherent sum of fields and (2) incoherent sum of powers. The predictions are then compared with the measurements of various one, two and three blocker configurations. Here the blocking gain is defined as the ratio of received power with blockers to received power without blockers. Assuming there are negligible reflections from the ground and nearby objects, the blocking gain is equivalent to the ratio of received power to free-space power.

A brief overview of the physical optics approach used to compute the blocking gain is given in Section II. Our measurement setup and measurement campaign are described in Section III. A comparison of the simulations with human blocking measurements for a single blocker and multiple blockers is given in Section IV.

II. Piazzi Physical Optics Method

To investigate the suitability of the absorbing screen approximation, the human blockers are modeled as absorbing screens of infinite height with two vertical knife edges as seen in Fig. 1. To compute the diffraction gain, i.e., the ratio of diffracted power to free-space power, from an arbitrary number of screens, we employ a physical optics method developed by Piazzi [11] to treat diffraction past multiple absorbing screens with knife-edges. The code is based on the same physical optics principles used by others, such as Vogler [14] and Whitteker [15], [16] to evaluate multiple knife-edge diffraction. All methods make the following assumptions: 1) the knife-edges are of infinite length and the edges are all parallel to each other; and 2) the additional diffraction gain in a plane perpendicular to the screens for a point source is the same as for a line source that is parallel to the screens and intersects the plane at the source point.

With these assumptions, the physical optics description of diffraction around an absorbing screen is expressed as multiple integrations in the planes containing the absorbing screens (x-z plane). Furthermore, the integrations in the coordinate along a knife-edge (z-plane) can be approximated analytically, so that one is left with integration in the x-coordinate away from the knife-edges. This is seen in the following expression for the magnetic field \( H(x_{n+1}, y_{n+1}) \) in the plane containing the \( n + 1 \) absorbing screen [12]

\[
H_{x_{n+1}, y_{n+1}} = e^{j \pi/4} \sqrt{\frac{k}{2\pi}} \int_{-\infty}^{\infty} H_{x_n, y_n} e^{-jk\rho} \sqrt{\rho} \, dx_n. \tag{1}
\]
Here \( \rho \) is the distance from the secondary source point \((x_n, y_n)\) in the plane \(x = x_n\) to the receiver point \((x_{n+1}, y_{n+1})\) in the plane \(x = x_{n+1}\), and \(k\) is the free-space wave number. \(H(x_n, y_n)\) is the field in the plane \(x = x_n\) containing the \(n^{th}\) screen. Note that to arrive at an expression with multiple integrals, we substitute \(H(x_n, y_n)\) with (1), but with \(H(x_n, y_n)\) replaced by \(H(x_{n,t}, y_{n,t})\). \(H(x_{n,t}, y_{n,t})\) is the field in the plane \(x = x_{n,t}\) containing the \(n - 1\) screen and can similarly be written in integral form, and so on.

To predict the diffraction gain from the multiple screens, the integrals must be carried out numerically. To do so, it is necessary to terminate the integral in (1) with finite lower and upper limits (i.e., for the right and left sides of the screen), and to replace the integration by a discrete summation. An abrupt termination of the integral is equivalent to placing an absorbing screen outside the termination point, and would therefore artificially generate diffracted waves that are not present in the actual problem.

In [15], [16], Whitteker used quadratic approximations for the amplitude and phase of the integrands over intervals of less than one wavelength to discretize the integrals. Spurious diffraction effects were removed by using asymptotic approximations to analytically evaluate the integral outside of the termination points of the numerical analysis. This allowed for larger intervals, but an additional cost was incurred to evaluate the complex error functions. In contrast, the Piazzi method used simple linear approximations of the amplitude and phase, and introduced a smoothing procedure which utilized a Kaiser-Bessel function to terminate the integration without introducing spurious diffraction effects. For more details on the methodology of the Piazzi method refer to [11]-[13].

In our comparison with measurements, the blocking gain found using the Piazzi method is compared with the time averaged measurement for a given blocker configuration. To compute the complex field for each diffracted path, the aforementioned integrals are separated. As an example, consider the scenario depicted in Fig. 1 where there are 3 absorbing screens with two edges each. Clearly, there are \(2^3 = 8\) forward diffracted paths. Now, consider the diffracted path that travels along the \(x^+\) sides of the screens. The diffraction gain for this path is found by assuming that that all screens are semi-infinite with knife-edges located at \(x^+\) edges. This is equivalent to setting the lower \(x\) limit of each integral to the position of the \(x^+\) edges.

Since the human blockers in the test set-up will inadvertently have small movements between measurements, their movements are captured in the measurements. These movements are small relative to the distances of the blockers to the transmitting and receiving antennas, so that the amplitude of the field of each diffracted path can be assumed constant. However, the exact phase of each path cannot be known since: 1) the inadvertent movements cause path length differences on the order of or greater than the 5mm wavelength at 60 GHz; and 2) the exact electromagnetic interactions with the human body cannot be known. Depending upon the configuration of blockers, a particular measurement may have a large uncertainty due to the movements. If we assume these movements are sufficient to obtain a well mixed sampling of possible phases, the time averaged measurements can be approximated by assuming the phases of the different diffracted contributions are uncorrelated uniform random variables. Thus, the time-averaged diffraction gain can be modeled as the incoherent power sum of gains from the different paths. Conversely, if we do not assume the phases are random, the diffraction gain found from coherently adding the complex magnetic fields is equivalent to not separating the aforementioned integrals. In practice, the small inadvertent movements, may not be sufficient to produce well mixed averages and we could expect some hybrid model to produce more accurate predictions. In Section IV, we will compare our measurements with both the Piazzi Method (coherent sum of fields) and the incoherent power sum approach.
III. Measurement Description

A. Measurement Setup

Our 60GHz measurement setup is illustrated in Fig. 2. On the transmit side, the SMAF100A Microwave Signal Generator provides a 10 GHz sine wave to the SMZ90 Frequency Multiplier which multiplies the frequency by six. The resulting 60 GHz signal then travels through a straight section waveguide to a V-band horn antenna with 24dBi of gain and 7 degree 3 dB beamwidth. The radiated signal level can be adjusted via a 25dB mechanically controlled attenuator included in the multiplier assembly.

On the receive side, the signal is received with an identical horn antenna that is connected to a N12-3387 LNA with a straight waveguide section. The amplified signal is sent to a FS-Z90 Harmonic Mixer where it is down converted and then captured on a FSQ26 Spectrum Analyzer.

B. Measurement Procedure

To test the modeling of human blockers as absorbing screens, we recorded measurements made in the presence of multiple human blockers. From [3], it was found that the majority of human blocking cases involved three or less blockers. Therefore, we have conducted 60 GHz measurements for one, two and three blockers. Utilizing the setup described in Section III.A and the Cartesian coordinate system of Figs. 1 and 3, the transmitting and receiving antennas were placed 7 m apart at a 1 m height with coordinates of (0,0,1) and (0,7,1), respectively. The measuring environment was a large empty conference room (8 m x 10 m). The reflections from the walls were heavily attenuated by the antenna patterns, longer path length and reflection loss, so that the receiving antenna primarily measured the contribution from propagation paths going through and around the blockers.

In the one person blocking measurement scenario, a blocker of width 0.43 m (17 in) was located half way between the antennas. The blocker moved perpendicular to the direct line (y-axis in Fig. 1 and 3) between the antennas and measurements were taken at intervals of either 0.05 m (2 in) or 0.10 m (~4 in)
depending on how close the blocker was to the direct line. For the two person blocking measurement scenario, two blockers of width 0.46 m (18 in) were spaced 1 m apart halfway in between the antennas. The first blocker had four positions while the second blocker had six positions. For the three person blocking measurement scenario, the blockers were also spaced 1 m apart halfway in between the antennas. The first blocker of width 0.48 m (19 in) had three positions while the second and third blockers of width 0.46 m (~18 in) each had five positions. The positions of the blockers for the two and three person blocking scenarios were chosen such that the Line of Sight (LOS) was almost always blocked and that various practical blocking scenarios were considered as seen in Fig. 3. Their positions are listed in Table 1. In the two person and three person scenarios, the received powers for all possible blocking configurations were recorded. To maintain consistency, the blockers stood centered over their positions with their arms at their sides, facing in the direction of the receiving antenna.

In all scenarios, the five measurements were recorded for each blocking configuration. To compute the time-averaged measured blocking gain, the time-averaged received power in the absence of any blockers was also recorded. The blocking gain was then computed by taking the ratio of time-averaged measured power with blockers to without blockers.

Figure 3  To scale illustration of measurement positions for two and three blocker positions in an 8 m by 10 m room
<table>
<thead>
<tr>
<th>Blocking Scenario</th>
<th>Positions (x,y) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Blocker 1 (x)</td>
</tr>
<tr>
<td><strong>Two People</strong></td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>0.61</td>
</tr>
<tr>
<td><strong>Three People</strong></td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>0.31</td>
</tr>
</tbody>
</table>

Table 1  Blocker Positions using the Cartesian coordinate system of Fig. 1

IV. Results and Analyses

The measured transmission gain through a single blocker is less than -50 dB, and reflection and scattering from nearby objects are negligible. Therefore, the blocking gain is essentially the diffraction gain around the blockers. In this section, the variability of the measurements is first discussed and then the measurements from the various blocker configurations are compared to the diffraction gains predicted using the Piazzi method and the incoherent power sum approach described in Section II.

A. Measurement Variability

Due to the inadvertent movement of the blockers, variability was introduced into the received signal for a given blocker configuration as mentioned in Section II. The time-averaged blocking gain effectively captures and averages these movements. Because the ranges of the actual blocker movements are unknown, we compare the time-averaged measurements with the predicted blocking gains from both the Piazzi Method and incoherent power sum approach. For measurements where the blockers have a relatively small range of movement, the measurements are expected to more closely match the Piazzi Method. On the other hand, if the blockers have a greater range of inadvertent movement during the measurement period, the time-averaged measurement is expected to more closely match the predicted blocking gain from the incoherent power sum approach. Though, due to the limited measurements samples taken for each configuration, deviations from the incoherent power sum blocking gains are expected.

B. One Person Blocking

The measurements (green triangles) for the one person blocking scenario are plotted in Fig. 4. The blocking gain predicted by the Piazzi method (red line) and the incoherent power sum (blue dashed line) are also plotted. From Fig. 4, the incoherent power sum has a relatively good agreement with the measurements with a maximum deviation of 4.7dB. Agreement with the Piazzi Method is also supported when considering the blocker’s positions. When the blocker’s center location x coordinate is less than 0 m, the measurements appear to land on the Piazzi method’s curve. Here x = 0 m refers to when the
blocker is located at (0, 3.5) in Figs. 1 and 3. When the blocker’s center location x coordinate is greater than 0 m, the measured results seem to be slightly offset from the Piazzi Method’s curve. A reason may be that the blocker was improperly centered and the blocker’s effective width was actually narrower than 0.432 m. These results suggest that the absorbing screens also model the phase information of a human blocker at millimeter frequencies relatively well.

For sake of comparison with [3], we have also plotted the worst case and best case blocking gains (black dotted lines) found from a direct ray and two diffracted rays, computed using the uniform theory of diffraction (UTD) [12]. Note that the blocking gain from the direct ray is $\infty$ dB and 0 dB when the blocker does and does not obscure the LOS, respectively. The worst case scenario is found assuming the secondary contributions are 180 degrees out of phase with the dominant contribution. Conversely, the best case assumes that all contributions are in phase. The measurements mostly fall between the worst case and best case curves. Because the physical optics solution and UTD are nearly identical when only one screen is present, the physical optics solution as expected lies in between the best case and worst case curves. The rapid variation of the Piazzi method curve suggests that a simplified model for human blocking wherein approximate positions are used to compute the incoherent power sum mean gain and the small random movements of the humans are captured as a random variable with an appropriate distribution.

Figure 4  Comparison of one person blocking gain measurements with blocking gain predicted by the Piazzi method, incoherent power sum and UTD.
C. Multiple People Blocking

The time-averaged measurements (black triangles) for two and three people blocking scenarios are plotted in Figs. 5 and 6 in increasing measured blocking gain order. The predicted blocking gain from the Piauzzi method (red asterisks) and incoherent power sum (blue circles) are also plotted. Depending on the configuration of the two and three people blocking scenarios, there can be deep fades in the measurements where the blocking gain is < -30 dB. The measured blocking gain in all scenarios has a range from 2.7 dB to -50.7 dB. This range is much larger than those reported in [1] and [2] and further justifies the need to include human blocking models in the channel simulators.

To evaluate the accuracy of the prediction, the prediction errors of the Piauzzi Method and incoherent power sum approach for two and three person blocking scenarios are plotted in bar graphs in Figs. 7 and 8. The prediction error is defined as the predicted blocking gain in dB subtracted from the time-averaged measured blocking gain in dB. The mean and standard deviation of the prediction error for the Piauzzi Method and incoherent power sum are given in Table 2. The Piauzzi method has smaller mean error, but has a larger standard deviation of error compared to the incoherent power sum approach which should be expected due to the uncertainty in the exact location of the blockers and the time averaging done in the measurements. The percentage of configurations with prediction error between ±5 dB was also found. The percentages of configurations exceeding 5dB error for the Piauzzi method in 2 people and 3 people blocking scenarios are 75% and 68%, respectively. While the percentages for the incoherent power sum in 2 people and 3 people blocking scenarios are 83% and 68%, respectively.

From Figs. 5-8, the majority of blocking configurations with large measured blocking loss (possibly caused by large diffraction angles) typically have negative prediction error. This suggests that another model (e.g. cylinder) may better predict the diffraction around blockers at large diffraction angles. Though generally, from the standard deviation of error, we conclude that an absorbing screen model is sufficient for the computation of blocking gain in most applications.

For the two people blocking measurements in Fig. 5, the span of the measurements are also plotted. The lower limit of each bar is the minimum blocking gain measured for that given blocker configuration while the upper limit is the maximum blocking gain measured. Note that since only five measurements were taken per configuration, the possible span is likely larger. From Fig. 5 and Fig. 6, most of the blocking configurations with span (not shown in Fig. 6) larger than 10 dB have blocking gain < -30 dB and larger predictions errors. The variability and large negative gains could be caused by the constructive and destructive interference of the various diffracted paths and the uncertainty of exact positioning and movements of the blockers. Thus, we should expect that in these configurations, the Rician K-factor defined as the power ratio of the dominant arrival (i.e. path with the largest received power) to all other arrivals is small. Note that the Rician K-factor is a metric which is negatively correlated with the level crossing rate and positively correlated with the fading depth [17] of the received field. From the predicted powers of the two person blocking configurations, the computed K-factors are small (all less than 2 dB). However, the majority of the three people blocking configurations have predicted K-factor greater than 10 dB. The large predicted K-factor in the three people blocking scenarios may allude to some other significant multipath which was not considered.
Figure 5  Comparison of two people blocking gain measurements with blocking gain predicted by Piazzi method and incoherent power sum approach for blocker positions listed in Table 1.

Figure 6  Comparison of three people blocking gain measurements with blocking gain predicted by Piazzi method and incoherent power sum approach for blocker positions listed in Table 1.
Figure 7  Error of the incoherent power sum approach and Piazzi method predicted blocking gain of two person measurements for blocker positions listed in Table 1.

Figure 8  Error of the incoherent power sum approach and Piazzi method predicted blocking gain of three person measurements for blocker positions listed in Table 1.
Table 2  Prediction error statistics over all configurations for two and three people blocking scenarios

<table>
<thead>
<tr>
<th>Blocking Scenario</th>
<th>Piazzi Method</th>
<th>Incoherent Power Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two People</td>
<td>-1.3</td>
<td>5.5</td>
</tr>
<tr>
<td>Three People</td>
<td>-0.7</td>
<td>5.0</td>
</tr>
</tbody>
</table>

IV. Conclusion

Multiple human blockers are treated as absorbing screens of infinite height to provide a model for the computation of blocking gain in 60 GHz links. The model is found to give good agreement with one, two and three people blocking gain measurements in the range of 2.7 dB to -50 dB. In a few select cases with large incoherent sum blocking gain < -30 dB, the predicted errors are larger than 5 dB. This coupled with a large predicted Rician K-factor alludes to the presence of un-accounted for multipath and/or the need for more accurate models of the human blockers at large diffraction angles. Though, as seen in our comparison with measurements, our model is sufficient in determining the impact of multiple blocking humans.

To perform deterministic system level simulations of the millimeter wave radio channel, the Piazzi Method can be used in conjunction with a ray-tracing simulator to determine the blocking gain experienced by paths with human blocking. However, in scenarios with human blockers, a statistical component of the model is preferred since it is often not practical to include the small random motions of humans in a simulated environment. In these scenarios, we propose to utilize the incoherent power sum approach coupled with a random variable to predict the blocking gain on paths that are blocked by humans. This random variable is dependent on the exact complex fields of the various multipath and the movement of the blockers. Further research should be performed to determine the statistical nature of this random variable.

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Prior to his transition to wireless communications in 2000, he was a Research Engineer at Brookhaven National Laboratory, National Synchrotron Light Source, responsible for beam-line instrumentation and developing spectroscopic and imaging, solid-state and gaseous, X-ray detectors. He has also conducted research at the Polytechnic University for the Office of Naval Research (ONR) in underwater source localization using passive SONAR.