Description of the MATLAB® implementation of a MIMO channel model suited for link-level simulations

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1. Introduction

This document describes the content of the two MATLAB® directories *Correlation_Multiple_Cluster* and *UMTS_Testbed*. They contain MATLAB® scripts that enable their user to

- Derive the spatial correlation properties of a Uniform Linear Array (ULA) impinged by a variety of Power Azimuth Spectra (PAS), namely uniform, truncated Gaussian and truncated Laplacian, where the waves are gathered in a single or in multiple clusters. The relations applied to derive these properties are detailed in [1].
- Simulate a Multiple-Input Multiple-Output (MIMO) radio channel at link-level in compliance with 3GPP specifications [2]. The simulated model is of stochastic type. It is fully described in [3, 4].

Figure 1 summarises the interactions between the scripts of the two directories.

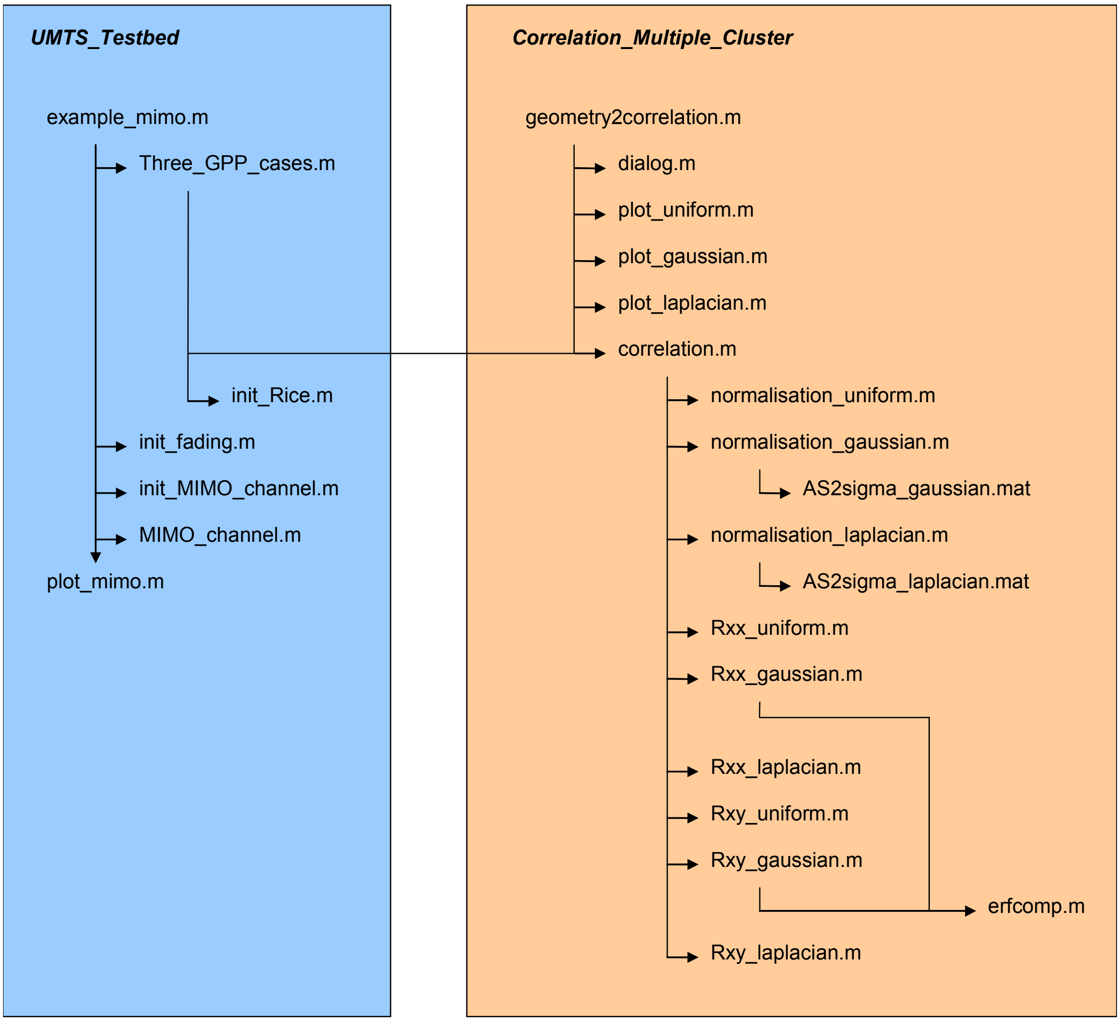

Figure 1: Interactions between the MATLAB® scripts

Following the description of these packages, validation results are presented. The distribution terms of these packages are stated at the end of the document.

2. Spatial correlation – Directory *Correlation_Multiple_Cluster*

The main script is *geometry2correlation.m*. Through a dialogue with the user, this script first collects all the information requested to fully characterise the scenario, namely the number of antenna elements of the ULAs at the User Equipment (UE) and at the Node B, their spacings, the PAS types of the impinging waves, their Azimuth Spreads (AS), and their Angle of Departure (AoD)/Angle of Arrival (AoA).

In a second phase, the spatial correlation properties are derived by the script *correlation.m*.

The first step of this phase is to normalise the PAS such that it can be regarded as a probability distribution, which means that

$$\int_{-\pi}^{\pi} PAS(\varphi)d\varphi = 1 \tag{1}$$

On the other hand, this normalisation step, performed in *normalisation_*.m* scripts, serves to derive the standard deviation of this pdf, based on the AS defined by the user, as there is not necessarily an identity between them.

Being normalised, the PAS is then integrated over its definition domain according to the relations established in [1] to derive the spatial correlation coefficients. The coefficients of the homogeneous products between real (imaginary) parts are derived in *Rxx_*.m* scripts, while the mixed products between real and imaginary parts are handled by *Rxy_*.m* scripts. Their outcome is combined to produce either complex field spatial correlation coefficients or real power ones, depending on the value of a calling variable of the *correlation.m* script.

Finally, the correlation coefficients fill two matrices defined at the UE and at the Node B, respectively $\mathbf{R}_{UE}$ and $\mathbf{R}_{Node\ B}$. These spatial correlation matrices are combined through a Kronecker product as proposed in [3, 4]. The structure of the Kronecker product depends whether one wants to simulate a downlink transmission

$$\mathbf{R} = \mathbf{R}_{Node\ B} \otimes \mathbf{R}_{UE} \tag{2}$$

or an uplink one

$$\mathbf{R} = \mathbf{R}_{UE} \otimes \mathbf{R}_{Node\ B} \tag{3}$$

where $\otimes$ represents the operator of the Kronecker product.

As a matter of illustration, Figure 2 shows 2-cluster PASs, where both clusters are constrained within [-60°, 60°] around their AOAs {-90°, 90°} and exhibit an AS of 30°. Note that the second cluster has half the power of the first one. The envelope correlation coefficient of two distant antennas impinged by these PASs is shown in Figure 3 as a function of the distance between the antennas. One can notice the wider oscillations obtained with the truncated Laplacian PAS. They could be due to the strong confinement of the Laplacian PAS.

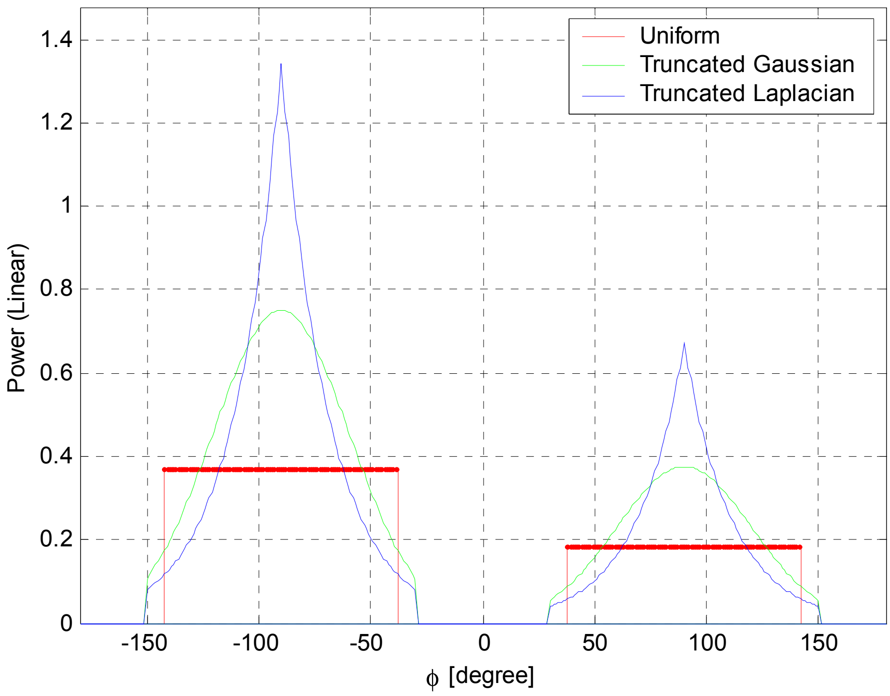

Figure 2: Examples of 2-cluster PASs

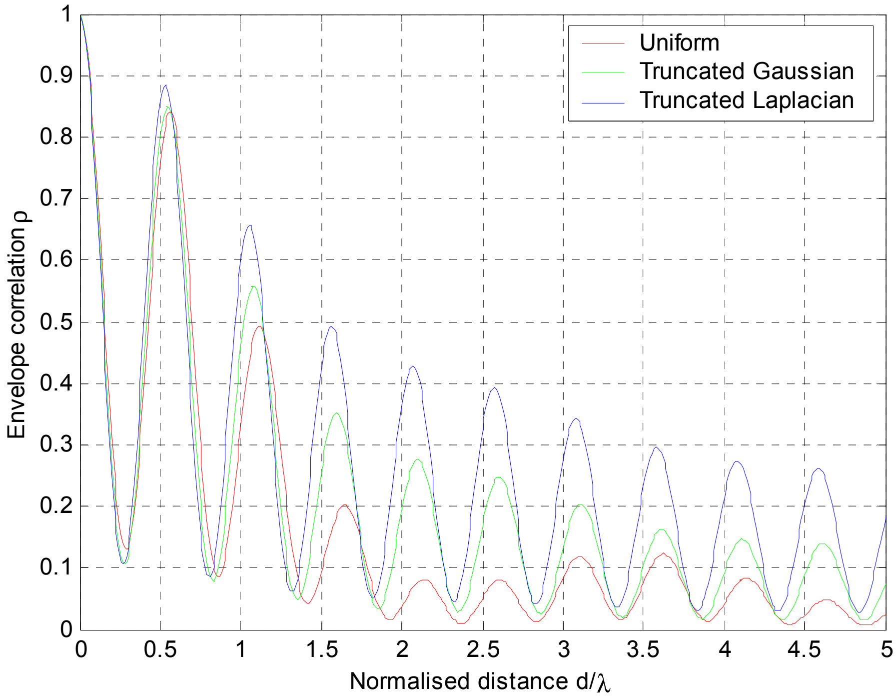

Figure 3: Envelope correlation coefficient of the PASs shown in Figure 2

3. MIMO radio channel – Directory *UMTS_Testbed*

The main script is *example_MIMO.m.* It shows how the scripts written to generate a MIMO radio channel can be embedded in a broader link-level simulation.

Following the approach of Synopsys' COSSAP/CCSS (CoCentric System Studio) [5], the script distinguishes an initialisation phase, during which parameters are read and global variables are initialised, and a processing phase, during which the actual simulation runs.

1. Initialisation phase

At initialisation, the parameters of the set-up (PAS, AoD/AoA, AS, PDP, etc.) are initialised in the *Three_GPP_Cases.m*. This is the script that ought to be updated, should 3GPP agree on new parameter set-ups for link-level simulations. Note that, for the time being, it is compliant with [2], whereas a more recent version [6] had been issued at the time of writing the present document. However, the main differences between [2] and [6] are the value of the Rice factor in Case 2 (changed from 3 to 6 dB) and the mention of additional options. As far as the essence of the scenarios is concerned, there is no major difference between the two releases. Hence, the functionalities embedded in the MATLAB® package to simulate [2] would easily enable to simulate [6] as well.

Since all the geometric information required to derive the spatial correlation properties is available in the *Three_GPP_Cases.m* script, the computation of the spatial correlation matrices at Tx and Rx is performed from that script, by a call to the *correlation.m* script described in the previous section. Its outcome, two spatial correlation matrices, are combined in the main loop through a Kronecker product into matrix $\mathbf{R}$, and a spatial correlation shaping matrix $\mathbf{C}$ is derived from $\mathbf{R}$ by Cholesky or Square-Root Matrix decomposition [8], depending whether one is willing to deal with complex field correlation coefficients or real power ones.

Additionally, a Rice steering matrix is computed from the outer product of the steering vectors defined in Appendix B of [2], which writes as follows

$$\begin{bmatrix} 1 \\ \exp\left\{2j\pi\frac{d_{Rx}}{\lambda}\sin(AoA_{Rx})\right\} \\ \vdots \\ \exp\left\{2j\pi\frac{d_{Rx}}{\lambda}\sin[(n_{Rx}-1)AoA_{Rx}]\right\} \end{bmatrix} \cdot \begin{bmatrix} 1 \\ \exp\left\{2j\pi\frac{d_{Tx}}{\lambda}\sin(AoD_{Tx})\right\} \\ \vdots \\ \exp\left\{2j\pi\frac{d_{Tx}}{\lambda}\sin[(n_{Tx}-1)AoD_{Tx}]\right\} \end{bmatrix}^T \tag{4}$$

where λ is the wavelength, n_{Tx} and d_{Tx} represent respectively the number and the spacing of the antenna elements for the transmit ULA, n_{Rx} and d_{Rx} represent respectively the number and the spacing of the antenna elements for the receive ULA, AoD is the angle of Departure and AoA the angle of Arrival. This steering matrix is to be used later to shape the Rice component of Case 2.

Having initialised the parameters of the set-up, especially the ones related to the fading properties, the script *init_fading.m* is called to generate $n_{Paths}.n_{Tx}.n_{Rx}$ vectors of *FadingNumberOfIterations* fading samples, sampled every $\lambda / 2.FOF.v$ second, where n_{Paths} is the number of delays of the PDP, FOF is the oversampling factor of the fading process and v is the speed. The $n_{Paths}.n_{Tx}.n_{Rx}$ vectors of *FadingNumberOfIterations* independent fading samples are generated by performing the inverse Fourier transform of an oversampled Doppler spectrum whose shape has been defined in the *Three_GPP_Cases.m* script. A random phase is applied to each vector in the frequency domain so as to generate independent fading processes in the time domain from a single, common Doppler pattern. This procedure is explained in full detail in [7, p. 12] and is illustrated in Figure 4.

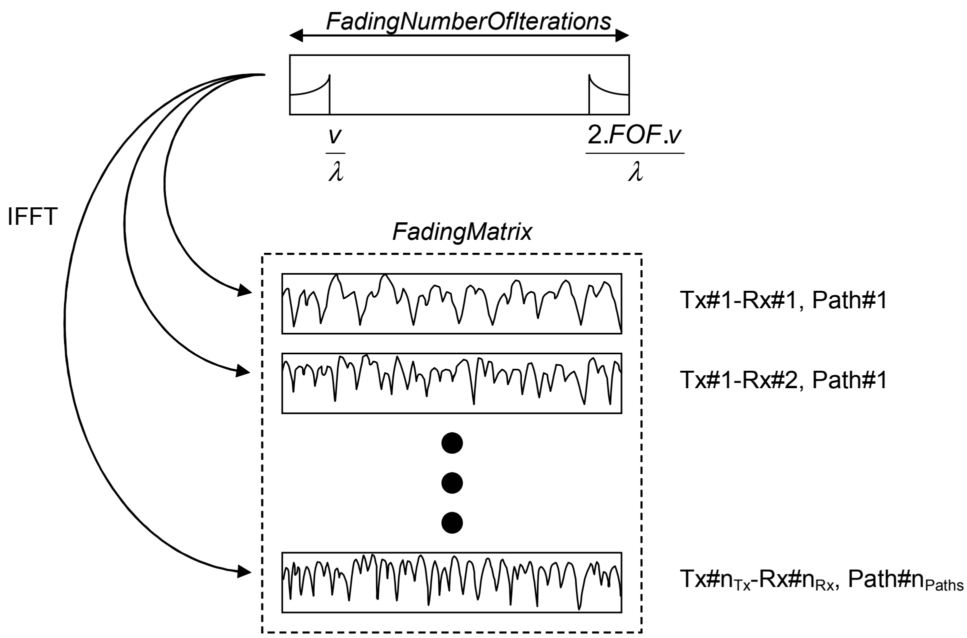

Figure 4: Generation of *FadingMatrix*

These vectors are then gathered into a single matrix, *FadingMatrix*, which is correlated using the spatial correlation shaping matrix **C** derived earlier. The whole philosophy of the process is to provide the main loop with a reference library of correlated fading samples in which the actual tap coefficients to be used during the simulation will be derived by simple linear interpolation. Therefore, one should make sure that these fading vectors span at least a distance of 40λ, such that, when wrapping around, the last samples of the fading vector can be regarded as uncorrelated in the time domain with respect to the first ones.

Finally, the lines of *FadingMatrix*, where each line correspond to a tap coefficient, are scaled according to the PDP and the Rice component is added, if necessary.

2. Processing phase

As a foreword, it should be mentioned that the main loop of the *example_MIMO.m* script has been written having in mind the formalism presented in [9, p. 22]. However, a user willing to use the MATLAB® package for the sole purpose of generating a MIMO radio channel could create his/her own link-level simulations, using the spatially correlated *FadingMatrix* generated at the end of the initialisation phase. In that perspective, the main loop of *example_MIMO.m* is just an example of the way to use this channel generator in the broader scope of a link-level simulation.

Anyway, the main loop of *example_MIMO.m* is designed to process one burst of *NumberOfChipsPerIteration*, possibly oversampled chips per iteration. A global variable keeps track of the running time instant, for book-keeping purposes, but also to enable the simulation of burst transmissions. As it is, the running time instant is incremented by the length of *NumberOfChipsPerIteration* chips at each iteration. This could be easily changed, in order to simulate burst transmissions. The incremental step could then be defined according to a given probability distribution function depending on the corresponding traffic model.

For each iteration, the script *MIMO_channel.m* performs two linear interpolations in the spatially correlated *FadingMatrix*. The first interpolation is applied in the time domain. It consists in collecting (possibly fractionally if oversampling) chip-spaced fading samples in *FadingMatrix*. The second interpolation is performed in the tap domain. It consists in distributing every tap of the PDP on the two closest sampling instants of the simulation, according to the time distance with respect to them, as described in [10, p. 23]. This second interpolation is required by the fact that the PDP is not necessarily sampled at the simulation rate. Figure 5 illustrates these two interpolation processes, in the case of a chip-spaced simulation of the ITU Pedestrian A profile. Note that the weights of the second interpolation are the square-roots of the time differences, in order to preserve the correlation properties.

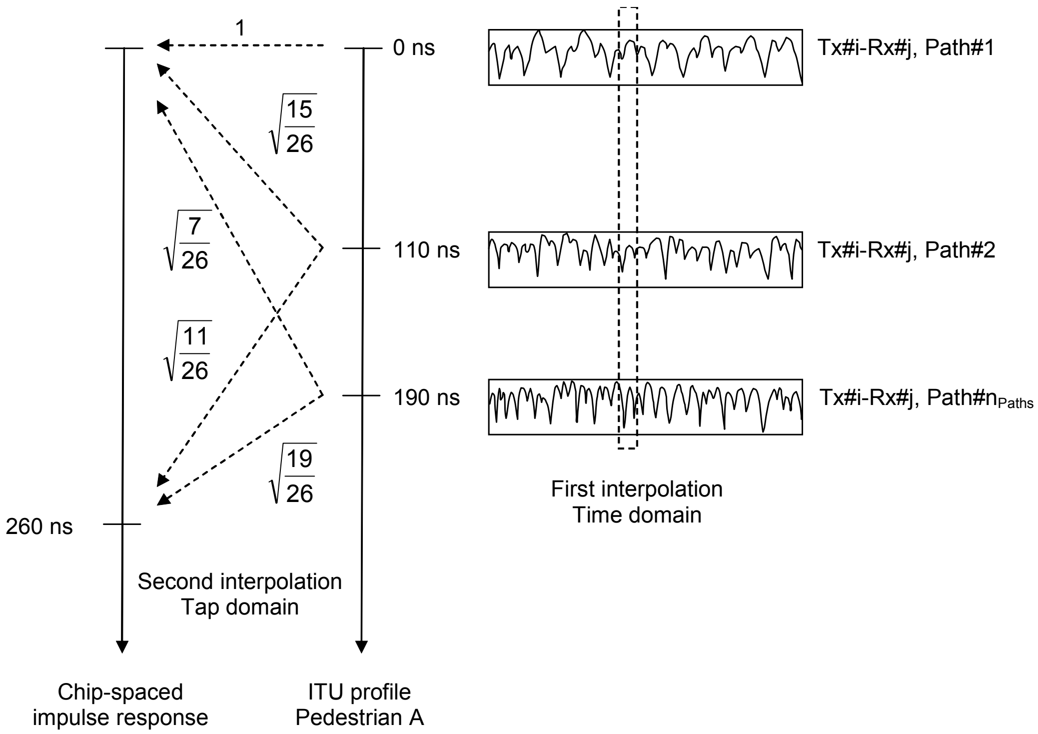

Figure 5: Double interpolation of the correlated fading process in the main loop

The outcome of *MIMO_channel.m* is two matrices containing the same information, namely the MIMO channel to be applied to the current burst. One of these two matrices, the *Channel* variable in *example_MIMO.m*, has a sliding structure compliant with the formalism of [9, p. 22] illustrated in Figure 6. The second matrix, *CorrelatedFading*, has the same row structure than *FadingMatrix*. However, its columns span the simulation sampling space instead of the fading one.

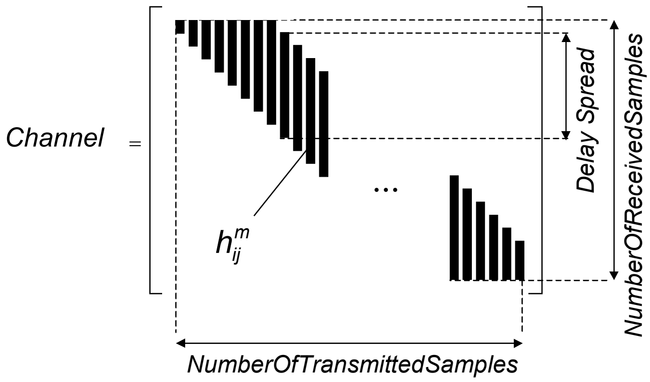

Figure 6: Sliding structure of *Channel*

3. Post-processing phase

As a matter of post-processing, the package contains the script *plot_MIMO.m*. It plots the $n_{Paths}.n_{Tx}.n_{Rx}$ impulse responses generated by *example_MIMO.m*, the $n_{Tx}.n_{Rx}$ PDPs, the n_{Paths} spatial correlation functions and the $n_{Paths}.n_{Tx}.n_{Rx}$ Doppler spectra. Whenever possible (PDP, correlation, Doppler spectrum), the characteristics of the simulated MIMO channel are compared to the desired ones. Note that *plot_MIMO.m* uses a downsampled version of the *CorrelatedFading* matrix mentioned here above.

The following pages present the PDP, the spatial correlation properties and the Doppler spectra of a 2x2 MIMO set-up in 3GPP Cases 2, 3 and 4. Dashed red curves/circles are the original values, blue curves/circles are the simulated ones. The shift of Taps 2 to 4 in the PDP of Case 2 (Figure 7) is due to the additional 3-dB Rice component on Tap 1. Figure 12 shows Doppler spectra of impinging waves constrained within a Laplacian PAS. Finally, note the changing spatial correlation properties of Case 4 in Figure 15, reflecting the changing propagation conditions from one tap to the other.

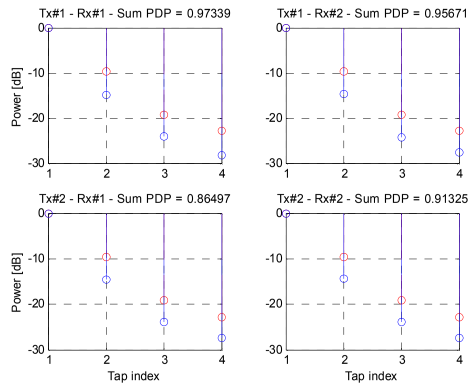

Figure 7: PDP of 3GPP Case 2 (4 taps)

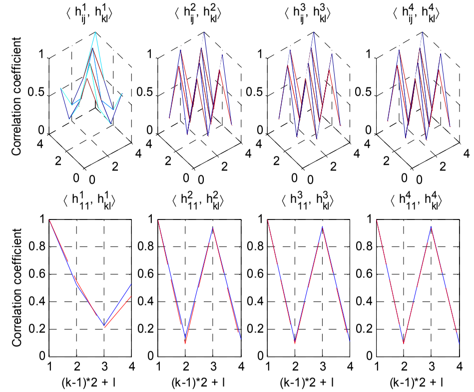

Figure 8: Spatial correlation properties of 3GPP Case2

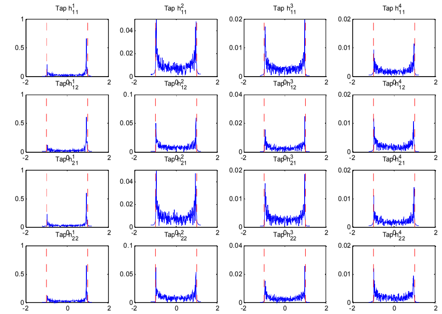

Figure 9: Doppler spectra of the 2*2*4 = 16 taps of a 3GPP 2x2 MIMO channel Case 2

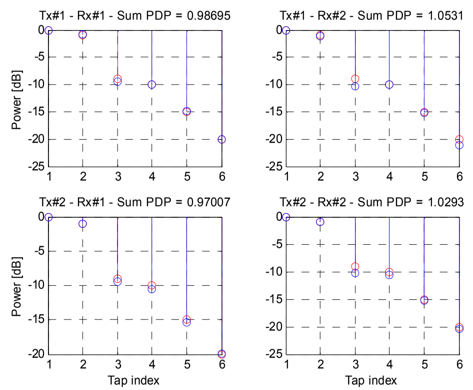

Figure 10: PDP of 3GPP Case 3 (6 taps)

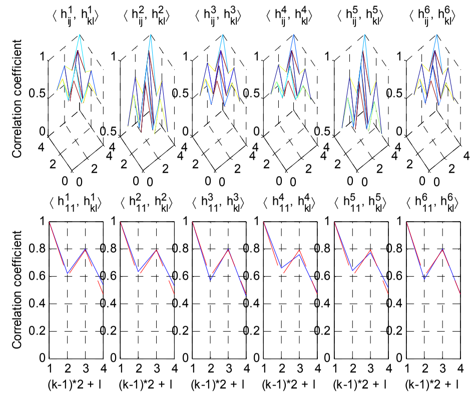

Figure 11: Spatial correlation properties of 3GPP Case 3

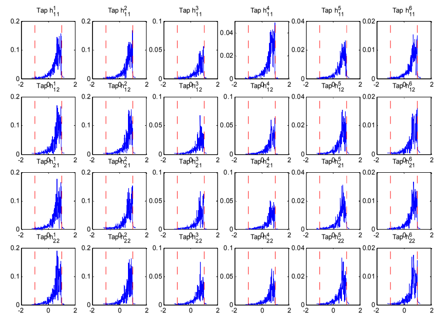

Figure 12: Doppler spectra of the 2*2*6 = 24 taps of a 3GPP 2x2 MIMO channel Case 3

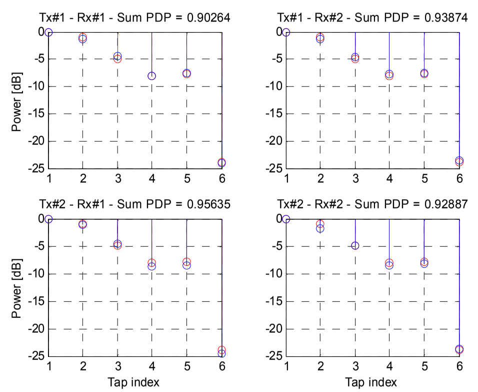

Figure 13: PDP of 3GPP Case 4 (6 taps)

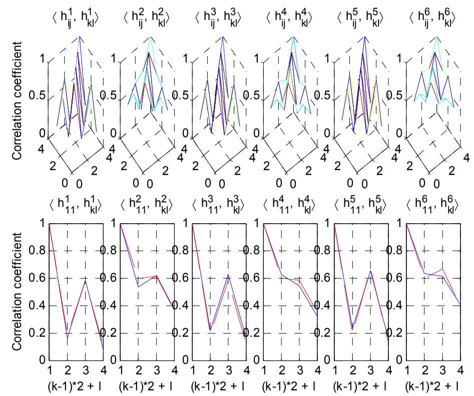

Figure 14: Spatial correlation properties of 3GPP Case 4

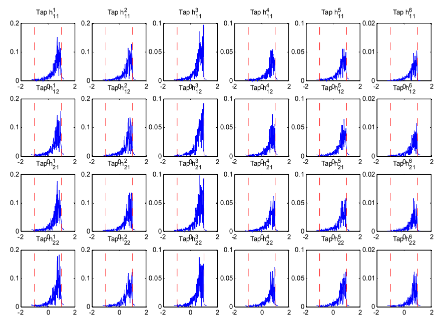

Figure 15: Doppler spectra of the 2*2*6 = 24 taps of a 3GPP 2x2 MIMO channel Case 4

4. Distribution terms

The MATLAB® packages developed by CSys are free of use to any party having approved beforehand and on an individual basis the terms of the following agreement:

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2. The receiving party agrees to acknowledge cooperation with IST project IST-2000-30148 I-METRA [11] in every publication it may produce in the future based on the use of these packages.

3. The receiving party agrees not to distribute the source code to third parties.

4. In order to ensure that any enhancement might benefit to the whole community using the packages, the receiving party agrees to notify CSys of any change and/or improvement of the source code, and to document it.

As soon as the approval of a party on these terms will have been received, the MATLAB® packages will be sent to this party.

5. Conclusion

This document has described the content and the working of two MATLAB® packages, *Correlation_Multiple_Cluster* and *UMTS_Testbed*, aimed at deriving the spatial correlation properties of a MIMO radio channel and at simulating it. These packages have been validated by showing their outcome in the case of the 3GPP cases described in [2]. Finally, the terms of their distribution have been stated.

6. References

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[2] MIMO Rapporteur, 3GPP document R1-02-0141 "MIMO conference call summary", January 2002.

[3] Kermoal J.P., Schumacher L., Pedersen K. and Mogensen P., "A Stochastic MIMO Radio Channel Model with Experimental Validation", *submitted for publication in IEEE Journal on Selected Areas in Communications*, February 2002.

[4] Pedersen K., Andersen J.B., Kermoal J.P. and Mogensen P., "A stochastic multiple-input-multiple-output radio channel model for evaluation of space-time coding algorithms", Proceedings of 52^{nd} IEEE Vehicular Technology Conference VTC 2000 Fall, Boston (USA), September 2000, vol. 2, pp. 893-897.

[5] http://www.synopsys.com

[6] MIMO Rapporteur: 3GPP TSG R1-02-0181, "MIMO discussion summary", January 2002.

[7] Schumacher L., Kermoal J.P., Frederiksen F., Pedersen K.I., Algans A., Mogensen P., "MIMO Channel Characterisation", IST Project IST-1999-11729 METRA Deliverable D2, February 2001.
[8] Golub, G.H. and Van Loan, C.F., "Matrix Computation", The Johns Hopkins University Press, 3rd edition, 1996.
[9] Heikkilä M.J., Majonen K., Fonollosa J.R., Gaspa R., Lagunas M.A., Lamarca M., Mestre X., Palomar D.P., Pérez-Neira A., Tiirola E., Ylitalo J., Dowds M., Lister D., "Review and Selection of Relevant Algorithms", IST Project IST-1999-11729 METRA Deliverable D3.2, June 2000.
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