

USER'S
GUIDE

SPATIAL CHANNEL MODEL FOR MIMO
SIMULATIONS



A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide

Version 1.0

Spatial Channel Model for Multiple Input Multiple Output (MIMO) Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v. 6.1.0

Developed by:

Ioannis A. Xirouchakis

Undergraduate Student

Physics Department

University of Athens

Email: Hjohnxirou@gmail.com

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

History

Version	Date	Author	Comments
1.0	July, 28, 2008	Ioannis Xirouchakis	Initial version

Table of Contents

1	Description	5
2	Scope	5
3	Glossary, Assumptions and Simplifications	6
3.1	Glossary	6
3.2	Assumptions and Simplifications	7
4	Spatial Channel Model for Simulations	8
4.1	Environments and Cases	8
4.2	Channel realization	9
5	Installation	13
6	Options and Parameters	13
6.1	Options	13
6.1.1	Initial Options	14
	Environment	14
	Polarization	14
	Enable Plotting	15
6.1.2	Menu Options	16
	Antenna Patterns	16
	Assign Path Power and Delays	19
	Orientation Options	21
	Plot Options	22
6.2	Channel Parameters	22
	Primary Input Parameters	22
	Additional/Secondary Input Parameters	24
	Orientation Parameters	25
	Correlated Parameters σ_{AS} , σ_{DS} , σ_{SF}	26
7	Functions	30
	Multipath and MultipathPol	30
	FastFading and FastFadingPol	30
	PDPmacro and PDPmicro	30

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

CorParameters	30
OrientationsFixBS	31
G3, G6	31
DIST	31
Capacity	31
8 Output Parameters	32
9 Plots	34
9.1 Correlations	34
9.2 Channel Capacity	41
References	46

1 Description

This document suggests a user's guide to a MATLAB application which simulates a Spatial Channel Model (SCM) based on reference [1] with some minor adjustments. It focuses on how to use the Graphical User Interfaces (GUIs) and the functions of the application and avoids going into specifics about the nature of the parameters as this is done analytically in the reference document. The user should at any point consult [1] for additional information.

The MIMO spatial channel model simulates a wireless propagation channel in various cases and applies the concept of diversity (spatial and polarization) assuming multiple antennas at both the transmitter and receiver, thus forming a Multiple Input Multiple Output antenna system.

2 Scope

The scope of the present SCM application is to provide an easy-to-use MATLAB developed application to any user who requires a practical tool to perform MIMO simulations and to obtain statistical data which can be later further analyzed. Much effort was made so that all the parameters involved are user-selective, something that allows this application to be flexible to any desired case.

3 Glossary, Assumptions and Simplifications

3.1 Glossary

[SISO] Single Input Single Output

[MIMO] Multiple Input Multiple Output

[IR] Impulse Response

[SNR] Signal to Noise Ratio

[PDF] Probability distribution function

[CDF] Cumulative distribution function

[LOS] Line of Sight

[NLOS] No Line of Sight

[BS] Base Station

[MS] Mobile Station

[SF] Shadow Fading

[PL] Path Loss

[PDP] Power Delay Profile

[DS] Delay Spread

[AoA] Angle of Arrival

[AoD] Angle of Departure

[AS] Angle (Azimuth) Spread

[PAS] Power Azimuth Spectrum

[DoT] Direction of Travel

[DL] Downlink

[UL] Uplink

[LN] Log-Normal

[RV] Random Variable

3.2 Assumptions and Simplifications

In this section we note some general assumptions and simplifications made by [1] and adopted by the application. Further assumptions will be made for each case scenario but those will be noted in each corresponding section.

1. Ray Tracing Simulator

This application uses a ray-based method, where the reception at a given point is composed by the sum of all rays (paths) arriving to the antenna at every instant after being scattered by objects of the area. Each ray is described by its power and delay and can be decomposed to a large number of sub-rays (subpaths) which we assume to be plane electromagnetic waves who share a common frequency (the carrier frequency of the transmitted signal), each one arriving with a random phase. The sub-rays that belong to the same ray have common powers and delays.

2. Limitation to 2 Dimensions

This simulator assumes that all waves propagate parallel to the x-y plane i.e. it neglects the elevation spectrum. This is a common assumption made when we refer to outdoor scenarios as in those cases the z-axis wave components are not significant. Contrarily, this assumption cannot be made when we study indoor scenarios where a 3-D model is required. Indoor scenarios are not included in this application but should be included in future versions.

3. Uplink-Downlink Reciprocity

Since there is no indication of alternate channel behavior during the uplink and the downlink, the AoD/AoA values are identical between both propagating directions, although this does not apply to the random subpath phases during the UL and DL which will be assumed to be uncorrelated. In other words, we assume that the channel is a double directional system where the BS and MS can both be the receiver and transmitter despite the fact that we will refer to the BS as the transmitter.

4. Single Base Station-Single Mobile Station link

The application simulates a (NLOS) link between a single transmitter (Base Station) who is placed in the center of a hexagonal cell and a single receiver (Mobile Station) who can move within the same cell. Cases of additional BSs or MSs are not included i.e. shadowing effects from other antennas are not examined.

5. Linear Arrays (space diversity)

The concept of space diversity is applied by using antenna arrays at both the BS and the MS. Here, only linear arrays are simulated. Every element of each array is described by the same antenna pattern which is selected by the user. We define the arrays broadside to be a vertical line to the line connecting the array elements.

6. Polarized Arrays (polarization diversity)

Since hand-held devices have limited dimensions, space diversity might be difficult to be applied to them. For that reason, polarized arrays which use cross shaped, co-located dipole antenna pairs might be the primary way to apply (polarization) diversity. This application also simulates this type of diversity.

7. Line of Sight

In this version, only NLOS cases are considered. LOS cases will be included in future versions.

8. Noise

Noise is neglected.

4 Spatial Channel Model for Simulations

4.1 Environments and Cases

During the BS/MS link there are a large number of phenomena that take place and affect the signal reception like the *Path Loss*, the *Shadow Fading*, the *Fast Fading*, the *Doppler shift* etc. For that reason, there are many parameters and variables that should be taken under consideration during a simulation in order for it to produce reliable results for each scenario. Let us now present a rough description of the environments and cases examined in this application. More details about them can be found in [1].

- **Environments**

We study three different environments; the Suburban Macrocell, the Urban Macrocell and the Urban Microcell. The first two have statistical similarities and they follow the same modeling process with some parameter adjustment so we can categorize them both as Macrocell. In general, the code follows the same simulation steps for all three environments shown in the reference document [1]. For this reason, we will limit our presentation to the areas where the application handles some parameters differently. However, let us note some basic characteristics for each environment.

- Macrocell –

- Approximately 3 km distance BS to BS
- BS antenna above rooftop height
- The adopted pathloss model is the modified COST231 Hata urban propagation model
- Angle spread, Delay spread and Shadow fading will be treated as correlated, LN random variables

- Microcell –

- Less than 1 km distance BS to BS
- BS antenna is at rooftop height
- The adopted pathloss model is the COST 231 Walfish-Ikegami NLOS model

- Angle spread, Delay spread and Shadow fading will not be treated as correlated RV

- **Cases**

The sub-rays leaving the BS can change their polarization before reaching the MS. For example, while the BS transmits only vertical polarized sub-rays, the MS can receive vertical, horizontal and off-axis polarized sub-rays. The Cross Polarization Discrimination (*XPD*) describes the intensity of this phenomenon and it is defined as the ratio of the co-polarized average received power (P_{co-pol}) to the cross-polarized average received power ($P_{cross-pol}$). Note that since: $P_{co-pol} \geq P_{cross-pol} \Rightarrow XPD_{\{dB\}} \geq 0$.

- Case I –

- It neglects the cross polarization
- BS and MS antennas transmit and receive only vertical polarized sub-rays
- BS antennas will be assumed directional (sector) or omnidirectional antennas (vertical polarized ideal dipoles), while the MS antennas will be assumed omnidirectional (vertical polarized ideal dipoles).

- Case II –

- It includes the cross polarization
- BS and MS antenna can transmit and receive both vertical and horizontal polarized sub-rays
- BS and MS array elements will be assumed (tilted) ideal dipoles or (tilted) cross-polarized, co-located dipoles, forming dipole pairs. Note that when dipole pairs are used, the number of the antennas at each array is twice the number of the array elements.

Cases I and II are handled by different functions and some of their features are not the same. For example, the first case assumes three kinds of antennas for the BS; hence, the signal's attenuation will also be dependent from the antenna's gain function.

We should note that since Case I is less complicated, it produces faster simulations and for that reason it should be used when there is interest for space diversity results or results concerning the usage of directional antennas. Case II should be used for polarization diversity or mixed (spatial and polarization) diversity results. More will be said about the diversification of the two cases since we will examine them separately when needed.

4.2 Channel realization

At this point, let us define 'drop' as a single simulation run where a BS using an array of S elements transmits inside a terrestrial environment to a moving MS using an array of U elements for a given number of time frames. The signal arrives to the receiver through N independent paths which are described by their powers and delays. In this way we form N , time evolving, $S \times U$ matrixes and their sum would describe the total channel realization:

$$H_{S,U}(t) = \sum_{n=1}^N \int_{-\infty}^{+\infty} H_{S,U,n}(t, \tau_n) \delta(\tau - \tau_n) d\tau_n \quad (1)$$

$$H_{S,U,n}(t) = \begin{bmatrix} h_{1,1,n}(t) & \cdots & h_{S,1,n}(t) \\ \vdots & \ddots & \vdots \\ h_{1,U,n}(t) & \cdots & h_{S,U,n}(t) \end{bmatrix} \quad (2)$$

Our goal is to generate the coefficients $h_{s,u,n}(t)$ ($s = 1 \dots S$, $u = 1 \dots U$) for every $H_{S,U,n}(t)$ ($n = 1 \dots N$) for every time frame.

The equation that describes these time dependant coefficients is common for each environment but it alters when we refer to cases I and II. Next, we will present these equations for each case giving the description for every participating parameter. Some of these parameters are handled as Input parameters selected by the user while others derive from RV and are generated inside the application's code. Each parameter will be analyzed in chapter 6.

Case I

The (s, u) matrix component for $H_{S,U,n}(t)$ for all three environments will be:

$$h_{u,s,n}^{(I)}(t) = \sqrt{\frac{P_n}{M}} \sum_{m=1}^M \left[\frac{\sqrt{G_{BS}(\theta_{n,m,AoD})} \exp[j(kd_s \sin(\theta_{n,m,AoD}) + \Phi_{n,m})]}{\sqrt{G_{MS}(\theta_{n,m,AoA})} \exp[j(kd_u \sin(\theta_{n,m,AoA}))]} \times \exp(jkv \cos(\theta_{n,m,AoA} - \theta_v) t) \right] \quad (3)$$

P_n is the power of the n th path.

N is the number of paths (clusters).

M is the number of subpaths per-path.

S is the number of the BS linear array antenna elements.

U is the number of the MS linear array antenna elements.

$\Phi_{n,m}$ is the phase of the m th subpath of the n th path.

$\theta_{n,m,AoD}$ is the AoD for the m th subpath of the n th path.

$\theta_{n,m,AoA}$ is the AoA for the m th subpath of the n th path.

$G_{BS}(\cdot)$ is the BS antenna gain of each array element.

$G_{MS}(\cdot)$ is the MS antenna gain of each array element for.

j is the square root of -1.

k is the wave number $2\pi / \lambda$ where λ is the carrier wavelength in meters.

d_s is the distance in meters from BS antenna element s from the reference ($s = 1$) antenna. For the reference antenna $s = 1$, $d_1=0$.

d_u is the distance in meters from MS antenna element u from the reference ($u = 1$) antenna. For the reference antenna $u = 1$, $d_1=0$.

v is the magnitude of the MS velocity vector.

θ_v is the angle of the MS velocity vector.

.

Case II

The (s, u) matrix component for $H_{S,U,n}(t)$ for all three environments will be:

$$h_{u,s,n}^{(II)}(t) = \sqrt{\frac{P_n}{M}} \sum_{m=1}^M \begin{bmatrix} G^{(v)}(\theta_{n,m,AoD}) \\ G^{(h)}(\theta_{n,m,AoD}) \end{bmatrix}^T \begin{bmatrix} \exp(j\Phi_{n,m}^{(v,v)}) & \sqrt{r_1} \exp(j\Phi_{n,m}^{(v,h)}) \\ \sqrt{r_2} \exp(j\Phi_{n,m}^{(h,v)}) & \exp(j\Phi_{n,m}^{(h,h)}) \end{bmatrix} \begin{bmatrix} G^{(v)}(\theta_{n,m,AoA}) \\ G^{(h)}(\theta_{n,m,AoA}) \end{bmatrix} \times \exp(jkd_s \sin(\theta_{n,m,AoD})) \exp(jkd_u \sin(\theta_{n,m,AoA})) \exp(jkv \cos(\theta_{n,m,AoA} - \theta_v) t) \quad (4)$$

$G_{BS}^{(x)}(.)$ is the BS antenna gain of each array element for the x direction (either horizontal h or vertical v).

$G_{MS}^{(x)}(.)$ is the MS antenna gain of each array element for the x direction (either horizontal h or vertical v).

r_1 is the power ratio of waves of the n th path leaving the BS in the vertical direction and arriving at the MS in the horizontal direction ($v-h$) to those leaving in the vertical direction and arriving in the vertical direction ($v-v$).

r_2 is the power ratio of waves of the n th path leaving the BS in the horizontal direction and arriving at the MS in the vertical direction ($h-v$) to those leaving in the vertical direction and arriving in the vertical direction ($v-v$). We assume that: $r_1 = r_2$.

$\Phi_{n,m}^{(x,y)}$ is the phase of the m th subpath of the n th path between the x component (either the horizontal h or vertical v) of the BS element and the y component (either the horizontal h or vertical v) of the MS element. Note that all the other parameters inside eq. (4) are the same as Case I.

To help us with the spatial description of the BS, the MS and all the angles we introduce the following angle parameters (common for all environments and cases).

Ω_{BS} is the BS antenna array orientation, defined as the difference between the broadside of the BS array and the absolute North (N) reference direction.

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

θ_{BS} is the LOS AoD direction between the BS and MS, with respect to the broadside of the BS array.

$\delta_{n,AoD}$ is the AoD for the n th ($n = 1 \dots N$) path with respect to the LOS AoD.

$\Delta_{n,m,AoD}$ is the offset for the m th ($m = 1 \dots M$) subpath of the n th path with respect to $\delta_{n,AoD}$.

Ω_{MS} is the MS antenna array orientation, defined as the difference between the broadside of the MS array and the absolute North (N) reference direction.

θ_{MS} is the angle between the BS-MS LOS and the MS broadside.

$\delta_{n,AoA}$ is the AoA for the n th ($n = 1 \dots N$) path with respect to the LOS AoA.

$\Delta_{n,m,AoA}$ is the offset for the m th ($m = 1 \dots M$) subpath of the n th path with respect to $\delta_{n,AoA}$.

Note that (see Fig. 1):

$$\theta_{n,m,AoD} = \theta_{BS} + \delta_{n,AoD} + \Delta_{n,m,AoD}$$

$$\theta_{n,m,AoA} = \theta_{MS} + \delta_{n,AoA} + \Delta_{n,m,AoA}$$

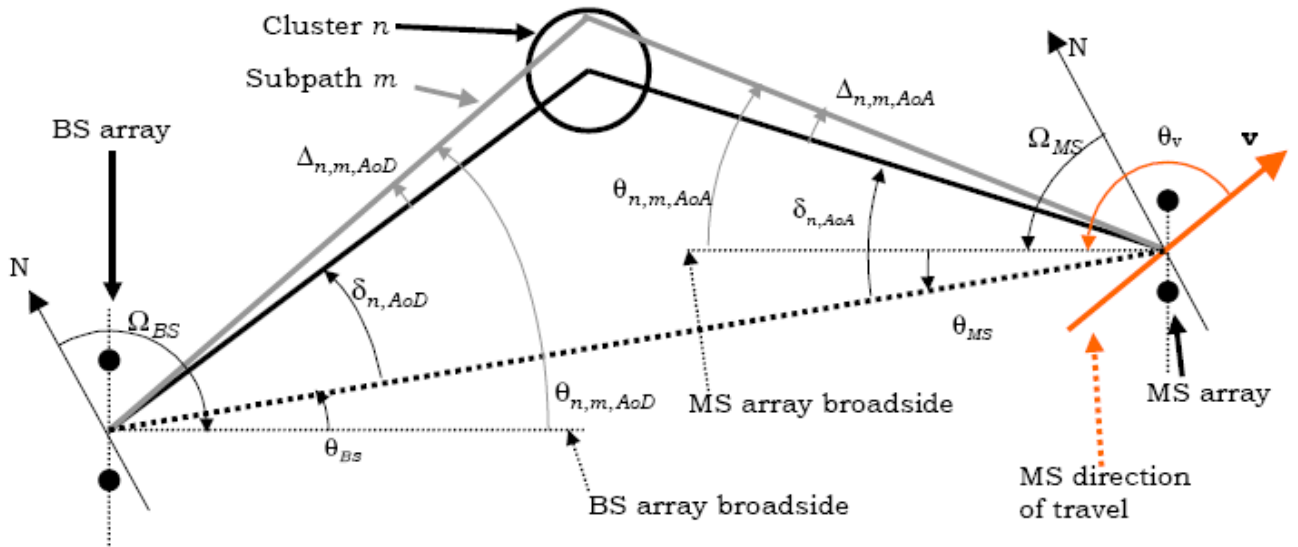


Fig. 1 Angle Parameters

Finally, we note that clockwise angles are considered positive and anti-clockwise are considered negative. Concerning angles Ω_{BS} , Ω_{MS} , θ_{BS} , θ_{MS} for simplicity, instead of negative values we are going to use their complementary positive values. For example, if $\theta_{MS} = -15^\circ$ we will assume that: $\theta_{MS} = 360^\circ - 15^\circ = 345^\circ$. This way we only handle positive angles. However, this does not apply to angles $\delta_{n,AoD}$, $\delta_{n,AoA}$, $\Delta_{n,m,AoD}$ and $\Delta_{n,m,AoA}$ which can also take negative values.

Then:

$$\theta_{MS} = |\Omega_{BS} - \Omega_{MS} + \theta_{BS} + 180^\circ|$$

5 Installation

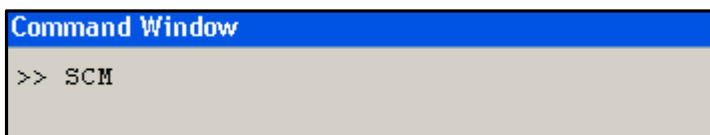
This application was developed using MATLAB 7.1.0.246 (R14) Service Pack 3 August 02, 2005 though older versions might also support it.

Installation and Running:

- 1) Extract all 'SCM.zip' file content to a folder (e.g. C:\Matlab\work\SCM).
- 2) Change MATLAB's 'Current Directory' to the directory used above for extraction.

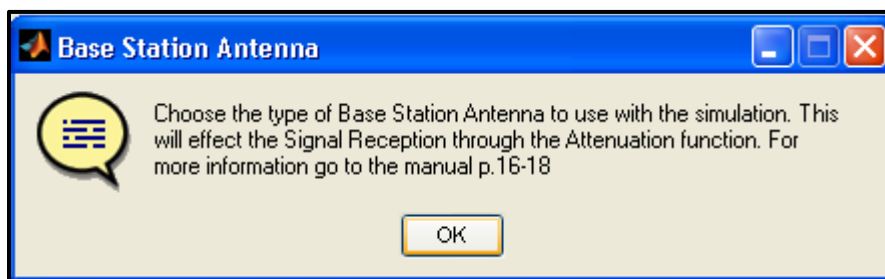


- 3) Type 'SCM' to MATLAB's Command Window to run the application.



6 Options and Parameters

In this section we will analyze the simulator's options and parameters. The user can get some first information about them when using the program by clicking on the graphic interface of the application on the option or parameter of interest. The application will pop-up a help dialog window, as shown below, giving some basic information about the parameter or option and providing the corresponding pages in the manual.



6.1 Options

The application's options are subcategorized to Initial and Menu options.

6.1.1 Initial Options

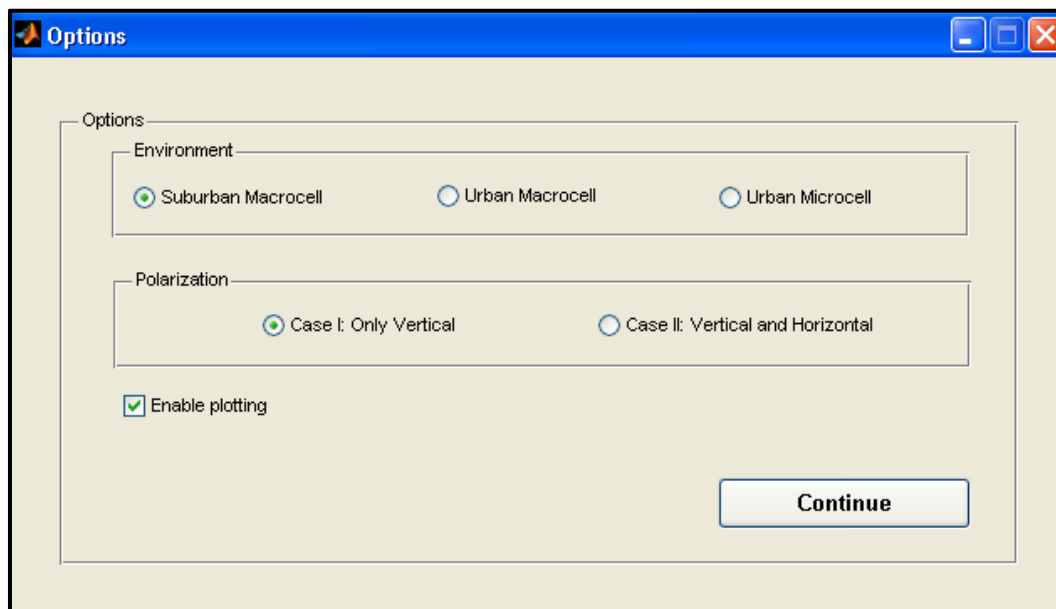


Fig. 2 The application initializes by displaying this first window where the Initial Options are shown.

Environment

Following the instructions found in [1] the model simulates three different environments:

- the Suburban Macrocell
- the Urban Macrocell
- the Urban Microcell

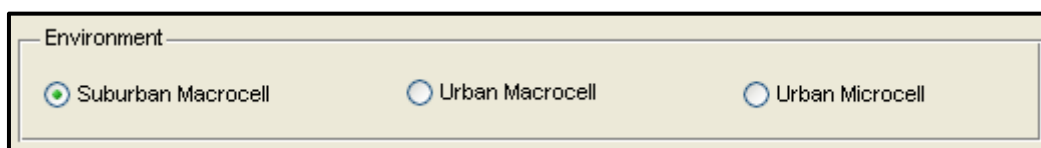


Fig. 3 Choose which environment to simulate

Polarization

This option determines whether the simulations will include only vertical polarized sub-paths or both vertical and horizontal polarization. If the user chooses Case I: 'Only Vertical' then the BS and MS antennas will receive and transmit only vertical propagating sub-rays and the XPD will not affect the simulation. If the user chooses Case II: 'Vertical and Horizontal' then the BS and MS can receive and transmit both vertical and horizontal polarized sub-paths.

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

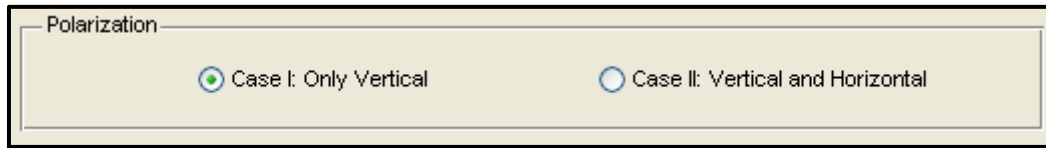
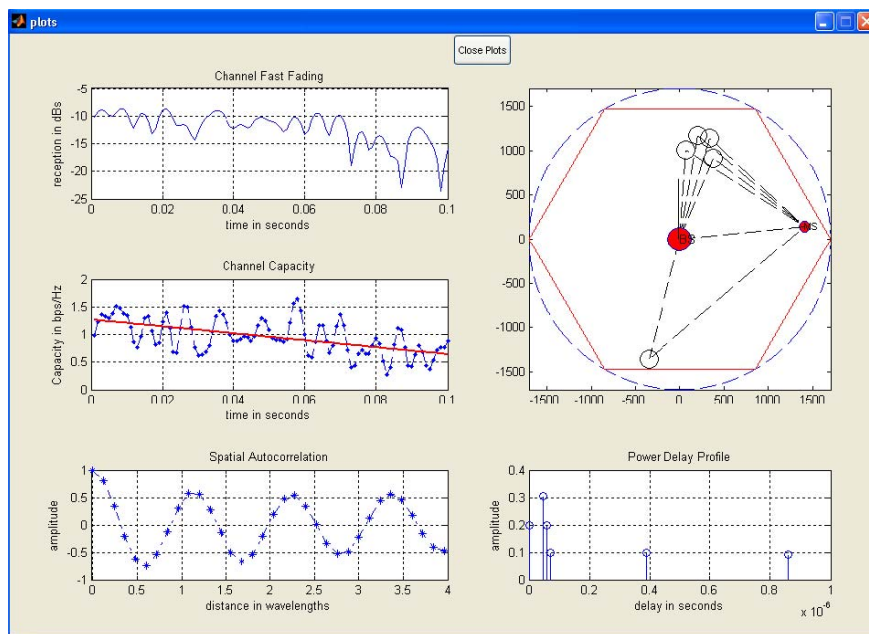


Fig. 4 Choose between Case I and Case II

Enable Plotting

Here the user toggles plotting 'on' and 'off' i.e., whether there's going to be a graphical display of various parameter plots like the signal's fast fading, the total channel capacity, the MS temporal autocorrelation and the power-delay profile after the completion of each simulation run. Plotting also includes a graphic display of the cell, the scatters, the BS and the MS and the AoDs/AoAs.



After the user is done with the Initial Options he should press the 'Continue' button placed at the bottom right corner of the window shown in Fig. 2. The application will proceed to the next window where all the rest of the Options and Input Parameters can be found.

6.1.2 Menu Options

Antenna Patterns

CASE I

▪ Base Station Antenna Pattern

There are three options for the BS antenna; the 3 sector, the 6 sector and the omnidirectional antenna (vertical polarized ideal dipole). Real cellular systems usually use directional antennas at the BS (sector antennas). Each element of the BS array will be described by the same selected antenna pattern and the signal attenuation will be a given by:

$$A_{BS}(\theta) = -\min \left[12 \left(\frac{\theta}{\theta_{3dB}} \right)^2, A_m \right] \quad \text{where } -180 < \theta < 180$$

θ is defined as the angle between the direction of interest and the boresight (the direction of the maximum gain) of the antenna, θ_{3dB} is the 3dB beamwidth in degrees and A_m the maximum attenuation. For the 3 sector antenna, $A_m=20$ dB and $\theta_{3dB}=70^\circ$ while for the 6 sector antenna $A_m= 23$ dB and $\theta_{3dB}=35^\circ$.

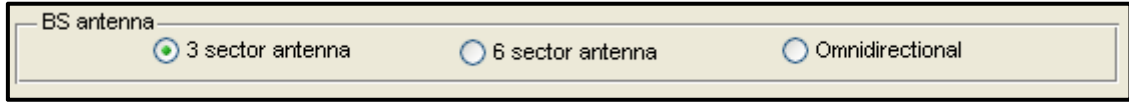


Fig. 5 Choose the antenna pattern for every BS antenna array element.

▪ Mobile Station Antenna Pattern

Each element of the MS array will be assumed as an ideal, vertical polarized dipole with respect to the x-y plane (omnidirectional antenna), hence:

$$A_{MS}(\theta) = 0 \text{ dB.}$$

For all antennas, the antenna numeric gain function is given by:

$$G(\theta) = 10^{A(\theta)/10} \quad (5)$$

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

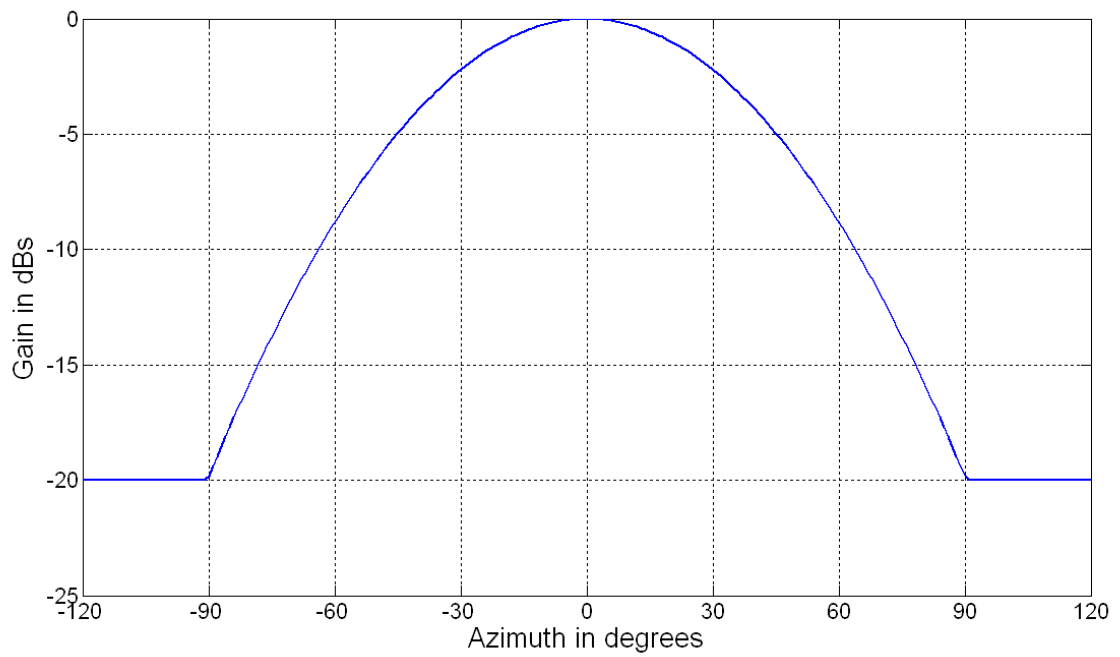


Fig. 6 The antenna pattern for the 3 sector cell.

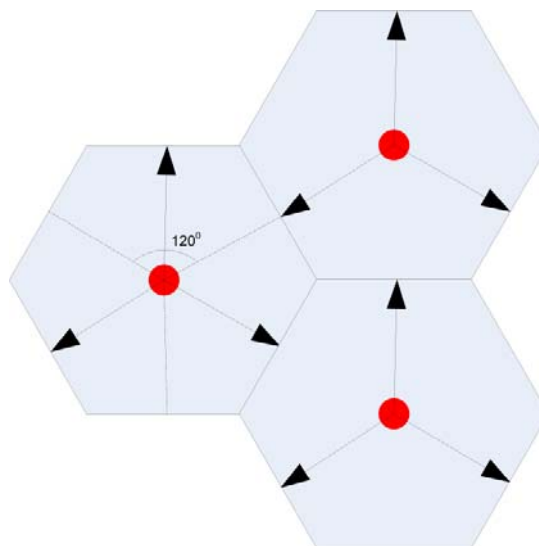


Fig. 7 The directions of the arrows show the boresights of the 3 antennas that transmit inside a 3 sector cell.

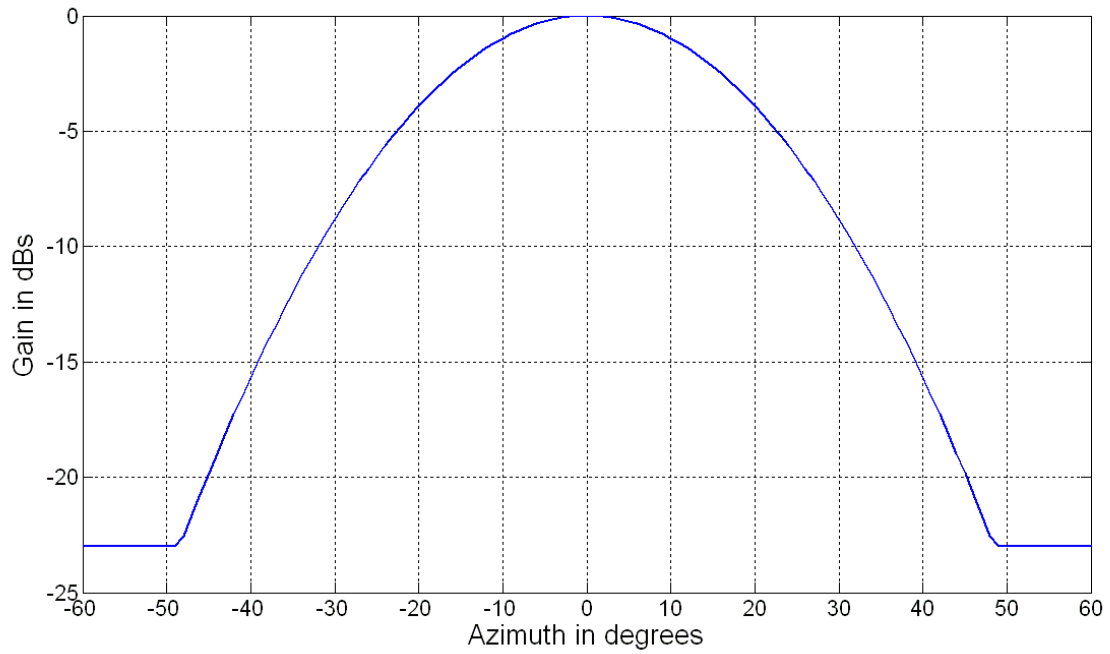


Fig. 8 The antenna pattern for the 6 sector cell.

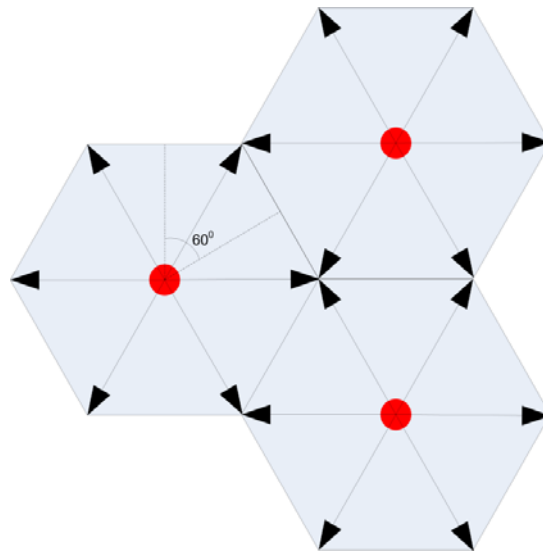


Fig. 9 The directions of the arrows show the boresights of the 6 antennas that transmit inside a 6 sector cell.

Note: Since we assume only one BS and one MS inside a cell, we place the BS in the center of the cell with its boresight facing the absolute North. In other words, the boresight and the broadside of the BS linear array are identified. This applies to both cases I and II. More will be said about this when we discuss the Orientation Options.

CASE II

In Case II we have both vertical and horizontal polarized sub-paths propagating inside the channel, hence, it would be more practical to assume arrays of ideal dipoles at both the BS and MS. These dipoles can be tilted with respect to the z-axis by a common polarization angle α_{BS} and β_{MS} respectively. The antenna gain for the vertical and horizontal reception will be given by the matrix:

$$\begin{bmatrix} G^{(v)}(\theta) \\ G^{(h)}(\theta) \end{bmatrix} = \begin{bmatrix} \cos \alpha \\ \sin \alpha \cos \theta \end{bmatrix}$$

θ is the angle that the sub-ray arrives/departs to/from the dipole and α is the polarization angle.

This case was developed to perform spatial and polarization diversity simulations and it gives the user the ability to choose from two different array elements for both the BS and MS separately. The first choice assumes single (tilted) dipoles which form a linear array while the second assumes that every array element is formed by two (tilted) cross polarized co-located dipoles (dipole pairs). In this way, there are four different combinations of BS and MS arrays.

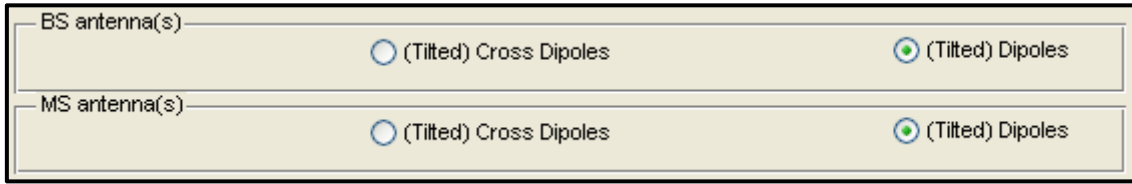


Fig. 10 Choose between a dipole array and a cross-polarized co-located dipole pair array for both the BS and MS

Note that two dipoles, i and $i+1$ in a dipole pair, have the same spacing from the reference element of the array hence: $d_i = d_{i+1}$ and for their polarization angles: $|\alpha_i - \alpha_{i+1}| = 90^\circ$.

Note: To go from 'Primary' to 'Secondary' Options and Parameters click 'Additional Properties'.

Assign Path Power and Delays

While the reference document calculates the power and the delay of each path through parameters that are randomly distributed, this application can provide the freedom to manually input the power and the delay of each path. In other words, setting this option to 'on', the user can form the PDP according to his own likings. If this option is set to 'off', then those parameters will be calculated through the step procedure of [1]. The number of $\{\tau_n, P_n\}$ pairs in the PDP is dependant from the value of N which gives the number of paths (clusters). These input values have an effect to some other parameters which derive from random procedures (see Table 2).

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

☒ Assign Path Powers and Delays

Path Power in dBs

-3

-21

-6

-24

-9

-27

-12

-30

-15

-18

Path Delay in microseconds

10

70

20

80

30

90

40

100

50

60

Fig. 11 Switch this option 'on' to manually input the Power and the Delay for each Path forming the Power Delay Profile

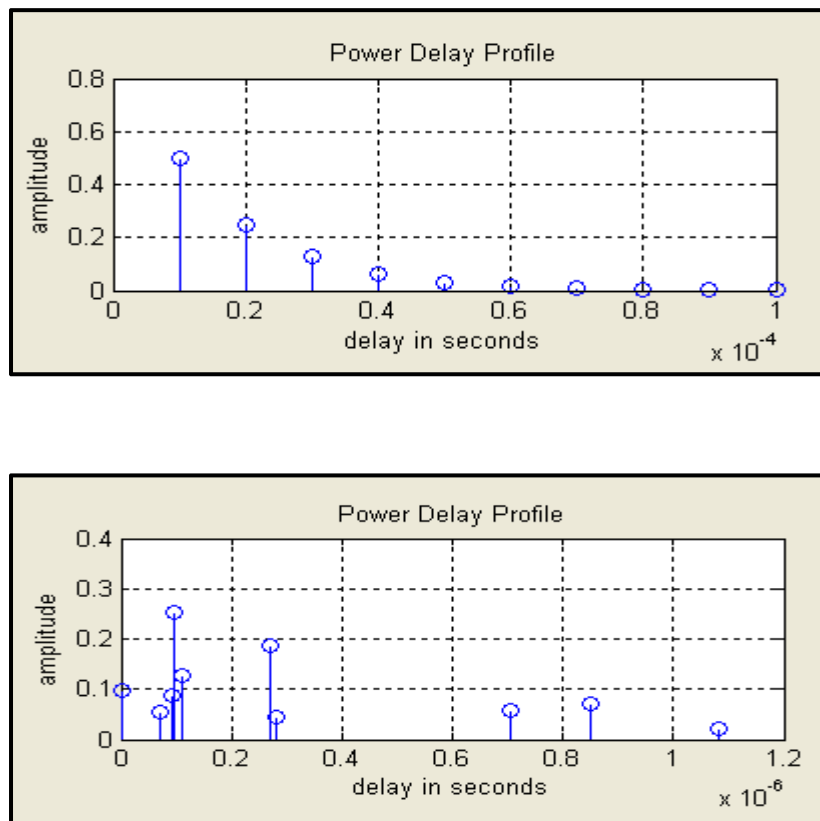


Fig. 12 Two Power Delays Profiles, the first one using the default power-delay values and the second one formed by the random procedure of the code

Orientation Options

This option dictates whether the orientation of the MS (i.e. its distance from the BS and all its angle parameters) will be random (through an automatic random procedure provided by the application) or custom (where the user inputs all the orientation parameters manually). All of the orientation parameters will be explained analytically when we discuss the channel's parameters.

Orientation Options

Orientations

☒ Random
☐ Custom

Distance between BS and MS in meters	d =	1615	Angle between the broadside of the MS array and the absolute North reference direction	Omega MS =	83
LOS AoD direction between the BS and MS with respect to the broadside of the BS array	Theta BS =	218	Angle of the velocity vector with respect to the MS broadside	Theta v =	175
Angle between the BS-MS LOS and the MS broadside	Theta MS =	315	Angle between the broadside of the BS array and the absolute North reference direction	Omega BS =	0

Fig. 13 Choose between Random and Custom Orientations for the MS

However, when 'Random' is chosen we place the Base Station array at a fixed location with its broadside and boresight facing the Absolute North as shown in Fig. 14. This can be changed when 'Custom' is chosen though angle Ω_{BS} (see orientation parameters).

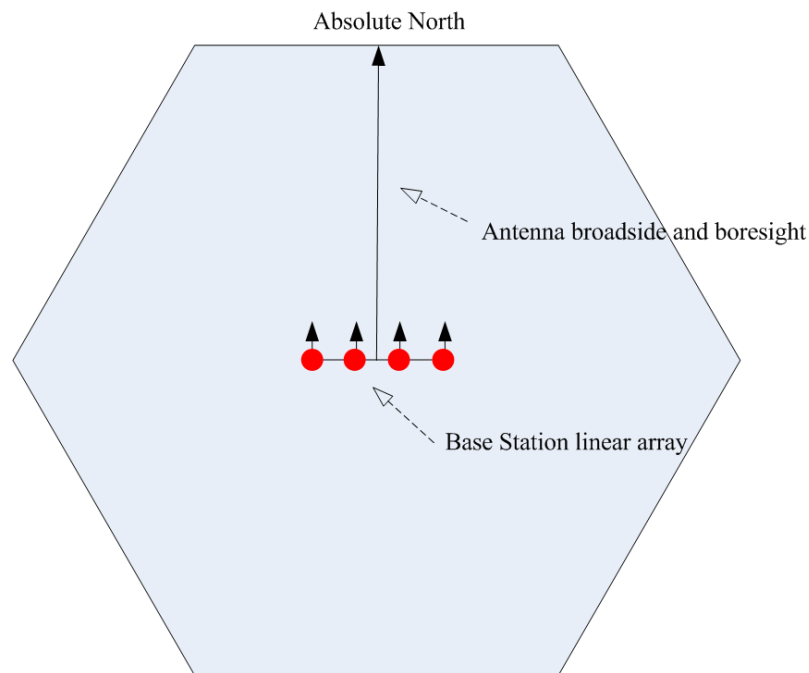
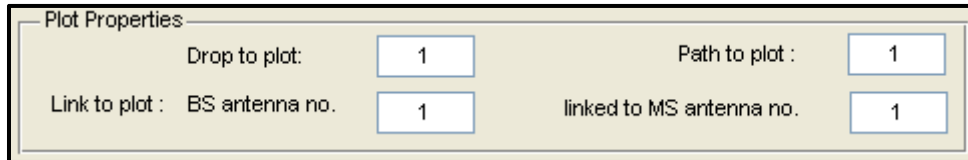


Fig. 14 The BSs fixed location inside the cell when 'Random' option is chosen

Plot Options

At the bottom right part of the 'Additional Properties' are the 'Plot Properties' where the user chooses which drop, path and link between the $D \times N \times S \times U$ links to plot after the simulation is over.



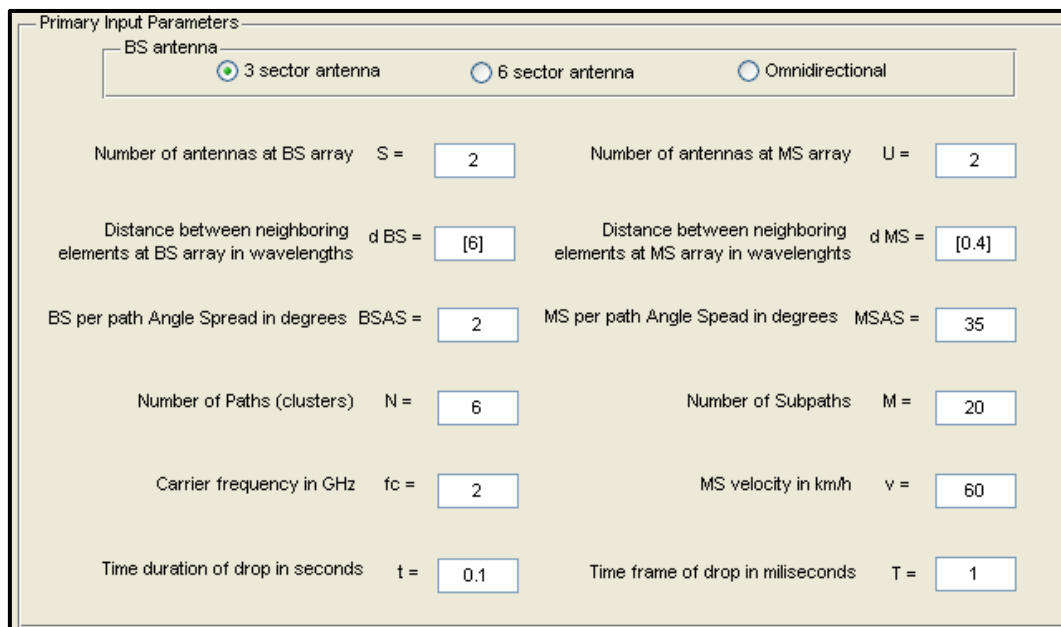
Plot Properties	
Drop to plot:	1
Path to plot:	1
Link to plot: BS antenna no.	1
linked to MS antenna no.	1

Fig. 15 Choose which link to use for plotting

6.2 Channel Parameters

The channel's parameters are subcategorized to primary and secondary. Secondary parameters can be found when clicking 'Additional Properties'.

Primary Input Parameters



Primary Input Parameters	
BS antenna: <input checked="" type="radio"/> 3 sector antenna <input type="radio"/> 6 sector antenna <input type="radio"/> Omnidirectional	
Number of antennas at BS array S =	2
Number of antennas at MS array U =	2
Distance between neighboring elements at BS array in wavelengths d BS =	[6]
Distance between neighboring elements at MS array in wavelengths d MS =	[0.4]
BS per path Angle Spread in degrees BSAS =	2
MS per path Angle Spread in degrees MSAS =	35
Number of Paths (clusters) N =	6
Number of Subpaths M =	20
Carrier frequency in GHz fc =	2
MS velocity in km/h v =	60
Time duration of drop in seconds t =	0.1
Time frame of drop in milliseconds T =	1

Fig. 16 Primary Input Parameters for Case I

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

Fig. 17 Primary Input Parameters for Case II

Let us now explain each parameter, giving instructions where needed.

- S Number of the BS linear antenna array elements.
- U Number of the MS linear antenna array elements.
- d_{BS} Distance between neighboring elements at the BS linear array in wavelengths.
Input a $1 \times (S-1)$ matrix where its element s gives the spacing in wavelengths between array elements s and $s+1 (s=1 \dots S-1)$.
- d_{MS} Distance between neighboring elements at the MS linear array in wavelengths.
Input a $1 \times (U-1)$ matrix where its element u gives the spacing in wavelengths between array elements u and $u+1 (u=1 \dots U-1)$.
- $BSAS$ Base Station per path Angle Spread in degrees.
 $BSAS$ defines the statistics of the BS sub-paths AoD through RV Δ_{AoD} (see Table 2).
- $MSAS$ Mobile Station per path Angle Spread in degrees.
 $MSAS$ defines the statistics of the MS sub-paths AoA through RV Δ_{AoA} (see Table 2).
- N Number of Paths (clusters or rays).

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

- M Number of sub-paths (sub-rays).
- f_c Carrier frequency in GHz.
The carrier frequency is associated with the wave number k through: $k=2\pi f_c/c$ where c is the propagating velocity ($c=3 \times 10^8$ m/sec).
- v Mobile Station velocity vector magnitude in km/h.
The velocity of the MS will affect the intensity of the Doppler shift (the maximum Doppler shift is given by: $f_{d,max} = \pm \frac{v}{\lambda}$ where λ is the carrier wavelength). For pedestrian cases v should be around 3 km/h while for vehicular cases it should be around 30 km/h (slow vehicular) or 120 km/h (fast vehicular).
- t Time duration of 'drop' in seconds.
Define the simulation's duration.
- T Time frame of 'drop' in milliseconds .
Define the sampling period. The number of simulation instants will be: $t = \text{floor}(t/T)$.
- D Number of 'drops'.
The application supports multi-simulation runs defined by D . These simulations will have all the input parameters common while all the parameters that are randomly distributed will be re-generated in each 'drop'.
- XPD Cross Polarization Discrimination in dB (Case II only).
In [1], the XPD (defined in chapter 4) is handled as a RV. Here we find it plausible to consider it as an input parameter.
- a_{BS} Base Station antenna(s) tilt with respect to the z-axis in degrees (Case II only).
Define the antenna tilt at the BS array. Note that this tilt will be common for every antenna at the BS array.
- β_{MS} Mobile Station antenna(s) tilt with respect to the z-axis in degrees (Case II only).
Define the antenna tilt at the MS array. Note that this tilt will be common for every antenna at the MS array.

Additional/Secondary Input Parameters

- R Cellular hexagon radius in meters.
If d is the BS to BS distance in meters, then $R = d/\sqrt{3}$.
- SNR Signal to Noise Ratio in dB

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

SNR is needed to calculate the channel's capacity.

Suburban and Urban Macrocell secondary input parameters

- r_{DS} $\sigma_{delays}/\sigma_{DS}$
 r_{DS} defines the statistics of the path delays through RV τ (see Table 2).
- r_{AS} σ_{AoD}/σ_{AS}
 r_{AS} defines the statistics of the BS paths AoD through RV δ_{AoD} (see Table 2).

Secondary Input Parameters			
sigma delays/ sigma DS	$r_{DS} =$	1.4	sigma AoD/ sigma AS
Cellular hexagon radius in meters	$R =$	1000	Signal To Noise Ratio in dBs
			$r_{AS} =$
			SNR =
			15

Urban Microcell secondary input parameters

- DS Delay Spread in microseconds.
 DS defines the statistics of the path delays through RV τ (see Table 2).
- $BSppD$ BS per-path AoD Distribution
 $BSppD$ defines the statistics of the BS paths AoD through RV δ_{AoD} (see Table 2).

Secondary Input Parameters			
Delay Spread in microseconds	$DS =$	1.2	BS per path AoD distr in degrees
Cellular hexagon radius in meters	$R =$	1000	Signal To Noise Ratio in dBs
			$BSppD =$
			SNR =
			15

Orientation Parameters

- d Distance between the BS and the MS in meters.
- Ω_{BS} BS antenna array orientation, defined as the difference between the broadside of the BS array and the absolute North (N) reference direction.
- Ω_{MS} MS antenna array orientation, defined as the difference between the broadside of the MS array and the absolute North (N) reference direction.
- Θ_{BS} array LOS AoD direction between the BS and MS, with respect to the broadside of the BS.

- Θ_{MS} Angle between the BS-MS LOS and the MS broadside.
- Θ_{tav} Angle of the velocity vector, with respect to the broadside of the MS array.

Correlated Parameters σ_{AS} , σ_{DS} , σ_{SF}

- r_{DS-AS} Correlation between Delay Spread and Angle Spread.
- r_{SF-DS} Correlation between Shadow Fading and Delay Spread.
- r_{SF-AS} Correlation between Shadow Fading and Angle Spread.
- σ_{SH} Shadow Fading standard deviation in dB.
- e_{DS} Delay Spread logarithmic standard deviation, $e_{DS} \equiv \varepsilon_{DS} = \sqrt{E[\log_{10}^2(\sigma_{DS})] - \mu_{DS}^2}$
- m_{DS} Delay Spread logarithmic mean, $m_{DS} \equiv \mu_{DS} = E(\log_{10}(\sigma_{DS}))$
- e_{AS} Angle Spread logarithmic standard deviation, $e_{AS} \equiv \varepsilon_{AS} = \sqrt{E[\log_{10}^2(\sigma_{AS})] - \mu_{AS}^2}$
- m_{AS} Angle Spread logarithmic mean, $m_{AS} \equiv \mu_{AS} = E(\log_{10}(\sigma_{AS}))$

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

The figure displays two screenshots of a software interface titled "Correlated Parameters DS AS SF". Each screenshot contains a grid of input fields for various parameters. The top screenshot shows the following values: DS-AS Correlation r_{DS-AS} = 0.6, SF-AS Correlation r_{SF-AS} = -0.5, SF-DS Correlation r_{SF-DS} = -0.5, SF std deviation σ_{SH} in dB = 8, DS logarithmic std dev σ_{DS} = 0.288, DS logarithmic mean m_{DS} = -6.8, AS logarithmic std dev σ_{AS} = 0.13, and AS logarithmic mean m_{AS} = 0.69. The bottom screenshot shows the same interface with some values updated: σ_{SH} in dB = 10, m_{DS} = -6.08, and σ_{AS} = 0.44. The other parameters remain the same as in the top screenshot.

Parameter	Value (Top Screenshot)	Value (Bottom Screenshot)
DS-AS Correlation r_{DS-AS}	0.6	0.6
SF-AS Correlation r_{SF-AS}	-0.5	-0.5
SF-DS Correlation r_{SF-DS}	-0.5	-0.5
SF std deviation σ_{SH} in dB	8	10
DS logarithmic std dev σ_{DS}	0.288	0.35
DS logarithmic mean m_{DS}	-6.8	-6.08
AS logarithmic std dev σ_{AS}	0.13	0.44
AS logarithmic mean m_{AS}	0.69	0.95

Fig. 18 Define here the correlation properties for the correlated RV delay spread, angle spread and shadow fading. Notice that when the Urban Microcell environment is chosen, all Correlated Parameter properties are disabled except σ_{SH} .

In Table 1 we concentrate all the primary, secondary and additional parameters, their symbols, their default or suggested value for each environment and case and their numerical type or numerical limitations. Here, we should comment that the user must be careful when inputting the parameter values because some of them have a direct effect on the simulation duration (parameters N , M , D , S , U , t , T). We confine ourselves to limit only parameters N and M (to 18 and 200 respectively).

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

Option/Parameter	Symbol	Default/Suggested Value			Type			
Environment Option	ENV	Suburban Macrocell	Urban Macrocell	Urban Microcell	N/A			
Number of BS linear array antenna elements	S	2			Natural	Case I & Case II	Primary Parameters	
Number of MS linear array antenna elements	U	2			Natural			
BS array elements spacing	d_{BS}	6λ	4λ	2λ	Pos. Real			
MS array elements spacing	d_{MS}	0.4λ			Pos. Real			
Per path AS at BS	$BSAS$	2^0	2^0	5^0	Pos. Real			
Per path AS at MS	$MSAS$	35^0			Pos. Real			
Number of paths	N	6			Natural			
Number of subpaths	M	20			Natural			
Carrier frequency	f_c	2 GHz			Pos. Real			
MS velocity magnitude	\mathbf{v}	60 km/h			Pos. Real			
Time duration of drop	t	0.1 s			Pos. Real			
Time frame of drop	T	1 ms			Pos. Real			
Number of drops	D	2			Natural			
Cross Polarization Discrimination	XPD	15 dB	10 dB	8 dB	Pos. Real	Case II		
BS array antenna(s) tilt	α_{BS}	0^0			$[0^0, 90^0]$			
MS array antenna(s) tilt	β_{MS}	0^0			$[0^0, 90^0]$			
Hexagonal Radius	R	1700	1200	500	Pos. Real	Macro	Additional/Secondary Parameters	
Signal To Noise Ratio	SNR	15 dB			Real			
σ_{AoD}/σ_{AS} ratio	r_{AS}	1.2	1.3	N/A	Pos. Real			
$\sigma_{delays}/\sigma_{DS}$ ratio	r_{DS}	1.4	1.7	N/A	Pos. Real			
BS per-path AoD Distr.	$BSppD$	N/A		40^0	$[0^0, 180^0]$			Micro
Delay Spread	DS	N/A		$1.2\text{ }\mu\text{s}$	Pos. Real			
LN Shadowing std dev	σ_{SH}	8 dB	8 dB	10 dB	Real			AS, DS, SF
Angle Spread at BS	σ_{AS}	$\mu_{AS}=0.69$ $\epsilon_{AS}=0.13$	$\mu_{AS}=0.81$ $\epsilon_{AS}=0.34$	N/A	Real			
Delay Spread	σ_{DS}	$\mu_{DS} = -6.80$ $\epsilon_{DS} = 0.288$	$\mu_{DS} = -6.18$ $\epsilon_{DS} = 0.18$		Real			
AS-DS Correlation	ρ_{AS-DS}	0.6	0.6		Real			
SF-AS Correlation	ρ_{SF-AS}	-0.5	-0.5		Real			
SF-DS Correlation	ρ_{SF-DS}	-0.5	-0.5		Real			

Table 1 Primary and Secondary channel parameters and their default/suggested values for each Environment and Case.

Note: Parameters $BSAS$ and $MSAS$ are the per-path AS at the BS and MS respectively. If we combine all path angles, they should result to the mean AS at the BS and MS, $E(\sigma_{AS,BS})$, $E(\sigma_{AS,MS})$. The user should be careful that the combination of N and the BS and MS angle spread values produces the corresponding mean AS. For example, if we set $N=1$, we should set $BSAS= E(\sigma_{AS,BS})$, $MSAS= E(\sigma_{AS,MS})$. For Table 1, the corresponding BS and MS mean angle spreads are shown in the table below. For more information see: [1], p. 17, Table 5.1.

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

Environment Option	ENV	Sub. Macro	Urb. Macro	Urb. Micro
Mean AS at BS	$E(\sigma_{AS,BS})$	5^0	8^0	19^0
Mean AS at MS	$E(\sigma_{AS,MS})$	68^0		

Random Variables

As mentioned before, there are parameters generated inside the code through a number of random variables, each one following its own distribution. In Table 2 we note these variables and the statistics that company them. It is obvious that some distributions depend on some Input parameters which we also include in Table 2. Since details about the origin of these distributions can be found in [1], we will limit our report on them by just presenting Table 2. Note that angles Δ_{AoA} , Δ_{AoD} are RV and not fixed values like in [1].

Random Variable	Suburban Macrocell	Urban Macrocell	Urban Microcell
τ	$-r_{DS}\sigma_{DS}\ln z, z\sim N(0,1)$		$U(0,\sigma^2_{DS}), \sigma^2_{DS}\equiv DS$
P	$\exp((1-r_{DS})\tau/ r_{DS} \sigma_{DS})*10^{(-\xi/10)},$ $\xi\sim N(0,\sigma^2_{\text{RND}}), \sigma^2_{\text{RND}}\text{=3dB}$		$10^{-(\tau+z)/10}, z\sim N(0,3\text{dB})$
δ_{AoA}	$N(0,\sigma^2_{AoA}), \sigma_{AoA}\text{=104.12(1-exp(-0.2175 10log(P}_n\text{)))}$		$N(0,\sigma^2_{AoA}), \sigma_{AoA}\text{=104.12(1-exp(-0.265 10log(P}_n\text{)))}$
δ_{AoD}	$N(0,\sigma^2_{AoD}), \sigma_{AoD} = r_{AS}\sigma_{AS}$		$U(-b,+b),$ $b \equiv BSppD$
Δ_{AoA}	$N(0, \sigma^2_{AS}), \sigma^2_{AS}\equiv BSAS$		
Δ_{AoD}	$N(0, \sigma^2_{AS}), \sigma^2_{AS}\equiv MSAS$		
Φ	$U(0^0, 360^0)$		
θ_v			
Ω_{MS}			
θ_{BS}			
θ_{MS}	$\theta_{MS} = \Omega_{BS} - \Omega_{MS} + \theta_{BS} + 180^0 $		
σ_{AS}	$\sigma_{AS} = 10^{(\epsilon_{AS}\alpha + \mu_{AS})}$		N/A
σ_{DS}	$\sigma_{DS} = 10^{(\epsilon_{DS}\beta + \mu_{DS})}$		
σ_{SF}	$\sigma_{SF} = 10^{(\sigma_{SH}\chi)}$		$\sigma_{SF} = 10^{(\sigma_{SH}\chi)}, \chi\sim N(0,1)$

Table 2 Overview of the RV and their distributions

Since experimental measurements indicate that σ_{SF} , σ_{AS} and σ_{DS} follow a LN distribution and, in addition, are correlated to each other, a model should reproduce these correlations. Thus, RV α , β and γ of Table 2 are correlated Gaussian RV and they derive from the procedure presented in [1], Chapter 5.6. Since we assume only one site, we set $\zeta = 0$, hence matrix $B = 0$. In other words the procedure simplifies to the one given in [2], p.530. However, this does not apply to urban micro environment where the correlation of σ_{SF} , σ_{AS} and σ_{DS} is not reproduced (see Table 2).

7 Functions

In this section we describe the code's functions. We will be very brief since MATLAB allows access to the functions' code where someone can observe more details and even make alterations on it.

Multipath and MultipathPol

Functions 'Multipath' and 'MultipathPol' are the main functions of the application. 'Multipath' handles Case I while 'MutipathPol' handles Case II. When executed they can process all the environments, they generate the angles $\delta_{AoA,n}$, $\delta_{AoD,n}$, and the SxU matrix $H_{S,U,n}$ for every n ($n=1 \dots N$) and for every instant. They also call functions 'DIST', 'CorParameters', 'FastFading' or FastFadingPol respectively, PDPmacro or PDPmicro (depending on the chosen environment) and 'OrientationsFixBS'.

FastFading and FastFadingPol

'FastFading' and 'FastFadingPol' are called by functions 'Multipath' and 'MultipathPol' and handle cases I and II respectively. They generate angles: $\Phi_{n,m}$ or $\Phi_{n,m}^{(x,y)}$, $\Delta_{AoA,n,m}$, $\Delta_{AoD,n,m}$ and the summations (3) or (4) respectively, for every instant which represents the channel's fast fading. 'FastFading' can also call functions 'PDPmarco' or 'PDPmicro' when a sector antenna is selected in Case I.

PDPmacro and PDPmicro

Functions PDPmacro and PDPmicro provide the Power Delay Profile for the macrocell and microcell environment respectively. They generate parameters P_n and τ_n following the directions given in [1] (also see Table 2).

CorParameters

Function 'CorParameters' generates σ_{AS} , σ_{DS} , σ_{SF} following the procedure in [1] or [2] and reproduces the correlation between angle spread, delay spread and shadow fading. It is called by function 'Multipath' or 'MultipathPol' as σ_{AS} is used to generate angles δ_{AoD} , and σ_{DS} is used to generate delays τ_n (see Table 2) while σ_{SF} is the output parameter for shadow fading. 'CorParameters' is not called when the user has selected the Urban Microcell environment.

OrientationsFixBS

If 'Random' is chosen at the 'Orientation Parameters', function 'OrientationFixBS' gives random values to: d , Ω_{MS} , θ_{BS} , θ_v while it sets $\Omega_{BS} = 0$ (fixed boresight and broadside direction, see Fig. 14) and calculates:

$$\theta_{MS} = |\Omega_{BS} - \Omega_{MS} + \theta_{BS} + 180^0|$$

G3, G6

Functions 'G3' and 'G6' determine the antenna attenuation and give the numeric gain $G(\theta)$ for the 3-sector and the 6-sector directional antenna respectively. In other words they reproduce the numeric gain of the antenna patterns of Fig. 6 and Fig. 8. They are called inside function 'FastFading' when the BS is calibrated to use a 3-sector or a 6-sector antenna.

DIST

Function 'DIST' calculates the spacing in meters between the reference antenna element of an array (the first one in the linear array) and each other elements of the same array.

Capacity

Function 'Capacity' calculates the channel's total capacity $C(t)$ for every time instant t , through the equations shown below. Equation (7) is the classic equation used to estimate the capacity in a MIMO antenna system.

$$C(t) = \sum_{n=1}^N C_n(t) \quad (6)$$

$$C_n(t) = \log_2 \left[\det \left(\mathbf{I}_U + \frac{SNR}{S} \mathbf{H}_{U,S,n}(t) \mathbf{H}_{S,U,n}^\dagger(t) \right) \right] \quad (7)$$

where: N is the number of paths, S and U are the number of the antenna elements at the transmitter and the receiver respectively, SNR is the signal to noise ratio, \mathbf{I}_U is the $U \times U$ unit matrix, 'det' indicates the determinant, $\mathbf{H}_{U,S,n}$ is given in equation (2) and $\mathbf{H}_{S,U,n}^\dagger$ is its inverse complex conjugate matrix.

8 Output Parameters

In this chapter we are going to discuss the Output Parameters of the application. Firstly, every output of each simulation can be found inside a $\text{data}\{i\}.\text{mat}$ file which is exported to a folder chosen from the user, where i represents the number of simulation (try not to confuse 'simulation' with 'drop' since a simulation may include a number of 'drops' that depends on Input parameter D). The default path is: $C:\text{Matlab}\backslash\text{work}$ but the user can change this path by clicking the 'Save to...' button and choosing another folder to save the file. These files (.mat) can be opened with MATLAB and further processed by the user.

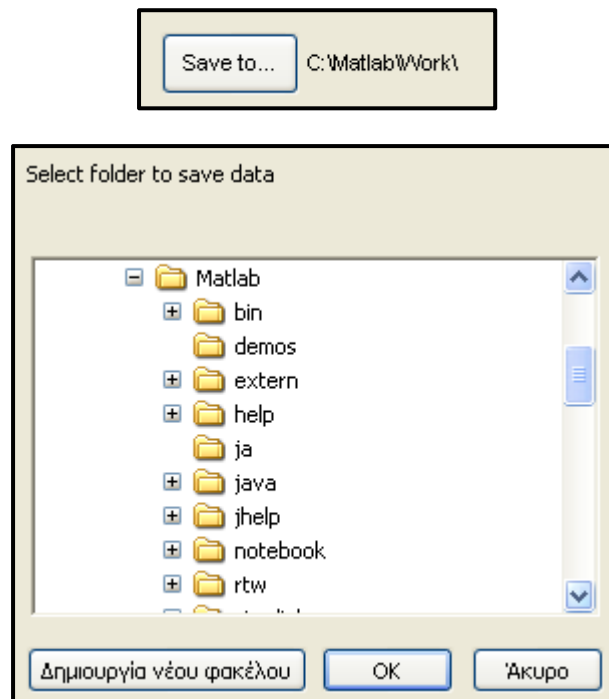


Fig. 19 Choose a folder to save the output parameters as a $\text{data}\{i\}.\text{mat}$ file

Each $\text{data}\{i\}.\text{mat}$ contains ten output parameters shown in Table 3. These outputs are in a form of arrays either *Double* or *Cell*. Double is an array of double-precision numbers while Cell is an array of indexed cells, each capable of storing an array of a different dimension and data type. In Table 3 one can observe each parameter's name, symbol, type, dimension and unit.

Note: Output Parameters AS and DS are not generated when we study the urban microcell environment.

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

Output Parameter	Symbol	Array Type	Dimensions	units
Channel coefficients, $h_{s,u,n}(t)$	H	Cell	$\{1 \times D\} \{N \times 1\} \{t \times 1\} \{S \times U\}$	$10^{(dB/10)}$
Path Angle of Arrival, $\delta_{n,AoA}$	AoA	Cell	$\{1 \times D\} \{N \times 1\}$	Degrees
Path Angle of Departure, $\delta_{n,AoD}$	AoD	Cell	$\{1 \times D\} \{N \times 1\}$	Degrees
Path Power, P_n	P	Cell	$\{1 \times D\} \{N \times 1\}$	$10^{(dB/10)}$
Path Delay, τ_n	t	Cell	$\{1 \times D\} \{N \times 1\}$	μs
Angle Spread, σ_{AS}	AS	Double	$1 \times D$	Degrees
Delay Spread, σ_{DS}	DS	Double	$1 \times D$	μs
Shadow Fade, σ_{SF}	SF	Double	$1 \times D$	$10^{(dB/10)}$
Path Loss, $PL\{dB\}$	PL	Double	$1 \times D$	dB
Channel Capacity, $C(t)$	C	Cell	$\{1 \times D\} \{t \times 1\}$	bps/Hz

Table 3 Properties of the Output parameters stored inside each *data{i}.mat* file

For example, if we set $D = 2$, $N = 6$, $t = 0.1s$, $T = 1$ ms (thus we have $t = t/T = 100$ time instants), $S = 2$ and $U = 3$, the H output parameter will be an $\{1 \times 2\} \{6 \times 1\} \{100 \times 1\} \{2 \times 3\}$ cell array as shown in Fig. 20.

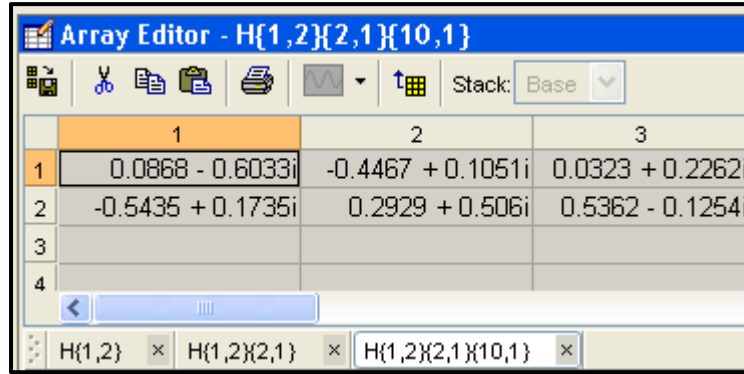


Fig. 20 The $S \times U$ complex channel coefficients for the 2nd ‘drop’, the 2nd path and the 10th time instant

We should also comment that *.mat* files can also be handled outside MATLAB for users using *C* or other platforms. The way to do that can be found analytically inside MATLAB Help.

9 Plots

In this final chapter we will present a number of plots that derive from the usage of the application's functions. These plots have two purposes; firstly to test the correctness of the code by plotting a number of correlations and comparing them with the theoretical correlation curves. Secondly, we can estimate the channel's capacity and view its dependence on a number of parameters and make conclusions about the usage of MIMO antennas as a way to increase the wireless propagation channel's capacity.

9.1 Correlations

For correlations we will be using the normalized correlation coefficient:

$$r(x) = \text{Re} \left\{ \frac{\int_{-\infty}^{+\infty} h(\chi) h^*(\chi - x) d\chi}{\int_{-\infty}^{+\infty} h^2(\chi) d\chi} \right\}$$

χ can represent time, distance or angle depending on the type of correlation and x is its relative shift.

Parameter	Value	Parameter	Value
D	20	M	20
θ_{BS}	0^0	θ_{MS}	0^0
SNR	15 dB	f_c	2 GHz
θ_v	0^0	\mathbf{v}	30 km/h
θ_{AoD}	$N(0, \sigma_{AS,BS}^2)$	$\sigma_{AS,BS}$	8^0
θ_{AoA}	$U(0, 2\pi)$	XPD	0 dB
Case I	Omni (Vpol dipoles)	Case II	Tilted dipoles

Table 4 Values for Fig. 20 to 24.

Let us begin by estimating the spatial cross correlation between two closely separated antennas at both the MS and the BS, as a function of their spacing, d . We will examine both cases I and II and for the simulations we use the parameter values of Table 4. Note, that in Table 4 we only have one path ($N=1$) and for that reason, we use the mean AS at the BS and not the per-path AS. In addition, we assume that $\theta_{AoA} \sim U(0, 2\pi)$. These adjustments are necessary because most bibliography assumes only one path and unity distribution for the AoA.

We will study the correlation at the MS first. The MS spatial correlation functions for eq. (3) and (4) will respectively be:

$$r^{(I)}(d) = \frac{1}{M} \sum_{m=1}^M \exp(jkd \sin \theta_{n,m,AoA}) \quad (8)$$

$$r^{(II)}(d) = \frac{1}{M} \left[\cos(a - a') \sum_{m=1}^M \exp(jkd \sin \theta_{n,m,AoA}) - \sin(\alpha) \sin(\alpha') \sum_{m=1}^M \exp(jkd \sin \theta_{n,m,AoA}) \sin^2(\theta_{n,m,AoA}) \right] \quad (9)$$

where: α, α' are the tilts for each antenna (case II). Since we assume M to be a large number, we can replace the sums with integrals, and because $\theta_{AoA} \sim U(0, 2\pi)$ we will get:

$$r^{(I)}(d) = \frac{1}{2\pi} \int_{-\pi}^{+\pi} \exp(jkd \cos \theta_{AoA}) d\theta_{AoA} = J_0(kd) \quad (10)$$

$$r^{(II)}(d) = \frac{1}{2\pi} \left[\cos(a - a') \int_{-\pi}^{+\pi} \exp(jkd \cos \theta_{AoA}) d\theta_{AoA} - \sin(\alpha) \sin(\alpha') \int_{-\pi}^{+\pi} \exp(jkd \cos \theta_{AoA}) \sin^2(\theta_{AoA}) d\theta_{AoA} \right] \\ = \cos(a - a') J_0(kd) - \sin(\alpha) \sin(\alpha') J_2(kd) \quad (11)$$

where: $J_0(\cdot)$ is the first kind, zero order Bessel function and $J_2(\cdot)$ is the first kind, second order Bessel function. Note that in eq. (11), if $\alpha = \alpha' = 0^\circ$ (vertical polarized dipoles), we go back to $J_0(kd)$.

In Fig. 20 we can view the MS's spatial correlations $r^{(I)}$ and $r^{(II)}$ for cases I and II respectively. We see that in case I (i.e. vertical polarized dipoles) the correlation of eq. (1) is very close to $J_0(kd)$, where $r(d)$ reaches zero for the first time after 0.38λ . In case II we use the extreme case where $\alpha = \alpha' = 90^\circ$ and $XPD = 0$ dB ($r = 1$). We observe that the simulation is now close to $J_0(kd) - J_2(kd)$ and reaches zero approximately at 0.31λ . It is obvious that for all other dipole polarizations the correlation would reach zero somewhere between 0.31 and 0.38λ .

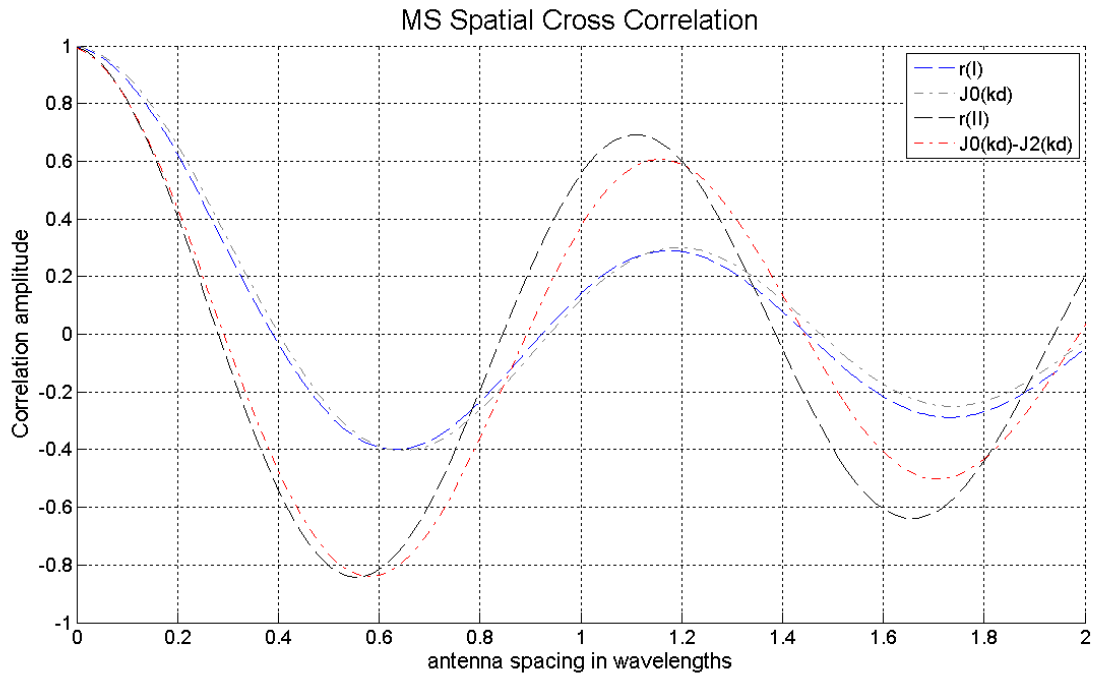


Fig. 21 Spatial Cross Correlation at the MS for Case I & II

When we study the BS, the correlations are the same as eq. (8) and (9) if we replace angles $\theta_{n,m,AoA}$ with $\theta_{n,m,AoD}$, but we cannot jump to eq. (10) and (11) because $\theta_{AoD} \sim N(0, \sigma_{AS,BS}^2)$. Nevertheless, there is a theoretical curve that estimates this type of correlations and stands for small angle spreads and is given by [3]:

$$f(d) = \exp[jkd \sin(\bar{\theta}_{AoD})] \exp\left[-\frac{1}{2}(kd\sigma_{AS,BS} \cos \bar{\theta}_{AoD})^2\right] = \exp\left[-\frac{1}{2}(kd\sigma_{AS,BS})^2\right] \quad (12)$$

because: $\bar{\theta}_{AoD} \equiv \theta_{BS} = 0$

For the BS we study four different angle spreads as shown in Fig. 22. We can see that the simulation plots are very close to $f(d)$. These curves derive using the values of Table 4 for Case I.

Let's go back to eq. (11); for co-located dipoles ($d = 0$) the correlation between them is a function of their relative antenna tilt $\alpha - \alpha'$. We can estimate this angular correlation by keeping one dipole vertical polarized and tilting the second one, hence:

$$r^{(II)}(a) = \cos(a) \quad (13)$$

The correlation result which is shown in Fig. 23 is in perfect agreement with eq. (13)

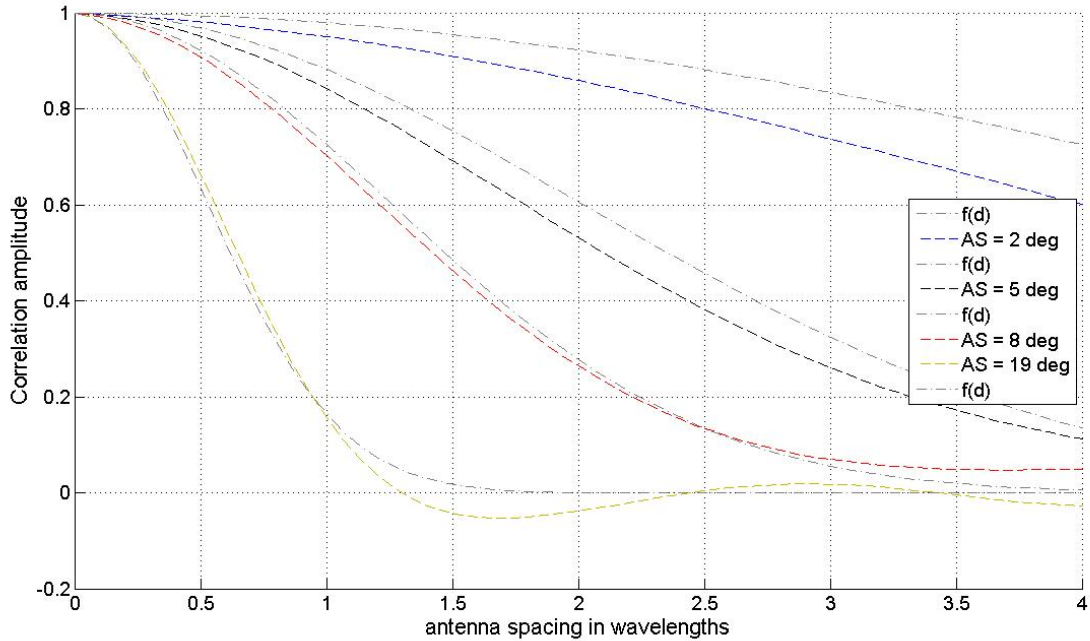


Fig. 22 Spatial Cross Correlation at the BS for Case I. Curve $f(d)$ is given in eq. (12)

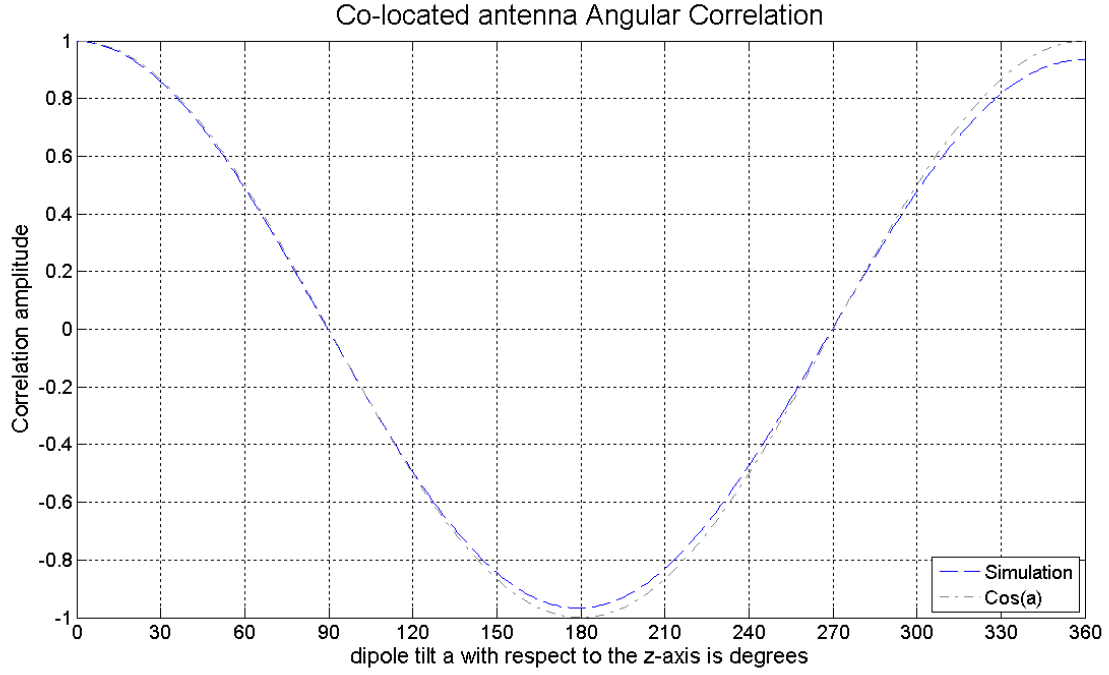


Fig. 23 Cross Correlation between two co-located dipoles as a function of their relative tilt a .

Next, we will discuss is the MS's temporal correlation. In Table 4 we assume $\theta_v = 0$, so the temporal correlation for each case will be:

$$r^{(I)}(t) = \frac{1}{M} \sum_{m=1}^M \exp(jkvt \cos \theta_{n,m,AoA})$$

$$r^{(II)}(t) = \frac{1}{M} \left[\sum_{m=1}^M \exp(jkvt \cos \theta_{n,m,AoA}) - \sin^2(\alpha) \sum_{m=1}^M \exp(jkvt \cos \theta_{n,m,AoA}) \sin^2(\theta_{n,m,AoA}) \right]$$

Here, $\alpha = \alpha'$ because we have the same dipole moving (autocorrelation). Hence:

$$r^{(I)}(t) = \frac{1}{2\pi} \int_{-\pi}^{+\pi} \exp(jkvt \cos \theta_{AoA}) d\theta_{AoA} = J_0(kvt)$$

$$r^{(II)}(t) = \frac{1}{2\pi} \left[\int_{-\pi}^{+\pi} \exp(jkvt \cos \theta_{AoA}) d\theta_{AoA} - \sin^2(\alpha) \int_{-\pi}^{+\pi} \exp(jkvt \cos \theta_{AoA}) \sin^2(\theta_{AoA}) d\theta_{AoA} \right]$$

$$= J_0(kvt) - \sin^2(\alpha) J_2(kvt)$$

We would have reached to the same conclusion if we set $d = vt$ in eq. (10) and (11). In other words, the MS's temporal correlation and spatial cross correlation are identified when: $\alpha = \alpha'$, something that is also confirmed by Fig. 24.

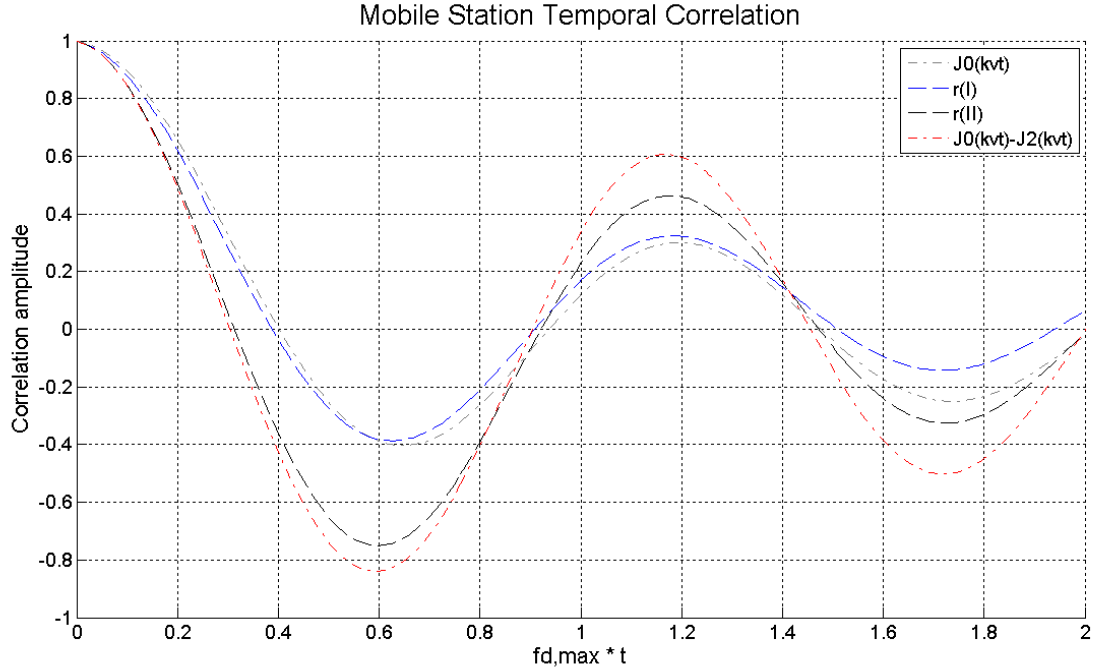


Fig. 24 Temporal Correlation at the MS for case I and II

The following plots concern the RV σ_{AS} , σ_{DS} , σ_{SF} which are correlated with each other. Remember that this correlation is taken under consideration for macrocell environments and not microcell. For the plots, we use the properties of suburban macrocell environment shown in Table 5. In Fig. 25 we can observe the positive correlation between σ_{AS} and σ_{DS} , while in Fig. 26 and 27 we notice the negative correlation of σ_{SF} with σ_{DS} and σ_{AS} respectively.

LN Shadowing std dev	σ_{SH}	8 dB
Angle Spread at BS	σ_{AS}	$\mu_{AS}=0.69$ $\epsilon_{AS}=0.13$ $E(\sigma_{AS})=5^0$
Delay Spread	σ_{DS}	$\mu_{DS} = -6.80$ $\epsilon_{DS} = 0.288$ $E(\sigma_{AS})=0.17 \mu s$
AS-DS Correlation	ρ_{AS-DS}	0.6
SF-AS Correlation	ρ_{SF-AS}	-0.5
SF-DS Correlation	ρ_{SF-DS}	-0.5

Table 5 Properties for σ_{AS} , σ_{DS} , σ_{SF} for the Suburban macrocell environment.

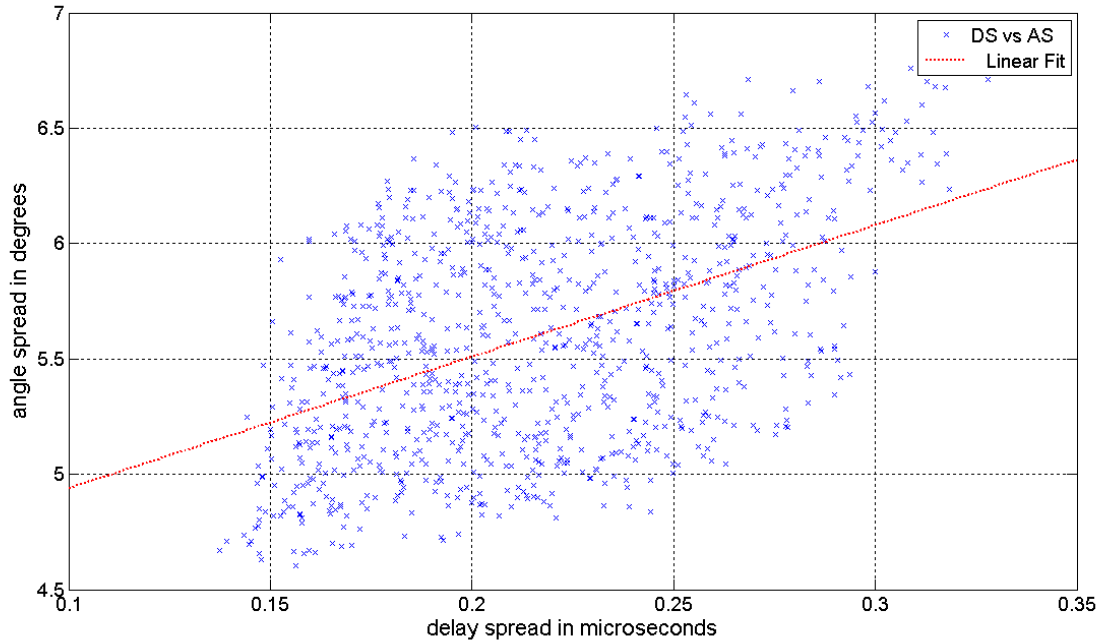


Fig. 25 Delay spread versus Angle spread for 1000 ‘drops’.

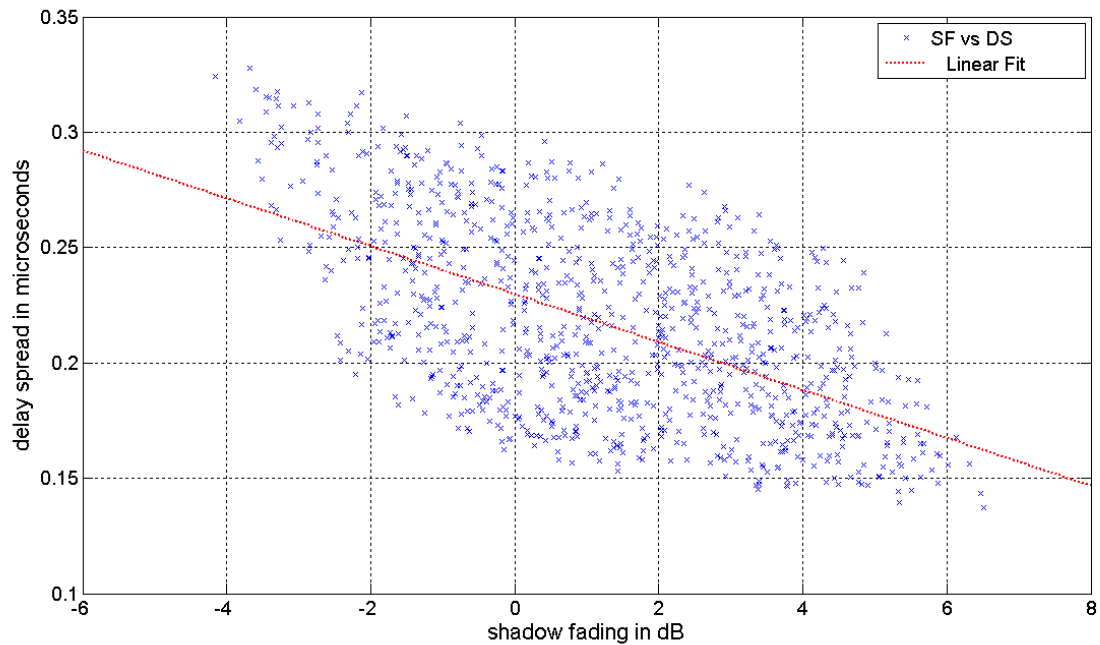


Fig. 26 Shadow fading versus Delay spread for 1000 ‘drops’.

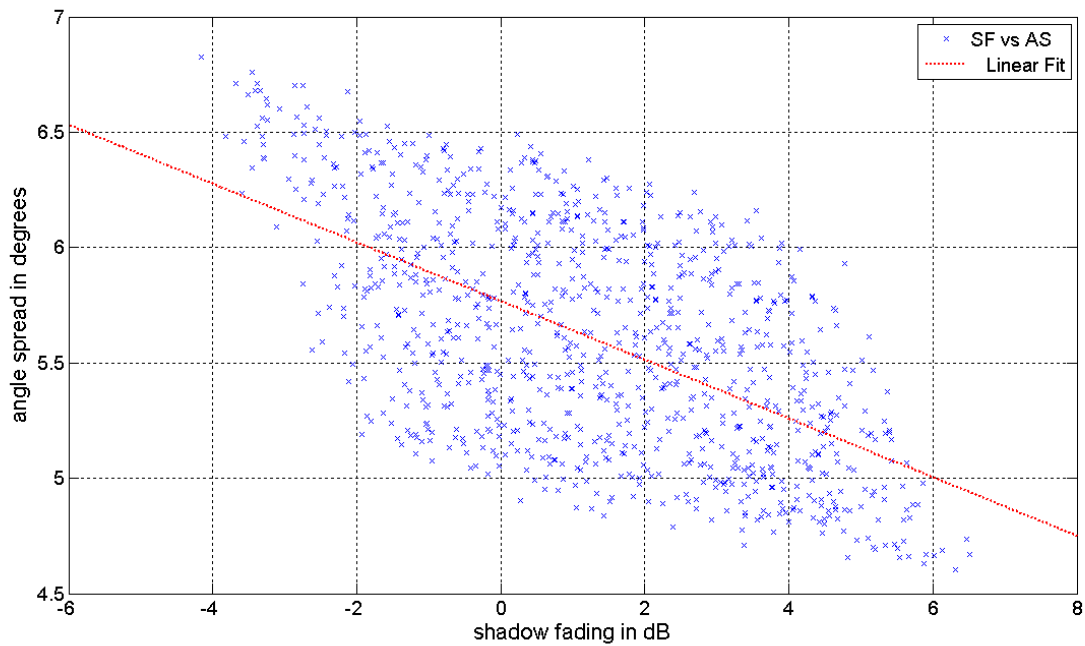


Fig. 27 Shadow fading versus Angles spread for 1000 ‘drops’.

Finally, it would be plausible to show that these correlated parameters actually follow a log normal distribution. This can be done by plotting their CDFs. We will do this for parameters σ_{AS} , σ_{DS} for the suburban and urban macrocell environment. The properties for each case show on Table 1.

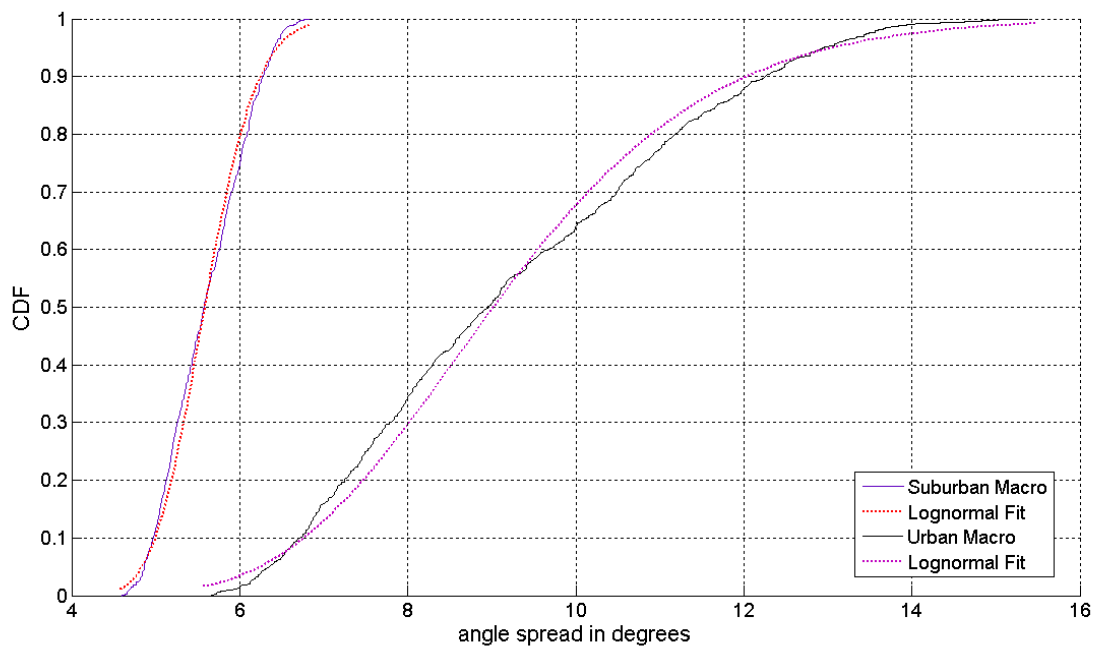


Fig. 28 Angle spread simulation CDFs for the Suburban macro and Urban macro environment and their lognormal fits.

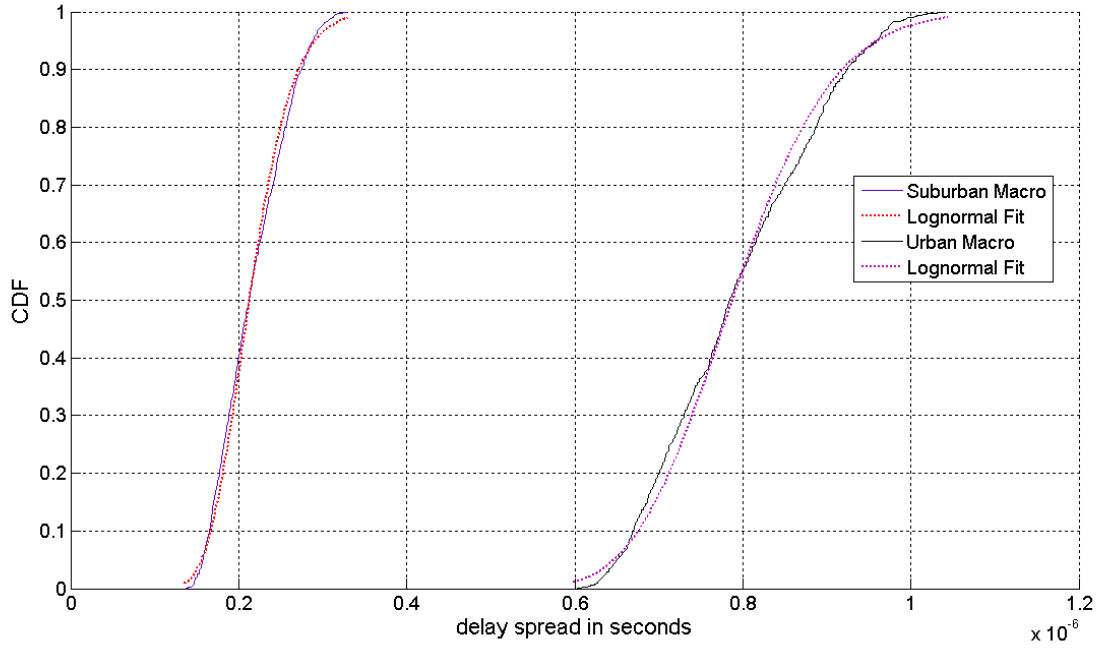


Fig. 29 Delay spread simulation CDFs for the Suburban macro and Urban macro environment and their lognormal fits.

9.2 Channel Capacity

On this final section of the manual we will display various channel capacity plots, each one showing the capacity's dependence on a different parameter. These plots use the parameter values of Table 6, unless a parameter is a plot's independent variable. We will again focus on a single path and the plot results are will be a mean of 20 'drops', except Fig. 30 and 31 which are a simulation of a single 'drop'. The number of BS and MS antenna elements and their type is noted in each plot.

Parameter	Value	Parameter	Value
D	20	M	20
θ_{BS}	0^0	θ_{MS}	0^0
$E(\sigma_{AS,BS})$	8^0	$E(\sigma_{AS,MS})$	68^0
λ	0.15 m	f_c	2 GHz
θ_v	0^0	\mathbf{v}	60 km/h
SNR	15 dB	XPD	8 dB
d_s	4λ	d_u	0.4λ

Table 6 Common parameter values for the capacity plots.

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

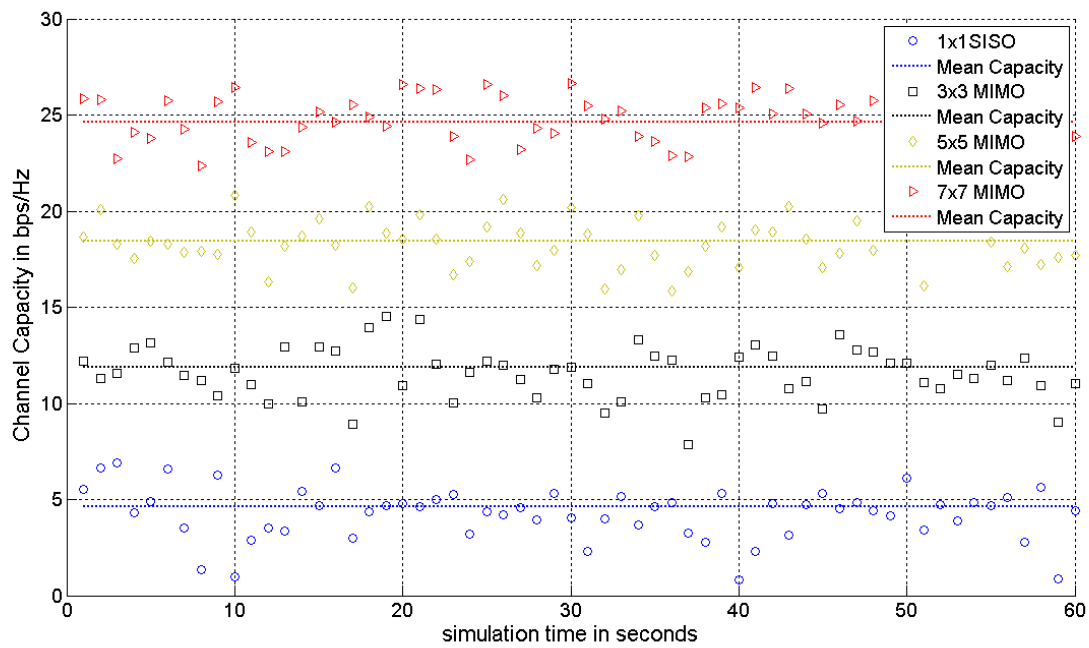


Fig. 30 The simulated channel capacity for the duration of one minute for 4 different MIMO antenna systems and their respective capacity means. Here we use omni antennas at both arrays.

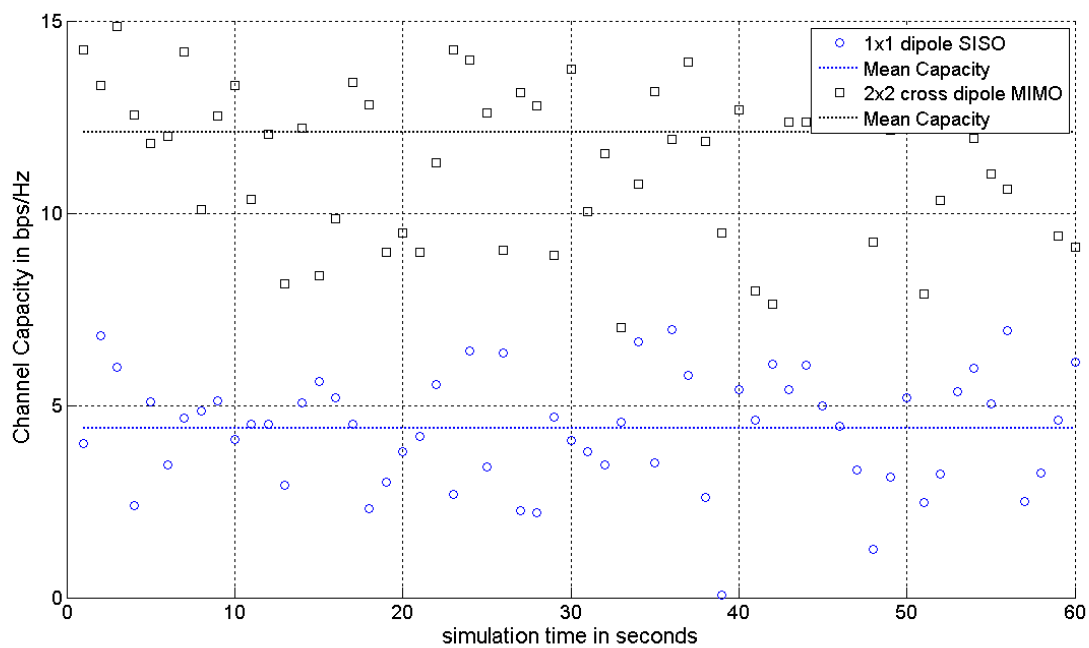


Fig. 31 Here we compare the capacities of an 1x1 SISO versus a 2x2 cross polarized, co-located dipole MIMO system. We notice that using co-located dipoles we increase the capacity without using multi-element arrays.

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

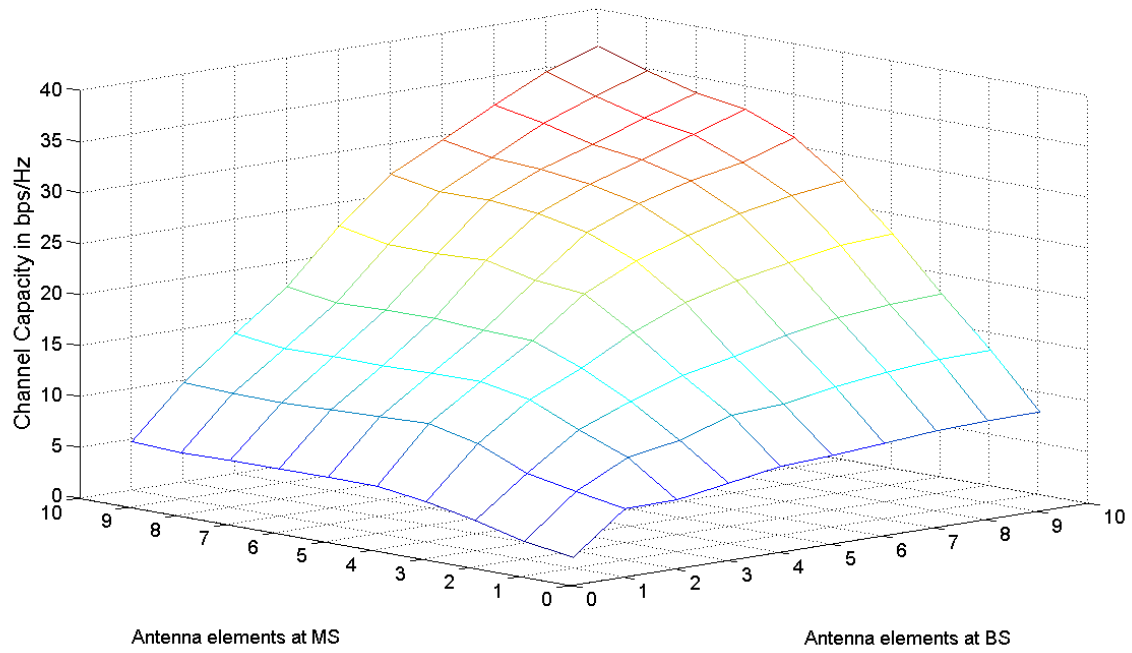


Fig. 32 A 3-D representation of the capacity versus the antenna elements at the BS and MS. We use omni antennas at both arrays.

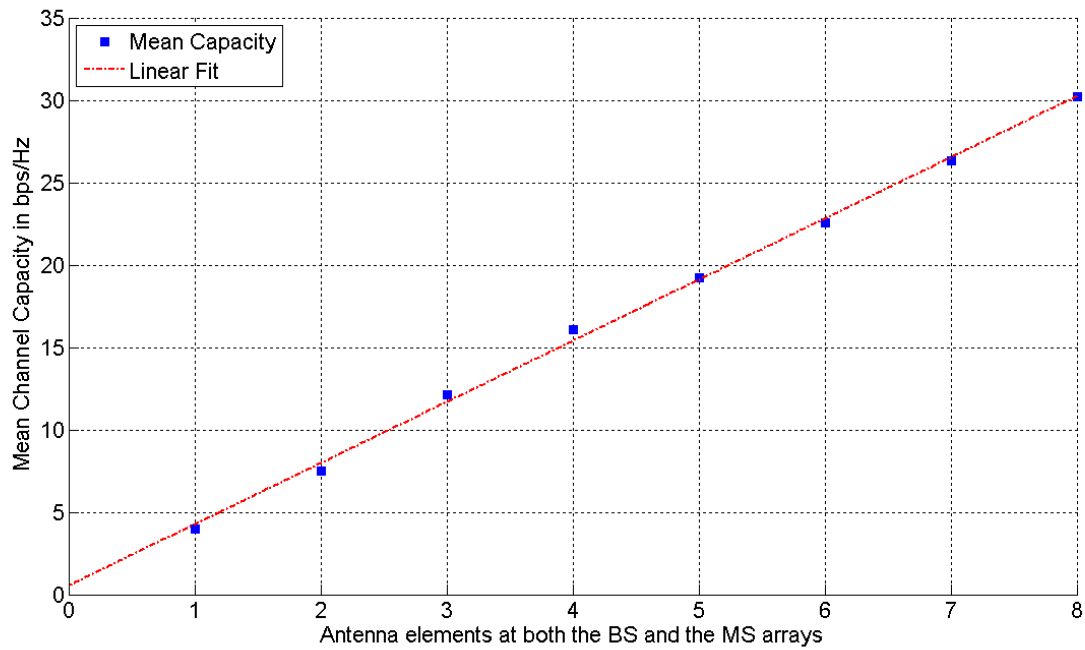


Fig. 33 Here we can observe that the capacity increases linearly with the number of antenna elements at both the BS and MS. We use omni antennas at both arrays.

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

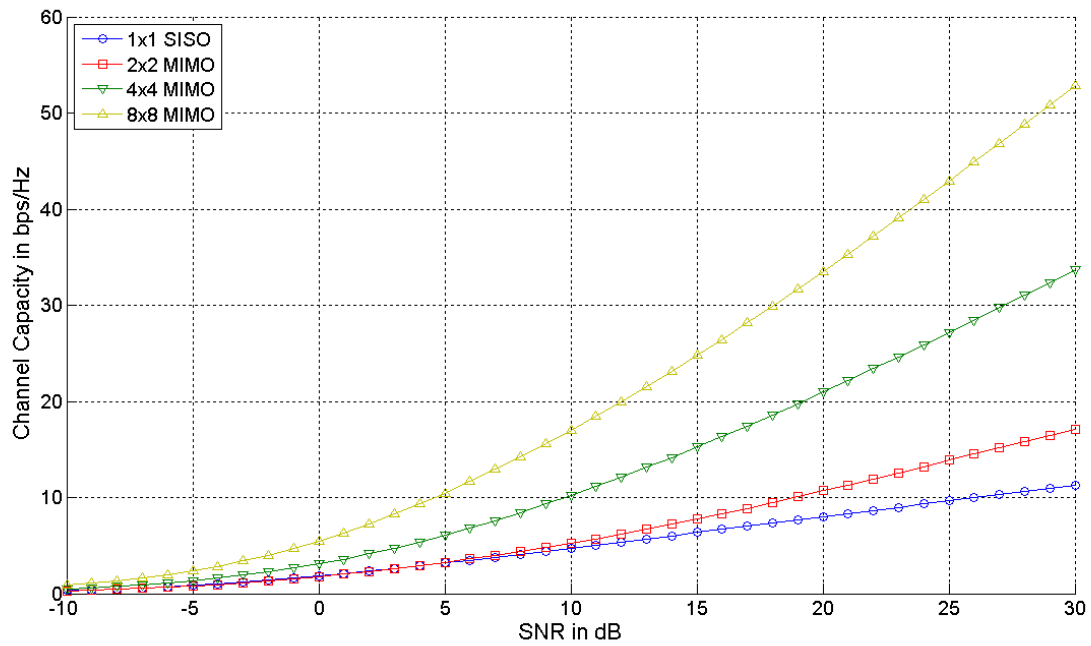


Fig. 34 The channel capacity versus the signal to noise ratio for 4 different MIMO using omni antennas at both arrays.

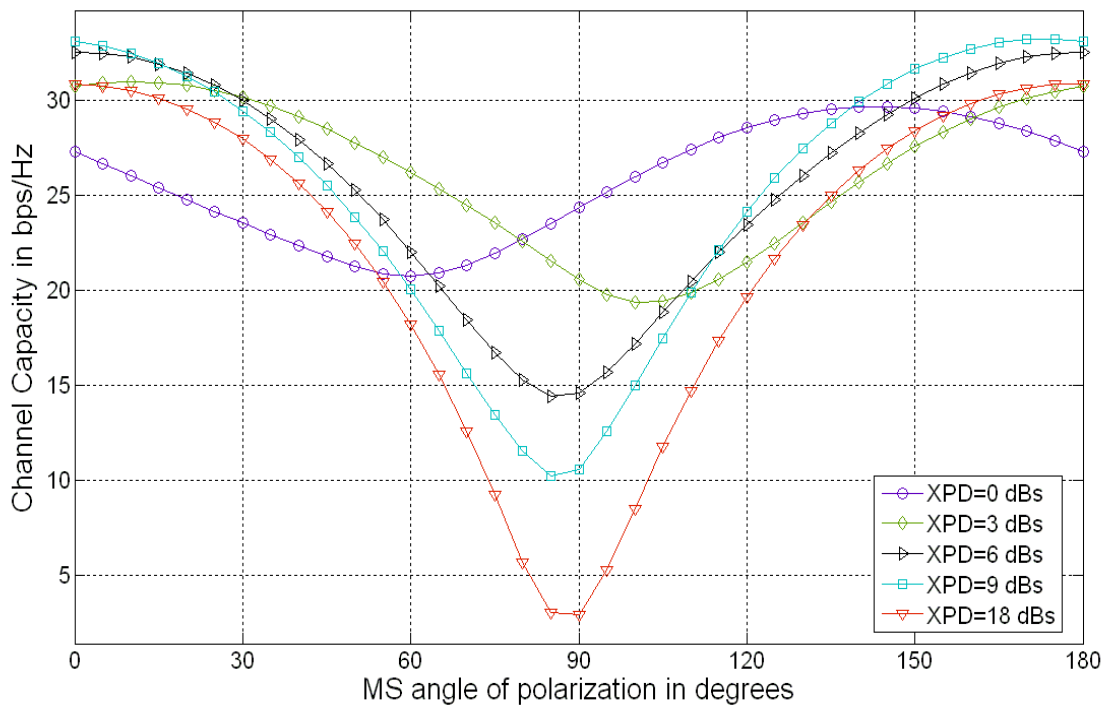


Fig. 35 The channel capacity of a 10x10 MIMO using omni antennas at the BS and dipole antennas at the MS as a function of the common MS antenna dipole tilt for different XPD values.

Spatial Channel Model for MIMO Simulations

A Ray Tracing Simulator Based on 3GPP TR 25.996 v.6.1.0

User's Guide v. 1.0

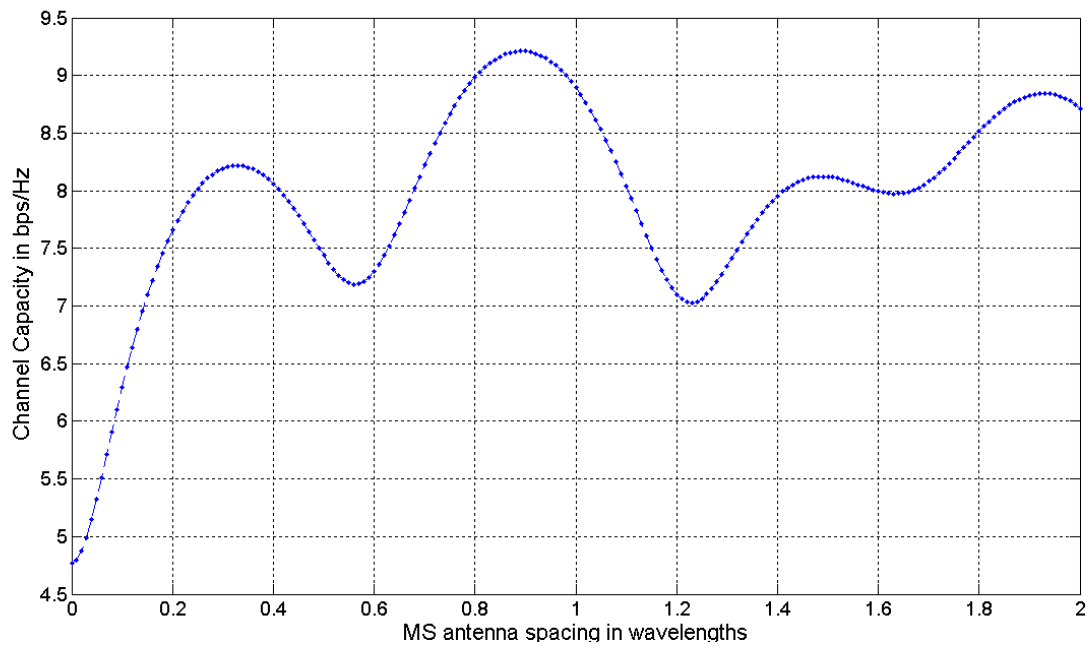


Fig. 36 The channel capacity of a 2x2 MIMO as a function of the MS antenna element spacing when the BS antenna element spacing is fixed at 2λ . We use omni antennas at both arrays and the result is the mean of 20 ‘drops’.

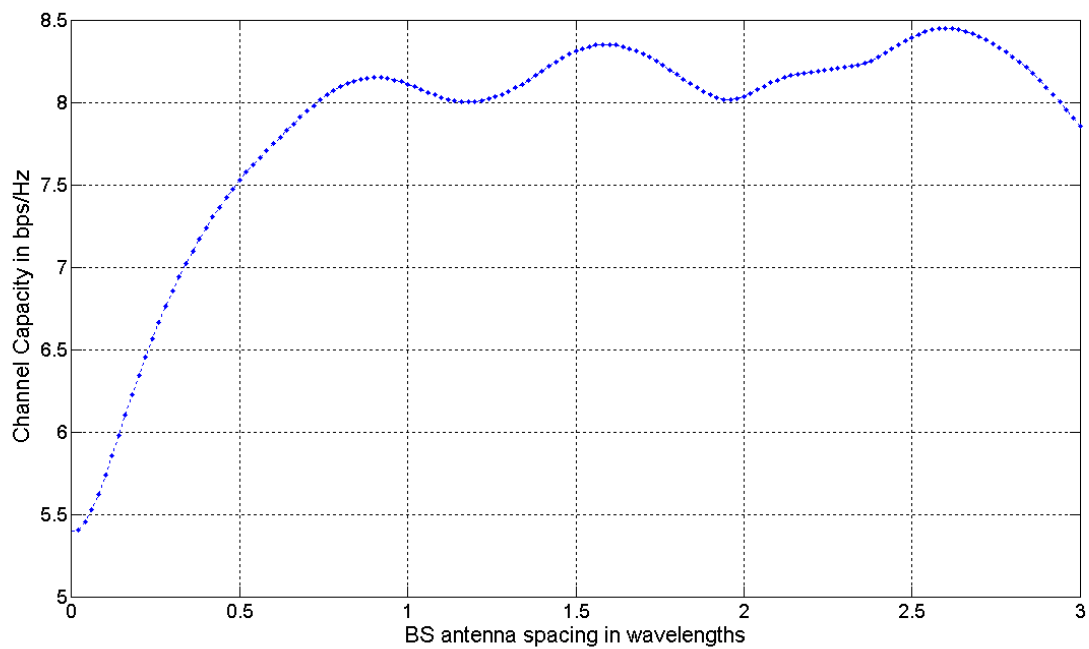


Fig. 37 The channel capacity of a 2x2 MIMO as a function of the BS antenna element spacing when the MS antenna element spacing is fixed at 0.4λ . We use omni antennas at both arrays and the result is the mean of 20 ‘drops’.

References

- [1] “Spatial Channel Model for Multiple Input Multiple Output (MIMO) Simulations”, *3GPP*, vol. TR 25.996, v6.1.0, Sep. 2003.
- [2] Albert Algans, Klaus Ingemann Pedersen “Experimental Analysis of the Joint Statistical Properties of Azimuth Spread, Delay Spread, and Shadow Fading”, *IEEE Selected areas in Communications*, Volume 20, NO. 3, pp. 523-531, April 2002.
- [3] R. M. Buehrer, “The Impact of Energy Distribution on Spatial Correlation”, *IEEE Trans. Veh. Tech.*, vol.56, no.2, Fall 2002.
- [4] L. Greenstein, V. Erceg, Y. S. Yeh, M. V. Clark, “A New Path-Gain/Delay-Spread Propagation Model for Digital Cellular Channels,” *IEEE Transactions on Vehicular Technology*, VOL. 46, NO.2, May 1997, pp.477-485.
- [5] M. Shafi, M. Zhang and A.L. Moustakas “Polarized MIMO Channels in 3D: Models, Measurements and Mutual Information”, *IEEE Selected areas in Communications*, Volume 24, Issue 3, pp. 514-527, March 2006.
- [6] J.D. Parsons, *The Mobile Radio Propagation Channel*, 2nd ed. John Wiley and Sons, 2000.
- [7] L. M. Correia, *Wireless Flexible Personalized Communications*, 3rd Edition Chichester, England: John Wiley and Sons LTD, 2000.