White Paper

Path-Based Spatial Channel Modeling

Introduction to SCM & SCME

The SCM specifies a set of paths between the Base Station (BS) and the Mobile Station (MS) based on a stochastic model of correlated random variables to establish the spatial, temporal, and propagation characteristics for a particular channel realization. The model is antenna-independent, and specifies path characteristics to establish the fading and correlation behavior between antenna elements. The SCM standard is based on a sum-of-sinusoids technique wherein the paths are assumed to be composed of a number of sinusoids representing plane waves. Due to the effects of scattering these plane waves are distributed across angle. The SCM may alternatively be implemented via a filtered noise approach where the temporal characteristics are set by a Doppler filter, and the spatial characteristics are set by a correlation matrix.

For large-scale channel characteristics such as delay Spread (DS), shadow fading (SF), and angle spread (AS), the model incorporates pre-defined correlated distributions extracted from measured data. The correlated spatial and temporal characteristics of the model are generated from random variables to produce a double-directional channel realization for evaluation. Each channel is unique and represents one possible channel out of an ensemble of possible channels.

The SCM has been extended by a modification proposed by, The European Wireless World Initiative New Radio (WINNER) project to increase the bandwidth from 5MHz up to 100MHz [iii]. The modified model is called the Spatial Channel Model Extended (SCME) and is fully described in [iv].

The Spatial Channel Model (SCM) [i][ii] was designed for evaluating multiple-antenna systems and algorithms. The model was developed within a combined 3GPP 3GPP2 ad hoc group to address the need for a precise channel model able to facilitate fair comparisons of various MIMO proposals. The model uses a system-level approach to simulate performance across the range of conditions expected in a cellular system. This ensures that multiple-antenna algorithms are not only optimized for a few test conditions, but across the system as a whole.

In the following sections, the concepts of spatial channel modeling are introduced and explained.

Model Overview

There are six different models included in the SCM. Each represents a unique environment and a unique set of conditions for testing multiple-antenna scenarios at the system level. The Urban model is the most popular and will be described further below. The six models presented in the SCM are:

1. **Urban–**This is a full system-level model. It uses correlated parameters in spatial and temporal domains to specifying the fading seen by a subscriber. It models medium-to-dense urban environments. The angle spread may be selected to be either 8° or 15°.
2. **Suburban–**This model has a reduced delay spread and is used for modeling lower density environments.
3. **Urban Micro-cell–**The micro-cell model uses a uniform departure distribution, a unique delay spread and propagation models, and includes the option for line-of-site paths.
4. **Polarization Model–**This model applies a cross-polarization discrimination function (XPD) to specify the ratio of powers of orthogonal vertical and horizontal components. The TX source polarization is mapped to vertical and horizontal components for calculating path correlation and XPD, and is then mapped to the polarization of the RX antennas.
5. **Far Scattering Cluster–**"Bad Urban" models typically have a component that arrives relatively late. Bad Urban models are described by the far-scattering cluster model.
6. **Urban Canyon Model–**When on a street with tall buildings on either side, the signal is often received from only one direction. This model aligns the AoAs to simulate this effect.

One additional model included in the SCM is a link-level model used for calibration. It is not listed as an SCM model because it was only designed for calibrating simulators and not as a way to compare multiple-antenna algorithms.

The SCM & SCME use a system-level approach to evaluate the range of possible channels. The channel is drawn randomly from a set of correlated random variables and is time-evolved for the duration of a call.

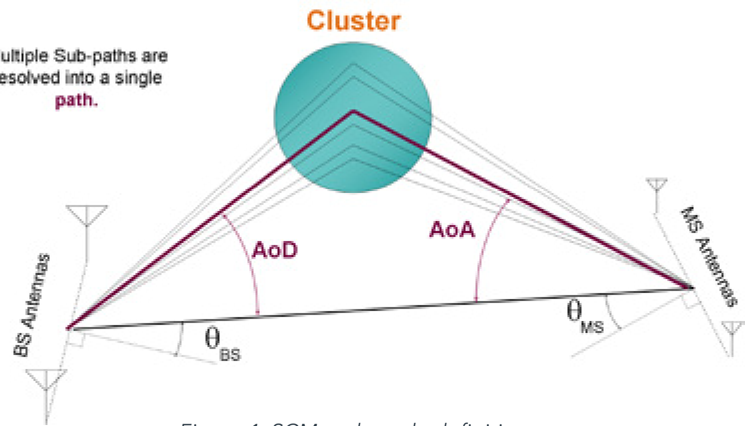

Figure 1: SCM path angle definitions.

As illustrated in Figure 1, the channel model can be described as a geometric model with one important caveat: due to the difficulty in concurrently generating angles at the BS and MS, the assumption here is that of a virtual connection, where the AoD and AoA do not need to align with a single reflector. Thus the model is somewhat more general that the diagram indicates. A detailed description of Figure 1 is given in [v].

Correlation Between Modeled Components

There are three separate large-scale parameters associated with the SCM. These are DS, AS, and SF. These parameters have been shown to be log-normally distributed and are highly correlated with each other.

The correlation coefficients are measured between the Gaussian random variables: α_n, β_n, and γ_n, which are used in the selection of the log-normal values: σ_{DSn}, σ_{ASn}, and σ_{SFn}, where the following equations represent the log-normally distributed variables:

$$\sigma_{DSn} = 10\ (\varepsilon_{DS}\alpha_n + \mu_{DS})$$
$$\sigma_{ASn} = 10\ (\varepsilon_{AS}\beta_n + \mu_{AS})$$
$$\sigma_{SFn} = \sigma_{LN}\gamma_n$$

The correlations selected by the model are:

Correlation between DS and AS: $\rho\alpha\beta = 0.5$

Correlation between SF and AS: $\rho\gamma\beta = -0.6$

Correlation between SF and DS: $\rho\gamma\alpha = -0.6$

Highly correlated parameters indicate that a common effect is present and that the path strength is the dominant cause of the high degree of correlation between the DS, AS, and SF. In addition to these three large-scale parameters, a site-to-site correlation ζ = 0.5 is applied to the SF component. This characteristic indicates the degree of independence between paths to different base stations.

The correlated parameters are produced from the correlation matrices A and B, wherein a difference matrix C = (A-B)½ is shown. C is then multiplied by a Gaussian white noise vector to obtain the correlated random variables. A common term between sites is added, being multiplied by a second noise term ξ, to produce the site-to-site correlation.

$$A = \begin{bmatrix} 1 & \rho_{\alpha\beta} & \rho_{\gamma\alpha} \\ \rho_{\alpha\beta} & 1 & \rho_{\gamma\beta} \\ \rho_{\gamma\alpha} & \rho_{\gamma\beta} & 1 \end{bmatrix}, \text{ and } \qquad B = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \zeta \end{bmatrix},$$

$$C = (A - B)^{1/2} = \begin{bmatrix} 1 & \rho_{\alpha\beta} & \rho_{\gamma\alpha} \\ \rho_{\alpha\beta} & 1 & \rho_{\gamma\beta} \\ \rho_{\gamma\alpha} & \rho_{\gamma\beta} & 1-\zeta \end{bmatrix}^{1/2}$$

$$\begin{bmatrix} \alpha_n \\ \beta_n \\ \gamma_n \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \begin{bmatrix} w_{n1} \\ w_{n2} \\ w_{n3} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \sqrt{\zeta} \end{bmatrix} \begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \end{bmatrix}$$

The resulting correlated Gaussian random variables: α_n, β_n, and γ_n, are obtained, and used to further specify the Channel Model.

$$\begin{bmatrix} \alpha_n \\ \beta_n \\ \gamma_n \end{bmatrix} = CWn + B^{1/2}\xi$$

Why are Wideband Parameters Correlated?

Consider a strong direct path, as illustrated in Figure 2. Only a few strong paths are shown in this plot as the remaining weaker paths are below the dynamic range of the receiver and can be ignored. In this case, the strong direct path dominates the rms DS calculation, producing a low delay spread. The direct path dominates the rms AS calculation, also producing a low angle spread. The direct path is responsible for a strong received signal with an above average shadow faded signal, for example, the shadow fade will be a large negative fade.

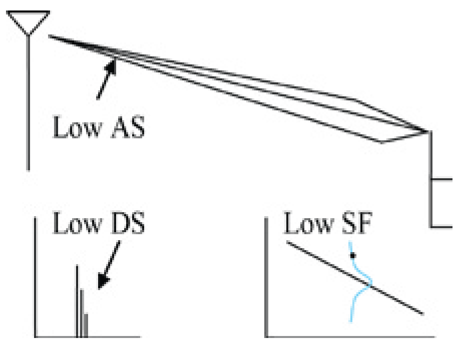

Figure 2: Sample correlation for strong signals.

For the weak signal case in Figure 3, the lack of a single dominant signal implies a large DS and AS. The SF will be a large positive value representing a deeper-than-average fade.

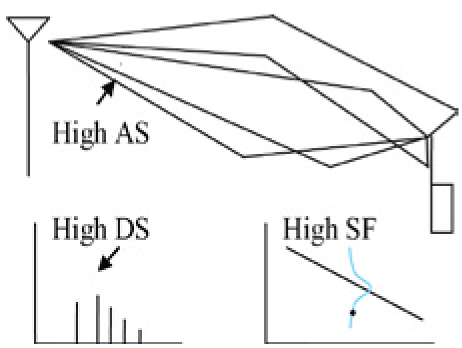

Figure 3: Sample correlation for weak signals.

It is clear that the magnitudes and the signs of the correlation coefficients for the DS, AS, and SF parameters in this illustration match the expected behavior in each case.

Generating the SCM Model Components

The model most commonly referenced in standards for multiple-antenna scenarios is the SCM Urban model. As an option within the Urban model, the Base Station AS may be selected as either 8° or 15°. The smaller value is consistent with data taken in European cities and the larger value is more consistent with data from US cities, but either value may be used. 3GPP typically uses 8°, and 802.16 typically uses 15°. Each model is described in [v] and [vi].

The Urban Macro-cell model is implemented in several steps, as described in the references. During a simulation, a random MS location is selected for evaluation. For this location, an SCM channel realization is calculated. This includes the corresponding Path Loss (PL) and SF to each simulated BS. The channel selected for this MS stays in effect for a predefined duration, after which a new MS location is selected. Many mobile locations and their corresponding randomly drawn channels will be evaluated during a system simulation.

Once the DS and AS are generated, the individual path delays and angles are generated based on random draws from scaled distributions as described here. Six paths are assumed for the urban model and used in the following abbreviated description.

The exponentially distributed random delays for each path $\tau'_1,\ldots,\tau'_N$ are generated from $\tau'_N = -r_{DS}\sigma_{DS} \ln z_n$, where n = 1,…,N and z_n (n = 1,…,N) are i.i.d. random variables with uniform distribution U(0,1). The value rDS describes how the powers are concentrated in time. It is given by the relationship comparing the sigma of the delays to the delay spread by: $\sigma_{Delays} = r_{DS}\sigma_{DS}$ and is further discussed in [v].

The un-normalized exponentially distributed path powers are given by:

$$P'_n = e^{\frac{(1-r_{DS})\cdot(\tau'_{(n)}-\tau'_{(1)})}{r_{DS}\,\sigma_{DS}}}$$

· 10−ξn/10, n = 1,…,6 where ξn (n = 1,…,6) are independent and individually distributed (i.i.d.) Gaussian random variables with standard deviation σRND= 3 dB, which is a shadowing randomization effect on the per-path powers.

Average powers are normalized so that the total average power for all six paths is equal to one:

$$P_n = \frac{P'_n}{\sum_{j=1}^{6} P'_j}$$

The AoD for each path is generated from i.i.d. zero-mean Gaussian random variables: $\delta'_n \sim \eta(0, \sigma^2_{AoD})$, n = 1… 6, where $\sigma_{AoD} = r_{AS}\sigma_{AS}$. The value r_{AS} describes the degree to which the power is concentrated in angle, and is based on measured data. The AoD angles are ordered in increasing absolute value so that $|\delta'_{(1)}| < |\delta'_{(2)}| < \cdots < |\delta'_{(N)}|$.

The AoA for each path is generated from i.i.d. zero-mean Gaussian random variables: $\delta_{n,AoA} \sim \eta(0, \sigma^2_{n,AoA})$, n = 1,…, 6, where $\sigma_{n,AoA} = 104.12\,(1-\exp(-0.2175|10\log_{10}(P_n)|))$ and P_n is the relative power of the nth path.

Additional steps are used in the SCM [v], which include adding propagation slope, correlated shadow fading, antenna patterns, etc.

Path Characteristics

The per-path fading behavior is characterized by a narrow angle spread consistent with numerous field measurements. A narrow angle spread produces a one-sided Doppler spectrum for most AoAs. The combination of sub-paths still produces a Rayleigh distributed envelope, but the narrow angle spread limits the individual sub-path Doppler shifts to a limited range of values based on the geometry of the AoA and direction of travel (DoT).

The per-path power azimuth spectrum (PAS) is a description of the power and angle distribution, and is typically assumed to follow a Laplacian distribution. This is a two sided exponential, which is an isosceles triangle when plotted in dB. The center of the distribution is at zero degrees relative to the average AoA or AoD, as shown in Figure 4.

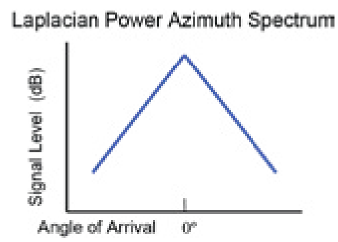

Figure 4: Power Azimuth Spectrum.

To emulate the Laplacian PAS, each path is comprised of 20 equal powered sub-path components, spaced with increasing angle from the center so that the average power falls at a rate that matches the envelope of the distribution. Equal powered sub-paths were chosen so that no one or two sub-paths dominate, affecting the fading behavior of the path. When a Path is defined, the angles of the sub-paths are shifted to match the path angle, and the power sum is scaled to match the path power.

Figure 5 illustrates the sub-path spacing in degrees relative to the path AoD at the BS. Since the BS antennas are somewhat isolated from the clutter, the angle spread (AS) is quite small. The AS is 2 degrees as defined by the model, with 20 sub-paths of equal power and a non-linear spacing as shown to approximate the Laplacian PAS.

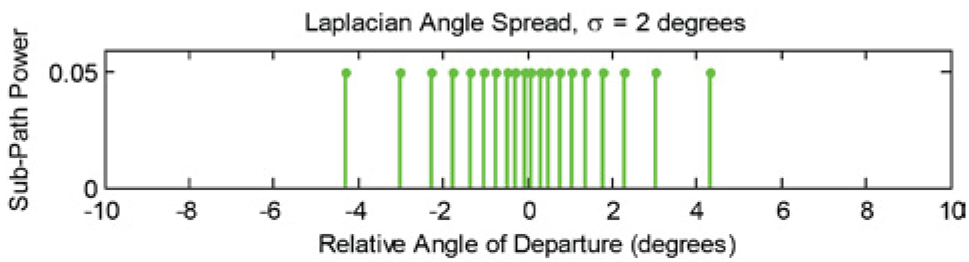

Figure 5: Path model at base station.

Figure 6 describes the sub-path spacing in degrees relative to the path AoA at the MS. The AS is 35 degrees, with 20 sub-paths of equal power and a non-linear spacing as shown to approximate the Laplacian PAS. This value is significantly larger than the AS at the BS, and is due to the significant clutter that is typically located near the MS.

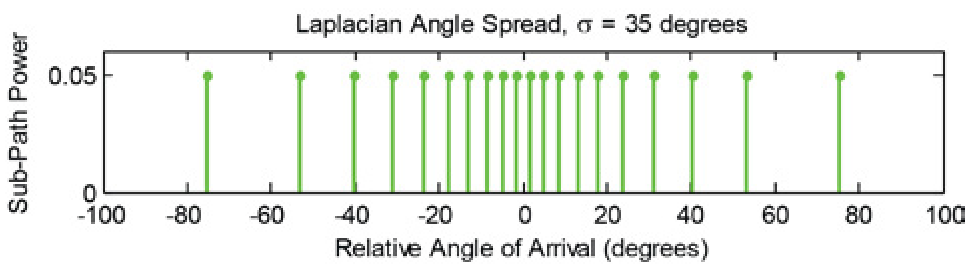

Figure 6: Path model at subscriber.

To generate a model with the correct temporal characteristics, the proper Doppler spectrum is required. When implementing the SCM with a sum-of-sine waves approach using sub-paths, the Doppler is accounted for automatically within the sum-of-sinusoids calculation based on the geometry shown in Figure 7. The fading rate is based on the AS, AoA, and DoT of the subscriber.

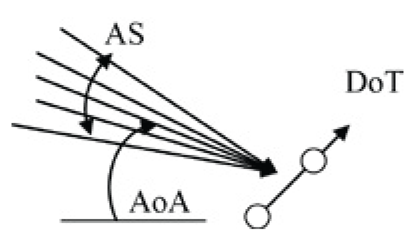

Figure 7: Signal and antenna positioning.

The Power Delay Profile (PDP), the PAS at the base station, and the PAS at the subscriber are shown in Figure 8 for a given channel realization.

The Laplacian PAS is also used at the base station, but it is observed as an average long-term envelope; the values used in the average are taken over many channel realizations of the composite multi-path signal. This is illustrated by example in Figure 8 where the average of many channel realizations is shown with a dashed line. The PDP plot also has a long term average exponential response shown with the dashed line.

Figure 8: Power delay and angle profiles.

Where the average of many channel realizations is shown with a dashed line. The PDP plot also has a long term average exponential response shown with the dashed line.

SCME

Due to the assumption that each path is flat-faded, there are some inherent bandwidth concerns with the SCM when operating in bandwidths above 5MHz. In order to address this, the Wireless World Initiative New Radio (WINNER) group proposed an extension to the SCM, called the SCM Extended (SCME).

This approach duplicates most of the original SCM, but changes the path characteristics to induce additional de-correlation in the frequency domain. For particular paths, the SCME distributes the path into 3 distinct "mid-paths" having slightly different powers and delays as shown in Figure 9. This adds a delay spread per path for those paths that are split in this way. If all of the original 6 paths of the SCM are modeled with mid-paths this effectively increases the model to 18 "paths", producing a slightly improved spaced-frequency correlation function. By dividing the 20 sub-paths into groups of 10, 6, and 4, the relative powers of each mid-path are now scaled by this ratio.

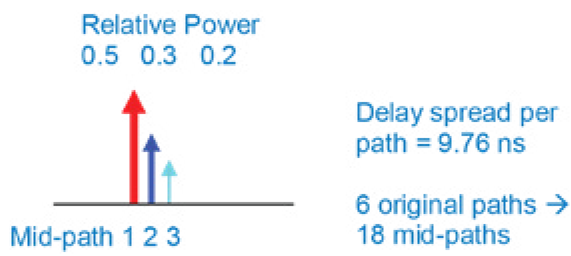

Figure 9: SCME path modification.

Mid-Path	# of Sub-paths	Relative Power	Excess Delay	Sub-path Index	ASmidpath/ASsubpath
1	10	0.5	0 ns	1,2,3,4,5,6,7,8,19,20	0.9865
2	6	0.3	12.5 ns	9,10,11,12,17,18	1.0056
3	4	0.2	25 ns	13,14,15,16	1.0247

Table 1: SCME mid-path details.

Table 1 illustrates the specific modifications that were made to each path. The original 20 sub-paths of the SCM were reallocated into the three mid-paths as shown. By specifying these specific allocations, the mid-paths maintain nearly the same AS as the SCM, with each mid-path having a zero inter-path delay as before. Figure 10 illustrates the sub-path AoA distribution for mid-path #1. Figure 11 shows the various mid-paths.

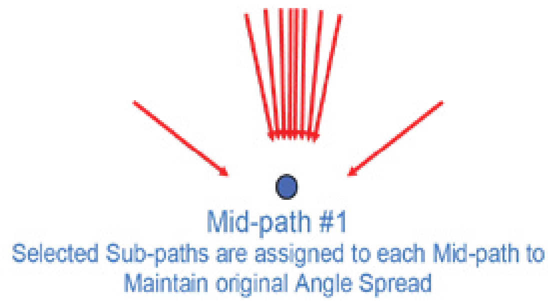

Figure 10: SCME – Mid-path #1 Sub-path distribution.

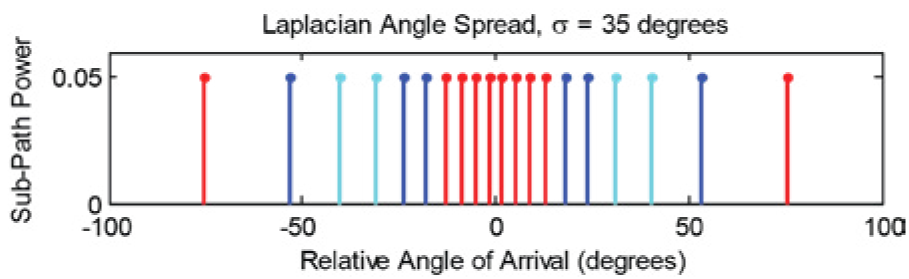

Figure 11: Distribution of SCME mid-paths.

By adding the mid-paths, the channel now behaves as if there are 18 paths. This tends to de-correlate the Spaced-Frequency Correlation function, as shown in Figure 12. For convenience, the Vehicular-A channel model is used as an example. It is clear that the path-splitting has produced some improvement.

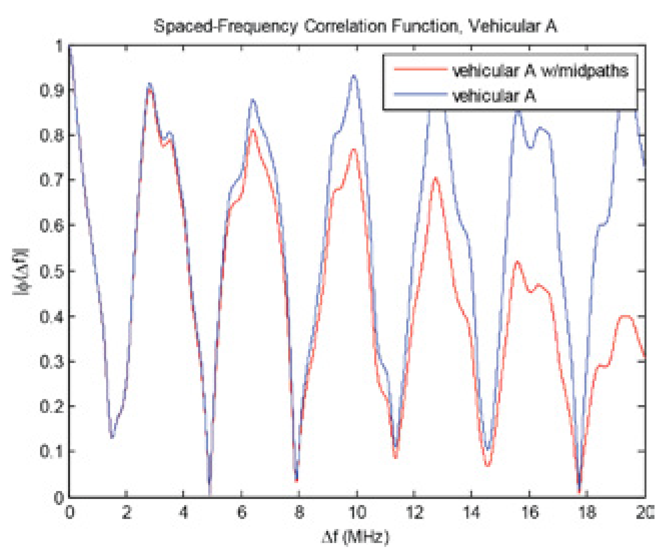

Figure 12: Effect of Mid-paths on Frequency De-correlation.

Tap Delay-Line Model

The WINNER group presented a simplified SCME Tap Delay-Line Model, also called Cluster Delay-Line Model, in [iv]. This model was created for calibration and comparison purposes and portions of this model have been adopted by the 3GPP. In this model, the specific AoDs and AoAs are specified and fixed for each path. Also, fixed delays are defined, resulting in a fixed PDP. Each path is modeled with a set of equal-powered sinusoids combined vectorially to produce a fading characteristic. The delays were selected to optimize the frequency decorrelation characteristic. The fading is determined from the Doppler characteristic and is a function of the AoA for the sub-paths, the MS speed, DoT, and antenna patterns.

Cluster Delay-Line models with parameter tables are described for the following scenarios:

- Indoor Small Office
- NLOS Indoor Environment
- Indoor to Outdoor / Outdoor to Indoor
- Urban Microcell
- Bad Urban Microcell
- Indoor Hotspot
- LOS model
- NLOS model
- Urban Macro-cell
- LOS model
- NLOS model
- Bad Urban Macro-cell
- Outdoor to Indoor (Urban) Macro-cell
- Rural Macro-cell
- Fixed Links
- Rooftop to Rooftop
- Street to Street

Tables of these fixed values are recorded in the WINNER document [vii].

WINNER-II

A second model proposed by WINNER is called WINNER-II [iv].

This model includes the following environment types:

- Indoor office
- Large indoor hall
- Indoor-to-outdoor
- Urban micro-cell
- Bad urban micro-cell
- Outdoor-to-indoor
- Stationary feeder
- Suburban macro-cell
- Urban macro-cell
- Rural macro-cell
- Rural moving networks

The WINNER-II models use a stochastic ray-based approach to generate geometry based random double directional channels. The model is antenna independent and generated from distributions extracted from measured data. Several different distributions are used to generate a channel, including: delay spread, delay values, angle spread, shadow fading, and XPD ratio. The parameters, which are stored in tables, are adjusted to obtain different scenarios. Some specific clustered delay line (CDL) models have been created for calibration purposes for making comparisons. An example is shown in Figure 13, showing the Urban Macro-cell NLOS CDL model.

Cluster #	Delay [ns]			Power [dB]			AoD [°]	AoA [°]	Ray power [dB]	Cluster ASD = 2°	Cluster ASA = 15°	XPR = 7 dB
1	0			-6.4			11	61	-19.5			
2	60			-3.4			-8	44	-16.4			
3	75			-2.0			-6	-34	-15.0			
4	145	150	155	-3.0	-5.2	-7.0	0	0	-13.0			
5	150			-1.9			6	33	-14.9			
6	190			-3.4			8	-44	-16.4			
7	220	225	230	-3.4	-5.6	-7.4	-12	-67	-13.4			
8	335			-4.6			-9	52	-17.7			
9	370			-7.8			-12	-67	-20.8			
10	430			-7.8			-12	-67	-20.8			
11	510			-9.3			13	-73	-22.3			
12	685			-12.0			15	-83	-25.0			
13	725			-8.5			-12	-70	-21.5			
14	735			-13.2			-15	87	-26.2			
15	800			-11.2			-14	80	-24.2			
16	960			-20.8			19	109	-33.8			
17	1020			-14.5			-16	91	-27.5			
18	1100			-11.7			15	-82	-24.7			
19	1210			-17.2			18	99	-30.2			
20	1845			-16.7			17	98	-29.7			

Figure 13: WINNER-2 Scenario C2 – NLOS Clustered Delay Line Model.

The corresponding PDP is shown in Figure 14. Based on this PDP, the Spaced-Frequency correlation function is shown in Figure 15. The performance of the SFCF is reasonable due to the 20 path model combined with an optimization of powers and delays to achieve a good roll-off in frequency.

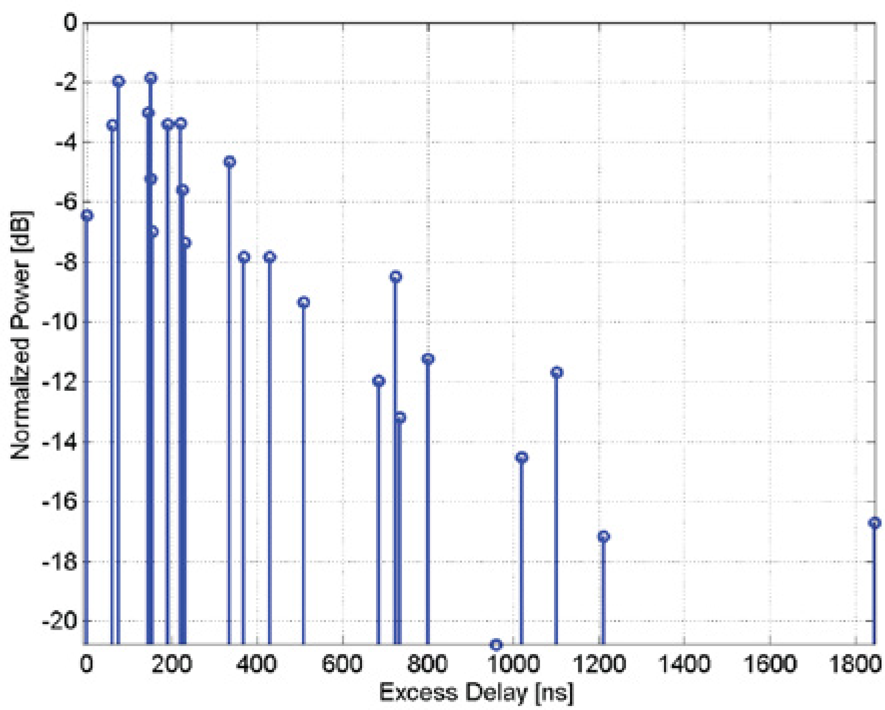

Figure 14: WINNER-2 PDP for Urban Macro NLOS CDL.

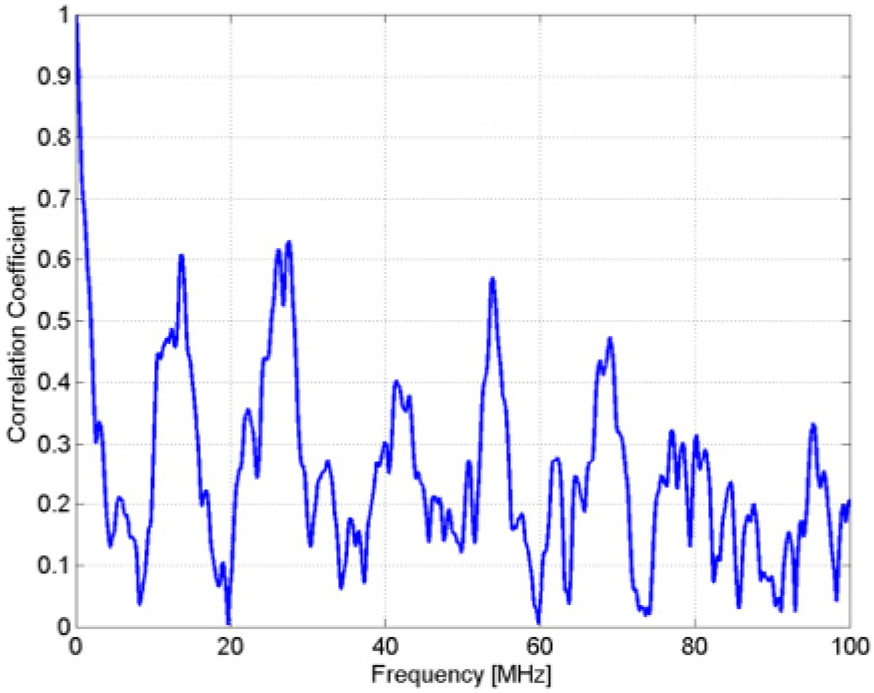

Figure 15: WINNER-2 Spaced-Frequency Correlation for Urban Macro NLOS CDL.

The WINNER II model is designed to operate in the 2-6 GHz band with up to 100MHz of bandwidth. The model includes polarization, and supports multi-user, multi-cell, and multi-hop networks.

SCM & SCME in Standards

The SCM & SCME is adopted in part or in whole in 3GPP, 3GPP2, and 802.16e. In addition, the WINNER models have been further included in the recent ITU-Advanced models.

References

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iii. D.S. Baum, et al., "An Interim Channel Model for Beyond-3G Systems," IEEE Vehicular Technology Conference, Spring, 2005.

iv. IST-4-027756 Winner II Channel Models, Deliverable D1.1.2V1.2

v. 3GPP, TR25.996, Spatial Channel Model for Multiple Input Multiple Output (MIMO)

vi. 3GPP2, C30-20030915-006, Spatial Channel Model for Multiple Input Multiple Output (MIMO)

vii. IST-2003-507581 WINNER D5.4 v. 1.0 Final Report on Link Level and System Level Channel Models

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