White Paper

Correlation-Based Spatial Channel Modeling

Introduction

The Spatial Channel Model (SCM) [i] is used to evaluate multiple-antenna systems and algorithms. This model was developed within a combined 3GPP-3GPP2 ad hoc group to address the need for a precise channel model definition that enables fair comparisons of various MIMO proposals.

The channel model was carefully designed to be consistent with field measurements, including the important narrow angle spread behavior observed in wide-band channels. The detailed model is described in [ii]. Later, the SCM was extended by a modification proposed in [iii] by The European Wireless World Initiative New Radio (WINNER) project to increase the bandwidth from 5MHz up to 100MHz. The modified model is called the Spatial Channel Model Extended (SCME) and is part of the WINNER models described in [iv].

The SCM and the SCME use a ray-based modeling technique wherein each path is modeled by a number of sub-paths as a sum-of-sinusoids, each representing individual plane waves received by the antenna array. The ray-based modeling technique is relatively simple to use and has advantages over other techniques because it automatically addresses many of the important aspects of the channel model by summing the sub-path sinusoids. These include spatial correlation between antenna elements and the autocorrelation resulting from the non-classical Doppler spectra. Both spatial correlation and autocorrelation are due to the effects of narrow angle spread, which is a function of angle.

Correlation-Based Spatial Channel Modeling

The subject of this paper is correlation-based modeling, which is another approach used in spatial channel modeling. Recently, correlation-based spatial channel models have become popular because of their simple mathematical form and ease of modeling. Technical comparisons show that correlation and ray-based modeling are equivalent [v]. Correlation-based spatial channel modeling refers to the use of filtered complex Gaussian noise samples to obtain independent temporal fading sequences. These are spatially correlated with a correlation matrix. A complete Spatio-Temporal fading model is defined by this technique.

Correlation-Based Modeling

Correlation-based modeling refers to the correlation present between samples. This can be correlation in the time, frequency, or spatial domains. For channel modeling purposes, it generally includes all three.

Time correlation is a description of the change in the fading signal as a function of time and is used to describe motion with a periodic sampling rate as an antenna moves at a constant velocity through a fading field. Time correlation is analogous to distance sampling, where the distance is normalized to wavelengths. The effects of coding, interleaving, automated packet repeats, control loops, and other temporal characteristics are all sensitive to these types of correlations.

Frequency correlation is a description of the frequency selectivity of the channel, which is the change in signal level that results from a change in frequency. This effect is produced by path differences present in the multi-path signal, and is related to the coherence bandwidth of the channel. For wide-band channels, where the bandwidth is > 1MHz, significant variations in signal level may be observed. This effect has led to techniques such as frequency diversity and frequency selective scheduling to mitigate these frequency dependent signal variations.

Spatial correlation describes the correlation between antenna elements. It is a function of signal conditions such as the angle-of-arrival (AoA), the power azimuth spectrum (PAS), antenna spacing and the system bandwidth. Spatial correlation may also include the effects of antenna polarization.

Time, Distance, and Spatial Correlation are related and produce the same result when the sampling represents identical locations in space. For example, the correlation between antenna elements at a fixed spacing is equivalent to the correlation produced from a moving antenna element that samples the same locations in space. Likewise, time sampling at a given velocity also results in the same correlation when the same points in space are sampled. These all result in a Bessel function for classical Rayleigh fading, but the result for narrow angle spread is quite different, as described in the following section.

Path Characteristics

Wide-band channel models include a number of delayed and attenuated replicas of the original transmission at the receiver, due to the numerous reflections that occur between the transmitter and receiver. Figure 1 depicts a set of delayed paths with relative amplitudes.

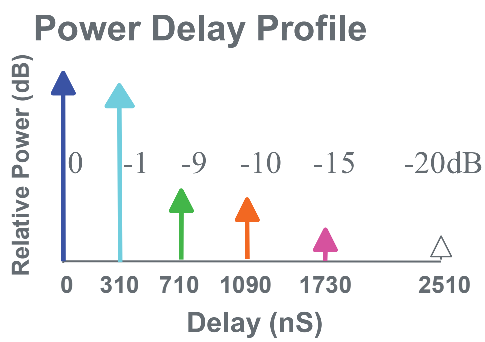

Figure 1: Sample power delay profile from the ITU Vehicular A Channel Model.

Modeling a spatial channel requires the proper modeling of each path, which is a function of the bandwidth. For wide-band signals, the fading behavior is characterized by a narrow angle spread of received plane-waves for each path, as observed in numerous field measurements.

The power azimuth spectrum (PAS) for each path is a description of its power and angle distribution, and is typically assumed to follow a Laplacian distribution. This is a two-sided exponential, or an isosceles triangle when plotted on a dB scale. As shown in Figure 2, the center of the distribution is at zero degrees relative to the average AoA or AoD of the path.

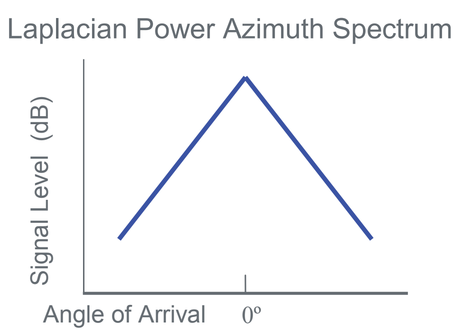

Figure 2: Power Azimuth Spectrum.

Doppler

A path with a narrow angle spread characteristic produces a one-sided Doppler spectrum for most AoAs because the signal is arriving from a limited set of angles relative to the direction of travel (DoT). When emulating the temporal fading behavior for a path with a Laplacian Power Azimuth Spectrum, a signal source must produce the appropriate Doppler spectrum. This spectrum is a function of the angle spread (AS), AoA, DoT, and speed.

Temporal fading is based on the time response of the channel and is often modeled by a series of random complex Gaussian samples to produce uncorrelated Rayleigh distributed amplitudes. This is followed by a Doppler filter that produces the expected time response. This is often called a filtered noise fader. This approach can be used with a Doppler filter based on the classical U-shaped Doppler spectrum or the Doppler spectrum based on the narrow AS. The classical Doppler spectrum is shown in Figure 3, and is based on the equation:

$$S(f) = \frac{3}{f_m}\left[1\frac{-}{2\pi}\left(\frac{f-f_c}{f_m}\right)\right]^{-1/2}, \text{ where } f_m = \frac{v}{\lambda}$$

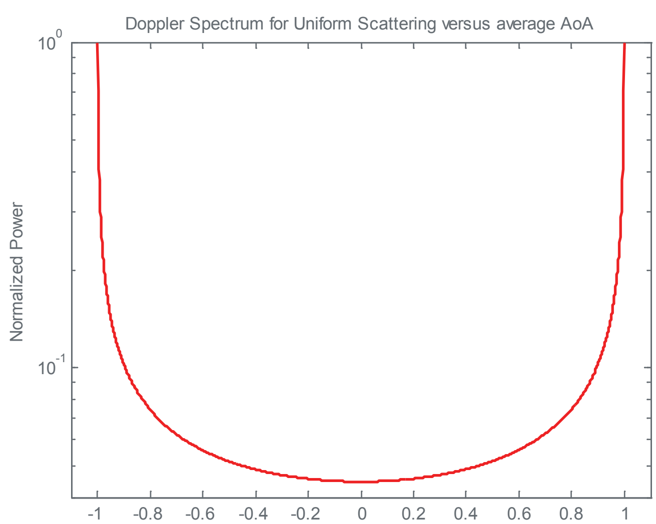

Figure 3: Classical u-shaped doppler spectrum.

The Doppler filter emulates the temporal behavior of the combined plane waves received at the antenna. Here, temporal behavior is a function of the AS, AoA, DoT, and speed. Figure 4 depicts a path with a narrow AS; the sub-paths represent individual plane waves. Note that this is different than the classical Rayleigh fading assumption, where a U-shaped Doppler spectrum that is only a function of speed results from a uniform arrival model.

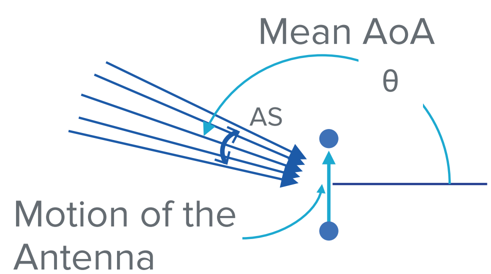

Figure 4: Signal and antenna positioning

The following equation describes the Doppler spectrum of the Laplacian distributed signal. It defines the Doppler filter required for the correct temporal behavior for a narrow angle spread.

$$S(f) = \frac{\sqrt{2}e^{-\frac{\sqrt{2}}{\sigma}\left|\cos^{-1}\left(\frac{f}{f_m}\right)-\mu\right|}}{f_m\sqrt{1-\left(\frac{f}{f_m}\right)^2}}$$

Where, $|f| \leq f_m$, and μ is the angle difference between the average AoA and the DoT, and f_m is the maximum Doppler frequency.

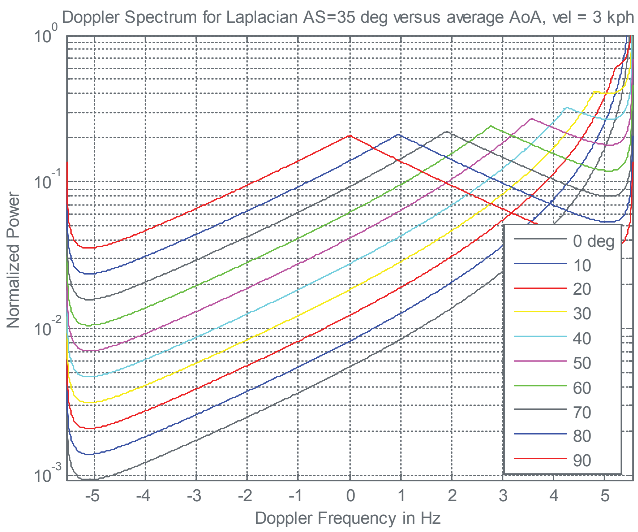

Figure 5: Doppler spectrum for a Laplacian path.

Figure 5 illustrates the variation in Doppler spectrum as a function of AoA relative to the direction of movement. Here, 0 degrees is defined as the direction moving towards the narrow AS path and 90° is moving orthogonal to the direction of the incoming path.

This filtered noise fader filters the complex uncorrelated Gaussian i.i.d. signals $\mathbf{H}_U$ with the Doppler spectrum $S(f)$ given above matching the AoA for the incoming path to obtain the faded temporal signal $\mathbf{H}_{tem}$.

The faded temporal signal $\mathbf{H}_{tem}$ is the result of filtering the complex uncorrelated Gaussian signals $\mathbf{H}_U$, where $\mathbf{H}_U$ are i.i.d. (independent and identically distributed). $S(f)$ is the Doppler spectrum, as given in the previous equation.

$$\mathbf{H}_{tem} = \mathbf{H}_U * S(f)$$

Spatial Correlation

The correlation for antennas separated by a distance d can be calculated using the following equations, similar to those in [vi]. The density function is given by $p(\phi)$ which is a Laplacian distribution in this example, with the average AoA given by ϕ_a. The limits of integration are set wide enough to accommodate the tails of the Laplacian distribution, although a truncated distribution is also commonly used.

$$R_{BS} = \int_{-4\pi+f_a}^{4\pi+f_a} p(f_i - f_a) \exp\left\{ j \frac{2\pi d_{BS}}{\lambda} \sin(f_i - f_a) \right\} df_i$$

$$R_{MS} = \int_{-4\pi+f_a}^{4\pi+f_a} p(f_i - f_a) \exp\left\{ j \frac{2\pi d_{BS}}{\lambda} \sin(f_i - f_a) \right\} df_i$$

Figure 6 illustrates the complex correlation that results from the Laplacian PAS when an AS of 2° is specified for BS antennas separated by a distance of 4λ. The magnitude indicates that the correlation magnitude between antenna elements is quite high, ranging from about 0.7 to 1.0.

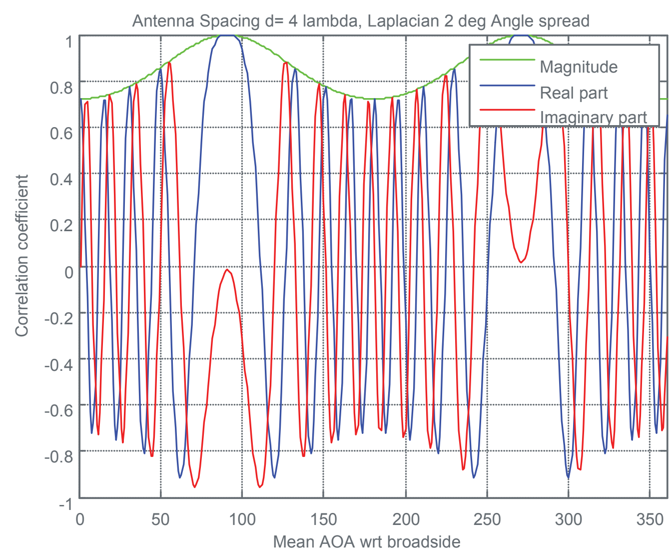

Figure 6: Base station antenna correlation.

Figure 7 illustrates the correlation between subscriber antennas separated by λ/2. Even though the antennas are closer together, the correlation is somewhat lower due to the larger AS of 35°. Note that the value of 35° was selected in the SCM for modeling purposes as a simplification. It was the median value for a distribution that varied from a few degrees to around 100°, and was selected for modeling each path rather than requiring yet another random distribution.

In general, having very low angle spreads correspond to the highest received powers, and result in the highest correlation. Thus the stronger the signal, the more likely that very high correlation will be observed between antennas. For both the base station and subscriber the antenna correlation is a function of the path angle.[1]

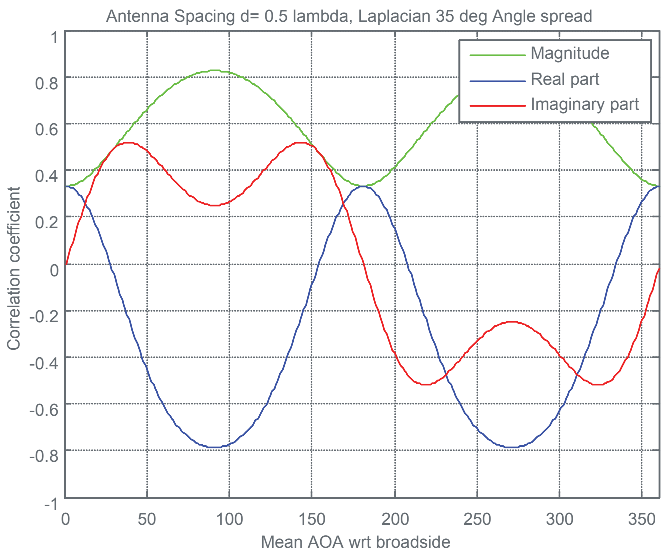

Figure 7: Subscriber antenna correlation.

Correlation can be plotted in another way as shown in Figure 8, based on the separation of antenna elements or the distance between samples. These two interpretations are exactly the same, and indicate how much the signal is changing versus distance.

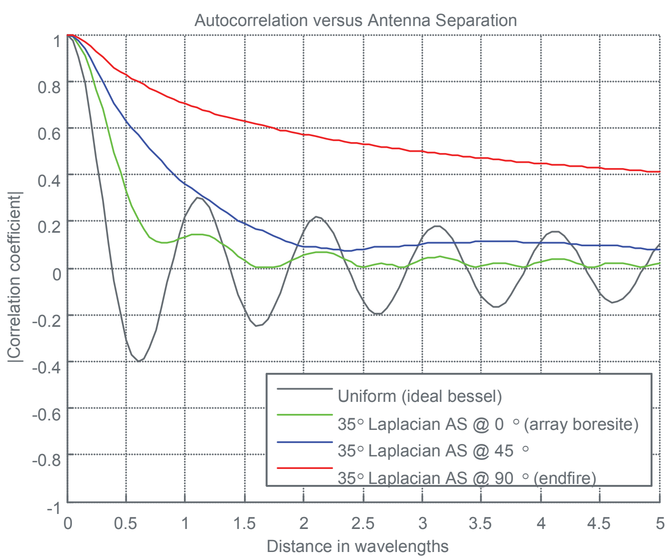

Figure 8: Autocorrelation.

Note that by using the narrow angle spread selected to match field measurements, an increased correlation is obtained when compared to the uniform or classical Doppler assumption. This result can be seen in Figure 8 where the difference between the Uniform model and the 35° Laplacian AS cases are shown with three different angles of arrival, 0°, 45°, and 90°. These narrow AS cases result in a reduced fading rate. This can be seen by observing that the correlation remains high for larger sampling distances (measured in wavelengths).

1. *Note that when m is a non-integer, there may be a counting ambiguity where depending on the starting phases (which is a function of the path difference) the BW may contain m or m+1 fades. Since the equation was derived assuming m is an integer then we should only obtain m fades, so this should not be a problem.*

Frequency Selectivity

When the channel is modeled by a number of discrete time-delayed multi-path components, the frequency response of the channel is based on the frequency selective effect of the combined multi-path components. This is a correlation known as a spaced-frequency-correlation function.

Most channel models to date have been limited to a small number of paths since channel bandwidths were limited to a few MHz. With wider bandwidths, the Spaced-Frequency Correlation Function [vii] exhibits periodic oscillations across frequency, indicating how different frequencies are correlated across the band. Figure 9 shows the result for the Vehicular A channel model, described earlier in Figure 1. The oscillations in correlation are due to having a limited number of paths, wherein the differences in path lengths result in different phase contributions at each frequency. As the frequency changes, the nominal path phases advance at a rate proportional to their path length and produce the oscillation in correlation. When the complex path components are combined, there are some frequencies in which paths cancel and other frequencies in which paths add constructively. When fading is added to these paths, the fading is correlated across frequency based on the phase relationships between paths.

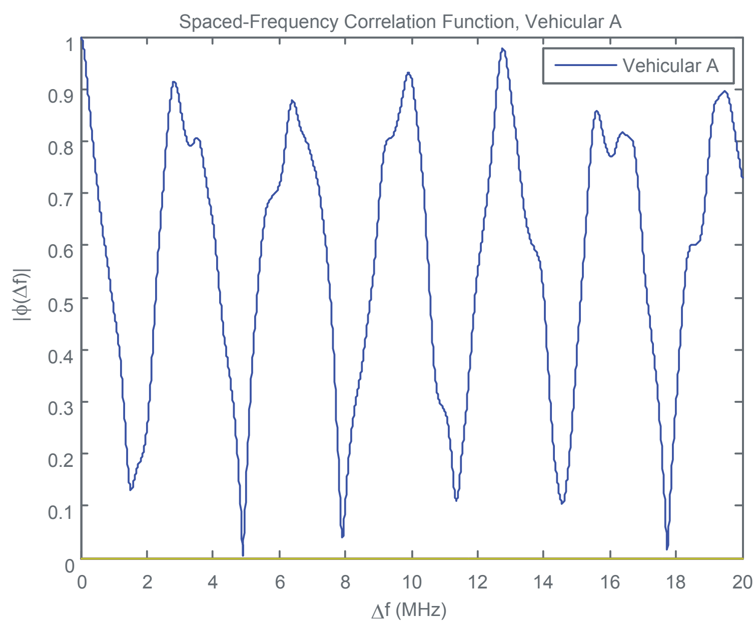

Figure 9: Spaced-frequency correlation function.

The result in Figure 9 is not desirable when modeling frequency dependent effects, as in the case of modeling frequency-selective schedulers. This is because wide-band measurements indicate that the spaced-frequency correlation of actual channels tends to drop to a low level and remain low. This occurs due to the large number of paths present in actual measured data. To reduce the level of oscillation and improve the wide-band characteristics of the channel, various techniques can be used, such as path splitting or adding additional paths. It is also possible to tweak the powers and delays slightly to reduce the oscillation.

Channel Modeling

Modeling multiple antenna approaches requires a fading channel with the proper correlation between antennas. Multiple antennas are usually expressed as an MxN combination, where M is the number of antennas at the transmitter, and N is the number of antennas at the receiver. Typical configurations may include 2x2, 4x4, 4x1, 1x4, and many others.

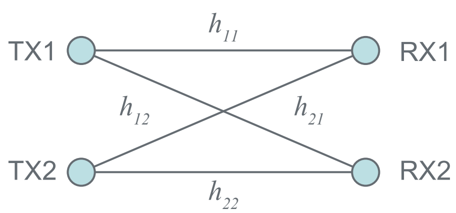

Figure 10: 2x2 Multiple antenna configuration.

A 2x2 example is shown in Figure 10 where a total of 4 connections are present between transmit and receive antenna elements. These connections are indicated by h11, h21, h12, and h22, each representing a virtual path between the base and the subscriber. For each path, gain and phase are measured with respect to a normalized average power. These terms are grouped together to form an H matrix as shown in Figure 11. There is a unique H matrix for each delayed path. For example, a 6 path channel will have 6 H matrices.

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$$

Figure 11: Complex Channel Matrix H.

In a realistic fading environment, the signals at the transmitter and receiver antenna elements are correlated, not independent. Extensive measurements have shown that the correlation is not constant, but varies significantly over a geographic area or drive route. The correlation between antenna elements is a mathematical function related to the make-up of the local scattering and is a function of the signal's angular spread (AS), angle of arrival (AoA), and the subscriber's direction of travel (DoT).

The output vector $\mathbf{r}$ of the 2x2 antenna system can be written in terms of the input vector $\mathbf{x}$, such that:

$$\mathbf{r} = \begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}$$

Where n_1 and n_2 are noise values and are ignored for this discussion.

The correlation between antennas can be written in terms of the signals observed on each antenna element:

$$\rho_{tx} = \frac{E(h_{11} h_{12}^{*})}{\sqrt{E(h_{11} h_{11}^{*})}\sqrt{E(h_{12} h_{12}^{*})}}$$

Notice that we define the channel gains of each path to be normalized such that $E(h_{11} h_{11}^{*}) = 1$, for all paths in the multi-antenna configuration.

Thus: $\rho_{tx} = E(h_{11} h_{12}^{*})$, but the correlation between transmit antennas can also be measured at the other receive antenna as: $\rho_{tx} = E(h_{22} h_{21}^{*})$

If there are differences between the measurements taken at the two receive antennas, these two correlations are also different. However, for omni-directional antennas with equal gains, the two correlations are the same. This is also true for the correlations between receive antennas.

Thus: $\rho_{rx} = E(h_{11} h_{21}^{*})$, and if omni-directional antennas are assumed this is also $\rho_{rx} = E(h_{22} h_{12}^{*})$

It is often convenient to express the correlation matrix in terms of the stacked vector: $vec(\mathbf{H}) = [h_{11} \;\; h_{21} \;\; h_{12} \;\; h_{22}]^T$, such that $R = E(vec(\mathbf{H})vec(\mathbf{H})^H)$, thus:

$$R = E\left(\begin{bmatrix} h_{11}h_{11}^* & h_{11}h_{21}^* & h_{11}h_{12}^* & h_{11}h_{22}^* \\ h_{21}h_{11}^* & h_{21}h_{21}^* & h_{21}h_{12}^* & h_{21}h_{22}^* \\ h_{12}h_{11}^* & h_{12}h_{21}^* & h_{12}h_{12}^* & h_{12}h_{22}^* \\ h_{22}h_{11}^* & h_{22}h_{21}^* & h_{22}h_{12}^* & h_{22}h_{22}^* \end{bmatrix}\right) = \begin{bmatrix} 1 & \rho_{tx} & \rho_{rx} & \rho_{rx}\rho_{tx} \\ \rho_{tx}^* & 1 & \rho_{rx}\rho_{tx}^* & \rho_{rx} \\ \rho_{rx}^* & \rho_{rx}^*\rho_{tx} & 1 & \rho_{tx} \\ \rho_{tx}^*\rho_{rx}^* & \rho_{rx}^* & \rho_{tx}^* & 1 \end{bmatrix}$$

These ρ combinations result since: E(AB*)E(BC*) = E(AC*)E(BB*) = E(AC*)

Typically, a correlation matrix is used to generate correlated channel path gains as in Figure 11. Correlation matrices may be given as part of a channel model, or calculated based on details of the antenna spacing, PAS, path AS, and AoA.

The correlation matrix for a multi-antenna channel model for a 2x2 multiple antenna can be written as a Kronecker product of the two individual simplified correlation matrices: $R = R_{rx}$ Ä R_{tx}, where:

$$R_{tx} = \begin{bmatrix} 1 & \rho_{tx} \\ \rho_{tx}^* & 1 \end{bmatrix} \text{ and } R_{rx} = \begin{bmatrix} 1 & \rho_{rx} \\ \rho_{rx}^* & 1 \end{bmatrix}$$

Generating Spatially Correlated Channels

These correlation matrices are sometimes given in terms of α and β, such as the notation in 3GPP [viii] where:

$$R_{BS} = \begin{pmatrix} 1 & \alpha \\ \alpha^* & 1 \end{pmatrix} \text{ for the Base Station and, } R_{MS} = \begin{pmatrix} 1 & \beta \\ \beta^* & 1 \end{pmatrix} \text{ for the Mobile Station.}$$

Using the Kronecker product described earlier, these two correlation matrices are combined into a double directional channel correlation matrix as:

$R_{spat} = R_{BS} \text{ Ä } R_{MS}$

The Kronecker product assumes that the individual cross terms are identical. This is not always a reasonable assumption. For instance, it assumes the correlation between receive antennas R1 and R2 measured at antenna T1 is identical to the correlation measured at antenna T2, and likewise, the correlation between transmit antennas T1 and T2 measured at antenna R1 is identical to the correlation measured at antenna R2. That is, the Kronecker product assumes:

$E(h_{11} h_{12}^*) = E(h_{21} h_{22}^*)^* = \alpha$, and

$E(h_{11} h_{21}^*) = E(h_{12} h_{22}^*)^* = \beta$

This assumption is not accurate for many conditions, including realistic antennas with pattern variations, branch imbalance between ports, and polarization effects. In these cases, a full correlation matrix with unique terms is required.

For the 2x2 MIMO configuration, the Kronecker product technique results in a spatial correlation matrix:

$$R_{spat} = R_{BS} \text{ Ä } R_{MS} = \begin{bmatrix} 1 & \alpha \\ \alpha^* & 1 \end{bmatrix} \text{ Ä } \begin{bmatrix} 1 & \beta \\ \beta^* & 1 \end{bmatrix} = \begin{bmatrix} 1 & \beta & \alpha & \alpha\beta \\ \beta^* & 1 & \alpha\beta^* & \alpha \\ \alpha^* & \alpha^*\beta & 1 & \beta \\ \alpha^*\beta^* & \alpha^* & \beta^* & 1 \end{bmatrix}$$

The values of α and β can be selected to represent different types of channels, and often real values in the range from 0-1 are used. One example set of values is shown in Table 1.

Low Correlation		Medium Correlation		High Correlation	
α	β	α	β	α	β
0	0	0.3	0.9	0.9	0.9

Table 1: 2x2 Correlation scenarios

When narrow angle spreads, a key characteristic of wide-band channels, are modeled using a correlation matrix, the correlation matrix is a function of the path angle and is complex-valued. Different transmit and receive correlation matrices are required for each path having a unique AoD or AoA. This is described in detail below.

$$R_{high} = \begin{pmatrix} 1 & 0.9 & 0.9 & 0.81 \\ 0.9 & 1 & 0.81 & 0.9 \\ 0.9 & 0.81 & 1 & 0.9 \\ 0.81 & 0.9 & 0.9 & 1 \end{pmatrix} \quad R_{medium} = \begin{pmatrix} 1 & 0.9 & 0.3 & 0.27 \\ 0.9 & 1 & 0.27 & 0.3 \\ 0.3 & 0.27 & 1 & 0.9 \\ 0.27 & 0.3 & 0.9 & 1 \end{pmatrix} \quad R_{low} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

For the 2x2 antenna configuration, the following correlation matrices illustrate the Low, Medium, and High Correlation cases in Table 1.

Correlation-Based Spatial Channel Modeling

For simplicity, these are all real-valued and represent a signal arriving broadside to the array. However, the fading present produces a random phase so that the observed AoA is a function of the phase difference between the antenna elements. Its distribution is a function of the correlation.

The final spatially correlated channel matrix will be: $\mathbf{H}_S = \sqrt{R_{spatial}}\mathbf{H}_U$, where $\mathbf{H}_U$ is a 4x1 vector of spatially uncorrelated Rayleigh fading samples, although they may be temporally correlated from sample to sample.

The spatially uncorrelated samples in $\mathbf{H}_U$ may be generated by a fader having a pre-defined Doppler characteristic, such as the generation of $\mathbf{H}_{tem}$ by the noise-based fader described earlier. They could also be random complex Gaussian i.i.d. samples. In the latter case, there is no temporal correlation, only the spatial correlation resulting from applying the correlation matrix.

An alternative and simpler equation for $\mathbf{H}_S$:

$$\mathbf{H}_S = \sqrt{R_{MS}}\mathbf{H}_U\sqrt{R_{BS}}^H$$

The spatial correlation equation for Hs produces spatially-correlated Rayleigh faded complex channel samples for h_{11}, h_{21}, h_{12}, and h_{22}. The amount of correlation present constrains the magnitude and phase differences between samples at the antennas.

Correlation-Based Spatial Channel Models with Narrow Angle Spread

The SCM and SCME took care to properly include the effects of narrow angle spread per path, which is commonly observed in wide-band field measurements. Narrow angle spread increases the correlation observed per path, and has a significant impact on both temporal and spatial correlation.

Figure 6 and Figure 7 illustrates the effect of typical macro-cell AS, and results in a correlation that is complex valued and varies with angle.

Figure 8 illustrates the effect of narrow angle spread on the temporal characteristics observed when moving in a fading field. Each of these behaviors can easily be included in generating the Spatial Channel.

Based on the BS and MS correlation in Figure 6 and Figure 7, Table 2 illustrates how the correlation matrix would be formed for several different AoDs or AoAs.

Mean AoD & AoA	RBS Correlation Matrix	RMS Correlation Matrix
0°	$\begin{bmatrix} 1 & 0.7222+0j \\ 0.7222+0j & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & 0.3315+0j \\ 0.3315+0j & 1 \end{bmatrix}$
30°	$\begin{bmatrix} 1 & 0.7762+0.0010j \\ 0.7762+0.0010j & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & -0.0680-0.4976j \\ -0.0680-0.4976j & 1 \end{bmatrix}$
60°	$\begin{bmatrix} 1 & -0.8875-0.2114j \\ -0.8875-0.2114j & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & -0.6164-0.4001j \\ -0.6164-0.4001j & 1 \end{bmatrix}$
90°	$\begin{bmatrix} 1 & -0.9993-0.0152j \\ -0.9993-0.0152j & 1 \end{bmatrix}$	$\begin{bmatrix} 1 & -0.7878-0.2485j \\ -0.7878-0.2485j & 1 \end{bmatrix}$

Table 2: Correlation matrices for narrow angle spread

As described earlier, a double-directional correlation matrix is formed for each path of the channel model by: $R_{spat} = R_{BS}$ Ä R_{MS} = Now, since the correlation varies for each AoD and AoA (due to the narrow AS), the correlation matrix is chosen according to the path angle. For example, a correlation matrix can be calculated for the appropriate angle, if different from those in the example shown in Table 2.

To compute the spatially correlated channel matrix $\mathbf{H}_S$ for the narrow angle spread model:

$$\mathbf{H}_S = \sqrt{R_{spatial}}\,\mathbf{H}_U$$

or:

$$\mathbf{H}_S = \sqrt{R_{MS}}\,\mathbf{H}_U \sqrt{R_{BS}}^H$$

The channel $\mathbf{H}_S$ represents the spatially-correlated values, but does not yet have a temporal correlation. A Doppler filter $S(f)$ corresponding to the AoA of the signal at the MS, combined with the AS, DoT, and MS speed, is generated. Based on the temporal effects of the Doppler filter, the temporally faded channel samples are specified in HTEM.

$\mathbf{H}_{TEM} = \mathbf{H}_U{}^* S(f)$

Finally, the temporal and spatial correlated channel HST is generated by the combination of the components:

$$H_{ST} = \sqrt{R_{Spatial}}\,H_{TEM}$$

or:

$$H_{ST} = \sqrt{R_{MS}}\,H_{TEM} \sqrt{R_{BS}}^H$$

H_{ST} represents a complete Spatially and Temporally correlated channel model representing a path between multiple antennas.

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