Study of the Temporal Dynamics of the Polarization of Received Electromagnetic Waves Based on an Indoor-to-Indoor Measurement Campaign

Ali Panahandeh [1,2], Claude Oestges[2], Jean-Michel Dricot[1], François Horlin[1]
and Philippe De Doncker[1]

[1]**OPERA Department, Université Libre de Bruxelles (ULB)**
[2]**ICTEAM Electrical Engineering Department, Université catholique de Louvain (UCL)**
Ali.Panahandeh@ulb.ac.be

***Abstract*—Compared to classical spatial MIMO wireless systems, cross-polarized MIMO systems are an interesting way to reduce equipment size while still maintaining low inter-antenna correlation. In this paper, the time-variation of the polarization of the received waves is investigated. In this scenario, a theoretical formulation is proposed in order to obtain the parameters of the elliptical polarization, based on the signals received on three perpendicularly polarized antennas. A measurement campaign has been performed in an indoor-to-indoor scenario and at a frequency of 3.6 GHz. Different measurement positions are considered in a Line-Of-Sight (LOS) and a Non-Line-of-Sight (NLOS) scenario. Based on these measurements and the proposed theoretical formulation, the time-variation of the parameters describing the polarization ellipse is analyzed and a time-variant statistical model is proposed.**

***Index Terms*—MIMO, polarization, channel modeling**

I. Introduction

Polarized MIMO systems have been proposed as a space- and cost-effective alternative to classical co-polar MIMO systems. By using perpendicularly polarized colocated antennas, the inter-antenna correlation remains low, while maintaining a compact antenna system [1]–[3].

Let's consider a MIMO system where the receive antenna is a tri-polarized antenna system made of three colocated perpendicular omnidirectionnal antennas. In an idealistic case where there are no Interacting Objects (IOs) in the environnement surrounding the transmitter and the receiver, the polarization of the wave transmitted from the transmitter antenna stays the same at the receiver side. However in a realistic scenario where the environnement is made of many IOs, the polarization of the transmitted wave will change. The multi-path components at the receiver will in this case, each have different polarization properties. A fraction of a linearly polarized wave will for instance be depolarized, into its perpendicular components leading to an elliptical polarization [4], [5] (the linearly and the circularly polarization could each be defined as a special case of an elliptical polarization).

The superposition of the different multi-path components having each a different elliptical polarization scheme will lead to another elliptical polarization scheme. In a dynamic scenario, the IOs could change their position and/or shape over time, leading to a more dynamic receive scheme where the global receive polarization ellipse also changes over time.

A classical approach in modeling the multi-polarized MIMO channel is to consider the signals received at one vertical and two horizontal perpendicular antennas. Previous works have been done in order to model the multi-polarized MIMO channel for different sources (spatial/temporal) and scales of variation [6]–[8]. [6]–[8]. While these works tend at characterizing the signals received at one vertical and two horizontal perpendicular antennas, no work has been done in order to model the polarization of the received waves from an electromagnetic point of view.

The aim of this chapter is to dynamically characterize the receive polarization ellipse for a particular scenario. This new approach has the advantage to be transposable to any orientation of a receiver with multi-polarized colocated antennas. Based on the theoretical analysis and a measurement campaign, a statistical model of the received polarization ellipse is developed. The measurements are made in an indoor-to-indoor scenario and at a frequency of 3.6 GHz. Different measurement positions are considered in a LOS and a NLOS scenario.

II. Theoretical formulation of the elliptical polarization

An elliptically polarized wave may be resolved in two linearly polarized waves having different phase and amplitude and being perpendicular to each-other. Different set of parameters may be used in order to define an elliptical polarization in the three dimensional (3D) space. Based on the signals received on one vertical and two horizontal perpendicular antennas, a particular set of parameters defining the elliptical polarization in the 3D space is obtained. In the two dimensional (2D) case, the passage from the received signals on two perpendicular antennas to the elliptical polarization parameters is immediate [9]. In a more realistic 3D scenario, this passage is less intuitive and requires the knowledge of the orientation of the polarization plane (characterized by the vector normal to its surface (Figure 1)).

Let's consider three received signals ($s_V(\vec{r},t)$,$s_{H1}(\vec{r},t)$,$s_{H2}(\vec{r},t)$) on three perpendicular antennas. The phasor associated with these signals is given by :

$$\vec{s} = \begin{pmatrix} s_x \\ s_y \\ s_z \end{pmatrix} = \begin{pmatrix} s_{H1}e^{j\phi_{H1}} \\ s_{H2}e^{j\phi_{H2}} \\ s_V e^{j\phi_V} \end{pmatrix} \tag{1}$$

where s_V,s_{H1} and s_{H2} are the amplitudes and ϕ_V, ϕ_{H1} and ϕ_{H2} are the phases of the received signals on the vertical and the two perpendicular horizontal antennas.

In [10], the normal to the polarization plane is obtained for an arbitrary electric or magnetic field. This analysis is based on the spectral density tensor which is a second rank tensor formed from the wave fields.

The normal to the polarization plane is given by the vector $\mathbf{V}$ [10]:

$$\mathbf{V} \equiv (\mathbf{V}_x, \mathbf{V}_y, \mathbf{V}_z) \tag{2}$$

where

$$\begin{aligned} \mathbf{V}_x &= -\frac{1}{2}\,\mathrm{Im}\{s_y s_z^*\} \\ \mathbf{V}_y &= -\frac{1}{2}\,\mathrm{Im}\{s_x s_z^*\} \\ \mathbf{V}_z &= -\frac{1}{2}\,\mathrm{Im}\{s_x s_y^*\} \end{aligned} \tag{3}$$

The normal to the polarization plane is characterized by its azimuthal and elevation angles ϕ and θ (where $0 < \phi < \pi$ and $0 < \theta < \pi$). These angles are defined in the coordinate system formed by the three receive antennas.

The signal components in the Cartesian basis ($\vec{1_x}$,$\vec{1_y}$,$\vec{1_z}$) are transformed into the spherical basis ($\vec{1_{e_\theta}}$,$\vec{1_{e_\phi}}$,$\vec{1_{e_r}}$) by the following transformation [11]:

$$\begin{pmatrix} s_r \\ s_\theta \\ s_\phi \end{pmatrix} = \begin{pmatrix} sin\theta cos\phi & sin\theta sin\phi & cos\theta \\ cos\theta cos\phi & cos\theta sin\phi & -sin\theta \\ -sin\phi & cos\phi & 0 \end{pmatrix} . \begin{pmatrix} s_x \\ s_y \\ s_z \end{pmatrix} \tag{4}$$

where the radial component s_r will be zero.

Having the two transverse components s_θ and s_ϕ, the elliptical polarization parameters in the polarization plane are obtained by the classical 2D relations (Figure. 2).

The phase angle between the two transverse components is given by:

$$\delta = phase(s_\phi) - phase(s_\theta) \tag{5}$$

The orientation of the polarization ellipse in the polarization plane is determined by the tilt angle of the ellipse in the transverse basis. The tilt angle is defined as the angle between the major axis of the polarization ellipse and the e_θ axis and is given by:

$$\psi = \frac{1}{2}\arctan\frac{2|s_\theta||s_\phi|\cos(\delta)}{|s_\theta|^2 - |s_\phi|^2} \tag{6}$$

The ellipticity angle τ is given by:

$$\tau = \frac{1}{2}\arcsin\frac{2|s_\theta||s_\phi|\sin(\delta)}{|s_\theta|^2 + |s_\phi|^2} \tag{7}$$

The ellipticity rate e is given by:

$$e = tan(\tau) \tag{8}$$

The amplitude of the wave A is given by :

$$A = \sqrt{|s_\theta|^2 + |s_\phi|^2} \tag{9}$$

Finally, the length of the semi-minor and the semi-major axis are given by:

$$\begin{aligned} A_{y'} &= |A\sin(\tau)| \\ A_{x'} &= |A\cos(\tau)| \end{aligned} \tag{10}$$

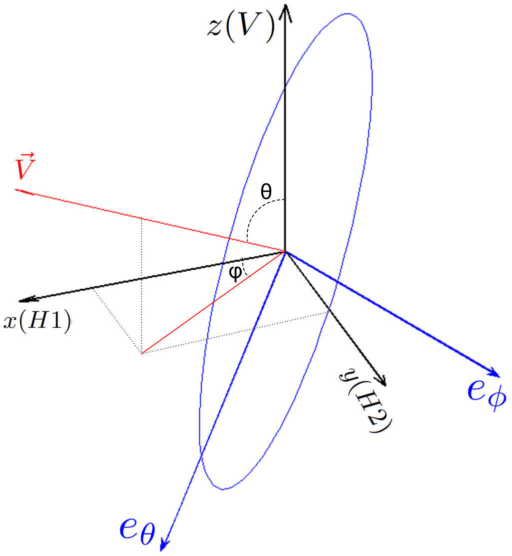


Figure 1. The 3D representation of the received polarization ellipse

A particular set of parameters which could be used in order to fully obtain the received polarization ellipse in the 3D space is for instance given by the orientation of the normal to the polarization plane (θ and ϕ), the orientation of the polarization ellipse in the polarization plane (ψ) and the length of the semi-major and the semi-minor axis.

In the following, the temporal variations of the polarization ellipse are characterized based on an indoor-to-indoor measurement campaign.

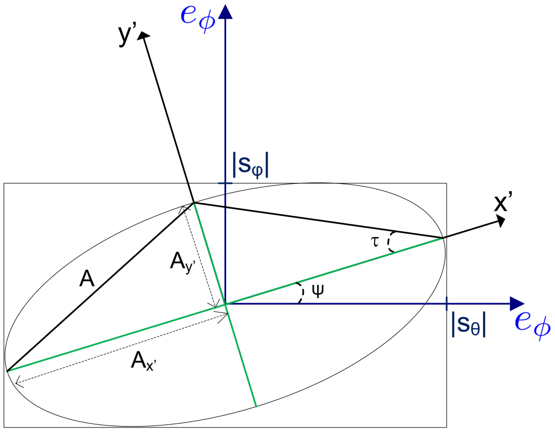


Figure 2. The representation of the polarization ellipse in the polarization plane

III. Experimental setup

A measurement campaign has been performed using the ULB/UCL Elektrobit MIMO channel sounder. The working frequency was 3.6 GHz with a 200 MHz bandwidth. The transmitter and receiver unit of the sounder were connected using a 32-meter N-cable, to run the sounder on a unique clock to avoid phase drift. Both the transmitter and the receiver were tri-pole antennas, composed of three perpendicular co-located short linear antennas. Although the used antennas are experimental measurement antennas, similar compact patch-antenna systems have already been developed for mobile applications [12]. The transmitter and the receiver were at about the same height. Each cycle recorded the complete 3×3 channel matrix. The channel sample rate was 281.171 Hz and a total of 30000 cycles were recorded (over 106 s recording time).

Three scenarios are investigated:

- *LOS Dynamic:* There is a LOS between the transmitter and the receiver which are both in the same room. Both the transmitter and the receiver are static during the measurements while people are randomly moving around. The measurements are made at a total of 4 different positions. The floor plan of the measurements is given in figure. 3.
- *LOS Back-Dynamic:* There is a LOS between the transmitter and the receiver which are both in the same room. Both the transmitter and the receiver are static during the measurements while people are randomly moving around without blocking the LOS between the transmitter and the receiver. The measurements are made at a total of 4 different positions. The floor plan of the measurements is given in figure. 3.
- *NLOS Dynamic:* There is non LOS between the transmitter and the receiver. A Lab-to-Lab scenario is considered where the transmitter is in a first room at the same place than the LOS scenario. The measurements are carried out in two successive rooms at a total of 12 different positions. At each position, the receiver and the transmitter were static during the measurement while people were randomly moving around. The floor plan of the measurements is given in figure. 3.

To allow the reproduction of the model and to have the same orientation of the basis, in all the measurement positions, the same orientation was imposed for the transmitter and the receiver tri-pole antennas. The measured impulse responses were averaged over 3 successive impulse responses to increase the measurement SNR, yielding a final channel sampling rate of 93.72 Hz. Finally, the narrowband MIMO matrices were obtained by summing the wideband impulse responses in the delay domain. While only the vertically polarized antenna is considered at the transmitter side, all the three antennas are considered at the receiver side.

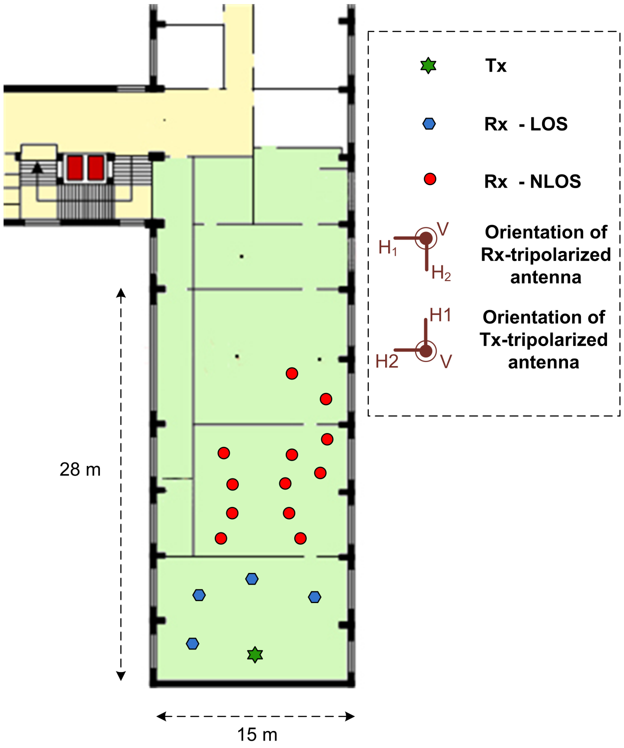


Figure 3. Floor plan of the measurements

IV. Results

Based on the measurements and the theoretical expressions presented earlier in this paper, the temporal variations of the parameters describing the receive polarization ellipse in the 3D space are analyzed and a statistical model is deduced.

In order to obtain the statistical distribution of each parameter, the temporal samples of each parameter are first averaged over ten successive samples yielding a total number of 984 samples. Based on these temporal samples, the statistical distribution that follows each parameter at each position is obtained using the Maximum Likelihood

Estimator. An overview of these Gaussian distributions and their respective parameters is given in Tables I, II and III for respectively the NLOS Dynamic, the LOS Dynamic and the LOS Back-Dynamic scenarios.

Table I
Overview of the statistical distributions of the parameters describing the polarization ellipse for the NLOS Dynamic scenario [1]

Parameters of the ellipse	μ			σ		
	min	max	mean	min	max	mean
$A_{x'}$	7.91e-4	0.009	0.0049	7.53e-5	0.0017	8.59e-4
$A_{y'}$	1.77e-4	0.0033	0.0014	6.19e-5	0.001	3.85e-4
A	8.16e-4	0.0091	0.0052	7.62e-5	0.0016	8.63e-4
e	-0.465	0.450	0.085	0.074	0.270	0.156
ψ $(radian)$	-0.148	0.165	0.052	0.046	0.187	0.140
ϕ $(radian)$	0.3133	2.2048	1.0989	0.3004	1.1110	0.6345
θ $(radian)$	1.2960	2.3254	1.9592	0.0692	0.5212	0.2509

Table II
Overview of the statistical distributions of the parameters describing the polarization ellipse for the LOS Dynamic scenario

Parameters of the ellipse	μ			σ		
	min	max	mean	min	max	mean
$A_{x'}$	0.0123	0.0237	0.0161	0.0026	0.0048	0.0036
$A_{y'}$	0.0052	0.0076	0.0061	0.0012	0.0026	0.0018
A	0.0135	0.0251	0.0174	0.0025	0.0050	0.0037
e	-0.300	0.325	0.013	0.140	0.312	0.261
ψ $(radian)$	-0.385	0.079	-0.143	0.177	0.247	0.210
ϕ $(radian)$	0.8109	2.7449	1.8462	0.4134	0.9088	0.6547
θ $(radian)$	1.4898	2.0490	1.8186	0.1716	0.6456	0.4172

For all the three scenarios, The mean elevation angle θ is on average around 90 degree which corresponds to the horizontal plane and is consistent with the measurements setup where the transmitter and the receiver were more or less at the same height. In Figure 4, the directions of the normal to the polarization plane are presented in 3D space and for the first measurement position in the LOS-Dynamic scenario . We notice the concentration of these vectors in a privileged direction which corresponds to the direction of incidence of the main beam.

Table III
Overview of the statistical distributions of the parameters describing the polarization ellipse for the LOS Back-Dynamic scenario

Parameters of the ellipse	μ			σ		
	min	max	mean	min	max	mean
$A_{x'}$	0.0118	0.0262	0.0177	0.0012	0.0018	0.0015
$A_{y'}$	0.0050	0.0076	0.0065	8.40e-4	0.0015	0.0011
A	0.0129	0.0275	0.0190	0.0011	0.0018	0.0015
e	-0.301	0.447	-0.009	0.071	0.289	0.168
ψ $(radian)$	-0.590	0.218	-0.217	0.108	0.171	0.143
ϕ $(radian)$	0.5463	2.9234	2.0212	0.2312	0.6221	0.4457
θ $(radian)$	1.5321	2.2711	1.8957	0.0823	0.7501	0.3205

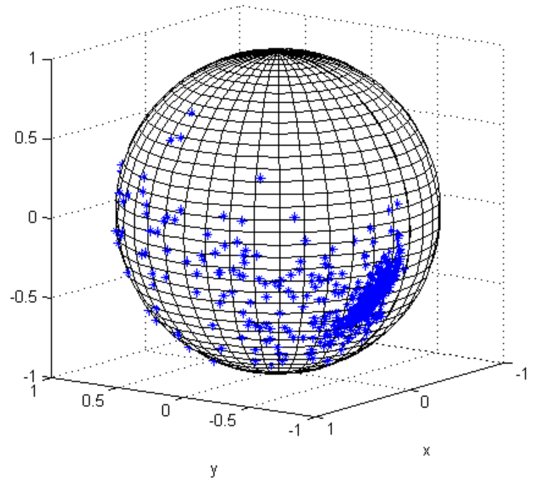


Figure 4. The directions of the normal to the polarization plane in 3D space

A high range of variation is obtained for the mean direction of the normal to the polarization plane. The mean direction of the normal to the polarization plane depends highly on the position of the receiver and the geometrical configuration of the environment.

We notice the close values of μ between the LOS Dynamic and LOS Back-Dynamic scenarios and higher values of σ in the LOS Dynamic scenario compared to the Los Back-Dynamic scenario. Regardless of how people moves around the receiver, the variations of the elliptical polarization parameters stay the same on average. However the parameters will be much more deviated from the mean values in case of a total dynamic scenario.

Considering the potential range of variation of the tilt angle ($-\pi < \psi < \pi$), we notice the actual low range of variation of this parameter for all the three scenarios. Also as the parameter A represents the amplitude of the wave, we notice the lower average value of this parameter in the NLOS scenario.

The ellipticity rate represents the degree of ellipticity of

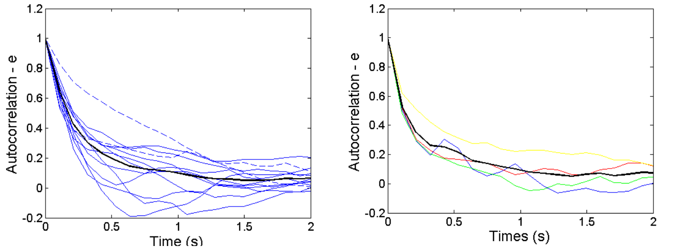
---

[1] μ and σ denotes respectively the mean and the standard deviation of the Gaussian distribution for each parameter and min, max and mean denote respectively the minimum, the maximum and the mean value of μ or σ between the different measurement positions.

an electromagnetic wave. The value $|e| = 1$ corresponds to a circularly polarized wave and the value $|e| = 0$ corresponds to a linearly polarized wave. We notice the high range of variation of the mean ellipticity rate parameter between the different positions. The transmitted vertically polarized wave is received in many different polarization schemes at the receiver. This polarization variability is not exploited in classical MIMO systems where a set of spatially separated co-polarized antennas is used. This problem is solved by using three perpendicularly polarized antennas which receive all incident polarizations.

As the interaction of the transmitted wave with the environment surrounding the transmitter and the receiver is higher in the NLOS scenario, the mean ellipticity rate is on average higher in the NLOS case and remains closer to zero in the LOS scenarios.

In order to study the time-variant dynamics of the channel, the autocorrelation functions of all the parameters have been analyzed. For a value of autocorrelation higher than 0.5, similar trends are obtained for the autocorrelation functions of most of the measurement positions. An exemple of this similarity is given in figure. 5 where the autocorrelation functions of the ellipticity rate is presented for different positions in the NLOS-Dynamic and Los Bac-Dynamic scenarios.



(a) NLOS Dynamic scenario (b) LOS Back-Dynamic scenario

Figure 5. Autocorrelation functions of e for different measurement positions in NLOS and LOS-Back Dynamic scenarios

For each scenario, the average autocorrelation function was obtained by averaging the autocorrelation functions of all the positions. For all the parameters the average autocorrelation functions have very similar trends between the three scenarios. This is presented in figure. 6 for the particular case of the ellipticity rate parameter. Regardless of how people moves around the receiver and the presence or not of a LOS between the transmitter and the receiver, the temporal dynamics of the parameters describing the polarization ellipse are the same on average. The average autocorrelation functions were best fitted with a decaying exponential model. The parameters of these exponential models are presented in Table. IV.

In previous works treating multi-polarized MIMO channels, no attention has been paid to fix a particular orientation for the receive antenna system. While this approach has the advantage to model the channel in a situation where the orientation of the receive antenna system does not stay the same all the time, it does not let the model to be transposable to a particular orientation of the receive antenna system. In fact the receive antenna system is made of three perpendicular co-located antennas and as the orientation of this antenna system changes, the channel changes as well. The approach used in this paper for modeling the multi-polarized channel could be applied to any orientation of the receive antenna system, by projecting the receive elliptical polarization to the receive antenna system. Moreover, with this new approach, the performance of wireless communications could be improved, by adapting the receive antenna system based on the informations on the receive elliptical polarization.

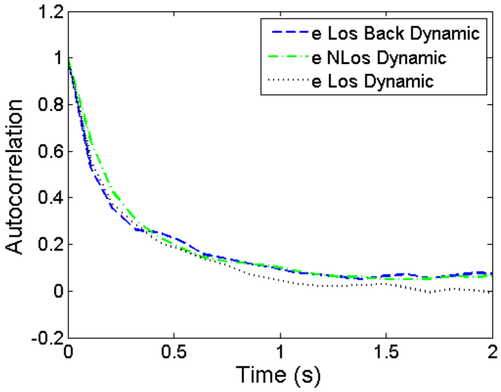


Figure 6. Average autocorrelation functions for the NLOS, LOS Dynamic and LOS Back-Dynamic scenarios

Table IV
Exponential models of the autocorrelation functions

$y = exp(-bt)$	b (s^{-1})
$A_{x'}$	3
$A_{y'}$	3.52
A	2.88
e	4.63
ψ	6.76
θ	5.31
ϕ	5.27

V. Conclusion

In this paper, a time varying statistical model of the elliptical polarization of the received waves was presented for a particular indoor-to-indoor scenario. The proposed model was based on a theoretical formulation which was applied to the results obtained from an indoor-to-indoor measurement campaign. The statistical distributions of the parameters describing the polarization ellipse in the 3D space were obtained. In order to study the time-variant dynamics of the channel, the autocorrelation functions of all the parameters have been analyzed and exponential models were proposed for the autocorrelation functions of the parameters. Regardless of how people moves around the receiver and the presence or not of a LOS between the transmitter and the receiver, the temporal dynamics of the parameters describing the polarization ellipse are the same on average. Although a linearly polarized transmitted wave is received in many different polarization schemes, the orientation of the normal to the polarization plane was found to have a privileged direction.

References

[1] B. Lindmark and M. Nilsson, "On the available diversity gain from different dual-polarized antennas," *Selected Areas in Communications, IEEE Journal on*, vol. 19, no. 2, pp. 287 –294, feb 2001.

[2] P. Kyritsi, D.C. Cox, R.A. Valenzuela, and P.W. Wolniansky, "Effect of antenna polarization on the capacity of a multiple element system in an indoor environment," *Selected Areas in Communications, IEEE Journal on*, vol. 20, no. 6, pp. 1227 –1239, aug 2002.

[3] L.C. Lukama, K. Konstantinou, and D.J. Edwards, "Performance of a three-branch orthogonal polarization diversity scheme," in *Vehicular Technology Conference, 2001. VTC 2001 Fall. IEEE VTS 54th*, 2001, vol. 4, pp. 2033 –2037 vol.4.

[4] V. Erceg, P. Soma, D.S. Baum, and S. Catreux, "Multiple-input multiple-output fixed wireless radio channel measurements and modeling using dual-polarized antennas at 2.5 ghz," in *IEEE Trans. wireless Commun*, Nov 2004, vol. 3, pp. 2288 – 2298.

[5] C. Oestges and B. Clerckx, *MIMO wireless communications: from real-world propagation to space-time code design*, Electronics & Electrical. Academic Press, 2007.

[6] François Quitin, Francois Bellens, Ali Panahandeh, Jean-Michel Dricot, Fabrice Dossin, François Horlin, Claude Oestges, and Philippe De Doncker, "A time-variant statistical channel model for tri-polarized antenna systems," in *PIMRC*, 2010, pp. 64–69.

[7] Ali Panahandeh, F. Quitin, J.M. Dricot, F. Horlin, C. Oestges, and Ph. De Doncker, "Multi-polarized channel statistics for outdoor-to-indoor and indoor-to-indoor channels," in *71st Vehicular Technology Conference (VTC2010 – Spring)*, 15-19 May 2010.

[8] Mansoor Shafi, Min Zhang, Andreas F. Molisch, Fredrik Tufvesson, and Steven H. Simon, "Polarized mimo channels in 3d: Models, measurements and mutual information," *IEEE J. Select. Areas Commun*, vol. 24, pp. 514–527, 2006.

[9] G.S. Smith, *An introduction to classical electromagnetic radiation*, Cambridge University Press, 1997.

[10] T. Carozzi, R. Karlsson, and J. Bergman, "Parameters characterizing electromagnetic wave polarization," *Physical Review E*, vol. 61, pp. 2024–2028, 2000.

[11] P.H. Moon and D.E. Spencer, *Field theory handbook: including coordinate systems, differential equations, and their solutions*, Springer-Verlag, 1961.

[12] N.K. Das, T. Inoue, T. Taniguchi, and Y. Karasawa, "An experiment on mimo system having three orthogonal polarization diversity branches in multipath-rich environment," in *60st Vehicular Technology Conference (VTC2004 – Fall)*, 26-29 Sep 2004, vol. 2, pp. 1528 – 1532.