Hindawi Publishing Corporation
EURASIP Journal on Wireless Communications and Networking
Volume 2007, Article ID 68512, 7 pages
doi:10.1155/2007/68512

Research Article

Modified Spatial Channel Model for MIMO Wireless Systems

Lorenzo Mucchi,[1] Claudia Staderini,[1] Juha Ylitalo,[2] and Pekka Kyösti[3]

[1] *CNIT, University of Florence, via santa marta 3, 50139 Florence, Italy*
[2] *Centre for Wireless Communications, University of Oulu, 90014 Oulu, Finland*
[3] *Elektrobit, 90570 Oulu, Finland*

Received 13 June 2007; Revised 19 September 2007; Accepted 11 November 2007

Recommended by G. K. Karagiannidis

The third generation partnership Project's (3GPP) spatial channel model (SCM) is a stochastic channel model for MIMO systems. Due to fixed subpath power levels and angular directions, the SCM model does not show the degree of variation which is encountered in real channels. In this paper, we propose a modified SCM model which has random subpath powers and directions and still produces Laplace shape angular power spectrum. Simulation results on outage MIMO capacity with basic and modified SCM models show that the modified SCM model gives constantly smaller capacity values. Accordingly, it seems that the basic SCM gives too small correlation between MIMO antennas. Moreover, the variance in capacity values is larger using the proposed SCM model. Simulation results were supported by the outage capacity results from a measurement campaign conducted in the city centre of Oulu, Finland.

1. INTRODUCTION

Future wireless communication aims at higher data rates. Since the radio spectrum is limited, the requirement of high spectrum efficiency can be fulfilled by exploiting the spatial dimension of the radio channel [1]. In sufficiently rich multipath environments, the channel capacity can be significantly increased by using multiple antennas at both the transmitter and the receiver sides of the link. Multiple-input multiple-output (MIMO) technique brings a relevant increase not only in capacity but also in coverage, reliability, and spectral efficiency. In MIMO case, the overall transmit channel is described as a matrix instead of a vector, and the spatial correlation properties of the channel matrix define the number of available parallel channels for data transmission [2, 3]. Depending on the channel gains of the parallel channels, the MIMO channel can have much higher channel capacity compared to a single-input single-output (SISO) channel in the same frequency range and with the same total transmit power.

The performance of such a system is largely determined by the MIMO channel characteristics, so it is critical to create channel models that accurately reflect realistic behavior.

In this paper, the spatial channel model proposed by the Third Generation Partnership Project (3GPP) [4, 5] is investigated and compared to a modified SCM model, which was derived in this study. Comparison is based on simulated and measured outage capacity. This study was motivated by the fact that the basic SCM model has fixed signal path directions and powers within a resolvable delay tap which is expected to over-simplify the MIMO channel model and thus affect the simulation results. Since it is important that a MIMO channel model is a realistic representation of real radio channels we compared the simulated results also to results obtained from measured MIMO radio channels. Measurements campaign was carried out in an urban environment.

The rest of the paper is organized as follow: the system model is described in Section 2, spatial channel modeling is presented in Section 3, simulation and measurement results are given in Sections 4 and 5, respectively, and finally, conclusions are summarized in Section 6.

2. SYSTEM MODEL

Consider a spatial multiplexing MIMO system with N_T transmit antennas and N_R receive antennas. At each time instant n, the system model can be expressed as

$$y(n) = \mathbf{H}(n)x(n) + \eta(n), \qquad (1)$$

Table 1: Table of measurements settings.

Propsound property	Setting
Center frequency	253 GHz
Transmit power	+23 dBm
Chip rate	100 Mchips/s
Code length	511 chips
Number of TX antenna elements	11
Number of RX antenna elements	32
Number of channels	352
Mobile speed	20 km/h

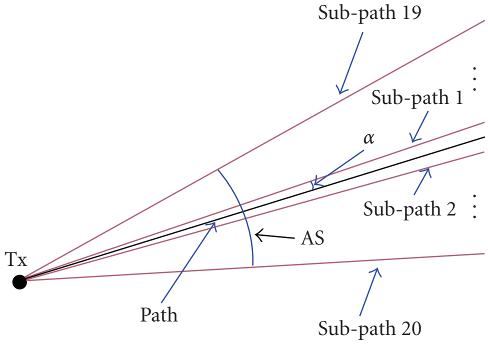

Figure 1: Angular spread model for a nominal path.

where $\mathbf{H}(n)$ is the $N_R \times N_T$ Rayleigh flat fading channel matrix given by

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{1,2} & \dots & h_{1,N_T} \\ h_{2,1} & h_{2,2} & \dots & h_{2,N_T} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_R,1} & h_{N_R,2} & \dots & h_{N_R,N_T} \end{bmatrix}, \tag{2}$$

where $h_{i,j}$ defines the channel gain from transmit antenna i and receive antenna j; symbols

$$x(n) = [x_1(n), \dots, x_{N_T}(n)]^T \tag{3}$$

($[*]^T$ stands for transpose), taken from a modulation constellation $A = [a_1, \dots, a_N]$, are transmitted from each antenna; $\eta(n)$ is $N_R \times 1$ zero mean complex circularly symmetric Gaussian noise.

Defining with N_T the number of the elements at the transmit array and with N_R the number of the elements at the receive array, the instantaneous capacity (in bps/Hz) under a transmit power constraint and assumption that there is perfect channel state information (CSI) at RX, while there is no channel state information at the TX, is given by

$$C = \log\left[\det\left(I_{N_R} + \frac{\gamma}{N_T}(\mathbf{H}\mathbf{H}^H)\right)\right], \tag{4}$$

where I_{N_R} is the identity $N_R \times N_R$ matrix, γ is the signal to noise ratio at the receiver, $\mathbf{H}$ is the channel matrix, and $\mathbf{H}^H$ is the Hermitian (conjugate transpose) of $\mathbf{H}$.

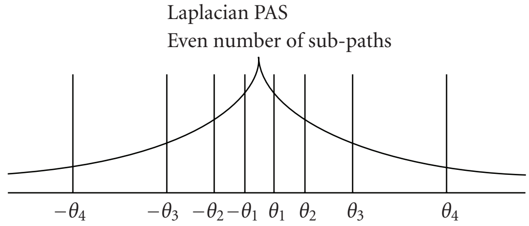

Figure 2: Subpaths distribution with equal power.

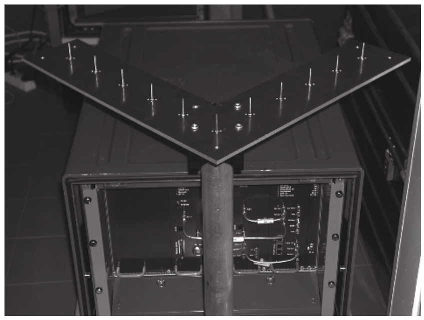

Figure 3: Transmitting antenna array.

In practice, the cumulative distribution function (CDF) of outage capacity is often used [6]; it is defined as the threshold below which the system capacity will be with a given outage probability P_{out}:

$$P_{\text{out}}(C_{\text{th}}) = \Pr[C \leq C_{\text{th}}], \tag{5}$$

where C_{th} is the threshold capacity and C is the capacity.

It is evident that the smaller is the spatial correlation between antennas the larger is the MIMO capacity. The spatial correlation is dictated by the angular spread of the propagation paths at the transmitter and the receiver. Root mean square (RMS) angular spread (AS) is given by

$$\phi_{\text{RMS}} = \sqrt{\frac{\sum_{k=1}^{K}(\phi_k)^2 P_A(\phi_k)}{\sum_{k=1}^{K} P_A(\phi_k)} - (\phi_M)^2}, \tag{6}$$

where ϕ_k is the kth azimuth AoA and $P_A(\phi)$ is the power azimuth spectrum (PAS) and ϕ_M is the mean azimuth given by [7]

$$\phi_M = \frac{\sum_{k=1}^{K}(\phi_k) P_A(\phi_k)}{\sum_{k=1}^{K} P_A(\phi_k)}. \tag{7}$$

The power azimuth spectra at TX and RX are related to the spatial correlation matrices of the MIMO radio channel at the TX and RX, respectively. Accordingly, the PAS can be calculated using the Fourier beamforming [8]:

$$P_A(\phi) = \mathbf{a}(\phi)^H \mathbf{R} \mathbf{a}(\phi), \tag{8}$$

where $\mathbf{R}$ denotes the corresponding spatial correlation matrices, ϕ scans the angular aperture, and $\mathbf{a}(\phi)$ represents the

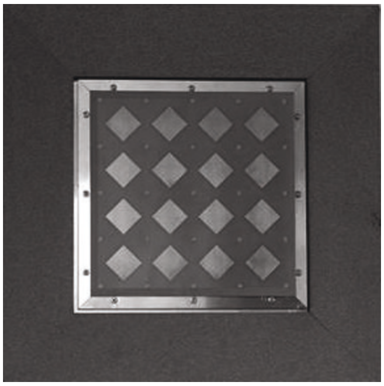

FIGURE 4: Receiving antenna array.

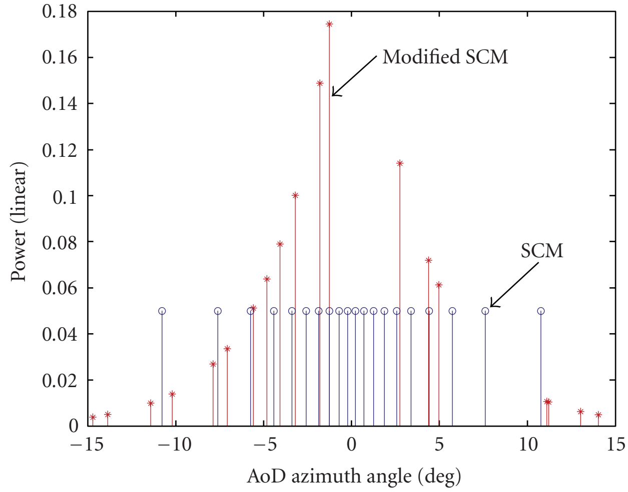

FIGURE 5: Laplacian PAS with 5 degrees RMS AS with basic and modified SCM.

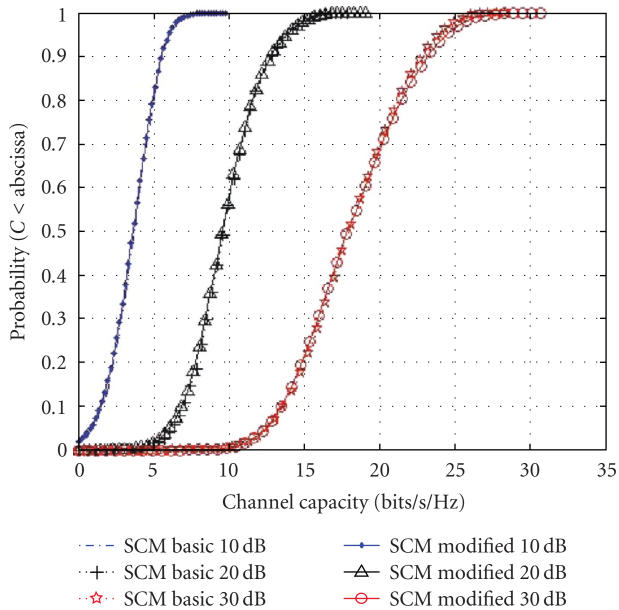

FIGURE 6: Simulated outage capacity; RMS = 8 degrees

normalized steering vector of either the TX array or the RX array and is expressed as

$$\mathbf{a}(\phi) = \left[1, e^{-j2\pi d\sin(\phi)/\lambda}, e^{-j4\pi d\sin(\phi)/\lambda}, \ldots, e^{-j\pi(L-1)d\sin(\phi)/\lambda}\right]^T, \quad (9)$$

where λ is the wavelength, $d = \lambda/2$ and T denotes the transpose. Equation (9) is valid only for uniform linear array. The spatial correlation matrix at the RX side is given by

$$\mathbf{R}_{\text{RX}} = \begin{bmatrix} \rho_{1,1} & \rho_{1,2} & \cdots & \rho_{1,N_R} \\ \rho_{2,1} & \rho_{2,2} & \cdots & \rho_{2,N_R} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{N_R,1} & \rho_{N_R,2} & \cdots & \rho_{N_R,N_R} \end{bmatrix}, \quad (10)$$

where $\rho_{i_1,i_2}^{\text{RX}}$ is the complex correlation coefficient at the RX between antennas i_1 and i_2 given by

$$\rho_{i_1,i_2} = \frac{E\{h_{i_1,j}h_{i_2^*,j}\}}{\sqrt{E\{|h_{i_1,j}|^2|h_{i_2,j}|^2\}}}. \quad (11)$$

It is worth to note that the PAS can be calculated by using (8) which involves a relation between PAS and the spatial correlation matrix **R**, while in the 3GPP SCM model the PAS is given and not calculated. Moreover, the procedure of estimating RMS AS, PAS, and **R**, shown above for RX side (AoA), is analogous for TX side (and AoD).

3. SPATIAL CHANNEL MODELLING

The 3GPP SCM model is serving as the basis for evaluation of MIMO performance of candidate MIMO concepts for UMTS [4]. In the following we first introduce the 3GPP SCM model and then propose a modification of it.

3.1. 3GPP SCM

The 3GPP spatial channel model has been defined for CDMA systems with 5 MHz bandwidth and 2 GHz center frequency. The procedure for obtaining the channel coefficients matrix is described in [4]. Each of the N received paths has M subpaths (cluster). In 3GPP SCM model, each resolvable path is characterized by its own spatial channel parameters: angular spread (AS), angle of departure (AoD), angle of arrival (AoA), and power azimuth spectrum (PAS). The array topology at the BS is, for example, a typical 3-sector antenna patterns. The half-power beam width is 70 degrees and the antenna gain is 14 dB. The receiving antenna element radiation pattern is, for example, omnidirectional with antenna gain equal to −1 dB. The resolvable paths amplitudes are modeled as Rayleigh distributed variables. This implies a correlation between consecutive elements of the array that can be modeled with the well-known Jakes model [9]. Several measurements show that in an urban environment, the AS could be relatively narrow, thus implying a higher correlation between the array elements. In order to take into

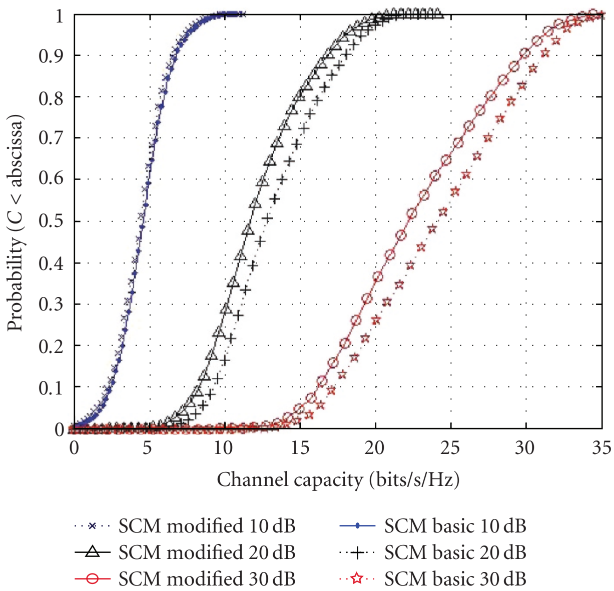

Figure 7: Simulated outage capacity; RMS = 15 degrees

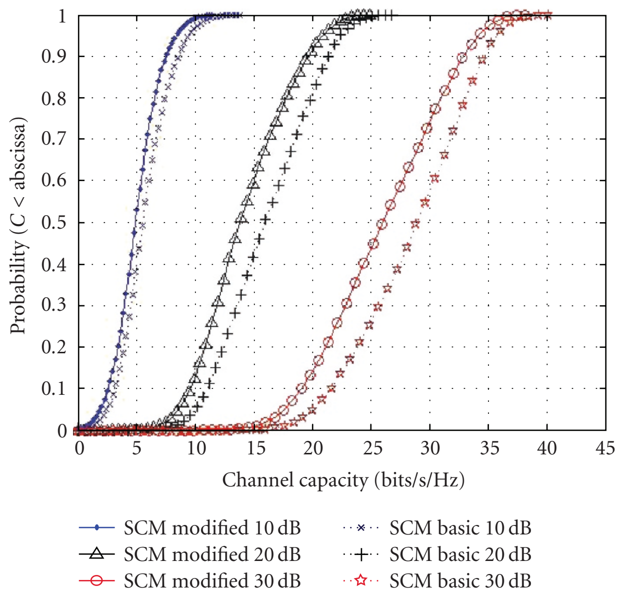

Figure 8: Simulated outage capacity; RMS = 24 degrees

account this effect, the 3GPP associates 20 subpaths to each path (Figure 1) to model the AS through their AoA and AoD at the mobile station and the base station, respectively. The subpaths are symmetrically placed about the nominal path direction. It is important to emphasize that the 20 angular values of the subpaths offsets are fixed (see [4]) and that all the subpaths have identical powers equal to $P/20$, where P is the power associated to the main path. The resulting power azimuth spectrum (PAS) follows the shape of Laplacian distribution (Figure 2) with a certain variance, which varies according to the chosen environment: urban macrocell, urban microcell, suburban macrocell. It is expected that due to fixed subpath directions and powers, the model does not bring all the variability which is present in real radio channels. Moreover, equally strong subpaths may require large angular separation in order to obtain eligible AS. This reduces the correlation between MIMO antennas and thus over-estimates the MIMO capacity.

3.2. Modified SCM model

As discussed above, the 3GPP SCM may not reproduce the dynamic nature of a real MIMO channel due to its static modeling of the subpaths. In order to achieve a better match with the measured channels from the capacity point of view, a slightly different modeling of the spatial properties is proposed in this paper. We propose to choose the 20 azimuth angle values of the subpaths at the BS randomly from a uniform angular distribution in the interval $(-15, +15)$ degrees around the received path delay position and to assign the relative power values from a Laplace function:

$$P(\phi) = \frac{1}{\sqrt{2}\sigma}\exp\left(\frac{-\sqrt{2}|\phi|}{\sigma}\right), \tag{12}$$

where σ is the standard deviation of the Laplacian distribution and ϕ are the azimuth values chosen according to

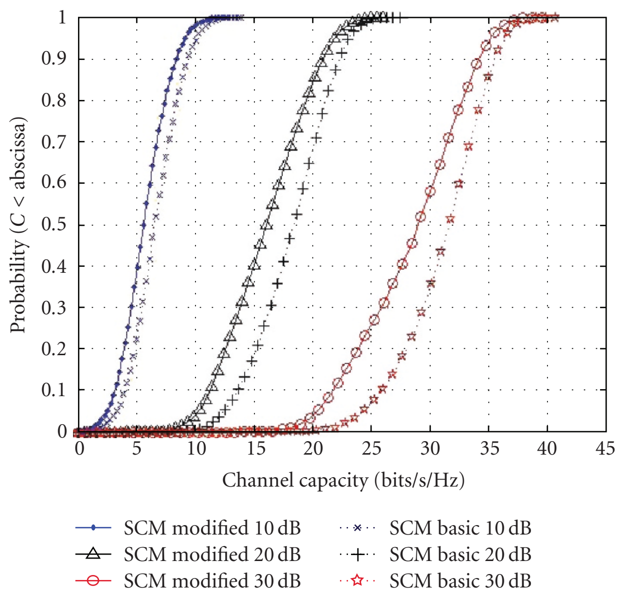

Figure 9: Simulated outage capacity; RMS = 40 degrees.

the uniform distribution. The resultant PAS distribution is Laplacian. At the MS, the 20 azimuth values of the subpaths were randomly chosen from uniform distribution, and the relative power values were assigned according to a uniform distribution. As a result, the PAS distribution is uniform.

Figure 5 compares the generation of Laplacian PAS, both in 3GPP SCM method with fixed subpath angles and in the modified SCM method with random subpath angles. In the modified SCM case, one possible realization of angles and powers is depicted. In the basic SCM, angles and powers always remain unchanged and the specific angular positions of the subpaths define Laplacian PAS.

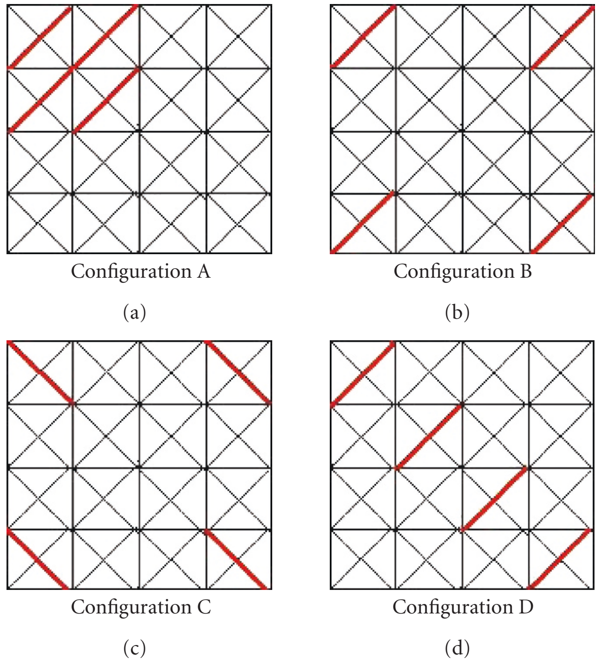

FIGURE 10: Chosen combinations of RX antenna elements. Four antenna elements can be chosen out of 16 dual-polarized (±45 degrees) antenna elements.

4. SIMULATION RESULTS

Simulations of outage capacity were run using both the 3GPP SCM model and the modified SCM for a 4×4 MIMO case. In each case of comparison, the RMS angular spreads of the basic and modified SCM models were set to be equal. Thus, at least two channel parameters are the same, namely, the angular spread and the delay spread properties (flat fading case). At the BS, four different RMS AS values were considered: 8, 15, 24, and 40, while at the MS, the RMS AS was set to 35. An urban macrocell environment was supposed with the mobile station having a speed equal to 20 km/h and the antenna spacing equal to $0.5\,\lambda$ for both the BS and the MS.

One simulation run includes 10 000 links, which corresponds to 10 000 independent MIMO channel samples (drops in 3GPP terminology). The results for SNR values of 10 dB, 20 dB, and 30 dB, and for RMS AS value varied between 8 and 40 degrees are drawn in Figures 6–9. The comparison between the 3GPP SCM and the modified SCM case shows that the modified SCM gives systematically smaller outage capacity values. The difference is becoming more significant as the angular spread is increasing. This obviously demonstrates the fact that the 3GPP SCM model has a static nature to bring relatively small spatial correlation values between MIMO antennas. Furthermore, it does not cover the extreme channel states in which the propagation paths (subpaths) are heavily concentrated in the nominal path direction.

5. MEASUREMENTS RESULTS

The measurement campaign was held in the city of Oulu, Finland, in July 2005. Propsound radio channel sounder (the block diagram and all the details can be found in [10]) has been used in the field measurements. The sounder has been designed so that it suits very well to realistic radio channel measurements both in time and spatial domains. This sounder is based on time division multiplexed (TDM) switching of transmit and receive antennas. Thus, sequential radio channel measurements between all possible transmit (TX) and receive (RX) antenna pairs is achieved.

The setup consists of a BS RX antenna equipped with a 16-element dual polarized planar array (Figure 3) and an MS TX antenna with an L-shaped 11-element array composed of two uniform linear arrays (ULA) of vertically polarized monopoles (Figure 4).

The results shown in this paper are related to the urban macrocell case: the base station RX antenna height was 32 m and it was few meters above the average rooftop level. The mobile station was car-mounted and moved at street level with a speed of 20 km/h, and the mobile TX antenna height was 2 m.

The sounding signal consists of chip sequences of typical spread spectrum signals, maximum length sequences (M-sequences); measurements were carried out with a code length of 511, a chip rate of 100 Mchip/s, and a carrier frequency of 2.53 GHz (Table 1). The transmit power was 26 dBm.

Since the measured MIMO channel matrices include the path loss, a proper normalization is required; the normalization factor is given by

$$F=\left(\frac{1}{N_T N_R}\sum_{i=1}^{N_T}\sum_{j=1}^{N_R}\left|h_{i,j}\right|^2\right)^{-1}, \tag{13}$$

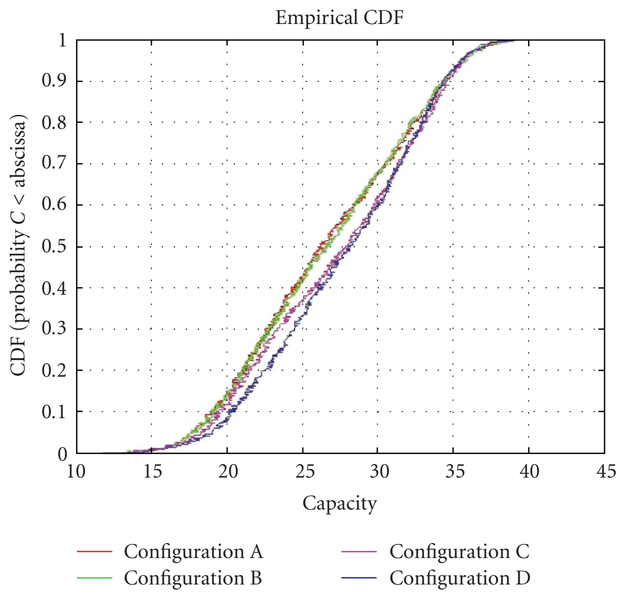

FIGURE 11: CDF curves of MIMO capacity (measured data) with different antenna configurations as in Figure 10.

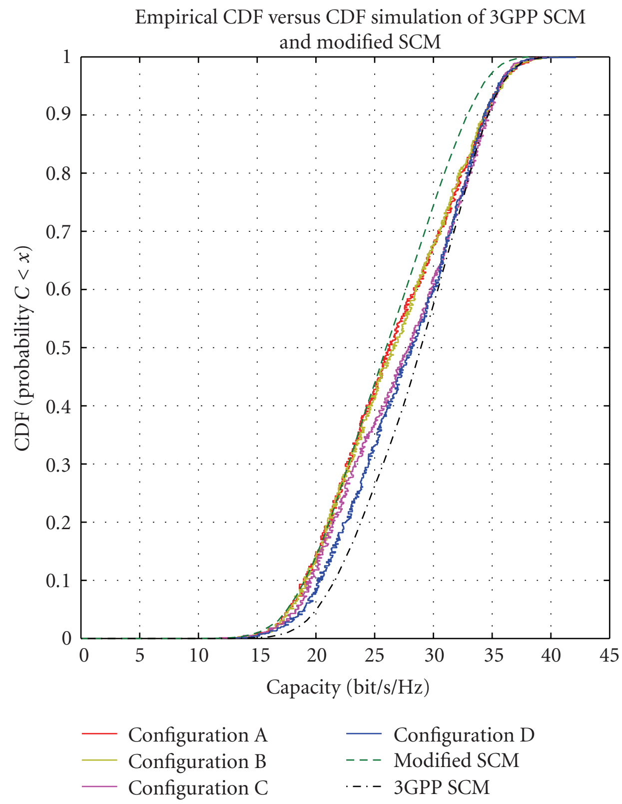

FIGURE 12: CDF curves of MIMO capacity: measured data (full lines) versus 3GPP SCM (dash-dotted line) and modified SCM (dashed line).

where N_T is the number of transmitting antennas, N_R is the number of receiving antennas, and $h_{i,j}$ is the element of the channel matrix **H** defining the channel impulse response between antennas i and j.

5.1. Data postprocessing

The reasonable threshold for the multipath noise floor must be defined to avoid the effects of noise on the results. If the threshold was set too low, it would result in too large outage capacity values. The noise threshold is calculated as

$$T = m + 2\frac{1}{P}\sqrt{\sum_{p=1}^{P}\left(\left|h_p\right| - m\right)^2}, \qquad (14)$$

where P extends typically from the 1st delay position to the 50th delay position of the signal impulse response and m is the mean value of $|h_P|$. Evaluating the measured impulse response, we saw that the first 50 delay positions of the impulse response do not usually have the signal, and therefore it represents well the spurious noise interval after the correlation. The number of the effective delay positions is then the number of the delay positions above the noise threshold.

In order to obtain a 5 MHz bandwidth to study the narrow band case, 20 delay positions were combined to 1 because the aimed bandwidth was equivalent to 1/20 of the original one.

The size of the measured channel matrices is $32 \times 11 \times n_t \times n_c$, where n_t is the number of delay positions and n_c is the number of channel samples (cycles). In order to calculate the capacity for a 4×4 system, several combinations of 4 elements at the receiver array (Figure 10) were chosen to have more statistic, while at the transmitter, a combination of 4 elements was fixed (antenna shape can be seen in Figure 3; the chosen active elements are then 1, 4, 8, and 11, from the left). It was noted that the RMS angular spread in the measurement data was approximately 24 degrees.

The CDF curves of the capacity calculated for each combination are shown in Figure 11. They were calculated for signal to noise ratio (SNR) of 30 dB.

A critical point to focus on is the capacity value guaranteed for 90% of the channel realization. Its level of confidence is reasonable since it reflects the MIMO channel matrix conditions in which the degree of antenna correlation is relatively large. Thus, it corresponds to cases in which the AS happens to be fairly small and in which the MIMO channel does not offer best capacity. As we can notice from Figure 11, such a value (0.1 on the vertical axis) yields a channel capacity strictly minor of 20 bps/Hz for each of the calculated cases (configurations A–D of the antennas).

Corresponding outage capacity simulations were run using both the 3GPP SCM and the modified SCM with angular spread of 24 degrees (Figure 8). Again, 4×4 MIMO outage capacities were calculated over 10 000 independent MIMO channel samples. The SNR levels were set to 10 dB, 20 dB, and 30 dB. In Figure 12, the comparison between the empirical CDF (by real measurements) and the CDF by simulation of the 3GPP SCM and the modified SCM proposed in this paper is presented. It is evident that the 3GPP SCM model gives (at 30 dB SNR level) capacities larger than 20 bps/Hz for 90th percentile of the channel realizations, while it was in the measured cases constantly less than 20 bps/Hz. On the contrary, the modified SCM model gives also less than 20 bps/Hz. The outage capacity results from the channel models and the measured data were comparable also due to the fact that the average power of the MIMO channel matrices is normalized to be the same in both cases. Since the noise is fixed, the average SNR could be set to be equal for both the simulated and the measured cases.

6. CONCLUSION

In this paper, the spatial channel model proposed by the Third Generation Partnership Project (3GPP) has been studied by numerical simulations. It was found out that the 3GPP SCM model tends to over-estimate the MIMO outage channel capacity. This is due to the static nature of the 3GPP SCM in which each signal path is modeled by 20 subpaths having fixed azimuth directions and fixed power levels. Thus, the model is characterized by relatively small spatial correlation between MIMO antennas, which does not have strong variability. A modified SCM model is proposed which brings more variability to the MIMO channel states, which is also the usual case in real radio channels. The modified model produces also systematically smaller capacity values than the 3GPP SCM model. The difference between the two models increases as the angular spread of the radio channel is increasing. The simulated results were also compared to outage capacity results from a measurement campaign. It was found out that the simulated capacity results using the modified SCM model had a surprising good match with the capacity calculated from the empirical data.

ACKNOWLEDGMENT

This work was conducted within the European Network of Excellence for Wireless Communications (NEWCOM).

REFERENCES

[1] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Communications*, vol. 6, no. 3, pp. 311–335, 1998.

[2] B. Vucetic and J. Yuan, *Space-Time Coding*, John Wiley & Sons, Chichester, UK, 2003.

[3] M. Steinbauer, D. Hampicke, G. Sommerkorn, et al., "Array measurement of the double-directional mobile radio channel," in *Proceedings of the IEEE Vehicular Technology Conference (VTC '00)*, vol. 3, pp. 1656–1662, Tokyo, Japan, May 2000.

[4] 3GPP, "SpatialChannel Model for Multiple Input Multiple Output MIMO simulations," Technical Specification Group Radio Access Network TR 25.996 v6.1.0, 3GPP, September 2003.

[5] J. Salo, G. Del Galdo, J. Salmi, et al., "MATLAB implementation of the 3GPP spatial channel model," Tech. Rep. TR 25.996, 3GPP, January 2005, http://www.elektrobit.com/index.php?209.

[6] F. M. Reza, *An Introduction to Information Theory*, Courier Dover Publications, Mc-Graw Hill, New York, NY, USA, 1994.

[7] J. Ylitalo and M. Juntti, "MIMO communications with applications to (B)3G and 4G systems-tutorial," University of Oulu, Dept. Electrical and Inform. Engeneering, CWC, 2004.

[8] J. Ylitalo, "On spectral efficiency in spatially clustered MIMO radio channels," in *Proceedings of the IEEE Vehicular Technology Conference (VTC '06)*, vol. 6, pp. 2906–2910, Melbourne, Australia, May 2006.

[9] D. Gesbert, T. Ekman, and N. Christophersen, "Capacity limits of dense palm-sized MIMO arrays," in *Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM '02)*, vol. 2, pp. 1187–1191, Taipei, Taiwan, November 2002.

[10] "Propsound, radio channel sounder," http://www.propsim.com/index.php?1983.