

A DELAY-CENTRED WIDEBAND INDOOR CHANNEL MODEL FOR MM-WAVE COMMUNICATIONS

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SUMMARY

The frequencies of operation of mm-wave radio networks are the highest of any current radio system, allowing for higher data rates and greater system capacity at the expense of coverage area per base station. Also, the channel has to be carefully modeled, accounting for most propagation mechanisms. Traditionally, rough surface scattering is not taken into account, but the very short wavelength of mm-wave systems demands a more careful approach.

The proposed model can be used indoors and within rooms, where coverage from a mm-wave network is not always achieved. Since the path loss for such frequencies is extremely high, the link must be able to overcome shadowing and would often rely on reflected or scattered paths to sustain communication. The simulation model takes rough scattering and specular reflection into account, and comparison with wideband measurements at 5.4GHz show that the effect of scattering at that frequency is marginal. On the other hand, at the highest frequency of 60 GHz, the wavelength is 5mm and scattering effects become significant.

The model presented here follows a novel approach and was initially developed for infrared communications. The physical characteristics of the room are the input to the channel, but instead of discretising the geometry of the channel, the delay range is calculated before the calculations are initiated. In this way, the computation is efficient as well as accurate. The delays are modeled sequentially, in order to calculate the power received for every delay bin.

The results show that the effect of scattering on the link is important and should not be neglected. The impulse response exhibits negative exponential decaying pulses instead of rapid delta-like waveforms which provides a better agreement with measurements. The following figure illustrates one result of the channel model compared to the measurement of a simple environment at 5.4GHz.

CHANNEL MODEL

The analysis presented here concentrates on empty rectangular rooms. The drive for this research was originally infrared communications [1], where communication only takes place within a rectangular room, but the recent advance of radio communications in higher frequencies has lead to the use of

this model in millimeter-wave (mm-wave) systems. Since the frequency of operation is so high, very large bandwidths are available for a communication link, but such a high frequency leads to a very high path loss. Also, scattering is important at such frequencies, since most walls may appear rough compared to the wavelength. There has a significant interest in these bands lately [2], since the available bandwidth is very large. Communication at such a high frequency would confine the cell in a small area and the waves would probably not penetrate walls. There is also severe atmospheric attenuation at 60GHz [3], which may significantly improve frequency reuse between buildings. It has also been reported that communication links at 60GHz rely solely on LOS communication, since the absorption loss of typical materials and humans is very high [4]. In this case, even a human obstructing the link would degrade the communication, and diversity has to be used.

Modelling

The model presented here does not follow the principles of ray tracing techniques that discretise the physical characteristics of the simulated geometry. Initially, the simulation is defined in terms of the delays that will be simulated, and calculation only takes place within these delay limits. Since traditional techniques do not take into account the delay range in the channel and calculate for a certain amount of time, this technique will prove to be efficient for higher order accuracies. The next section describes the theory behind the model.

Reflection Definition

Having a fixed receiver and transmitter, the geometric locus of points that are a fixed distance from the receiver and transmitter is an ellipse in two dimensions and an ellipsoid in three dimensions. This is true if it is assumed that the ellipsoid results from the revolution of the ellipse around one axis or symmetry. This distance represents the delay between the receiver and transmitter.

When a wall intersects the ellipsoid, the intersection forms a shape that defines all the points on the wall that are a fixed delay away from receiver and transmitter. This shape depends on the orientation of the transmitter, receiver and reflecting wall, and is an intersection of an ellipsoid. Based on this argument, the analysis continues to calculate the first order re-

flection for a defined surface. The main diagram of the channel is presented in Fig. 1.

The ellipse drawn on the plane is the locus of points that intersect the wall for a given delay. The goal of this technique is to characterise the locus of these points given an input parameter, θ in our case.

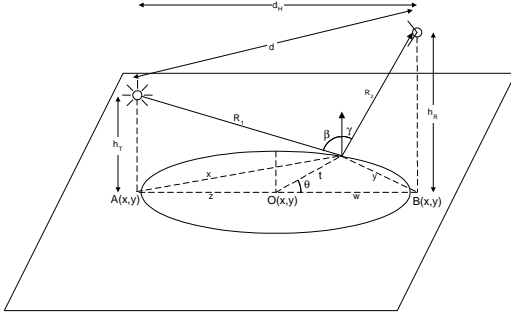


Figure 1: Radio ellipse model

It is possible to express the lengths R_1 , R_2 and the angles β and γ in terms of θ for the calculations. The angle θ can be set during simulation, while the rest of the parameters can be calculated. The ellipsoid formed from the constant delay shape intersects the walls, forming ellipses or other similar closed curves. The center of the ellipse will always be the specular point on the wall and can be calculated given the position of the transmitter, receiver and wall. This simplifies analysis, since the algorithm is calculated around this point and the angle θ . After some calculations, the lengths R_1 and R_2 can be expressed in terms of θ .

$$R_1^2 = h_T^2 + z^2 + a^2 \cos^2(\theta) + b^2 \cos^2(\theta) - 2z \sqrt{a^2 \cos^2(\theta) + b^2 \sin^2(\theta)} \cos(\theta) \quad (1)$$

The result is similar for R_2 , but includes the height of receiver instead of transmitter. The angles β and γ can then be calculated with a simple cosine expression

$$\cos(\beta) = \frac{h_T}{R_1} \quad (2)$$

Now it is possible to proceed with the calculations of the radio channel, in order to calculate the impulse response of any configuration. The power of a single path p reaching the receiver is

$$P_{path} = P_{1m} l_p \quad (3)$$

and the power of all the paths for a transmitting and receiving points is

$$P_{link} = P_{1m} l \quad (4)$$

where l_p and l are the path losses for a single path and all possible paths to a certain point.

Given the above equations, it is only necessary to calculate the reflection coefficients for the scatterers. In

the infrared domain, Lambert's law is used for diffuse reflection which leads to the assumption of a perfect rough surface. This may not be valid in the radio domain, since not all surfaces can be characterised as rough.

Even if scattering is not considered for the lower frequencies of WLANs, the radio wave may penetrate the first layer of a scatterer, undergo several reflections, and transmit out of the scatterer in a random direction. A typical example is an office ceiling, which is covered by soft tiles and is usually backed by reinforced concrete. The wave will penetrate the tiles, reflect on the wall, and retransmit through the tiles. It may be assumed that the resulting wave will have a strong scattered component. Since Phong's Law caters for both scattering and reflection, it can be used in the radio case. Phong's law [5] is described by the following equation

$$\rho_{total}(\theta_o, \theta_i) = \frac{\rho_{diff}}{\pi} [r_d \cos(\theta_o) + (1 - r_d) \cos^n(\theta_o - \theta_i)] \quad (5)$$

where $\rho_{total}(\theta_o, \theta_i)$ is the reflection coefficient and depends on the observation angle θ_o and the incident angle θ_i . Also, ρ_{diff} is the reflection coefficient of the surface, r_d is a factor that describes the amount of radiation that is scattered and ranges from 0 to 1 and n is the specular transmission mode, and characterises the directionality of the specular component. The parameters n and r_d specify the reflection characteristics of the surface, and can be empirically calculated.

According to Eq. 4, the received power for a single reflection at the specified point will be

$$P_{point} = \frac{\lambda^2}{(4\pi)^2} \frac{\prod_{i=1} \rho_i}{p^2} \quad (6)$$

where p can be substituted by the path length, and the reflection coefficient for a single point is ρ_1 . Hence

$$P_{point} = \frac{\lambda^2}{(4\pi)^2} \frac{\rho_1}{(R_1 + R_2)^2} \quad (7)$$

After some manipulation, and introduction of a closed integral to account for all points lying in an ellipse,

$$P_{wall} = \int_0^{2\pi} \frac{\lambda^2}{16\pi^3} \rho_{point} [r_d \cos(\cos^{-1}(\gamma)) + (1 - r_d) \cos^n(\cos^{-1}(\beta) - \cos^{-1}(\gamma))] / (R_1 + R_2)^2 d\theta \quad (8)$$

Every unknown parameter in this equation can be expressed in terms of θ , so that the integration can take place.

Numerical methods have been selected to solve the final equation. Since the integration cannot be performed simultaneously for all walls, all but one angle

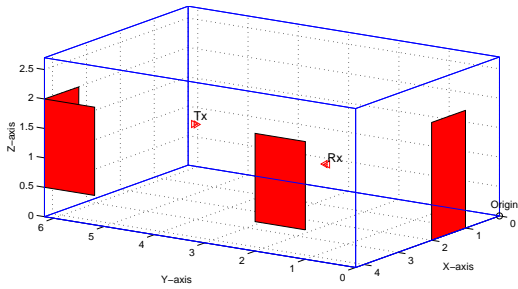


Figure 2: Simulation Geometry

are fixed, and the integration takes place with respect to this angle. The integration then proceeds for all other angles on all walls.

Antenna Patterns

In order to simulate the antenna pattern of the transmitter and receiver, the beamwidths of the antennas have been divided in four 45° segments. Within the segment, the antenna pattern is continuous and homogenous. The pattern is described by a three-dimensional shape so that an antenna is carefully and correctly modelled.

Materials

In order for the model to be complete, different materials can be introduced in the simulated geometry. The simulated geometry of a room may not be homogenous in materials, and the presence or windows, doors or other materials have to be taken into account. As shown in Fig. 2 the door and windows have been taken into account in the simulations since their presence will have an impact on results.

MEASUREMENTS

The measurements presented here were performed solely for the purpose of comparison. A set of measurements has been performed in an empty rectangular room, which has then been simulated using the channel model. The model has been developed to be used in a rectangular room and takes into account the scattering and reflection characteristics of the involved materials. Using the results of the simulation model, one can estimate the amount of radiation that is scattered and reflected and draw conclusions for the materials that are present during the measurements. The following section presents some information on the sounder and the measurement techniques.

Measurement Setup

As mentioned above, the setup consisted of a sliding correlator that probed the channel with a 100MHz

sequence rate. The transmitter and receiver were placed in the same room.

The room was of rectangular shape, with windows at one end and a door at the other. The transmitter was placed at one end of the room, facing the receiver, and was mounted with an omnidirectional antenna with gain of $0dBi$. The receiver was placed at the other end of the room, at two different locations, with several measurements in each one. The height of the receiving antenna was variable, and its gain was $5dBi$ with a beamwidth of about 120° .

RESULTS

Two sets of simulations and measurements have been performed, two for each of the receiver positions shown. The height of the receiver was either 1.8 or $1.12m$. The antenna of the transmitter was omnidirectional, while the receiver employed a sectored antenna with a FOV of about 120° . The room measured is similar to that of Fig. 2 shown above, with the exception of windows present in the real room. These have been included in the simulation, since their effect could be significant given that the materials present in the room are mostly specular reflectors and the windows may not have reflected an incoming wave specularly.

The first case results are presented in Fig. . In this case, the receiver was placed at the center of the room opposite the transmitter and at a height of $1.8m$. The same configuration was simulated with the ellipse model with a resolution of $0.1nsec$ and convolved with the back to back response of the sounder.

As seen from the first results illustrated in Fig. , both curves are similar with an exception at the base of the decaying pulse. Both measurements and simulation results have two main components that show in the impulse response graphs. The simulation has been run with reflection coefficients of 0.2 for all the walls, while the scattered energy was in the region of $0.1\% - 0.2\%$. As seen, the scattered component is not significant at this frequency range, since the materials in the room could be considered smooth.

The next case is measured and simulated at a different receiver position. The receiver was placed near one of reflecting walls. In this way, the impulse response should show the reflected components from each wall more clear, since the delay from each reflection is different. The height of the receiver was $1.8m$ for the first case and the results for this case are presented in Fig. . As seen from Fig. , there are more components that can be identified in the impulse response.

The results confirm that there is good correlation between the simulation model and measurements, although the two are quite different since many as-

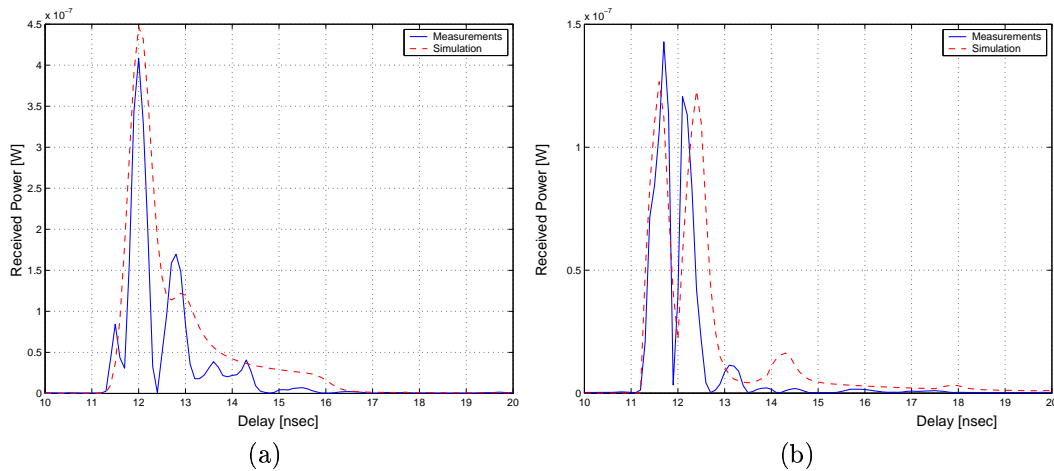


Figure 3: Results for (a) Scenario 1 and (b) Scenario 2

assumptions are undertaken and the received components measurements are not completely identifiable.

CONCLUSION

A novel channel model for in-room mm-wave channels has been presented. The model does not follow the principles of ray tracing, although it may be classified as one. The powerful and efficient approach of the delay range offers increased accuracy and efficiency. The simulation is only performed within the calculated delay range of the impulse response, leading to the possibility of increased accuracy without a large memory or simulation duration requirement.

The results of the simulation tool were compared with the results from a measurement campaign specifically planned for comparison. The comparison showed that the model results were a good fit to the measurements, and that the walls mostly reflected the radio waves specularly instead of scattering. Only a very low percentage of the incoming radiation was scattered, typically in the range of 2%. This shows that in this frequency, the scattering effect is not important since all surfaces appear smooth. The only case this may appear is when the incoming wave penetrates the first reflecting layer, undergoes several reflections within the materials and exits at a random direction.

In higher frequencies however, the scattering effect is more important and has to be included in the simulation tool. Although at 5.4 GHz a typical impulse response does not include any scattered components, a large receiver dynamic range will eventually lead to negative exponential components as implied by the Saleh-Valenzuela model. This model has been implemented and its results have shown good similarity with the novel model presented here.

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