

A Link-Level MIMO Radio Channel Simulator for Evaluation of Combined Transmit/Receive Diversity Concepts within the METRA project

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Abstract: *This document presents a simple framework for Monte-Carlo simulations of a multiple-input-multiple-output (MIMO) radio channel. A stochastic model including the partial correlation between the paths in the MIMO channel, as well as fast fading and time dispersion is proposed. Its implementation in a COSSAP[®] primitive model is described. Simulations verify the features of this primitive model. However, the stochastic model still needs to be validated by comparison with results of measurement campaigns currently in progress [1,2]. This COSSAP[®] block will later help to investigate combined transmit/receive diversity concepts as part of the European IST (Information Society Technologies) METRA (Multi Element Transmit and Receive Antennas) project [3].*

1. Introduction

The remarkable Shannon capacity gains available from deploying multiple antennas at both the transmitter and receiver of a wireless system, has generated great interest recently [4, 5]. Large capacity is obtained via the potential decorrelation in the multiple-input-multiple-output (MIMO) radio channel, which can be exploited to create many parallel subchannels. However, the potential gain is highly dependent on the multipath richness in the radio channel, since a fully correlated MIMO channel only offers one subchannel, while a completely decorrelated channel offers multiple subchannels depending on the antenna configuration. Today, most simulation studies have been conducted assuming either fully correlated/decorrelated channels, while a partially correlated channel should be expected in practice. The objective of this document is therefore to derive and to implement in COSSAP[®] a realistic MIMO channel model, which is applicable for link level simulations in order to perform evaluation studies of combined transmit/receive diversity concepts under realistic propagation conditions, including channel estimation errors and other algorithmic imperfections. During the last decade, there has been many studies focusing on single-input-multiple-output (SIMO) radio channel models for evaluation of adaptive antennas at the base station [6]. In this study, the goal is to take advantage of the numerous results obtained from studying SIMO channels, and to try to extrapolate these findings into a simple wideband stochastic MIMO channel model to be implemented in a COSSAP[®] primitive model.

2. Stochastic model

Let us consider the set-up pictured in Fig. 1 with M antennas at the base station (BS) and N antennas at the mobile station (MS). The signals at the BS antenna array are denoted $\mathbf{y}(t) = [y_1(t), y_2(t), \dots, y_M(t)]^T$, where $y_m(t)$ is the signal at the m^{th} antenna port and $[\cdot]^T$ denotes

transposition. Similarly, the signals at the MS are the components of the vector $\mathbf{s}(t) = [s_1(t), s_2(t), \dots, s_N(t)]^T$.

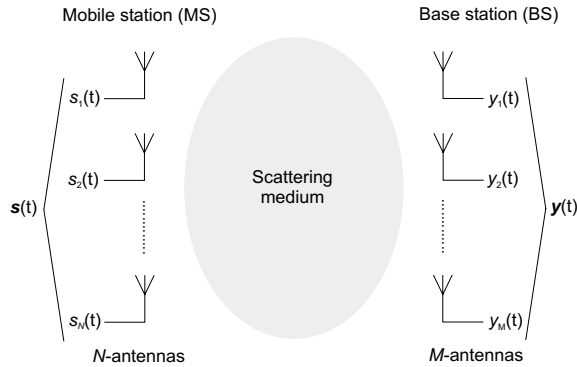


Figure 1: Arrays in a scattering environment

The wideband MIMO radio channel which describes the connection between the MS and the

BS can be expressed as $\mathbf{H}(\tau) = \sum_{l=1}^L \mathbf{A}_l \delta(\tau - \tau_l)$

where $\mathbf{H}(\tau) \in \mathbb{C}^{M \times N}$, $\mathbf{A}_l = [\alpha_{mn}^{(l)}]_{M \times N}$ is a complex matrix which describes the linear transformation between the two considered antenna arrays at delay τ_l and $\alpha_{mn}^{(l)}$ is the complex transmission coefficient from antenna n at the MS to antenna m at the BS.

Notice that this is a simple tapped delay line model, where the channel coefficients at the L delays are represented by matrices. The relation between the vectors $\mathbf{y}(t)$ and $\mathbf{s}(t)$ can thus be expressed as

$$\mathbf{y}(t) = \int \mathbf{H}(\tau) \mathbf{s}(t - \tau) d\tau \quad (1) \quad \text{or} \quad \mathbf{s}(t) = \int \mathbf{H}^T(\tau) \mathbf{y}(t - \tau) d\tau \quad (2)$$

depending on whether the transmission is from MS to BS, or vice versa. The potential gain from applying diversity concepts is strongly dependent on the correlation coefficient between the components of $\mathbf{H}(\tau)$ and thus of \mathbf{A}_l .

The spatial correlation function observed at the BS has been studied extensively in the literature for scenarios where the MS is surrounded by scatterers, while there are no local scatterers in the vicinity of the BS antenna array, i.e. typical urban environment [7-10]. This basically means that the power azimuth spectrum (PAS) observed at the BS is confined to a relatively narrow beamwidth. Consequently, the correlation coefficient between antennas m_1 and m_2 at the BS,

$$\rho_{m_1 m_2}^{BS} = \left\langle \left| \alpha_{m_1 n}^{(l)} \right|^2, \left| \alpha_{m_2 n}^{(l)} \right|^2 \right\rangle \quad (3)$$

is easily obtained from the literature assuming that the BS antenna array is elevated above the local scatterers. Notice from (3) that it is assumed that the spatial correlation function at the BS is independent of n . This is a reasonable assumption provided that all antennas at the MS are closely co-located and have the same radiation pattern, so they illuminate the same surrounding scatterers and therefore also generate the same PAS at the BS, i.e. the same spatial correlation function.

The spatial power correlation function observed at the MS has also been extensively studied in the literature [11,12], among others. Assuming an MS surrounded by local scatterers, antennas separated by more than half a wavelength can be regarded as practically uncorrelated [13], so

$$\rho_{n_1 n_2}^{MS} = \left\langle \left| \alpha_{m n_1}^{(l)} \right|^2, \left| \alpha_{m n_2}^{(l)} \right|^2 \right\rangle \quad (4)$$

nearly equals zero for $n_1 \neq n_2$. However, experimental results reported in [14] show that in some situations antennas separated with half a wavelength might be highly correlated, even in indoor environments. Under such conditions, an approximate expression of the spatial correlation function averaged over all possible azimuth orientations of the MS array is derived in [15]. The latter expression is a function of the azimuth dispersion $\Lambda \in [0;1]$, where $\Lambda = 0$ corresponds to a scenario where the power is coming from one distinct direction only, while $\Lambda = 1$ when the PAS is uniformly distributed over the azimuthal range $[0^\circ; 360^\circ]$ [16]. As the MS is typically non-stationary, the results presented in [15] are very useful since they are averaged over all orientations of the MS array.

Given (3) and (4), let us define the symmetrical correlation matrices $\mathbf{R}_{BS} = \left[\rho_{pq}^{BS} \right]_{M \times M}$ and $\mathbf{R}_{MS} = \left[\rho_{pq}^{MS} \right]_{N \times N}$ for later use. The spatial correlation function at the BS and at the MS does not provide sufficient information to generate the matrices \mathbf{A}_l . The correlation of two transmission coefficients connecting two different sets of antennas also needs to be determined, i.e.

$$\rho_{n_2 m_2}^{n_1 m_1} = \left\langle \left| \alpha_{m_1 n_1}^{(l)} \right|^2, \left| \alpha_{m_2 n_2}^{(l)} \right|^2 \right\rangle \quad (5)$$

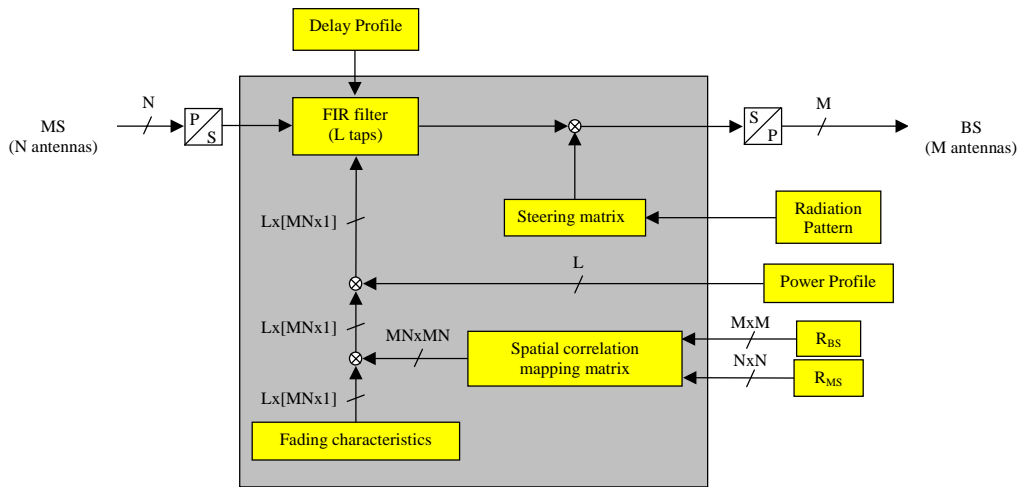
$$\cong \rho_{n_1 n_2}^{MS} \rho_{m_1 m_2}^{BS} \quad (6)$$

Neither a theoretical expression for (5) nor experimental results have been published according to the authors' knowledge. An approximation of (5) is therefore proposed in (6). This approximation is motivated by [17], where it was found that the correlation between two spatially separated antennas with different polarisations is given by the product of the spatial and polarisation correlation coefficients. Relation (6) can be shown to be exact using definitions (3) and (4) and assuming that the average power of the transmission coefficients is identical for a given delay, so $P_l = E \left\{ \left| \alpha_{mn}^{(l)} \right|^2 \right\}$ for all $n \in [1, 2, \dots, N]$ and $m \in [1, 2, \dots, M]$.

3. Simulation of the MIMO channel

3.1. General description

The proposed stochastic model is implemented in a COSSAP[®] primitive model called MIMO_CHANNEL whose functional sketch is shown in Fig. 2. It is a complex single-input single-output (SISO) Finite Impulse Response (FIR) filter whose taps are computed so as to simulate time dispersion, fading and spatial correlation. To simulate MIMO radio channels, it has to be preceded by a parallel-to-serial (P/S) converter with turns the N signals transmitted from the MS into a single complex signal. Similarly, at the output side, the complex signal is serial-to-parallel (S/P) converted into M signals impinging the BS. On the other hand, its FIR structure enables the user willing to shape the envelope of the impulse response either to define a synthetic power delay profile, or to use profiles recorded during measurement campaigns. In the former case, the attenuation and the delay with respect to the first tap are given for each tap in external files read at the initialisation step of the block. In the latter case, sampled profiles would be fed directly to the FIR filter. However, this functionality has not been implemented yet. A steering matrix is also applied to take into account Direction of Arrival (DoA).



COSSAP PRIMITIVE MODEL
Parameters: M, N, L, Max_L, Sampling_Frequency_Hz, Velocity_kmh,
Carrier_Frequency_Hz, IFFT_Length, Doppler_Oversampling,
Doppler_Spectrum_Type, Mean_DoA_BS_deg, Element_Spacing_BS_m,
Step_gai_deg, Random_Seed

Figure 2: Functional sketch of COSSAP[®] primitive model MIMO_CHANNEL

3.2. Fast fading

Following the approach in [18], the correlated transmission coefficients can be obtained according to $\tilde{\mathbf{A}}_l = \sqrt{P_l} \mathbf{C} \mathbf{a}_l$ where $\tilde{\mathbf{A}}_l = [\alpha_{11}^{(l)} \alpha_{21}^{(l)} \dots \alpha_{M1}^{(l)} \alpha_{12}^{(l)} \alpha_{22}^{(l)} \dots \alpha_{MN}^{(l)}]_{MN \times 1}^T$, $\mathbf{C} \in \mathbb{C}^{MN \times MN}$ is a symmetrical mapping matrix defining the spatial correlation and $\mathbf{a}_l = [a_1^{(l)} a_2^{(l)} \dots a_{MN}^{(l)}]_{MN \times 1}^T$ with $a_x^{(l)}$ defined as random processes. The fading characteristics of the taps $\alpha_{mn}^{(l)}$ are defined by shaping an oversampled Doppler spectrum in the spatial frequency domain. The inverse Fourier transform of this Doppler spectrum defines the complex random fading coefficients $a_x^{(l)}$ in the spatial domain. Then, it is a simple operation to convert them into the time domain, by taking into account the speed of the mobile.

3.3. Spatial correlation

The symmetrical mapping matrix \mathbf{C} results in a correlation matrix $\mathbf{\Gamma} = \mathbf{C} \mathbf{C}^T$ where the $(x, y)^{th}$ element of $\mathbf{\Gamma}$ is the root power correlation coefficient $\sqrt{\rho_{n_2 m_2}^{n_1 m_1}}$ between the x^{th} and y^{th} element of $\tilde{\mathbf{A}}_l$. These coefficients are computed according to (6) from the symmetrical correlation matrices \mathbf{R}_{BS} and \mathbf{R}_{MS} fed through external files. The symmetrical mapping matrix \mathbf{C} is easily obtained by applying square root matrix decomposition [19], provided that $\mathbf{\Gamma}$ is non-singular.

3.4. Steering matrix

The proposed stochastic model only reproduces the correlation metrics and fast fading characteristics of the radio channel, while the phase derivative across the antenna arrays is not necessarily reflected correctly in the model. The current model gives rise to a mean phase variation of 0° across the antenna array. This basically means that the mean direction-of-arrival (DoA) of the impinging field correspond to broadside. However, the stochastic model is easily modified to comply with scenarios like the one pictured in Fig. 3, where the mean DoA at the BS $\bar{\varphi}_{BS} \neq 0^\circ$.

(1) is then modified to (7) where the steering diagonal matrix is expressed as (8) with $w_m(\varphi)$ describing the average phase shift relative to antenna number one assuming that the mean azimuth DoA of the impinging field equals φ . Thus, for an uniform linear antenna array with

element spacing d , $w_m(\varphi) = f_m(\varphi) \exp[-j(m-1)d\lambda^{-1}2\pi \sin(\varphi)]$ where $f_m(\varphi)$ is the complex radiation pattern of antenna m , λ is the wavelength, and j is the imaginary unit. In situations where the antenna signals at the array are assumed statistically independent (uncorrelated), it does not make sense to define a mean DoA, so (1) is applicable without the modification proposed in (7).

3.5. Validation

Tests have been performed in order to check the consistency of the COSSAP[®] primitive model with respect to the phenomena it simulates. Spatial correlation results are presented in Fig. 4, which shows

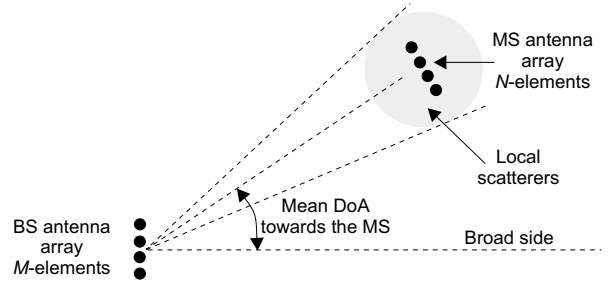


Figure 3: Sketch of a scenario where all scatterers are located near the MS so the impinging field at the BS is confined to a narrow azimuth region with a well defined mean DoA

$$y(t) = \mathbf{W}(\bar{\varphi}_{BS}) \int \mathbf{H}(\tau) \mathbf{s}(t - \tau) d\tau \quad (7)$$

$$\mathbf{W}(\varphi) = \begin{bmatrix} w_1(\varphi) & 0 & \dots & 0 \\ 0 & w_2(\varphi) & \dots & 0 \\ \vdots & \vdots & \ddots & \dots \\ 0 & 0 & \dots & w_M(\varphi) \end{bmatrix}_{M \times M} \quad (8)$$

the correlation between the 16 possible pairs of received signals in a 2×4 scenario, using white gaussian noise sources at the transmitting end. Correlations are compared in a completely uncorrelated case ($\mathbf{R}_{BS} = \mathbf{R}_{MS} = \mathbf{I}$), in a fully correlated case ($\mathbf{R}_{BS}(p,q) = \mathbf{R}_{MS}(p,q) = 1 \forall p,q$) and in a partially correlated situation where \mathbf{R}_{BS} and \mathbf{R}_{MS} are worth respectively:

$$\mathbf{R}_{BS} = \begin{bmatrix} 1 & 0,7 & 0,4 & 0,1 \\ 0,7 & 1 & 0,7 & 0,4 \\ 0,4 & 0,7 & 1 & 0,7 \\ 0,1 & 0,4 & 0,7 & 1 \end{bmatrix} \quad (21); \quad \mathbf{R}_{MS} = \begin{bmatrix} 1 & 0,3 \\ 0,3 & 1 \end{bmatrix} \quad (22)$$

As expected, the cross-correlation functions exhibit non-zero values in the correlated cases, whereas they are close to zero in the uncorrelated case. It is also interesting to notice that in the partly correlated case, the value of the cross-correlation peak does reflect the correlation degree of the BS antennas as set through \mathbf{R}_{BS} . Notice in that respect the decrease of the peak of the cross-correlation for BS₁, corresponding to the decrease of $\mathbf{R}_{BS}(1,m)$ for increasing m . Similar remarks can be made for the three other BS antennas.

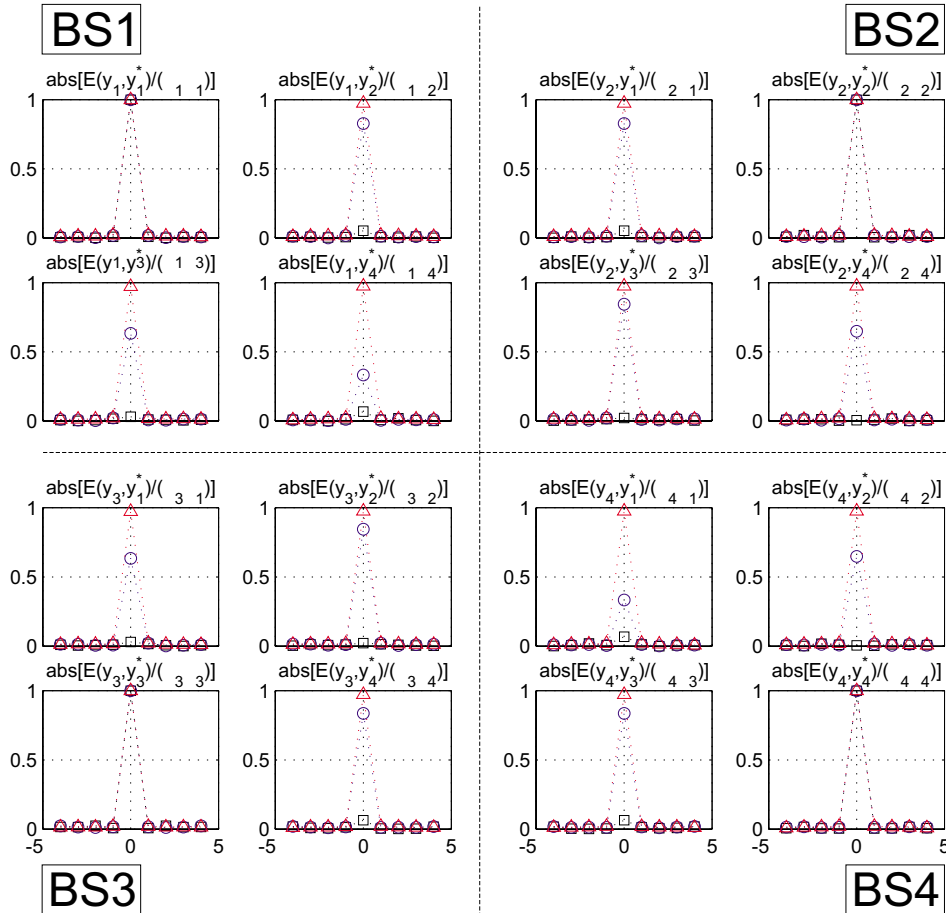


Figure 4: Magnitude of the correlation function of the signals received at the BS, 2×4 scenario. Square markers: uncorrelated; circular markers: partly correlated; triangular markers: fully correlated.

4. Concluding Remarks

It is believed that the proposed MIMO channel model and its corresponding COSSAP[®] implementation provide a simple framework for simulation of such channels. The model is designed so that the required parameters are accessible in the open literature for various types of environments. Thus, existing wideband tapped delay line SISO channel models are easily extended to include

MIMO. However, the assumption stated in (6) still need to be verified in order to determine whether the knowledge of \mathbf{R}_{BS} and \mathbf{R}_{MS} are sufficient to simulate the channel, or whether $\mathbf{\Gamma}$ is required.

5. Future work

Future versions of MIMO_CHANNEL will lift up its current limitations. The first one is related to the hypotheses leading to relations (3) and (6), namely that all antennas at the MS are closely co-located and have the same radiation pattern on the one hand, and that the average power of the transmission coefficients is identical for a given delay on the other hand. Another limitation is to be circumvented. As is, the model does not address some cases of polarisation diversity, where cross-polarisation is experienced. Improved support of polarisation diversity is thus an item for future work. Besides these issues, the following improvements will be included in later versions of the primitive model:

- Upload of user-defined sampled impulse responses instead of using only simulated ones
- Application of a steering matrix also at the transmitting end in order to apply beamforming
- Definition of spatial correlation on basis of Doppler spectra in a similar way to the fading
- Interface with network-level simulators

6. References

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