MODELLING THE WIDEBAND INDOOR CHANNEL COMPLEX IMPULSE RESPONSE

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INDOOR CHANNEL MODELS

The accuracy of a wideband indoor channel model is evaluated by its ability to predict detection errors for various modulation methods in line-of-sight (LOS) links, obstructed line-of-sight (OLOS) links, or both. The model must be able to simulate the complex impulse response of the channel for these predictions. Current wideband indoor channel models include the geometric model, the stochastic Gaussian wide-sense stationary uncorrelated scattering (GWSSUS) model, and the statistical power delay profile model. This paper will describe each modelling method briefly, point out how the complex impulse is derived from each one, and discuss each model's advantages and disadvantages.

I. GEOMETRIC MODEL

The indoor channel can be modeled using geometric optics, physical optics, and the geometrical theory of diffraction (GTD). Geometrical optics is characterized by its ray tracing techniques of reflection and refraction. The reflection can be specular or diffuse. Physical optics and GTD are used to predict shadow phenomenon such as diffraction around edges. Lawton [Lawton,1991] and McKown [McKown,1992] have presented geometric models for the indoor channel. Allen [Allen,1991] has presented a geometric model for the urban canyon channel.

SPECULAR REFLECTION OFF CONDUCTIVE SURFACES

The simplest indoor channel to model is an empty rectangular room with smooth and conductive wall, ceiling, and floor surfaces. Room openings such as doors and windows are not included. Transmit and receive antennas are described by an antenna pattern and location in the room. Since the room is empty, a direct ray exists between the transmitter and receiver. Single reflections include a reflection from each wall, the ceiling, and the floor. Multiple reflections can be included to increase model accuracy.

REFLECTION AND REFRACTION OFF COMMON BUILDING MATERIALS

Incident rays divide between reflected and refracted components when the walls, ceiling, and floor have lossy dielectric properties.

The attenuation of the reflected ray is determined by a reflection coefficient. The reflection coefficient has vertical and horizontal components that predict the attenuation of the normal and tangential E fields respectively. The reflection coefficient is determined by the dielectric properties of the building material and the angle of incidence. Some building materials reflect very little power.

Power that is not reflected is refracted and transmitted into the adjoining room or outside the building. To return to the receiver, the ray will experience at least one more reflection and refraction before reentering the room.

Allen simplified the urban canyon model by ignoring contributions from refracted paths and attenuating the reflected path's amplitude with fixed horizontal and vertical reflection coefficients that were independent of the angle of incidence [Allen,1991].

DIFFUSE REFLECTION

The reflection will be diffuse if the surfaces are not smooth. Diffuseness is accounted for by introducing a reflection coefficient "reduction factor" that is dependent upon the angle of incidence, rms height of the surface irregularities, and wavelength [Boithias,1987]. Rayleigh's criterion is used to determine if a reduction factor is necessary [Brown,1973]. Using Rayleigh's criterion, it can be shown that indoor wall, ceiling, or floor surfaces are not likely to support diffuse reflection at low microwave frequencies (i.e., 1.5 GHz).

LOST RAYS DUE TO ROOM OPENINGS

If door and window openings are added to the model, a possibility of "lost rays" exists. Lost rays leave a room through an opening and never return. When modeling the urban canyon with geometric optics, Allen found that lost rays caused by cross streets degraded model performance. This degradation was eliminated by assuming the rays were not lost but attenuated. Allen reasoned that urban canyons are dominated by long and narrow streets. This geometry caused rays to have angles of incidence near 90 degrees. With a rough building exterior, the lost ray's first Fresnel zone is an ellipsoidal area. The cross street subtracted from the Fresnel zone's surface area and thus attenuated the ray rather than "lose" it. This reasoning may not apply to the indoor channel since wall, ceiling, and floor surfaces are smooth and angles of incidence are not always near 90 degrees. Thus, for the indoor channel, lost rays may exist.

DIFFRACTION

The prediction of diffraction effects due to the addition of doors and room partitions into the model requires the use of physical optics or GTD.

The physical optics solution to "knife edge" diffraction is given by Jordon [Jordon, 1968], for example. Jordon describes the ratio of the magnitude of the obstructed path's electric field to the magnitude of the unobstructed path's electric field in terms of the Fresnel integral. The value of the Fresnel integral is determined by a parameter that is a function of wavelength and the geometry of the obstructed path. Diffraction attenuation decreases with increasing wavelength.

GTD postulates "diffracted rays" result when rays strike edges, tips, and corners. The initial conditions of the ray are determined by diffraction coefficients. GTD diffraction coefficients have been determined for several "canonical" objects such as an edge or corner [Keller,1962]. After diffraction, the diffracted ray obeys laws of geometrical optics such as reflection and refraction.

SCATTERING AND RADAR CROSS SECTION

When objects such as desks, file cabinets, shelves, and machinery clutter the room, the diffraction problem becomes considerably more complex. Radar cross section principles are useful for describing the behavior of rays incident on complex objects. The bistatic radar equation can predict the received ray magnitude given the object's radar cross section. Ray phase information is lost with this method.

POLARIZATION EFFECTS IN THE INDOOR CHANNEL

The indoor channel model may need to account for polarization effects. Diffraction and oblique reflections depolarize the rays. Depolarization from oblique reflections can be predicted by using accurate horizontal and vertical reflection coefficients which are dependent on the angle of incidence. Crosspolarization is the ratio of magnitude of the electric field in the copolarized wave to the magnitude of the electric field in the crosspolarized wave. Cox [Cox,1986] has reported median crosspolarization factors at 800 MHz of -2.5 dB in residential houses to 1 dB in large buildings.

NARROWBAND COVERAGE PREDICTION

The multipath rays are assumed to be cw signals when predicting narrowband signal coverage. The instantaneous amplitude and phase of each multipath ray is vectorially added at each location. The power in each ray is assumed to attenuate with the square of the distance. Losses from the antenna pattern as a function of ray departure angle and arrival angle are included. Frequency selective fading statistics can be constructed from an ensemble of closely spaced ray amplitudes.

SIMULATION OF THE COMPLEX IMPULSE RESPONSE

Because narrowband coverage predictions assume a cw signal, the time delay due to path length is not used. Frequency selective predictions of the complex channel impulse response are possible using the method outlined in narrowband coverage predictions if path time delay is taken into account. With path time delay, the impulse response can be built by summing amplitudes and phases at each time delay for each receiver location. The fading statistics for multipath components at each time delay can be determined from the ensemble of multipath components at that time delay in nearby impulse responses.

II. THE GWSSUS MODEL

The Gaussian Widesense Stationary Uncorrelated Scattering (GWSSUS) model was developed by P.A. Bello [Bello, 1963] who was studying multipath in the ionospheric and troposcatter channels. The model describes the channel as a function of channel dynamics and frequency selectivity. The channel dynamics can be shown to be in units of time or Doppler frequency. The frequency selectivity can be depicted in units of time delay or spaced frequency.

Although all channels can be described as a function of both channel dynamics and frequency selectivity, most channels can be simplified by elimination of one of the variables. If the channel is narrowband, it is subject to power fading caused by channel dynamics and weakly affected by intersymbol interference (ISI) caused by frequency selectivity. Intuitively this makes sense since as the symbol bandwidth decreases the symbol time increases. The increase in symbol period decreases the possibility of ISI, but increases the chance that the channel will change within the longer symbol period. Bello called this special case the "frequency flat" or the "time varying frequency nonselective" model. The impulse response for a narrowband channel is a single, complex value that is a function of time only.

On the other hand, if the channel is wideband, it is likely to have ISI caused by frequency selectivity, but unlikely to be affected by power fading caused by channel dynamics. This also is intuitive since as the symbol bandwidth increases, symbol period decreases. The decrease in symbol period increases the chance of ISI, but decreases the possibility of a change in the channel during the short symbol period. Bello called this special case the "time flat" or "time invariant frequency selective" model. The wideband impulse response is a complex function that is dependent on time and time delay.

THREE ASSUMPTIONS OF THE GWSSUS

The three assumptions of the GWSSUS can be inferred from its acronym. The first assumption is that the inphase and quadrature components of the complex impulse response at any time delay are defined by independent, identically distributed, zero mean Gaussian random variables. This assumption rules out the presence of specular components, i.e., those having a preferred phase at any time delay in the impulse response.

Any change that generates new inphase and quadrature components of the complex impulse response can drive the process defined by these random variables. If the channel is dynamic, the process is randomized by time. If the channel is static, the process can be randomized by spatial displacement.

The widesense stationarity (WSS) of the process assures that the complex impulse response's expectation is a constant that is independent of starting time, and its autocorrelation is a constant dependent only on time difference. For static channels, starting time and time difference can be replaced by starting location and distance difference. Spatial WSS is assumed to apply only over small areas (less than 5 wavelengths) for the indoor channel [Devasirvatham,1987].

The assumption of uncorrelated scattering assures that the autocorrelation of the channel's impulse response is zero for all delta time delays but zero. The assumption of uncorrelated scattering is experimentally validated by observing the Doppler spectrum as a function of time delay. If the Doppler spectrum is different at each time delay, it can be assumed that different (independent) objects were illuminated by the measurement system transmitter.

GWSSUS IMPULSE RESPONSE

The GWSSUS impulse response has a discrete and continuous component. The discrete component is an FIR filter with a finite number of taps. The location of the filter taps represent the delay times of the resolved paths. The amplitudes and phases of the taps represent each resolved path's amplitude and phase. The continuous component of the impulse response represents a continuum of uncorrelated multipath components. Mathematically it is represented by a positive function of time multiplied by white noise.

GWSSUS POWER SPECTRAL DENSITY

The wideband indoor channel is frequently modeled as a time invariant frequency selective channel. Because the impulse response is approximated as a WSS process, it follows that its transfer function can also be approximated as WSS. The Wiener-Khintchine theorem states that the power spectral density of a WSS process can be computed by taking the Fourier transform of the process's autocorrelation function. The resulting function is always real. The real power spectral density of the wideband channel is called the power delay profile (PDP).

Bello stated that the PDP is equivalent to the averaged impulse response magnitude squared and can be easily measured using a pulsed transmitter and a square law detector receiver. For dynamic channels, time averaging can be used. For static channels, spatial averaging can be used. In either case, the averaging is done over a time or space for which the transfer function is WSS.

SIMULATION OF THE COMPLEX IMPULSE RESPONSE

Using the assumptions given above, it can be shown that the PDP represents twice the variance of the zero mean Gaussian random variable, which defines the complex impulse response at that time delay. This fact is frequently used to simulate the complex impulse response from PDP measurements. To simulate the value of the complex impulse response at each time delay, a mean of zero and a variance equal to half the PDP value at that time delay is entered into a Gaussian random number generator twice. One number represents the inphase component, the other represents the quadrature component. The impulse response is completely simulated when this has been done for a finite number of time delays [Chuang,1987].

PREDICTION OF BER WITHOUT THE COMPLEX IMPULSE RESPONSE

Bello's bit error rate (BER) estimates are dependent upon the PDPs. Studies have shown [Winters, 1985] that the exact shape of the PDP (or complex impulse response) is not as important in BER estimates as the PDP's rms delay spread (standard deviation of the PDP) provided the ratio of the rms delay spread to the symbol period is less than 0.1. Chuang [Chuang,1986] has shown how closed form BER expressions for Gaussian noise can be used for predicting multipath BER by replacing the signal-to-noise power ratio with signal to intersymbol interference power ratio.

III. PDP STATISTICAL MODEL

Statistical models capable of simulating power delay profile (PDP) measurements have been used to characterize the wideband indoor channel. These models describe the behavior of discrete multipath components within a PDP. Rappaport [Rappaport,1991], Ganesh [Ganesh,1989], and Saleh [Saleh,1987] have published PDP statistical models.

Like the GWSSUS model, PDP statistical models assume the indoor channel's complex impulse response can be modeled as a linear FIR filter with a finite number of taps. PDP measurements provide a band-limited estimate of the strength and delay of these taps by convolving a pulse with the channel's impulse response. Phase information is lost because the measurements are square law detected.

The behavior of the multipath component is derived from PDP measurements made at many different locations. Time or spatial averaging is not always performed on the PDP measurements before fitting to the model.

POWER DELAY PROFILE STATISTICAL PARAMETERS

Rappaport's statistical model is capable of predicting the dynamic "shape" of the PDP as the transceiver is moved in a room. The model is built from a large ensemble of PDP profile measurements performed at widely dispersed locations. At each location, 19 PDP measurements were made 1/4 wavelength apart. The closely spaced measurements are used to predict changes in the PDP due to small changes in position. The model divides the statistical parameters between intra-PDP parameters and inter-PDP parameters. The behavior of a multipath component is conditioned on that of nearby multipath components in the same PDP and on multipath components at the same time delay in adjacent PDPs.

Intra-PDP parameters are (1) the number of multipath components, (2) the probability of multipath component arrival at any time delay, and (3) the power of the multipath component. Relationships between multipath components within the PDP are (1) the correlation with respect to a difference in time delay of multipath component arrival and (2) the correlation with respect to a difference of time delay of multipath component power.

Inter-PDP parameters include (1) fading statistics for multipath components over a large area, (2) fading statistics for multipath components over a small area, and (3) the correlation with respect to distance of multipath component powers at the same delay.

Ganesh used a modified Poison distribution to describe multipath component arrival time. The modified Poisson distribution allows the multipath component arrival rate to increase if the previous time delay bin had a multipath component present. Multipath component amplitudes at each delay were found to fit log-normal distributions. Average multipath component powers at each delay showed an exponential decrease with delay time. The exponential decrease established a correlation between closely spaced multipath components. These relationships were verified for LOS and OLOS paths.

In Saleh's model, ray clusters determine the PDP shape. The clusters are attributed to the "direct" path, reflections from internal walls (if constructed with reflective materials), and reflections from external walls. The clusters arrive at a Poisson distribution rate. The average power within each cluster decays exponentially with increasing time delay. Within a cluster, the rays also arrive at a Poisson distribution rate and average ray power decreases exponentially with time delay. Poisson rates and exponential time constants of clusters and rays are independent. The ensemble of normalized multipath component amplitudes for all time delays were fit to a Rayleigh distribution.

SIMULATION OF COMPLEX IMPULSE RESPONSE FROM THE SIMULATED POWER DELAY PROFILE

Complex impulse responses can be generated from any of the simulated PDPs using techniques described in the GWSSUS section--provided measurements without specular components were used to build the statistical model. Saleh pointed out that he did not use LOS measurements in building his model so that the GWSSUS method of generating the complex impulse response could be used.

Rappaport's method of generating complex impulse responses from PDPs differs markedly from the GWSSUS method because it deterministically predicts phase from an arbitrary channel geometry as the receiver is moved. Rappaport proposes that this is a reasonable method if the data used to build the PDP have the time delay resolution necessary to isolate specular multipath components with preferred (instead of random) phases. Measurement data have confirmed that the model is built from specular multipath components by showing that multipath component fading over small distances has significantly smaller standard deviations compared to multipath component fading over large distances.

At the start of a simulation, using Rappaport's model, a PDP is generated from the statistical model. As the transceiver is moved through the room, successive PDPs are generated following the rules of multipath component behavior over small distances.

To generate the complex impulse response from wideband PDPs, phase from a uniform distribution is assigned to each multipath component when it first appears in a PDP. In subsequent PDPs, the phase of the multipath component is determined from an arbitrary channel geometry. This geometry is constructed by assigning each path a single reflection point and a length that accounts for the time delay. The change of phase of the multipath component is determined from the change in the length of this reflected path as the transceiver is moved. Tests have shown that this method generates accurate narrowband fading statistics [Seidel,1991].

IV. CONCLUSIONS

Geometrical, stochastic GWSSUS, and statistical PDP modeling methods have been discussed. It was shown how all three modeling methods can be used to predict the complex impulse response. The geometric model can simulate complex impulse responses for LOS and OLOS links from architectural drawings. This eliminates the need for laborious channel measurements. Accurate predictions of mobile transceiver performance are possible because the geometric model's complex impulse responses are dependent upon location in a room. Performance predictions for different antenna locations and antenna patterns can be quickly executed on a computer. Transceiver designs that mitigate ISI with direction diversity are easily evaluated.

Predictions from geometric models are criticized because of their inability to account for rays that leave the building, reflect, and reenter via room openings such as windows and doors. The predictions are also questioned because estimated values of reflection coefficients of common building materials are used.

Bello cautioned that the stochastic GWSSUS model not be used for channels with specular components in the received signal. For this reason, most indoor channel studies that rely on the GWSSUS model have not used LOS measurements. This may not be a disadvantage since worst case estimates would not assume a specular component. The well behaved statistical functions used in the GWSSUS model make some computations easier. For example, Bello was able to derive expressions for BER analytically for various modulation methods using only the channel's PDP.

The GWSSUS model is incapable of linking changes in the complex impulse response to small spatial displacements. Instead the GWSSUS model can be used to differentiate performance between two different rooms or two different floors in a building.

The statistical PDP model can be applied to LOS and OLOS links. If the simulated PDP's are assumed to be free of specular components, they can be averaged and used as variances to a GWSSUS complex impulse response generator. Rappaport's method of deriving phase from simulated PDPs allows simulation of complex impulse responses to be linked to small spatial displacements. This method does not require the absence of specular components.

REFERENCES

[Allen,1991] K.C. Allen, "A Model of Millimeter-Wave Propagation for Personal Communication Networks in Urban Settings", NTIA Report 91-275, April 1991.

[Bello,1963] P.A. Bello, B.D. Nellin, "The Effect of Frequency Selective Fading on the Binary Error Probabilities of Incoherent and Differentially Coherent Matched Filter Receivers", IEEE Trans. on Communications Systems, Vol. CS-11, June 1963, pp. 170-186.

[Bothias, 1987] L. Boithias, Radio Wave Propagation, McGraw Hill Book Company, 1987.

[Brown,1973] R.G. Brown, et.al., Lines Waves and Antennas, Ronald Press Company, 1973.

[Chuang,1986] J.C.I. Chuang, "Modeling and Analysis of a Digital Portable Communications Channel with Time Delay Spread", IEEE Vehicular Technology Conf., 1986, pp. 246-251.

[Chuang,1987] J.C.I. Chuang, "The effects of Time Delay Spread on Portable Radio Communications Channels with Digital Modulation", IEEE Journal on Selected Areas in Communications, Vol. SAC-5, No. 5, June 1987, pp.879-889.

[Cox,1986] D.C. Cox, et. al., "Cross Polarization Coupling Measured for 800 MHz Radio Transmission In and Around Houses and Large Buildings", IEEE Trans on Antennas and Propagation, Vol., AP-34, No. 1, January 1986, pp. 83-87.

[Devasirvatham,1987] D.M.J. Devasirvatham, "Multipath Time Delay Spread in the Digital Portable Radio Environment", IEEE Communications Magazine, Vol. 25 No. 6, June 1987, pp. 13-21.

[Ganesh,1989] R. Ganesh, K. Pahlavan, "On the Modeling of Fading Multipath Indoor Radio Channels", Proc. IEEE Globecom'89, Dallas TX, Nov 30,1989, pp. 1346-1350.

[Jordan,1968], E.C. Jordan, K.G. Balmain, Electromagnetic Waves and Radiating Systems, 2nd ed., Prentice-Hall Inc., 1968.

[Keller,1962] J.B. Keller, "Geometrical Theory of Diffraction", Journal of the Optical Society of America, Vol. 52, No. 2, February 1962, pp. 116-130.

[Lawton,1991] M.C. Lawton, R.L. Davies, and J.P. McGeehan, "An Analytical Model for Indoor Multipath Propagation in the Picocellular Environment", 6th International Conf. on Mobile Radio and Personal Communications, Warwick U.K., December 1991, pp. 1-8.

[McKown,1992] John McKown, "Toward a Proper Model of the Portable Indoor Microwave Channel", IEEE 802 Standards Submission P802.11-92/70, July 1992, pp. 1-9.

[Rappaport,1991] T.S. Rappaport, S.Y. Siedel, K. Takamizawa, "Statistical Channel Impulse Response Models for Factory and Open Plan Building Radio Communication System Design", IEEE Trans. on Communications, Vol. 39, No. 5, May 1991, pp. 794-807.

[Saleh,1987] A.A.M. Saleh, R.A. Valenzuela, "A Statistical Model for Indoor Multipath Propagation", IEEE J. on Selected Areas in Communications, Vol. SAC-5, No. 2, February 1987, pp. 128-137.

[Seidel,1991] S.Y. Seidel, T.S. Rappaport, "Simulation of UHF Indoor Radio Channels for Open-Plan Building Environments", IEEE 40th Vehicular Technology Conf., 1990, pp. 597-602.

[Winters,1985] J.H. Winters, Y.S. Yeh, "On the Performance of Wideband Digital Radio Transmission Within Buildings Using Diversity", IEEE Globecomm 85, pp. 991-996.