MIMO Channel Models for Satellite Communications

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1. Introduction

In recent years considerable attention has been drawn to the systems with multiple element transmitter and receiver arrays. It has been demonstrated both in theory and practice that multiple-input multiple-output (MIMO) systems offer the promise of increased capacity, high spectral efficiency and high gains by exploiting space-time processing techniques in particular space-time coding (STC) techniques under different propagation environments. This superior performance is achieved by the decomposition of the radio channel into a set of independent spatially uncorrelated channels. The basic method to achieve diverse channels, in addition to the exploitation of time and frequency dimensions, is to use the additional dimension of space, i.e., antennas are spatially separated from each other resulting in space-time processing. The advantages obtained by MIMO channels are highly dependent on the orientations of scatterers and the correlations among signal carriers which limit the performance of MIMO systems. The antenna separation, in terms of wavelength of the operating frequency, has significant impact on the spatial correlation. To achieve uncorrelated fading paths adequate antenna spacing along with rich scattering environment is necessary. An alternative solution to achieve low fading correlation is to use antenna arrays with cross polarizations, i.e., antenna arrays with polarizations in orthogonal or near orthogonal orientations without increasing the bandwidth and in particular, the concept of three-dimensional (3D) polarization has a significant role in achieving diversity by polarization. It has been shown in recent research that it is possible to attain even more channels by using benefits of the combined spatial and polarization diversity in rich scattering environments.

Satellite communication systems are not immune from this wave of innovation. However, due to difference in the propagation conditions in satellite and terrestrial links, the applicability and designs of MIMO systems are different as well. Due to very large path lengths, transmit and/or receive antennas must be placed at appropriate distances from each other to realize diverse paths. To achieve this, the possible diversity sources, i.e., satellite diversity and site diversity can be exploited in forming the MIMO channels for satellites. In the case of satellite diversity, the satellites are far apart from each other to achieve diversity and as a result the path lengths and the time of arrival of signals can vary vastly between the satellites and the ground terminals resulting in synchronization problem. These issues can be dealt with by employing cooperative satellite diversity concept or the use of compact antennas in which the problem of synchronization does not exist. The frame work for the most recent developments in satellite communications includes satellite land mobile and fixed communication systems, satellite navigation systems, Earth Observation systems and the state of art propagation models and evaluation tools for these systems. The influence of radio channel is a critical issue for the design, performance assessment and real-time operation of these highly reconfigurable hybrid (satellite and terrestrial) radio networks providing voice, text and multimedia services operating at RF frequencies ranging from 100 MHz to 100 GHz and optical frequencies.

The organization of the chapter is as follows: in section 2, a brief introduction to directional channel modelling including MIMO channel modelling is presented. In section 3 we present an overview of MIMO channel models for satellite communications. Section 4 describes MIMO channel models for satellites based on polarization concept. Finally, conclusions and suggestions are given in section 5.

2. Directional Channel Modelling

The difficulties in modelling a radio channel are due to complex and varying propagation environments. In case of land mobile satellite (LMS) communications the signal travelling between a land mobile and a satellite suffers from different propagation impairments (chapter 1). The diverse nature of propagation media (e.g., ionosphere, troposphere and local effects) adds further a dimension of complexity in predicting the affects of propagation impairments on radio signals. It is important to note that the level of information obtained from a channel model about an environment is highly dependent on the type of system under assessment. In order to predict the performance of single sensor narrowband system it may be sufficient to consider the time varying amplitude distribution and the received signal power. Thus, classical channel models which provide information about signal power level distributions and Doppler shifts may be adequate for narrowband systems. Broadband communication systems build on the classical understanding of the received signal power distributions and Doppler spread also exploit spatial processing to operate in highly complex and diverse propagation environments. Thus, it is necessary to incorporate new concepts such as adaptive antenna arrays, angles of arrival (AoA), angles of departure (AoD), delay spread and multiple antennas at both the ends of a communication link, the so-called MIMO systems.

When investigating MIMO channels, the additional dimension that comes into play is space which needs to be modelled in a similar way as frequency and time variations have been modelled for the wideband single-input single-output (SISO) systems. In contrast to the systems which deal with only temporal spreading, the MIMO channels require the angular distribution of energy at both the ends of the communication link. The impulse response of the double directional channel between a transmitter positioned at P_t and a receiver positioned at P_r with n paths in 3D space can be written as (Steinbauer et al., 2001):

$$h(P_t, P_r, \tau, \Omega_t, \Omega_r) = \sum_{i=1}^{n} h_i(p_t, p_r, \tau, \Omega_t, \Omega_r) \tag{1}$$

where τ, Ω_t and Ω_r denote the delay, AoD and AoA, both in 3D space, respectively and h_i is the contribution of the i^{th} component, i.e.,

$$h_i(p_t, p_r, \tau, \Omega_t, \Omega_r) = \alpha_i e^{j\phi i} \delta(\tau - \tau_i)\delta(\Omega_t - \Omega_{t,i})\delta(\Omega_r - \Omega_{r,i}) \tag{2}$$

where α_i, φ_i, τ_i, $\Omega_{t,i}$ and $\Omega_{r,i}$ represent the amplitude, phase, time delay, AoD and AoA of the i^{th} multipath contribution, respectively.

These parameters are determined by the relative location of the transmitter and the receiver. When either the transmitter or the receiver moves, these variables become a function of time and can change drastically over large periods of time (long distances). Therefore a more compact representation of time variant double-directional channel impulse response is given by,

$$h(t, \tau, \Omega_t, \Omega_r) = \sum_{i=1}^{n} h_k(t, \tau, \Omega_t, \Omega_r) \tag{3}$$

In addition to these parameters, the double directional channel impulse response is also dependent on the antenna patterns and the modelling bandwidth.

2.1 The MIMO Propagation Channel

If multiple antennas are deployed at both the ends of a communication link, a MIMO system is obtained as shown in Fig. 1. The key idea underlying MIMO theory is that signals sampled in the spatial domain at both the ends are combined in such a way that multiple parallel channels are created. The double-direction description of the channel can be extended to MIMO channel by considering n_t transmit and n_r receive spatially separated antennas at both the ends. The corresponding MIMO channel matrix can be defined as:

$$H(t,\tau) = \begin{bmatrix} h_{11}(t,\tau) & h_{12}(t,\tau) & \cdots & h_{1m}(t,\tau) \\ h_{21}(t,\tau) & h_{22}(t,\tau) & \cdots & h_{2m}(t,\tau) \\ \vdots & \vdots & \ddots & \vdots \\ h_{n1}(t,\tau) & h_{n2}(t,\tau) & \cdots & h_{nm}(t,\tau) \end{bmatrix} \tag{4}$$

where $h_{nm}(.)$ denotes the narrowband channel (wide sense stationary uncorrelated scattering process) between the m^{th} transmit and n^{th} receive antenna. The elements of the channel matrix (i.e., individual narrowband SISO channels) are taken as independent circularly symmetric complex Gaussian variables with equal variance.

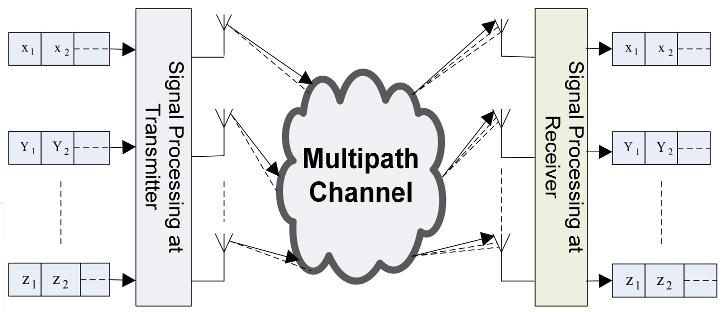

Fig. 1. The MIMO propagation channel.

The representation of a MIMO channel by individual SISO channels in not complete description of the multiple antenna systems. In order to get full benefit from MIMO systems (i.e., diversity gain, spatial multiplexing gain and array gain) certain trade-offs exist between these gains to achieve an adequate bit error rate at all times in an interference and noise limited system and at the same time maximizing throughput. The performance of MIMO techniques requires the exploitation of spatial correlation between all channel matrix elements. In (3) the elements of the channel matrix are assumed to be independent and therefore any two elements are uncorrelated. Practically, there is always some correlation between the channel matrix elements. These correlations are owing to small antenna array separation, antenna geometry and small amount of angular spread at the transmitter or the receiver side or both. Different studies have been found in literature to investigate the effects of correlation on the performance of systems employing multiple antenna techniques. In (Lokya, 2001) n equal power and equal rate parallel sub-channels are considered with 'r' as correlation coefficient between any two sub-channels. The capacity of such a channel can be written as:

$$C(r) = n.\log_2\left[1+\frac{\rho}{n}(1-r)\right] + \log_2\left[1+\frac{n\rho r}{n+\rho(1-r)}\right] \tag{5}$$

where 'ρ' represents the signal-to-noise ratio (SNR). When $r = 0$ the above equation reduces to the well-known formula for capacity:

$$C(r) = n.\log_2\left[1+\frac{\rho}{n}(1-r)\right] \quad \text{bps/Hz} \tag{6}$$

Comparison of (5) and (6) illustrate that the SNR decreases inversely with increase in the value of correlation coefficient (e.g., $r = 0.7$ results in 3 dB reduction in SNR). The MIMO channel capacity versus correlation coefficient for different values of 'n' at SNR value of 30 dB is shown in Fig. 2.

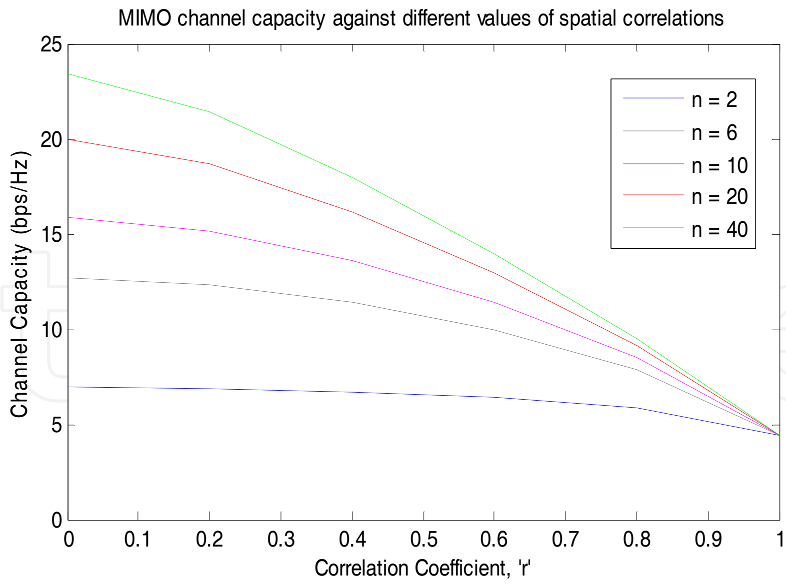

Fig. 2. MIMO channel capacity for 'n' channels against different values of correlation coefficient 'r'.

The other factors that limit the performance of MIMO channels are: number of scatterers, presence of line-of-sight (LOS) path, correlation between antenna elements at the transmitter or receiver side or both, keyholes, antenna patterns and geometry etc.

3. MIMO Channel Models for Satellite Communications

The wireless world has seen substantial increase in the demand of high quality broadband wireless services during recent years which results in the evolution of MIMO communication systems. The satellite communication systems are not immune to this change. In order to evaluate the performance of these systems employing MIMO technology, radio propagation models with high accuracy are required which can capture all those effects that affect different aspects of these systems whilst remaining computationally simple and require less simulation times.

Different approaches can be used to build a channel model with certain trade-offs (Almer et al., 2007). For example, physical or deterministic channel models based on ray-tracing algorithms can provide accurate results for a particular scenario, however due to global coverage of satellites this approach is not often used. On the other hand statistical models are built around measurement data and provide reasonable accuracy for the environments similar to that for which the model was built. However, they provide little insight into the propagation mechanisms and depend on the accuracy of measured data. An intermediate approach between these models is physical-statistical model. The physical-statistical modelling approach is the most appropriate in predicting the 'ON/OFF' nature and finding the small scale fading effects over large coverage areas applicable to LMS communication systems (Saunders et al., 2007). In this section some of the recently developed MIMO channel models based on different channel modelling approaches are presented.

3.1 The Physical-Statistical MIMO Channel Model

This physical-statistical MIMO channel (King et al., 2005) for LMS communications is based on 'clusters' concept and uses the same methodology given in (Correia, 2001; Molisch, 2004). The ray-tracing algorithm has been exercised to find different propagation effects like roof-top diffraction, specular reflection, shadowing caused by trees and foliage and blockage by buildings in LMS communication links in urban and high-way environments. The model can generate high resolution time series data and power delay profile for communication links between the satellite and mobile terminal antennas and can also predict the correlation between these links. In this model, obstacles (e.g., buildings, trees etc) are grouped into clusters of spherical shapes where clusters centers are randomly positioned. The building heights follow lognormal distribution. Twenty scatterers are placed randomly around the cluster centre each with dimension following Laplacian distribution (Correia, 2001). The building densities are assumed to be 90% in clusters representing urban environment, whereas trees are considered 90% of time in clusters for high-way environment. In order to validate the model, the parameters used are obtained from measurements data collected in Munich, Germany at L-band (1.54 GHz), for urban and high-way environments.

When signals reflected by distant clusters are blocked by buildings in the local clusters, these contributions are rejected. The signals from the satellite antennas to the mobile antennas are selected through appropriate clusters of scatters. Each scatterer in the cluster is assigned randomly the same reflection coefficient from a uniform magnitude distribution between 0 and 1 and phase 0 to 2π. This channel model considers three paths between a satellite and moving mobile terminal: a line-of-sight (LOS) path, a blocked LOS path and an attenuated path by trees. The time series data '*I*' for a satellite or a high altitude platform (HAP) antenna *M* and each moving mobile antenna *N* can be written as:

$$\alpha_{M,N} = \begin{cases} P_{M,N} + b\sum_{i=1}^{n} T_i F_i P_{M,N,i} exp(jkd_{M,N,i}) & \text{Clear Path} \\ D_{M,N} P_{M,N} + b\sum_{i=1}^{n} T_i \Gamma_i P_{M,N,i} exp(jkd_{M,N,i}) & \text{Blocked Path} \\ T_{M,N} P_{M,N} + b\sum_{i=1}^{n} T_i \Gamma_i P_{M,N,i} exp(jkd_{M,N,i}) & \text{LOS Path} \end{cases} \tag{7}$$

where $P_{M,N}$, $D_{M,N}$ and $T_{M,N}$ denote the LOS path loss, the diffraction loss and the LOS trees loss, respectively, between satellite antenna *M* and moving mobile terminal antenna *N*. The term '*b*' is the clutter factor derived from measurements in each environment, T_i is the tree attenuation from scatter *i*, Γ_i is the reflection coefficient at scatterer *i*, $P_{M,N,i}$ is the path loss and $D_{M,N,i}$ is the distance between satellite antenna *M* and mobile terminal antenna *N* via scatterer *i*. The small scale fading parameters such as AoA distribution, shadowing depth and wideband parameters like root mean square (RMS) delay spread or coherence bandwidth can be approximated in each environment using the output time series and spatial power delay profile data of the model.

3.2 Analytical MIMO LMS channel model at Ku-Band and above

The physical-statistical channel model described earlier is designed for L (1-2 GHz) and S (2-4 GHz) frequency bands for LMS communication systems. The application of MIMO systems for satellite communications at Ku frequency band (12-18 GHz) and above has been discussed in (Liolis et al., 2007). In this model, two features of MIMO technology are presented: (i) a 2x2 MIMO spatial multiplexing system is used to achieve capacity improvements and a closed form expression for the outage capacity is derived (ii) MIMO spatial diversity scheme with receive antenna selection is applied in order to reduce interference in LMS communication links. In addition, an analytical closed form expression for interference mitigation on forward link of a satellite 2x2 MIMO diversity system with antenna selection is also obtained. In order to discuss the features of MIMO techniques, the model assumes propagation phenomena such as clear LOS, high antenna directivity, rain fading and rainfall spatial homogeneity. The propagation delay offset (synchronization problem) in LMS communications is also considered and a practical solution to this problem is found where matched filters are applied, first to the received signals for the detection of propagation delay offset and then the resulting signals are fed to the timing aligner. Subsequently, the delay offsets are eliminated by adjusting the timing of a signal serial-to-parallel converter.

The figure of merit for the analysis of MIMO fading channel is the outage capacity. A dual-satellite MIMO communication channel at Ku-band and above is shown in Fig. 1 in (Liolis et al., 2007). The terminal station is equipped with two highly directive collocated antennas to communicate with two satellites S1 and S2. The separation, $\Delta\theta$, between the antennas is kept large enough so that the spatial correlation due to rain along the relevant paths is as low as possible. Considering the clear LOS between the terminal station and each satellite and that each terminal station antenna is at bore-sight with the corresponding satellite, the total path loss along each link can be written as follows (Liolis et al., 2007):

$$A_i = FSL_i + A_{Ri} \qquad i = 1, 2 \tag{8}$$

where $FSL_i = 10\log_{10}(4\pi\, d_i f / c)^2$ is the free space loss along each link, f is the operating frequency and c is the speed of light. The term A_{Ri} represents the rain induced attenuation. The convective raincell model using Crane's assumptions is employed for the description of vertical variation of the rain fall structure using the same approach as in (Panagopoulos & Kanellopoulis, 2002). Based on these suppositions if $\Delta\theta$ is sufficiently large, the spatial correlation between random variables A_{Ri} representing channel coefficients is low and a decorrelated (ideal) MIMO satellite channel model is obtained.

To find out the capacity of dual satellite MIMO channel, it is assumed that the two satellites transmit different and independent data streams and the channel is perfectly known at the terminal side while the transmitting satellites have no information about the channel. Equal powers are allocated to the two satellites owing to distributive nature of the system in the absence of channel state information (CSI). The capacity of the dual satellite MIMO channel based on the standard MIMO theory, taking into the account above assumptions, can be written as follows:

$$C = \sum_{i=1}^{2} log_2 (1 + 0.5 SNR_{CS_i} 10^{-A_{Ri}/10}) \tag{9}$$

where SNR_{CS_i} are the nominal SNR ratio values under clear sky conditions. The above equation gives the instantaneous capacity of deterministic 2x2 MIMO channel. However due to rain induced attenuation and stochastic behavior of the channel, the appropriate metric to characterize the resulting fading channel is the outage capacity which can be written in the following form:

$$(C \le C_{out,q}) = \frac{1}{2} \int_{u_A}^{+\infty} du_1 fv_1(u_1) erfc\left(\frac{u_B \rho_{n12} u_1}{\sqrt{2(1-\rho_{n12}^2)}} \right) = q \tag{10}$$

where $C_{out,q}$ is the information rate guaranteed for *(1-q) 100%* of channel realizations. The term ρ_{n12} is logarithmic correlation coefficient between normal random variables u_i and u_A, u_B. Complete mathematical details about these variables can be found in (Liolis et al., 2007) This model is applicable over a large range of SNR values and shows significant capacity gains of the MIMO systems over the SISO systems for moderate and high SNR levels.

The major factor limiting the capacity of LMS system is the adjacent satellite cochannel interference on its forward link. A satellite 2x2 MIMO diversity system based on receive antenna selection to mitigate the cochannel interference problem on the forward link due to differential rain attenuation from adjacent satellites is presented in (Liolis et al., 2007). In addition an analytical model is provided for interference mitigation based on satellite 2x2 MIMO diversity systems. To ease the complexity and cost associated with multiple RF chains only one RF chain is used at the receiver that performs antenna selection, i.e., it utilizes receive selection diversity to detect the signal related to the path with the highest SNR (Sanayei & Nosratinia, 2004). For optimal selection of a signal, the receiver scans the two antennas for a training signal transmitted along with data and the signal with the highest SNR is selected for the reception of the next data burst. This model uses a distinct approach for interference mitigation as compared to the conventional approaches found in MIMO theory. The effect of rainfall on interference analysis, differential rain attenuation related to an adjacent satellite and spatial inhomogeneity of rainfall medium are taken into account especially for congested urban areas where the increased demand for link capacity and radio coverage imposes the coexistence of many satellite radio links over the same geographical and spectral area. The satellite 2x2 MIMO diversity model using antenna selection and operating at Ku-band and above is illustrated in Fig. 4 in (Liolis et al., 2007). This model does not require channel knowledge at the transmitter side and only the information about wanted signals' channels at the receiver is desired. Mathematical derivation of this model and influence of various geometrical and operational system parameters on system performance can be found in (Liolis et al., 2007).

4. Application of Polarized MIMO Channels to Satellite Communications

The large MIMO gains can be achieved with low correlation between antenna elements at both ends of MIMO communication system. A fundamental way of achieving low antenna correlation is to use antenna elements with significant separation such that the relative phases of multipath contributions arriving at the receiving antennas are significantly different. However, owing to size restriction it is difficult to deploy multiple antennas with large separation at the mobile terminal. In addition, in communications where LOS is dominant (e.g., satellite communications), the MIMO systems offer reduced performance since LOS components overpower multipath components in the received signal. An alternative solution is to use polarized arrays for multiple antenna systems (Mohammed & Hult, 2008; Hult et al., 2010). With spatially separated cross-polarized antenna arrays, both the polarization diversity and polarization multiplexing can be achieved (Jiang et al., 2004; Moriatis et al., 2009) (e.g., two dual polarized spatially separated arrays form 4-antenna arrays).

In order to get benefit from polarization dimension, the cross-polar transmissions (e.g., transmission from vertically polarized antenna to horizontally polarized antenna) should be zero. However, in real scenarios there is always some polarization mismatch since linearly polarized antenna arrays have non-zero patterns for cross-polar fields (Hult & Mohammed, 2008). In addition, multipath effects (e.g., diffraction, scattering, reflection etc.) may change the plane of polarization of incident electromagnetic waves at the receiver.

4.1 Physical-Statistical Polarized MIMO Channel

In order to achieve additional diversity in satellite communication links, an extension of the physical-statistical MIMO model to 2x2 dual polarized MIMO model is presented in (Horvath et al., 2007) for a single satellite serving land mobile. A single satellite containing two antennas with right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP), respectively, communicates with mobile terminal using the same antenna configuration. It is assumed in this model that LOS paths between co- and cross-polar channels are fully correlated and diffused multipaths are fully uncorrelated between co- and cross-polar components. The polarization characteristics are described by Stoke's theorem and the related concepts. The channel model construction is similar to (King, 2005) with additional polarization features are included as follows: In the case of unobstructed LOS signal, path loss is applied to the co-polar channels while cross-polar channels are neglected. When the LOS signal is blocked by buildings, rooftop diffraction loss is applied to both the co- and cross-polar channels. In the case of LOS path through vegetation, attenuation is applied depending upon the path length and using an attenuation factor of -1.3 dB. A mathematical representation of data generated by this model can be found in (Horvath et al, 2007). Extensive measurements were carried out along tree-lined/highway and urban environments using an artificial platform in order to optimize the model by fitting its parameters to the measured data. The model is capable of producing statistically accurate wideband channel first and second order characteristics and can be used to evaluate the capacity and diversity benefits of MIMO applications in LMS communication systems. The use of dual polarized system results in 2-fold increase in capacity and 4-fold boost in diversity gain (Horvath et al., 2007). The diversity gain can be further increased by employing the concept of compact 3D-polarized antennas (Horvath & Friyges, 2006). In the case of synchronization problem in multi-satellite to ground links, one solution can be that MIMO antennas have to be collocated onboard a single satellite. This case is similar but not identical to handheld devices where the available space is limited. Here the available space is significant and antennas with large aperture and high gain can be applied. The channel statistics and power delay profiles are dependent on size and positioning of scatterers and reflection coefficients. The details of the experiments conducted to fine-tune the model can be found in (King, 2007).

4.2 Empirical-Statistical MIMO Channel Models for Satellites

The empirical-statistical channel models are built statistically around field measurements and can produce appropriate channel statistics for similar environments. An empirical-statistical 2x2 dual polarized LMS-MIMO channel model based on measurement campaigns is presented in (King, 2007). This MIMO channel model characterizes two models for LMS communication systems: the narrowband and the wideband channels. In order to describe 'ON/OFF' phenomenon occurring in LMS communication links, Markov chain approach is used. In narrowband model, single or dual lognormal fading, which is correlated over MIMO domain, is applied across each Markov state. In the case of wideband model lognormal fading is correlated over the delay domain as well and Rician factor is dependent on the large scale fading level.

To design a narrowband channel model, large scale data (lognormal fading) for each of the four channels in each Markov state is generated using a Gaussian random number generator with zero mean and unit standard deviation. The memoryless data streams (data samples) are then filtered using first order recursive linear time invariant digital filter in order to obtain correct temporal fading. The cross-correlation between large scale fading channels can be obtained in the following way:

$$vec(Y) = (\chi)^{1/2} vec(Y) \tag{11}$$

where χ is the correlation matrix obtained from measurements. Two large scale time series vectors are defined to represent dual lognormal fading which produces 8 time series correlated vectors: four vectors for each Markov state (each state represents a MIMO channel). Markov chains are illustrated by their state frame lengths, state vector *W* and transition matrix *P*. A minimum state frame of length 1 meter is found appropriate to capture the rapid changes in the level by observations. The probability of changing from state-*i* to state-*j* (both for co- and cross polar) can be calculated as follows:

$$P_{i,j} = \frac{M_{i,j}}{M_i} \tag{12}$$

where $M_{i,j}$ is the number of transitions from state-*i* to state-*j* and M_i is the number of state frames corresponding to state-*i*. A Markov chain Monte Carlo method can create random walk through the states for co- and cross polar channels using the Metropolis-Hastings algorithm (Chib & Greenberg, 1995). Markov states are associated with each of the two channels obtained from 4 MIMO channels (2 co-polar and 2 cross-polar) resulting in 4 channels for each MIMO channel. Now Rician factor is defined using polynomial approach for large scale fading and Rician samples are generated by Rice's sum of sinusoids method (Pätzold et al., 1998). The average correlation coefficient value can be calculated on the basis of small scale MIMO channel correlation measurement data. The small scale and large scale fading time series data for each MIMO channel are added at each sampling instant to get the narrowband channel model.

A wideband channel model is constructed based on measurement campaigns and the schematic diagram of such a model is shown in Fig. 7.4 in (King, 2007). The 2x2 LMS MIMO channel matrix for this model can be written as:

$$Y_{R,L} = \begin{bmatrix} h(t,\tau)_{R,R} & h(t,\tau)_{R,L} \\ h(t,\tau)_{L,R} & h(t,\tau)_{L,L} \end{bmatrix} X_{R,L} + N_{R,L} \tag{13}$$

where $\mathrm{Y}_{\mathrm{R,L}}$, $X_{R,L}$ and $N_{R,L}$ are the received, transmitted and noise vectors, respectively. The subscripts, *L* and *R*, are used to denote the antennas polarizations at each end of the radio link. The amplitudes, propagation delays and phases of each path are randomly time varying parameters due to motion of the vehicle or the satellite. The phases of the paths are assumed to be mutually independent random variables with uniform distribution in 0 to 2π interval. All taps are considered to maintain frequency and delay domain resolution spaced *10 ns* and maximum resolvable delay is *400 ns* for the tree-line roads and urban environments and *200 ns* for the suburban environment. Large scale fading samples with correct autocorrelation and cross-correlation properties are generated for each tap using parameters obtained from the measurement data by the method similar to the narrowband model. In the case of wide band, the lognormal fading is correlated across both the MIMO domain and the delay domain. All taps in the wideband case are represented by the Markov state probability and state transition probability matrices with all taps in state 1 or in state 2 simultaneously. Each state in Markov chain is assigned a set of lognormal fading generators obtained from Gaussian random number generator with zero mean and unit standard deviation. Rician samples are generated in a similar way as for the narrowband case. The first tap of the delay line model is correlated with large scale fading level using polynomial fit. The value of K factor for remaining taps, derived from the measurement data, is lognormally distributed and independent of large scale fading level. The small scale fading generators are uncorrelated for all taps due to uncorrelated scattering effects. The small scale MIMO matrix samples are partially correlated for each delay tap. Now the small scale and large scale fading generators are combined by summing the outputs of the taps to obtain the channel impulse response time series generator.

The models described above can generate the narrowband and wideband channel models with well conserved first order, second order statistics and MIMO channel cross-correlations. However the parameters used to generate these models are based on specific measurement campaigns for particular environments. Thus, these models can be used to generate fading effects for similar types of environments which limit the application of these models for different environments.

5. Conclusion

This chapter presented an overview of standard MIMO channel models for LMS radio communication systems. Standard channel models play a vital role in the design and performance assessment of advanced transceivers techniques and smart antennas employed to establish reliable communication links in LMS communication systems.

The quality of service and spectral efficiency in a LMS communication system suffer from limited transmit power, high path loss, blockage, shadowing and high link delay. In order to overcome these effects by employing MIMO techniques to enhance LMS performance, physical-statistical MIMO channel models including 3D polarization concept are developed. The ray-tracing algorithm is used which can model small and large fading effects in an efficient way and can cover large coverage areas for satellites systems. The physical-statistical channel models with multiple satellites and/or dual polarized antenna configurations can be simulated under different propagation environments and satellite elevations and show significant improvements in capacity and link reliability. Analytical channel models are developed to investigate the effects of MIMO techniques on capacity improvement and interference mitigation in LMS systems. The empirical-statistical MIMO channel models (narrowband and wideband) are constructed around experimental data. These channel models can generate the narrowband and wideband channel models with well conserved first order, second order statistics and MIMO channel cross-correlations. However, these models have some limitations since they are built from experimental data obtained from specific measurement campaigns for particular environments, they can be used to generate fading effects for similar types of environments which limit the application of these models for all environments.

The MIMO channel models for LMS systems are built and validated using some available experimental data and the data obtained from measurement campaigns. These channel models need to be refined to discover realistic hybrid physical-statistical channel models and satellite to indoor channel models using the data acquired from experimental campaigns that have been done or still going on in urban, sub-urban, rural, forest or indoor areas at L, S and C band and also the data gathered from Earth Observation systems. The spatial characteristics in multi-antenna channel modelling including polarization effects (especially 3D polarization) are expected to be crucial in future LMS communications systems. Thus, new and improved hybrid physical-statistical channel models, satellite-to-indoor propagation models and propagation impairment mitigation techniques based on multiple antennas techniques are necessary to assess the parameters and performance of satellite communication systems. The MIMO channel models for LMS/HAPs and indoor propagation environments employing compact antennas including 3D polarization concept based on different measurement campaigns and using the multiple antenna features similar to terrestrial communications systems will be the topic of interest for future satellite communication systems.

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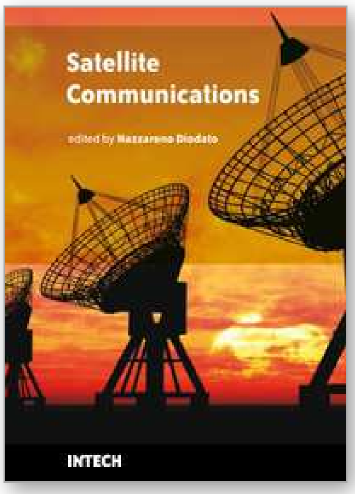

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This study is motivated by the need to give the reader a broad view of the developments, key concepts, and technologies related to information society evolution, with a focus on the wireless communications and geoinformation technologies and their role in the environment. Giving perspective, it aims at assisting people active in the industry, the public sector, and Earth science fields as well, by providing a base for their continued work and thinking.