Intro to Spatial Channel Models for Antenna Array Communications

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Abstract

Throughout the history of wireless communications, spatial antenna diversity has been important in improving the radio link between wireless

users. Historically, microscopic antenna diversity has been used to reduce the fading seen by a radio receiver, whereas macroscopic diversity provides multiple listening posts to ensure that mobile communication links remain intact over a wide geographic area. In recent years, the concepts of spatial diversity have been expanded to build foundations for emerging technologies, such as smart (adaptive) antennas and position location systems. Smart antennas hold great promise for increasing the capacity of wireless communications because they radiate and receive energy only in the intended directions, thereby greatly reducing interference. To properly design, analyze, and implement smart antennas and to exploit spatial processing in emerging wireless systems, accurate radio channel models that incorporate spatial characteristics are necessary. In this tutorial, we review the key concepts in spatial channel modeling and present emerging approaches. We also review the research issues in developing and using spatial channel models for adaptive antennas

ith the advent of antenna array systems for both interference cancellation and position location applications comes the need to better understand the spatial properties of the wireless communications channel. These spatial properties of the channel will have an enormous impact on the performance of antenna array systems; hence, an understanding of these properties is paramount to effective system design and evaluation.

The challenge facing communications engineers is to develop realistic channel models that can efficiently and accurately predict the performance of a wireless system. It is important to stress here that the level of detail about the environment a channel model must provide is *highly dependent* on the type of system under consideration. To predict the performance of single-sensor narrowband receivers, it may be acceptable to consider only the received signal power and/or time-varying amplitude (fading) distribution of the channel. However, for emerging wideband multisensor arrays, in addition to signal power level, information regarding the signal multipath delay and angle of arrival (AOA) is needed.

Classical models provide information about signal power level distributions and Doppler shifts of the received signals. These models have their origins in the early days of cellular radio when wideband digital modulation techniques were not readily available. As shown subsequently, many of the emerging spatial models in the literature utilize the fundamental principles of the classical channel models. However, modern spatial channel models build on the classical understanding of fading and Doppler spread, and incorporate additional con-

cepts such as time delay spread, AOA, and adaptive array antenna geometries.

In this article, we review the fundamental channel models that have led to the present-day theories of spatial diversity from both mobile user and base station perspectives. The evolution of these models has paralleled that of cellular systems. Early models only accounted for amplitude and time-varying properties of the channel. These models were then enhanced by adding time delay spread information, which is important when dealing with digital transmission performance. Now, with the introduction of techniques and features that depend on the spatial distribution of the mobiles, spatial information is required in the channel models. As shown in the next sections, more accurate models for the distribution of the scatterers surrounding the mobile and base station are needed. The differentiation between the mobile and base station is important. Classical work has demonstrated that models must account for the physical geometry of scattering objects in the vicinity of the antenna of interest. The number and locations of these scattering objects are dependent on the heights of the antennas, particularly regarding the local environment.

This article, then, explores some of the emerging models

for spatial diversity and adaptive antennas, and includes the physical mechanisms and motivations behind the models. A literature survey of existing RF channel measurements with AOA information is also included. The article concludes with a summary and suggestions for future research.

Wireless Multipath Channel Models

This section describes the physical properties of the wireless communication channel that must be modeled. In a wireless system, a signal transmitted into the channel interacts with the environment in a very complex way. There are reflections from large objects, diffraction of the electromagnetic waves
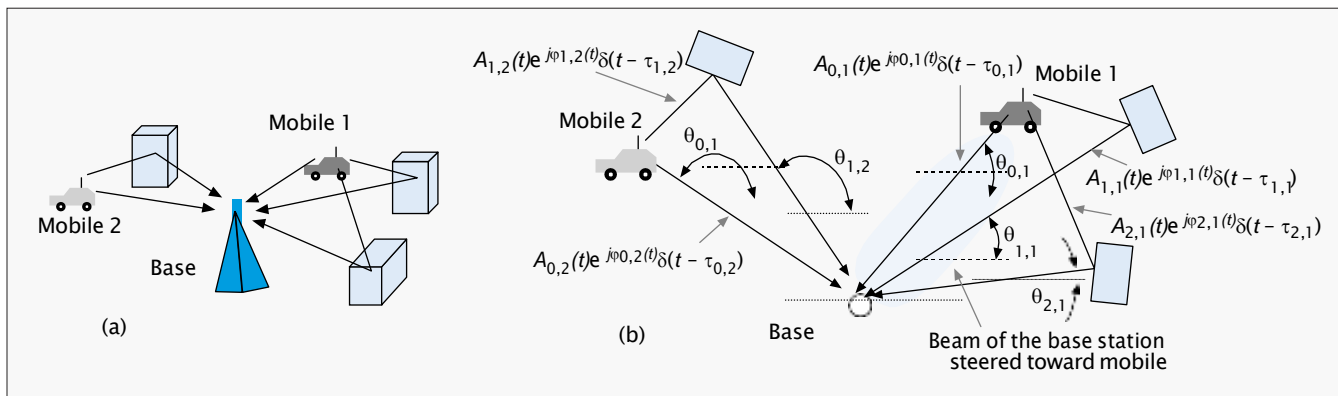
■ **Figure 1.** *Multipath propagation channel: a) side view; b) top view.*

around objects, and signal scattering. The result of these com - plex interactions is the presence of many signal components, or *multipath* signals, at the receiver. Another property of wire - less channels is the presence of Doppler shift, which is caused by the motion of the receiver, the transmitter, and/or any other objects in the channel. A simplified pictorial of the mul -tipath environment with two mobile stations is shown in Fig.

1. Each signal component experiences a different path envi - ronment, which will determine the amplitude $A_{l,k}$, carrier phase shift $\Box_{l,k}$, time delay $\Box_{l,k}$, AOA $\Box_{l,k}$, and Doppler shift f_d

where f_m is the maximum Doppler shift given by $v/\Box$ where $\Box$ is the wavelength of the transmitted signal at frequency f_c.

Figure 2 shows the received signals at the base station, assuming that mobiles 1 and 2 have transmitted narrow pulses at the same time. Also shown is the output of an antenna array system adapted to mobile 1.

The channel model in Eq. 1 does not consider the AOA of each multipath component shown in Figs. 1 and 2. For nar -rowband signals, the AOA may be included into the vector channel impulse response using of the *l*th signal component of t$_a$he *k* th mobile. In general, each of these signal parameters will be time-varying.

The early classical models, which were developed for nar -rowband transmission systems, only provide information about where L (t) is the number of multipath components and the other variables have already been defined. The amplitude $A_{l,k}$ of the multipath components is usually modeled as a Rayleigh distributed random variable, while the phase shift $\Box_{l,k}$ is uni-formly distributed.

The time-varying nature of a wireless channel is caused by the motion of objects in the channel. A measure of the time rate of change of the channel is the *Doppler power spectrum* ,introduced by M. J. Gans in 1972 [2]. The Doppler power spectrum provides us with statistical information on the varia -tion of the frequency of a tone received by a mobile traveling at speed v. Based on the flat fading channel model developed by R. H. Clarke in 1968, Gans assumed that the received sig - nal at the mobile station came from all directions and was uniformly distributed. Under these assumptions and for a vertical antenna, the Doppler power spectrum is given by

where $\Box_{l,i}(t) = [x_i\cos(\Box_i(t)) + y_i\sin(\Box_i(t))]\Box$ and $\Box = 2\Box/\Box$ is the wavenumber.

The spatial channel impulse response given in Eq. 2 is a summation of several multipath components, each of which has its own amplitude, phase, and AOA. The distribution of these parameters is dependent on the type of environment. In particular, the angle spread of the channel is known to be a function of both the environment and the base station anten - na heights. In the next section, we describe macrocell and microcell environments and discuss how the environment affects the signal parameters.

Macrocell vs. Microcell

Macrocell Environment — Figure 4 shows the channel on theforward link for a macrocell environment. It is usually
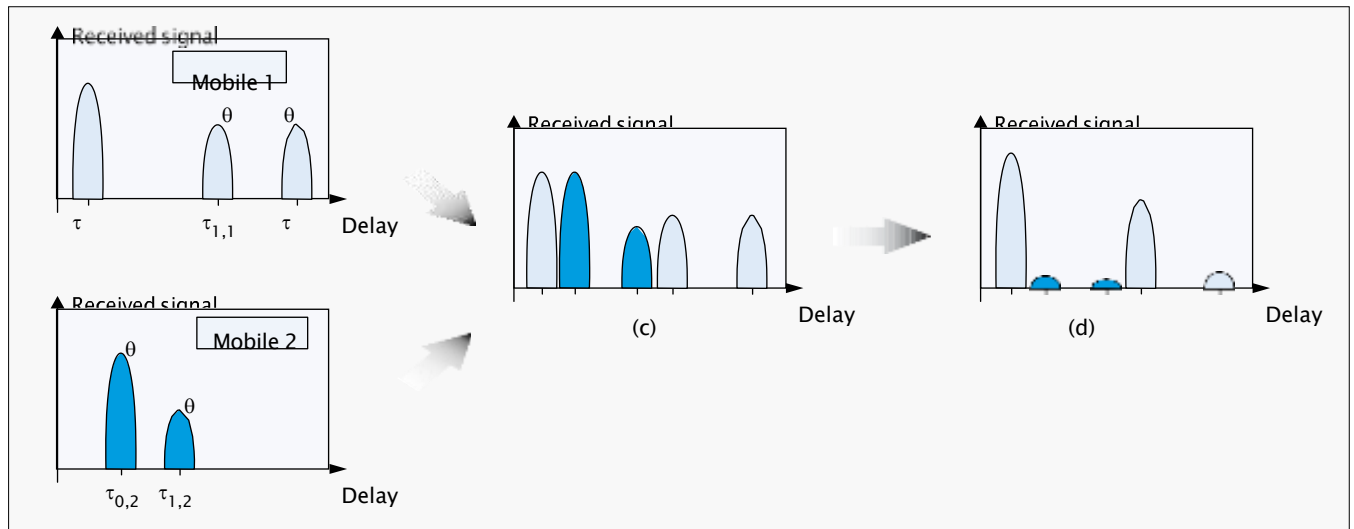
■ **Figure 2.** *Channel impulse responses for mobiles 1 and 2: a) received signal from mobile 1 to the base station; b) received signal from mobile 2 to the base station; c) combined received signal from mobiles 1 and 2 at the base station; d) received signal at the base station when a beam steered toward mobile 1 is employed.*

R ayleigh fading envelope with deep fades approximately apart emanates from this model [5].

However, the AOA of the receivedsignal at the base station is quite dif -ferent. In a macrocell environment, typically, the base station is deployed higher than the surrounding scatter - ers. H ence, the received signals at the base station result from the scat - tering process in the vicinity of themobile station, as shown in Fig. 5. The multipath components at the base station are restricted to a small - er angular region, $_{BW}$, and the dis - t ribution of the A O A is no longer uniform over [0,2]. Other AOA dis-tributions are considered later in this

Microcell Environment — In the micro- cell environment, the base station antenna is usually mounted at the same height as the surrounding objects. This implies that the scattering spread ofthe AOA of the received signal at the base station is larger than in the macrocell case since the scattering pro -cess also happens in the vicinity of the base station. Thus, as the base station antenna is lowered, the tendency is for the multipath AOA spread to increase. This change in the behavior of the received signal is very important as far as antenna array applications are con -cerned. Studies have shown that statis -tical characteristics of the receivedsignal are functions of the angle

article.

The base station model of Fig. 5 was used to develop the theory and practice of base station diversity in today's cellular system and has led to rules of thumb for the spacing of diver -sity antennas on cellular towers [3].
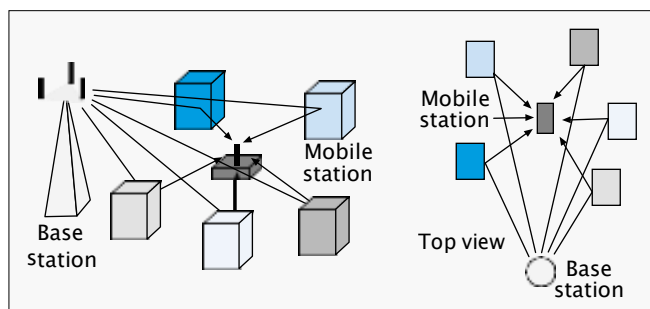
■ **Figure 4.** *Macrocell environment — the mobile station perspective.*

spread. Lee [3] and Adachi [6] found that the correlation between the signals received at two base station antennas increases as the angle spread decreases.

This section has presented some of the physical properties of a wireless communication channel. A mathematical expres -sion that describes the time-varying spatial channel impulse response was given in Eq. 2. In the next section, several mod -els that provide varying levels of information about the spatial channel are presented.

Space: The Final Frontier

Details of theSpatial Channel Models

In the past when the distribution of angle of arrival of multi -path signals was unknown, researchers assumed uniform dis -tribution over [0, 2 ⊐| [7]. In this section, a number of more realistic spatial channel models are introduced. The defining equations (or geometry) and the key results for the models

are described. Also provided is an exten -sive list of references.

Table 1 lists some representative active research groups in the field and their Web site addresses where more information on the subject can be found. (Note that this is by no means an exhaustive list.)

The Gaussian Wide Sense Stationary U ncorrelated Scattering (G WSSU S),Gaussian Angle of Arrival (GAA), Typi -cal U rban (T U) , and Bad U rban (B U)models described below were developed in a series of papers at the Royal Instituteof Technology and may be downloaded from the Web site. Further details of the

angle spreads and element spacings result in lower correlations, which provide an increased diversity gain. Measurements of the correlation observed at both the base station and the mobile are consistent with a narrow angle spread at the base station and a large angle spread at the mobile. Correlation measurements made at the base station indicate that the typical radiusof scatterers is from 100 to 200 wave - lengths [3].

Assuming that *N* scatterers are uniform - ly placed on the circle with radius *R* and oriented such that a scatterer is located on the line of sight, the discrete AOAs are [9]

G eometrically Based Single Bounce

(GBSB) models are given in theses at Vir -

ginia Tech, which are available at http://etd.vt.edu/etd/ index.html.

These various models were developed and used for differ -three models have nearly identical correlations. For larger ele -

ment separations (greater than two wavelengths), the correla - tion values using the continuous Gaussian AOA are close to zero, while the two discrete models have oscillation peaks with correlations as high as 0.2 even beyond four wavelengths. Additionally, it was found that the correlation of the discrete uniform distribution falls off more quickly than the correla - tion in Lee's model.

Again, while the model is useful for predicting the correla -tion between any pair of elements in the array (which can be used to calculate the array correlation matrix), it fails toinclude all the phenomena, such as delay spread and Doppler spread, required for certain types of simulations.

Geometrically Based Single-BounceStatistical Channel Models

poses. Use of the models for simulation involves randomlyplacing scatterers in the scatterer region according to the form
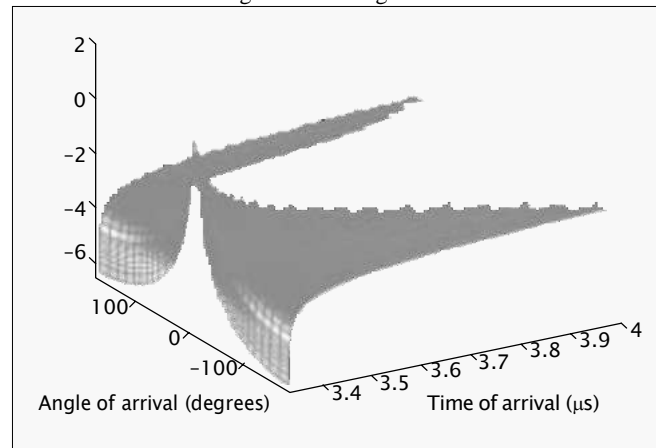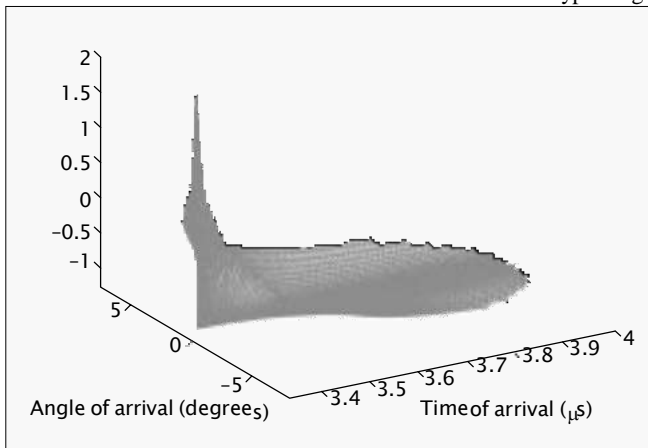
■ **Figure 9.** *Joint TOA and AOA probability density function atthe base station, circular model (log-scale).* **Figure 10.** *Joint TOA and AOA probability density function atthe mobile, circular model (log-scale).*

MHz, which provides a range of 30–60 m, roughly the width of wide urban streets.

The GBSBCM can be used to generate random channels for simulation purposes. Generation of samples from the GBSBCM is accomplished by uniformly plac -

AOA probability density functions. Knowledge of these statis -tics can be used to predict the performance of an adaptive array. Furthermore, knowledge of the underlying structure of the resulting array response vector may be exploited by beam -forming and position location algorithms.

The shape and size of the spatial scatterer density function required to provide an accurate model of the channel is sub -ject to debate. Validation of these models through extensive measurements remains an active area of research.

Geometrically Based Circular Model (Macrocell Model) — The geometry of the Geometrically Based Single Bounce Circular Model (GBSBCM) is shown in Fig. 8. It assumes that the scat - terers lie within radius Rm about the mobile. Often the require - ment that Rm < D is imposed. The model is based on the assumption that in macrocell environments where antenna heights are relatively large, there will be no signal scattering from locations near the base station. The idea of a circular region of scatterers centered about the mobile was originally proposed by Jakes [13] to derive theoretical results for the cor - relation observed between two antenna elements. Later, it was used to

determine the effects of beamforming on the Doppler spectrum [14, 15] for narrowband signals. It was shown that the rate and the depth of the envelope fades are significantly reduced when a narrow-beam beamformer is used.

The joint TOA and AOA density function obtained from the model provides some insights into the properties of the model. Using a Jacobian transformation, it is easy to derive the joint TOA and AOA density function at both the base sta - tion and the mobile. The resulting joint probability density functions (PDFs) at the base station and the mobile are shown in the box on this page [16].

The joint TOA and AOA PDFs for the GBSBCM are shown in Figs. 9 and 10 for the case of D = 1 km and Rm = 100 m from the base station and mobile perspec - tives, respectively. The circular model pre - dicts a relatively high probability of multipath components with small excess delays along the line of sight. From the base-station perspective, all of the multi - path components are restricted to lie with - in a small range of angles.
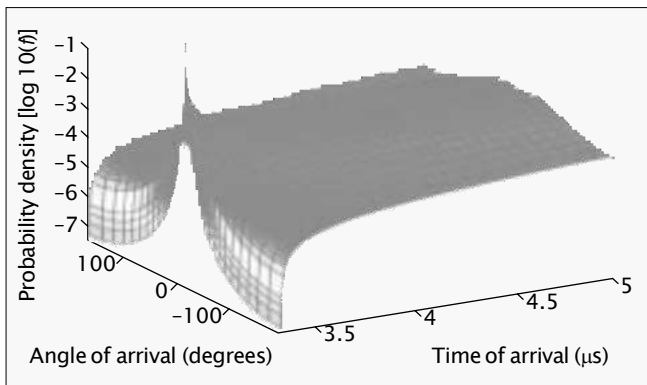
The appropriate values for the radius of scatterers can be determined by equat - ing the angle spread predicted by the model (which is a function of Rm) with measured values. Measurements reported in [9] suggest that typical angle spreads for macrocell environments with a T- R separation of 1 km are approximately two to six degrees. Also, it is stated that the angle spread is inversely proportional to the T- R separation, which leads to a radius of scatterers that ranges from 30 to 200 m [16]. In [3], i t is stated that the active scattering region around the mobile is about 100–200 wavelengths for 900

ing scatterers in the circular scatterer region about the mobile and then calculating the corresponding A O A, TO A, andpower levels.

Geometrically Based Elliptical Model (Microcell Wideband Model) — The Geometrically Based Single Bounce Elliptical Model (GBSBEM) assumes that scatterers are uniformly dis -tributed within an ellipse, as shown in Fig. 11, where the base station and mobile are the foci of the ellipse. The model was proposed for microcell environments where antenna heights are relatively low, and therefore multipath scattering near the base station is just as likely as multipath scatterering near themobile [17, 18].

A nice attribute of the elliptical model is the physical inter -pretation that only multipath signals which arrive with an absolute delay $\sqcup \sqcup_m$ are accounted for by the model. Ignoringcomponents with larger delays is possible since signals with longer delays will experience greater path loss, and hence have relatively low power compared to those with shorter delays. Therefore, provided that $\sqcup_m$ is chosen sufficientlylarge, the model will account for nearly all the power and AOA of the multipath signals.

The parameters a_m and b_m are the semimajor axis andsemiminor axis values, which are given by

GWSSUS. Figure 13 shows the geometry assumed for the GWSSUS model corresponding to $d = 3$ clusters. The mean AOA for the kth cluster is denoted $\sqcup_{0k}$. It is assumed that the location and delay associated with each cluster remains con - stant over several data bursts, b. The form of the received sig - nal vector is

■ **Figure 12.** *Joint TOA and AOA probability density function,elliptical model (log-scale).*

where c is the speed of light and $\sqcup_m$ is the maximum TOA tobe considered. To gain some insight into the properties of this model, consider the resulting joint TOA and AOA density function. Using a transformation of variables of the original uniform scatterer spatial density function, it can be shown thatthe joint TOA and AOA density function observed at the basestation is given by [16]

At the base station:

$$f_{\tau,\theta_b}\left(\tau,\theta_b\right)=$$

$$\begin{cases} \dfrac{\left(D^2-\tau^2c^2\right)\left(D^2c+\tau^2c^3-2\tau c^2D\cos\left(\theta_b\right)\right)}{4\pi R_m^2\left(D\cos\left(\theta_b\right)-\tau c\right)^3} & : \quad \dfrac{D^2-2\tau cD\cos\left(\theta_b\right)+\tau^2c^2}{\tau c-D\cos\left(\theta_b\right)} \le 2R_m \\[3mm] 0 & : \qquad else. \end{cases}$$

At the mobile:

$$f_{\tau,\theta_m}\left(\tau,\theta_m\right)=$$

$$\begin{cases} \dfrac{\left(D^2-\tau^2c^2\right)\left(D^2c+\tau^2c^3-2\tau c^2D\cos\left(\theta_m\right)\right)}{4\pi R_m^2\left(D\cos\left(\theta_m\right)-\tau c\right)^3} & : \quad \dfrac{D^2-\tau^2c^2}{D\cos\left(\theta_m\right)-\tau c} \le 2R_m \\[3mm] 0 & : \qquad else, \end{cases}$$

where θ_b and θ_m are the angle of arrival measured relative to the line of sight from the base station and the mobile, respectively.

phases $\zeta_{k,i}$ change much more rapidly. The vectors $\mathbf{v}_{k,b}$ are assumed to be zero mean, complex Gaussian wide sense, sta - tionary random processes where b plays the role of the time

where θ_b is AOA observed at the base station. A plot of the joint TOA and AOA PDF is shown in Fig. 12 for the case of $D = 1$ km and $\theta_m = 5$ Cs. From the plot of the joint TOA and AOA PDF, it is apparent that the GBSBEM results in a high probability of scatterers with minimum excess delay along the line of sight.

The choice of θ_m will determine both the delay spread and angle spread of the channel. Methods for selecting an appro -priate value of θ_m are given in [18]. Table 2 summarizes the

argument. The vector $\mathbf{v}_{k,b}$ is a multivariate Gaussian distribu -tion, which is described by its mean and covariance matrix. When no line of sight component is present, the mean will bezero due to the random phase $\theta_{k,i}$, which is assumed to beuniformly distributed in the range 0 to 2 π. When a direct path component is present, the mean becomes a scaled version of the corresponding array response vector $E\{\mathbf{v}_{k,b}\} \sqsupseteq \mathbf{a}\left(\theta_k\right)$ [9].The covariance matrix for the kth cluster is given by [21]

$$R \sqsupseteq E\ \mathbf{vv}^H$$

techniques for selecting θ_m where L_r is the reflection loss in dB, n is the path loss exponent, and θ_0 is the minimum path

To generate multipath profiles using the GBSBEM, themost efficient method is to uniformly place scatterers in the

Gaussian WideSenseStationaryUncorrelated Scattering

The G WSSUS is a statistical channel model that makes assumptions about the form of the received signal vector [19–22]. The primary motivation of

the model is to provide a general equation for the received signal cor -relation matrix. In the G WSSUSmodel, scatterers are grouped into clusters in space. The clusters are such that the delay differences with -in each cluster are not resolvablewithin the transmission signal band -width. By including multiple clus-ters, frequency-selective fading

Criteria	Expression
Fixed maximum delay, τ_m	$\tau_m = \text{constant}$
Fixed threshold T in dB	$\tau_m = \tau_0 10^{(T-L\hat{r})/10n}$
Fixed delay spread, σ_t	$\tau_m = 3.244\sigma_\tau + \tau_0$
Fixed max. excess delay, τ_e	$\tau_m = \tau_0 + \tau_e$

The model provides a fairly general result for the form of the covariance matrix. However, it does not indicate the number or location of the scattering clusters, and hence requires some additional information for application to typical environments.

Gaussian Angle of Arrival

The Gaussian Angle of Arrival (GAA) channel model is a special case of the GWSSUS model described above where only a single cluster is considered ($d = 1$), and the A O A statistics are assumed to be Gaussian distributed about some nominal angle, $\beth_0$, as shown in Fig.

14. Since only a single cluster is con-sidered, the model is a narrowband channel model that is valid when the time spread of the channel is small compared to the inverse of the signal bandwidth; hence, timeshifts may be modeled as simplephase shifts [23]. The statistics of the steering vec -tor are distributed as a multivariate Gaussian random variable. Similar channels can be modeled using the

where N is the number of scatterers, f_c the carrier frequency, c is the speed of light, $l_n(t)$ the path propagation distance, a random phase, and $\beth_t$ random delay. In general, the path propagation distance $l_n(t)$ will vary continuously with time; hence, Doppler fading occurs naturally in the model.

Typical Urban (TU) — In the TU model, 120 scatterers are ran -domly placed within a 1 km radius about the mobile [25]. Theposition of the scatterers is held fixed over the duration in which the mobile travels a distance of 5 m. At the end of the 5 m, the scatterers are returned to their original position with respect to the mobile. At each 5-m interval, random phases are assigned to the scatterers as well as randomized shadowing effects, which are modeled as log-normal with distance with a

where **a** is the array response vector, $\beth(t)$ is the complex path amplitude, $s(t)$ is the modulated signal, and **n**(t) is additive noise. This is equivalent to the impulse response given in Eq. 2.

The unique feature of the model is in the calculation of the complex amplitude term, $a_l(t)$, which is expressed as

$$\beth_1\beth t\beth\beth\beth_l\beth t\beth\beth \quad \beth_l \beth\beth\beth\beth_l\beth$$

where $\beth_l$ accounts for log-normal fading, $\beth(\beth_l)$ describes thepower delay profile, and $\beth_l(t)$ is the complex intensity of the radiation pattern as a function of time. The complex intensity is described by

$$\beth_l\beth t\beth\beth K \sum_{n\beth 1}^{N_l} |\hat{C}_n^l|\beth\beth_l\beth\exp\beth j\beth_d\cos\beth\beth_{n,l}\beth t\beth\beth$$

where N_l is the number of signal components contributing to the lth dominant reflecting surface, K accounts for the antenna gains and transmit signal power, $C_k(\beth_l)$ is the complex radiation of the nth component of the lth dominant reflecting surface in the direction of $\beth_j$, $\beth_d$ is the maximum Doppler shift, and $\beth_{n,l}$ is the angle toward the nth component of the lth dom- inant reflector with respect to the motion of the mobile. The result -ing complex intensity, $\beth_l(t)$
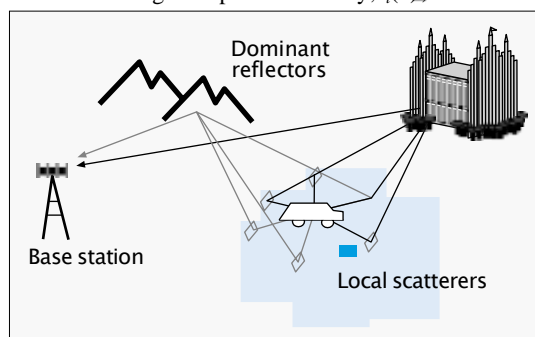
standard deviation of 5–10 dB [25]. The received signal is determined by brute force from the location of each of the scat - terers. An exponential path loss law is also applied to account for large-scale fading [21]. Simulations have shown that the TU model and the GSM-TU model have nearly identical power delay profiles, Doppler spectrums, and delay spreads [25]. Fur -thermore, the AOA statistics are approximately Gaussian and similar to those of the GAA model described above.

Bad Urban (BU) — The BU is identical to the TU model with the addition of a second scatterer cluster with another 120 scatterers offset 45 ° from the first, as shown in Fig. 16. The scatterers in the second cluster are assigned 5 dB less average power than the original cluster [25]. The presence of the sec -
ond cluster results in an increased angle spread, which in turn reduces the off-diagonal elements of the array covariance matrix. The presence of the second cluster also causes an increase in the delay spread.

Uniform Sectored Distribution
The defining geometry of Uniform Sectored Distribution (USD) is shown in Fig. 17 [26]. The model assumes that scatterers are uni - formly distributed within an angle

exhibits a complex Gaussian distri-
range of R centered about the mobile. The magnitude and phase associated with each scatterer is selected at random from a uniform distribution of [0,1] and [0, 2], respectively. As the number of scatterers approaches infinity, the signal fading envelope becomes Rayleigh with uniform phase [26]. In [26], the model is used tostudy the effect of angle spread on spatialdiversity techniques. A key result is that beam-steering techniques are most suit -able for scatterer distributions with widths slightly larger than the beamwidths.
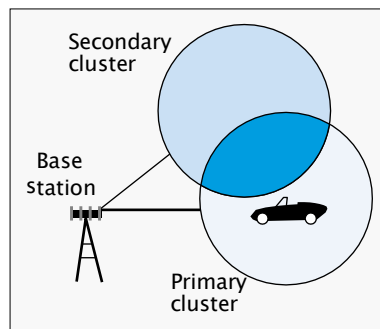

■ **Figure 16.** *Bad Urban vector chan-nel model geometry.*

mation was developed by Klein and Mohr [29]. The channel impulse response is rep - resented by

W

$$h\,t, \;=\; \sum_{w=1} a_w\, t\, \;-\;_w\;\;-\;_w\;.$$

This model is composed by W taps, each with an associated time delay $_w$, complex amplitude $_w$, and AOA $_w$. The joint density functions of the model parameters should be determined from measurements. As shown in [29], measure -ments can provide histograms of the joint

Modified Saleh-Valenzuela's Model

Saleh and Valenzuela developed a multipath channel model forindoor environment based on the clustering phenomenon observed in experimental data [27]. The clustering phenomenonrefers to the observation that multipath components arrive at the antenna in groups. It was found that both the clusters andthe rays within a cluster decayed in amplitude with time. Theimpulse response of this model is given by distribution of $|a|$, , and , and the density functions, whichare proportional to these histograms, can be chosen.

Elliptical Subregions Model(Lu, Lo, and Litva's Model)

Lu *et al.* [30] proposed a model of multipath propagation based on the distribution of the scatterers in elliptical subre -gions, as shown in Fig. 18. Each subregion (shown in a differ -ent shade) corresponds to one range of the excess delay time. This approach is similar to the GBS -

$$h\,t\;=\;\sum\sum_{ij}\;_{ij}\;t-T_i-\;_{ij}\;$$

$$i \sqsubset 0 \, j \sqsubset 0$$
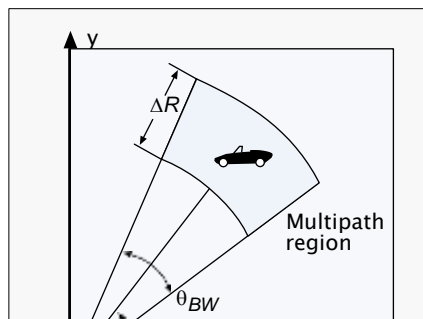
BEM proposed by Liberti and Rappa -port [18] in that an ellipse of scatterers

where the sum over i corresponds tothe clusters and the sum over j repre -sents the rays within a cluster. The vari -ables $\sqsupset_{ij}$ are Rayleigh distributed with the mean square value described by a double-exponential decay given by

is considered. The primary difference between the two models is in the selec -tion of the number of scatterers and the distribution of those scatterers. In the GBSBEM, the scatterers were uniformly distributed within the entire ellipse. In

Lu, Lo, and Litva's model, the ellipse is

$$\overline{\sqsupset_{ij}^2} \sqsupset \overline{\sqsupset_{00}^2} \exp\sqcup{-T_i} / \sqsupset \sqcup \exp\sqcup\vert\sqsupset_{ij} / \sqsupset \vert\sqcup$$

where $\sqsupset$ and $\sqsupset$ are the cluster and raytime decay constant, respectively. Moti -vated by the need to include AOA in the channel mode, Spencer *et al*. pro-posed an extension to the Saleh-Valen -zuela's model [28], assuming that time and the angle are statistically indepen -dent, or

$$h(t, \sqsupset) = h(t) h(\sqsubset).$$

first subdivided into a number of ellipti -cal subregions. The number of scatterers within each subregion is then selected from a Poisson random variable, the mean of which is chosen to match the measured time delay profile data.

It was also assumed that the multi -path components arrive in clusters due to the multiple reflecting points of thescatterers. Thus, assuming that there are L scatterers with K_l reflecting points

Similar to the time impulse response in Eq. 3, the pro -posed *angular impulse response* is given by

tributed.

Simulation results using this model were presented in [30], showing that a 60 ° beamwidth antenna reduces the mean RMS delay spread by about 30–43 percent. These results are consistent with similar measurements made in Toronto using a sectorized antenna [31].

where $f(\sqsupset)$ is the impulse response representing the joint transfer characteristic of the transmission system components (modulator, demodulator, filters, etc.), and $g(\sqcup, \sqcup)$ is the char -acteristic of the base station antenna. The term $\sqsupset(\sqsubset, t, \sqsupset)$ isthe time-variant directional distribution of channel impulse response seen from the base station. This distribution is time-variant due to mobile motion and depends on the location, orientation, and velocity of the mobile station antenna and the topographical and morphographical properties of the propagation area as well. Measurement is used to determine the distribution $\sqsupset(\sqsupset, t, \sqsupset)$.

By using directional antennas, it is possible to reduce thetime dispersion.

Another set of TOA and AOA measurements is reported in [39] for urban areas. The measurements were made using a two-element receiver that was mounted on the test vehicle with an elevation of 2.6 m. The transmitting antenna was placed 30 m high on the side of a building. A bandwidth of 10M Hz with a carrier frequency of 2.33 GHz was used. Thedelay-Doppler spectra observed at the mobile was used toobtain the delay-AOA spectra. The second antenna element isused to remove the ambiguity in AOA that would occur if only the Doppler spectra were known. The results indicatethat it is possible to account for most of the major features ofthe delay-AOA spectra by considering the large buildings in the environment.

Motivated by diversity combining methods, earlier mea -surements were concerned primarily with determining the correlation between the signals at two antenna elements as a function of the element separation distance. These stud - ies found that, at the mobile, relatively small separationdistances were required to obtain a small degree of corre -lation between the elements, whereas at the base station

very large spacing was needed.

Ray Tracing Models

The models presented so far arebased on statistical analysis and measurements, and provide us with the average path loss and delay spread, adjusting some parameters according to the envi -ronment (indoor, outdoor, obstructed, etc.). In the past few years, a *deterministic* model, called*ray tracing*, has been proposedbased on the geometric theory and reflection, diffraction, and scatter -ing models. By using site-specific
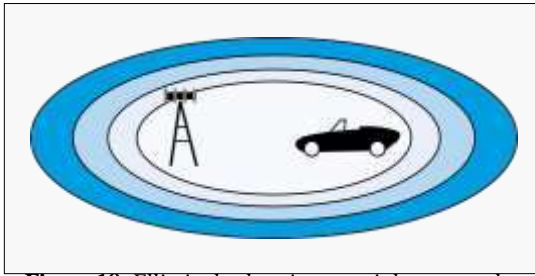
■ **Figure 18.** *Elliptical subregions spatial scattererdensity.*

These findings indicate that there is a relatively small angle spread observed at the base sta - tion [6].

Previously, an extension to Saleh-Valenzuela's indoor model, including AOA information, was presented. This extension was proposed based on indoor mea - surements of delay spread and AOA at 7 GHz made at Brigham Young University [40]. The AOAs were measured using a 60 cm parabolic dish antenna that had a 3 dB beamwidth of 6°. The information, such as building databases or architecture draw -ings, this technique deterministically models the propagation channel [33–36], including the path loss exponent and the delay spread. However, the high computational burden and lack of detailed terrain and building databases make ray trac -ing models difficult to use. Although some progress has been made in overcoming the computational burden, the develop -ment of an effective and efficient procedure for generating terrain and building data for ray tracing is still necessary.

Channel Model Summary

Table 3 summarizes each of the spatial models presented above.

Spatial Signal Measurements

There have been only a few publications relating to spatial channel measurements. In this section, references are given to these papers, and the key results are described.

In [38], TOA and AOA measurements are presented for outdoor macrocellular environments. The measurements were made using a rotating 9° azimuth beam directional receiver antenna with a 10 MHz bandwidth centered at 1840 MHz. Three environments near Munich were considered, including rural, suburban, and urban areas with base station antenna heights of 12.3 m, 25.8 m, and 37.5 m, respectively. The key observations made include [38]:

• Most of the signal energy is concentrated in a small interval of delay and within a small AOA in rural, suburban, and even many urban environments.

results showed a clustering pattern in both time and angle domain, which led to the proposed channel model described in [28]. Also, it was observed that the cluster mean angle of arrival was uniformly distributed $[0, 2\pi]$. The distribution of the angle of arrival of the rays within a cluster presented a sharp peak at the mean, leading to the Laplacian distribu -tion modeling. The standard deviation found for this distri -bution was around 25°. Based on these measurements, a channel model including delay spread and AOA informa -tion was proposed, supposing that time and angle wereindependent variables.

In [41], two-dimensional AOA and delay spread mea -surement and estimation were presented. The measure - ments were made in downtown Paris using a channel sounder at 900 MHz and a horizontal rectangular planar array at the receiver. The estimation of AOA, includingazimuth and elevation angle, was performed using 2D uni - tary ESPRIT [42] with a time resolution of $0.1 \mu s$ and angleresolution of 5°. The results presented confirmed assump -tions made in urban propagation, such as the wave-guiding mechanism of streets and the exponential decay of the power delay profile. Also, it was observed that 90 percent of the received power was contained in the paths with eleva - tion between 0° and 40° with the low elevated paths con -tributing a larger amount.

Finally, in [43] measurements are used to show the varia -tion in the spatial signature with both time and frequency. Two measures of change are given, the relative angle change given by

Model	Description	References
Lee's Model	Effective scatterers are evenly spaced on a circular ring about the mobile Predicts correlation coefficient using a discrete AOA model Extension accounts for Doppler shift	[3, 9, 11]
Discrete Uniform Distribution	N scatterers are evenly spaced over an AOA range Predicts correlation coefficient using a discrete AOA model Correlation predicted by this model falls off more quickly than the correlation in Lee's model	[9]
Geometrically Based Circular Model (Macrocell Model)	Assumes that the scatterers lie within circular ring about the mobile AOA, TOA, joint TOA and AOA, Doppler shift, and signal amplitude information is provided Intended for macrocell environments where antenna heights are relatively large	[12–14, 16, 37]
Geometrically Based Elliptical Model (Microcell Wideband Model)	Scatterers are uniformly distributed in an ellipse where the base station and the mobile are the foci of the ellipse AOA, TOA, joint TOA and AOA, Doppler shift, and signal amplitude information is provided Intended for microcell environments where antenna heights are relatively low	[17, 18]
Gaussian Wide Sense Stationary Uncorrelated Scattering (GWSSUS)	N scatterers are grouped into clusters in space such that the delay differences within each cluster are not resolvable within the transmission signal BW Provides an analytical model for the array covariance matrix	[19–22]
Gaussian Angle of Arrival (GAA)	Special case of the GWSSUS model with a single cluster and angle of arrival statistics assumed to be Gaussian distributed about some nominal angle Narrowband channel model Provides an analytical model for the array covariance matrix	[23]
Time-Varying Vector Channel Model (Raleigh's Model)	Assumes that the signal energy leaving the region of the mobile is Rayleigh faded Angle spread is accounted for by dominant reflectors Provides both Rayleigh fading and theoretical spatial correlation properties	[20]
Typical Urban	Simulation model for GSM, DCS1800, and PCS1900 Time domain properties are similar to the GSM-TU defined in GSM 05.05 120 scatterers are randomly placed within a 1 km radius about the mobile Received signal is determined by brute force from the location of each of the scatterers and the time-varying location of the mobile AOA statistics are approximately Gaussian	[21, 22, 25]
Bad Urban	Simulation model for GSM, DCS1800, and PCS1900 Accounts for large reflectors not in the vicinity of the mobile Identical to the TU model with the addition of a second scatterer cluster offset 45° from the first	[21, 22, 25]
Uniform Sectored Distribution	Assumes that scatterers are uniformly distributed within an angle distribution Δ_{BW} and a radial range of R centered about the mobile Magnitude and phase associated with each scatterer are selected at random from a uniform distribution of $[0,1]$ and $[0, 2\pi]$, respectively	[26]
Modified Saleh-Valenzuela's Model	An extension to the Saleh-Valenzuela model, including AOA information in the channel model Assumes that time and the angle are statistically independent Based on indoor measurements	[28]
Extended Tap-Delay-Line Model	Wideband channel model Extension of the traditional statistical tap-delay-line model which includes AOA information The joint density functions of the model parameters should be determined from measurements	[29]
Spatio-Temporal Model (Lu, Lo, and Litva's Model)	Model of multipath propagation based on the distribution of the scatterers in elliptical subregions, corresponding to a range of excess delay time Similar to the GBSBEM	[30]
Measurement-Based Channel Model	Parameters are based on measurement Characterizes the propagation environment in terms of scattering points	[32]

RayTracing Models	Deterministic model based on the geometric theory and reflection, diffraction, and scattering models Uses site-specific information, such as building databases or architecture drawings	[33–36]	two spatial signatures

(array response vectors) being compared. The measurements indicate that when the mobile and surroundings are stationary, there are relatively small changes in the spatial signature. Likewise, there are moderate changes when objects and the environ - ment are in motion and large changes when the mobile itself is moving. Also, it was found that the spatial signature changes significantly with a change in carrier frequency. In particular, the measurements found that the relative amplitude change in the spatial signal could exceed 10 dB with a frequency change of only 10 MHz. This result indicates that the uplink spatial signature cannot be directly applied for downlink beamform -ing in most of today's cellular and PCS systems that have 45 MHz and 80 MHz separation between the uplink and down -link frequencies, respectively.

Application of Spatial Channel Models

The effect that classical channel properties such as delay spread and Doppler spread have on system performance has been an active area of research for several years and hence is fairly well understood. The spatial channel models include the AOA properties of the channel, which are often characterized by the angle spread. The angle spread has a major impact on the correlation observed between the pairs of elements in the array. These correlation values specify the received signal vec - tor covariance matrix, which is known to determine the per - formance of linear combining arrays [44]. In general, the higher the angle spread the lower the correlation observed between any pair of elements in the array. The various spatial channel models provide different angle spreads and hence will predict different levels of system performance.

The channel models presented here have various applica - tions in the analysis and design of systems that utilize adaptive antenna arrays. Some of the models were developed to pro - vide analytical models of the spatial correlation function, while others are intended primarily for simulation purposes.

Simulation

More and more companies are relying on detailed simulations to help design and develop today's wireless networks. The application of adaptive antennas is no exception. However, to obtain reliable results, accurate spatial channel models are needed. With accurate simulations of adaptive antenna array systems, researchers will be able to predict the capacity improvement, range extension, and other performance mea -sures of the system, which in turn will determine the cost effectiveness of adaptive array technologies.

Algorithm Development

The availability of channel models also opens up the possibili - ty of developing new maximum likelihood smart antennas and AOA estimation algorithms based on these channel models. Good analytical models that will provide insights into the structure of the spatial channel are needed.

Conclusions

As antenna technology advances, radio system engineers are increasingly able to utilize the spatial domain to enhance sys - tem performance by rejecting interfering signals and boosting desired signal levels. However, to make effective use of the spatial domain, design engineers need to understand and appropriately model spatial domain characteristics, particular - ly the distribution of scatterers, angles of arrival, and the Doppler spectrum. These characteristics tend to be dependent on the height of the transmitting and receiving antennas rela -tive to the local environment. For example, the distributions expected in a microcellular environment with relatively low base station antenna heights are usually quite different from those found in traditional macrocellular systems with elevated base station antennas.

This article has provided a review of a number of spatial propagation models. These models can be divided into three groups:

General statistically based models

More site-specific models based on measurement data

Entirely site-specific models.

The first group of models (Lee's Model, Discrete Uniform Distribution Model, Geometrically Based Single Bounce Sta - tistical Model, Gaussian Wide Sense Stationary Uncorrelated Scattering Model, Gaussian Angle of Arrival Model, Uniform Sectored Distributed Model, Modified Saleh-Valenzuela's Model, Spatio-Temporal Model) are useful for general system performance analysis. The models in the second group (Extended Tap Delay Line Model and Measurement-Based Channel Model) can be expected to yield greater accuracy but require measurement data as an input. An example from the third group of models is Ray Tracing, which has the potential to be extremely accurate but requires a comprehensive description of the physical propagation environment as well as measurements to validate the models.

Further research is required to validate and enhance the models described in this article. Bearing in mind that an objective of modeling is to substantially reduce the amount of physical measurement required in the system planning pro - cess, it is important for design engineers to have reliable mod - els of A O A, T DO A, delay spread, and the power of the multipath components. Further measurement programs that focus on spatial domain signal characteristics are required. These programs would greatly benefit from the development of improved measurement equipment.

Armed with improved spatial channel modeling tools and a greater understanding of signal propagation, engineers can begin to meet the challenges inherent in designing future high-capacity/high-quality wireless communication systems, including the effective use of smart

antennas.

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