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Statistical Modeling of LEO Dual-Polarized MIMO Land Mobile Satellite Channels

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Abstract: This paper addresses a model for statistical simulation of narrow-band dual polarized Multi input Multi output (MIMO) land mobile satellite (LMS) channel for low earth orbit (LEO) satellites. It considers the change of the satellites elevations and hand over from one satellite to another during the same communication session. It introduces a detailed description and block diagrams to generate the time series signals with the desired power, probability distribution, covariance relations and spectrum. The simulation results are useful for the design of MIMO-LMS data communication systems.

I. Introduction

Satellite communication is facing a number of challenges due to limited available spectrum and prohibited power levels. While on the other hand there is an increasing demand for higher data rates and better quality of service. The successes of the MIMO in increasing the capacity of the terrestrial communication without the need of additional power or spectrum was a greet motive to investigate the nature of the MIMO channel in LMS communication. The dual polarized MIMO is considered as one of the most applicable methods to obtain the MIMO gain in LMS communication and overcome the rank deficiency in the LMS-MIMO channel matrix due to the line of site (LOS) nature of the channel and the absence of the scatters near the satellite [1].

The statistical model of narrow band and wide band dual polarized MIMO-LMS channel based on experimental results for low elevation satellites are investigated in a number of researches [2,3], and a statistical model for dual polarized MIMO-LMS are investigated in [1] based on experimental results for single input single output (SISO) LMS and extrapolated them to MIMO-LMS. Paper [4] presents a basic principle for statistical modeling LMS channel that can be used for studying single input single output (SISO) links with geostationary as well as non geostationary satellites, however much work is still required to model and simulate the MIMO-LMS channel .

This paper presents the model that simulates a complete scenario for LEO-LMS in the case of dual polarized MIMO channel. The main different between LEO satellites and the geostationary

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satellites is that the LEO satellite elevation angle (ϕ) and distance from the mobile station (d) is always changing during the communication session. The change in the distance (Δd) leads to changes in the received power and phase of the received signal while the change in the elevation leads to changes in the probability of being a line of site (LOS) or shadowed condition which is described by Markov chain (will be described lately), another main different is that the communication link may be handed over from one satellite to another during the same communication session.

The paper is organized as follows: Section II describes the channel model for dual polarized 2x2 MIMO-LMS, section III is concerned with the simulation model for dual polarized 2x2 MIMO-LMS channel, section IV provides the simulation results and section V concludes the paper .

II. The Channel Model

The dual polarized 2x2 MIMO LMS channel matrix (H) can be expressed as the sum of 2x2 direct LOS channel matrix ($\bar{\mathrm{H}}$) and a 2x2 multipath channel matrix ($\tilde{\mathrm{H}}$) as shown in figure 1

$$\mathbf{H} = \bar{\mathbf{H}} + \tilde{\mathbf{H}} \tag{1}$$

Each of the 4 elements of the H matrix (h_{ij}) is a complex random variable (RV) that represents a SISO channel
where:

$$\mathrm{h}_{\mathrm{ij}} \begin{cases} \text{complex copolar channel element} & \mathrm{i} = \mathrm{j} \\ \text{complex crosspolar channel element} & \mathrm{i} \neq \mathrm{j} \end{cases} \qquad (i, j = 1, 2.)$$

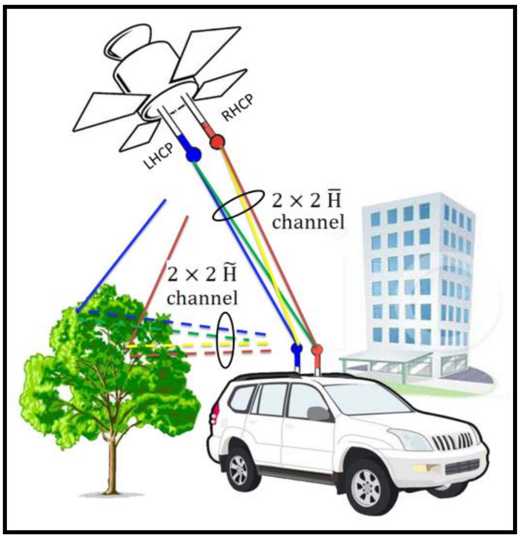

Figure 1. System configuration of dual-polarization MIMO-LMS system.

The SISO channel element h_{ij} can be simulated using the Loo model [5] by adding a direct LOS complex element ($\bar{\mathrm{h}}_{\mathrm{ij}}$) to a multipath complex element ($\tilde{\mathrm{h}}_{\mathrm{ij}}$), where ($|\bar{\mathrm{h}}_{\mathrm{ij}}|$) is log-normally distributed with dB mean and dB slandered deviation (α, ψ) respectively and ($|\tilde{\mathrm{h}}_{\mathrm{ij}}|$) is Rayleigh distributed with dB average power (**MP**), where ($\boldsymbol{\alpha}, \boldsymbol{\psi}$ and MP) are the Loo statistical parameter triplet experimental data set which is first presented in [4].

III. Simulation Model

In this section we will describe in details the steps of generating a time series for LEO-LMS dual polarized MIMO channels with the desired power, rate and covariance relations. The whole model is summarized as a block diagram in figure 2 and each block in this diagram will be described in detail in the next subsections.

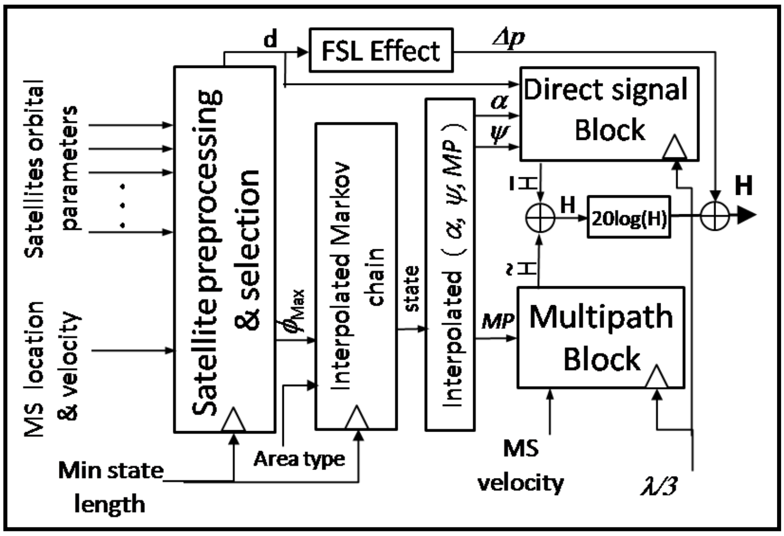

Figure 2. Block diagram for the model

A. Satellite preprocessing and selection

This block is a subprogram that takes mobile station (MS) location and the orbital parameters of all the LEO satellites in the system as inputs and predicts the satellites paths and calculates the elevation angle of each satellite as seen from the MS, then it will chose the satellite that will establish the link, and it is assumed for simplicity in this paper that, it is the satellite with the max elevation angle (φ_{max}) as shown in figure 3. The output of this block is the elevation angles of the selected satellite φ_{max} with its distance from the MS.

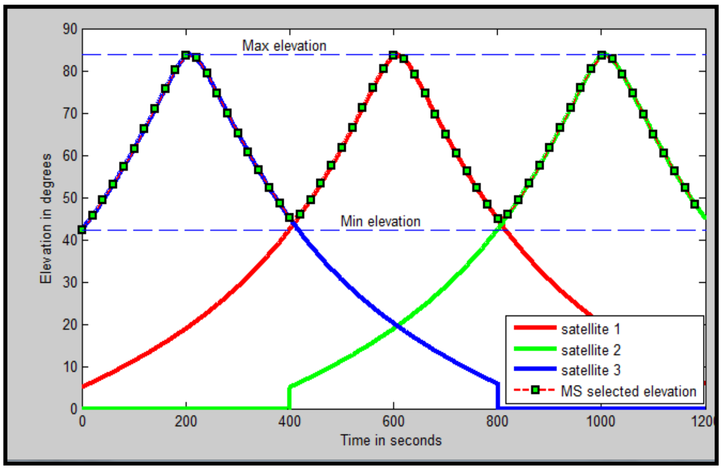

Figure 3. The change in φ during time for 3 satellites and the selected satellite to establish the link

B. Interpolated Markov chain

The Markov chain is used to account for the changes due to different shadowing conditions (e.g., if the MS goes from clear LOS to behind a tree or a building) the model uses 3 state Markov chains that represent:

- State 1: line of sight (LOS) conditions
- State 2: moderate fading conditions
- State 3: deep fading conditions

The three states Markov chain is described by 3x1 state probability matrix (**W**) and 3x3 state transition probability matrix (**P**). The **W** and **P** matrices are calculated for each shadowing condition from intense measurements and tabulated according to the antenna type. The environment of the MS, the used frequency and the satellite elevation angle (φ), the first three parameters will be considered constant during the communication session but the elevation angle is always changing and it will be taken from the previous block. The **W** and **P** matrices which can be written as **W(φ)** and **P(φ)** can be found in [4] but for φ with step of 10 degree which means that the effect of the change in satellite elevation will be taken in account every 10 degrees which will make sharp changes in the data in order to avoid this we will interpolate **W(φ)** and **P(φ)** to predict there values for φ steps of one degree. The Markov chain has three important properties which are:

- The sum of all elements in every **P** row equals one.
- The sum of all elements in matrix **W** equals one.
- The asymptotic behavior (convergence property) of the Markov chain is defined by the relation PW=**W**.

While interpolating the **p(φ)** and **W(φ)** matrices, it is important to preserve these three properties and so the predicted values of the **p(φ)** and **W(φ)** may be shifted slightly to satisfy the properties. It was found that the linear interpolation will need few or no data shifting rather than polynomial interpolation which will provide smother data transition but will take more effort to sustain the properties. The output of this block is simply one of the three states that represent the shadowing conditions.

C. (α, ψ and MP) interpolation

Based on experimental results the (α, ψ and MP) parameters of each shadowing are tabulated and categorized according to the antenna type, the environment of the MS, the used frequency, the satellite elevation angle (φ). We can consider all these parameters constant during the communication session except the last parameter. Knowing the elevation angle from the 1st block and the shadowing condition from the 2nd block, we can easily select the value of (α(φ) , ψ(φ) and MP(φ)) from the tables. But since the table contains the values of these parameters only for φ step of 10 degrees, we will use the interpolation to predict their values for φ steps of one degree; the interpolated parameters are shown in figure 4.

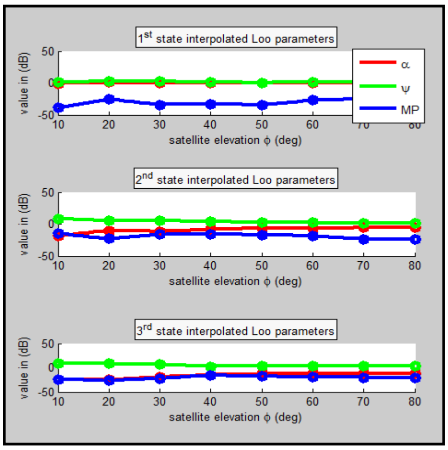

Figure 4. Interpolated (α, ψ and MP) parameters.

D. The multipath signal block

The multipath signal block is shown in figure 5, its function is to generate the small scale channel matrix $\tilde{H}$ matrix, the elements of this matrix denoted by $\tilde{h}_{ij}$ (i, j =1, 2.) are correlated zero mean complex Gaussian RV of variance$\sigma_{ij}{}^2$.

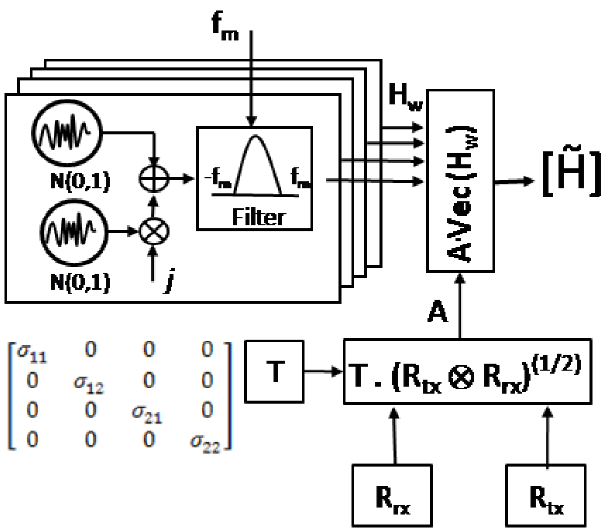

Figure 5. The Multipath signal block

The absolute values of the elements of complex Gaussian $\tilde{H}$ matrix elements ($|\tilde{h}_{ij}|$) are Rayleigh distributed we can apply the following equation

$$E\{|\tilde{h}_{ij}|^2\} = 2\sigma_{ij}{}^2 \qquad (2)$$

In the SISO channel, the MP parameter is equal to the average multipath signal power, in the 2x2 MIMO channel due to channel normalization, we can consider that output multipath power from each transmitter equals mp

$$\sum_{j=1}^{2} E\{|\tilde{h}_{ij}|^2\} = mp, i = 1, 2 \tag{3}$$

where: mp is expressed in linear scale not dB.

Due to the cross polarization discrimination of the multipath signal ($\widetilde{XPD}$) effect, the channel elements must satisfy the following equation:

$$\widetilde{XPD} = \frac{\text{copolar power}}{\text{crosspolar power}} = \frac{E\{|\tilde{h}_{ii}|^2\}}{E\{|\tilde{h}_{ij}|^2\}} \tag{4}$$

where: $\widetilde{XPD}$ is expressed in linear scale not in dB and it is not related to the antenna only but also to the environment [1,6].

From (2), (3) and (4) we can get that

$$\sigma_{ij}{}^2 = \begin{cases} \frac{MP(\widetilde{XPD})}{2(1+XPD)} & i = j \\ \frac{MP}{2(1+\widetilde{XPD})} & i \neq j \end{cases} \tag{5}$$

Due to the angular spread of the multipath components and the co-location of multiple antenna elements at the base station and mobile station the small-scale fading components suffer from polarization correlation,

In order to obtain a correlated complex Gaussian matrix $\tilde{H}$ that have a convarience matrix ($\tilde{C}$). This can be done by first generating a 2x2 $\tilde{H}_w$ matrix with independent identically distributed (i.i.d.) zero mean and unite variance complex Gaussian elements and then apply the following equation to form the correlation relations between the channel elements.

$$vec(\tilde{H}) = \tilde{C}^{(1/2)}.vec(\tilde{H}_w) \tag{6}$$

We can consider the multipath channel separable and according to The **Kronecker** model [6], we can find $\tilde{C}$ by knowing the transmit and receive covariance matrices (R_{tx}, R_{rx}) respectively from the following equation

$$\tilde{C} = (R_{tx} \otimes R_{rx}) \tag{7}$$

where: $\otimes$ denotes the Kronecker product operator, each of R_{tx} and R_{rx} is a 2x2 normalized (unity diagonal) covariance matrix and Polarization correlation coefficient ρ_{tx} and ρ_{rx} respectively. The values of ρ_{tx} and ρ_{rx} are obtained from experimental results.
In order to obtain the desired power properties of the channel as described in (3) and (4), we can redefine equation (6) to be

$$\mathrm{vec}\left(\tilde{\mathrm{H}}\right) = \mathrm{T}.\left(\mathrm{R}_{\mathrm{tx}} \otimes \mathrm{R}_{\mathrm{rx}}\right)^{(1/2)}.\mathrm{vec}\left(\tilde{\mathrm{H}}_{\mathrm{w}}\right) \qquad (8)$$

$$\mathrm{T} = \begin{bmatrix} \sigma_{11} & 0 & 0 & 0 \\ 0 & \sigma_{12} & 0 & 0 \\ 0 & 0 & \sigma_{21} & 0 \\ 0 & 0 & 0 & \sigma_{22} \end{bmatrix} \qquad (9)$$

where: σ_{ij}(i, j =1, 2) can be obtained from (5)

E. The direct signal block

The direct signal block is shown in figure 6, its function is to generate the large scale channel matrix $\bar{\mathrm{H}}$. The magnitude of the elements of $\bar{\mathrm{H}}$ matrix denoted by $|\bar{h}_{ij}|$are correlated log-normal random variables each with parameters (α_{ij}, ψ) in dB as mean and standard deviation of the generating Gaussian random variables. Where $(\alpha, \psi)$are the Loo parameters described previously and obtained from (α, ψ and MP) interpolation block and α_{ij} is calculated by shifting α with a certain calculated dB value to account for the direct LOS cross polarization discrimination ($\overline{\mathrm{XPD}}$) and channel normalization and it can be given by equation (10).

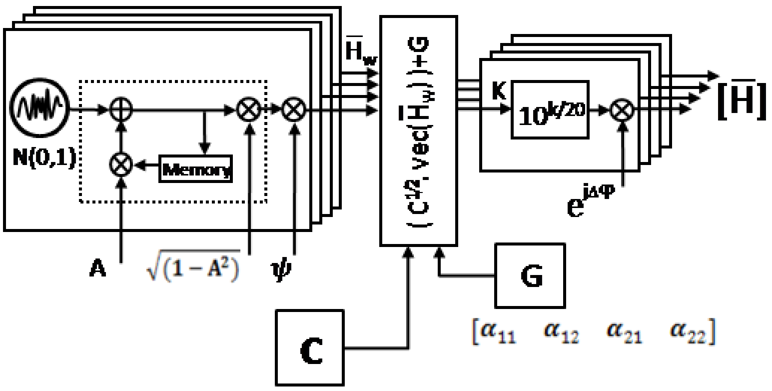

Figure 6. The Direct signal block

$$\alpha_{ij} = \begin{cases} \alpha + 20.\log\left(\sqrt{\dfrac{\overline{XPD}}{(1+\overline{XPD})}}\right) & i = j \\ \alpha + 20.\log\left(\sqrt{\dfrac{1}{(1+\overline{XPD})}}\right) & i \neq j \end{cases} \qquad (10)$$

where: $\overline{\mathrm{XPD}}$ is expressed in linear scale.

In the case of the LMS the small distance between each of the two antennas on the satellite with each other and the two antennas on the land with each other leads to high correlation values between the elements of the large scale channel matrix. In order to obtain the correlated log-normal distribution $\bar{\mathrm{H}}$ matrix, we first generate a 2x2 $\overline{\mathrm{H}}$w matrix with i.i.d. zero mean and unite variance Gaussian elements then change it to a correlated Gaussian matrix ($\overline{\mathrm{H}}_{\mathrm{G_corr}}$) by applying the following equation

$$\mathrm{vec}\left(\overline{\mathrm{H}}_{G\_corr}\right) = \overline{\mathrm{C}}^{(1/2)} .\ \mathrm{vec}\left(\overline{\mathrm{H}}_{w}\right) \tag{11}$$

where $\overline{\mathrm{C}}$is 4x4 large scale correlation matrix and typical values for the $\overline{\mathrm{C}}$ matrix can be found in [2] based on extensive experimental results. After that change $\overline{\mathrm{H}}_{G\_corr}$ to a correlated lognormal matrix $\overline{\mathrm{H}}$ with the wanted $\overline{\mathrm{XPD}}$and normalization parameters by applying the following equation:

$$\mathrm{vec}\left(\left|\overline{\mathrm{H}}\right|\right) = 10^{[\mathrm{vec}\,(\overline{\mathrm{H}}_{G_{corr}}).\psi)+G]/20} \tag{12}$$

where: G is a 1x4 matrix described as follows

$$G = [\alpha_{11}\alpha_{12}\alpha_{21}\alpha_{22}] \tag{13}$$

and α_{ij} are obtained from (10).

The$\left|\overline{\mathrm{H}}\right|$ matrix obtained from (12) is then changed to a complex $\overline{\mathrm{H}}$ by applying equation (14)

$$\left|\overline{\mathrm{H}}\right| = \overline{\mathrm{H}}\,.\,e^{j\Delta\theta} \tag{14}$$

where: $\Delta\theta = 2\pi\Delta d/\lambda$

F. Free space loss block

The values of the Loo parameters (α, ψ and mp) are normalized by removing the effect of the free space losses (FSL). The effect of the power changes due to the change in the satellite distance(d), is simulated by adding a dB value (Δp) to the decibel sum of the direct LOS channel and the multipath channel. In order to calculate Δp , we will assume that the channel is normalized at a certain distance (dn), which means that when the satellite is at this distance Δp=0 and if it is at a distance greater than dn Δp will be negative and vice versa, Δp can be calculated from the next formula

$$\Delta p = 20\log\left(\frac{d_n}{d}\right) \tag{15}$$

Figure 7 Shows the change in Δp due to the changes in d where dn is considered the minimum satellite distance from the MS.

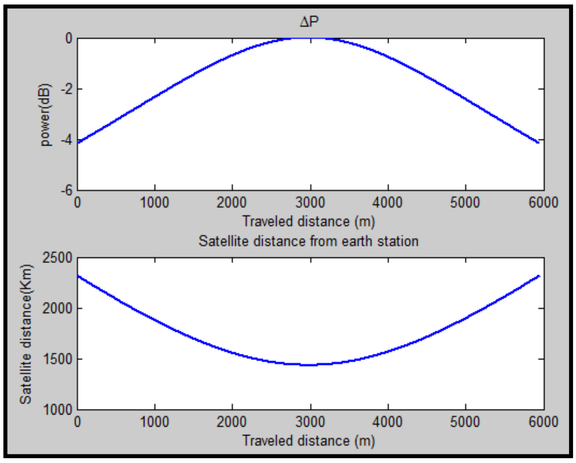

Figure 7. The change in satellite distance from the MS and the change in FSL.

G. Triggering and filtering

As described in [4] the LMS channel suffers from three types of shadowing variations:

a) Very slow variations: they are variations due to shadowing condition changes. They are simulated using the Markov chain which is characterized by its minimum state length and its value must be taken from the accompanied data that comes with the Markov tables. A value of 3–5 meter was observed in [4] and of 1 meter in [2].
b) Slow variations: they are the small-scale changes in direct signal component. They are log-normally distributed. They are simulated by the LOS block and this variations is characterized by correlation distance (L_{corr}) of (1-3) meter as observed in [4].
c) Fast variations: they are variations of the diffused multipath component which are characterized by the maximum Doppler spread frequency $f_m = (v/\lambda)$ where v is the speed of the mobile station and λ is the wave length of the signal.

IV. The Simulation Results

A. Simulation steps

In order to simulate and combine these three different rates of variations the following steps are followed:

a) The Markov chain sample spacing is set to its minimum state length. The output sample spacing of the (α, ψ and mp) interpolation block will be decreased by repeating the original samples to generate new intermediate samples with sample spacing equals to$(\lambda/3)$meter which is sufficient sample spacing for the next steps.

b) The multipath block engine will generate the samples with spacing equals to$(\lambda/3)$maters. These samples will then be filtered using a Butterworth filter in order to reshape its spectrum and reduce its maximum frequency to f_m as shown in figure 3.

c) The direct signal block must have the same sample spacing $d_s$as the multipath block (since they will be added together) in order to force them to have a correlation distance equals to L_{corr} . The samples must go throw first order recursive linear time-invariant digital filter [1] with the following difference equation:

$$y_n = x_n + Ay_{n-1} \tag{16}$$

where: $A = \exp(-d_s/L_{corr})$

The filtered samples are then multiplied by $\sqrt{1 - A^2}$ in order to restore the original mean and variance of the samples before the filtering as shown in figure 4.

B. Simulation output

This section presents the model output for the parameters in Table I.

Figure 8 shows the simulated time-series signal received from the low earth orbit satellite assuming that the satellite path is like that shown in figure 7. And the power degradation at the beginning and the end of the session with respect to its middle is due to the satellite varying distance from the MS.

Figure 9 is a closer look on the model output that shows the effect of the different Markov states on the signal power and variations.

TABLE I: Parameters used in the model

Parameter	value
Operating frequency	2.2GHz
MS speed	50km/h
Satellite orbit	LEO
Satellite elevation	10^0 - 88^0
Environment type	urban
$\overline{XPD}$	15dB
$\widetilde{\text{XPD}}$	4.629dB
ρ_{tx} , ρ_{rx}	0.5 , 0.5
$\overline{\mathbf{C}}$	$\begin{bmatrix} 1 & 0.86 & 0 & 0.92 \\ 0.86 & 1 & 0.89 & 0.85 \\ 0.86 & 0.89 & 1 & 0.93 \\ 0.92 & 0.85 & 0.93 & 1 \end{bmatrix}$

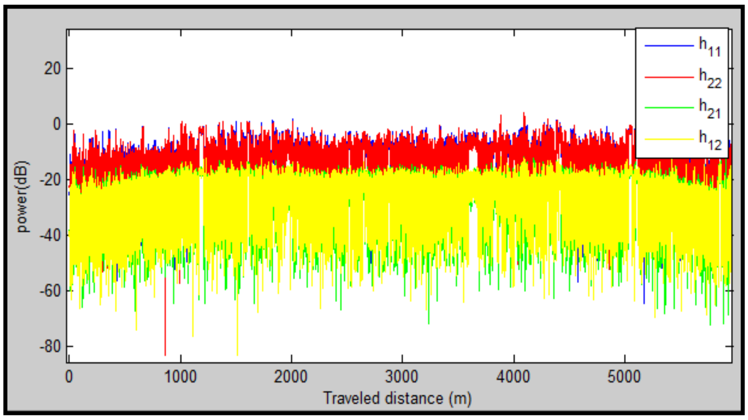

Figure 8. Simulated time-series signal received

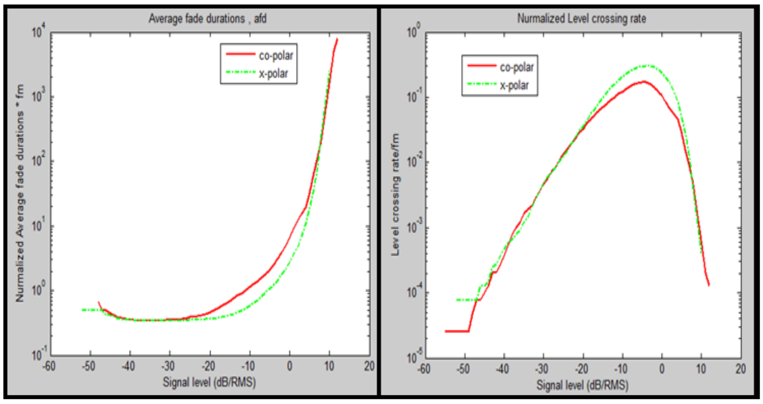

Figure 9. Simulated time-series signal and the different Markov states.

Figure 10 shows the normalized average fade duration and level of crossing rate with respect to the maximum Doppler spread frequency for the simulated signal.

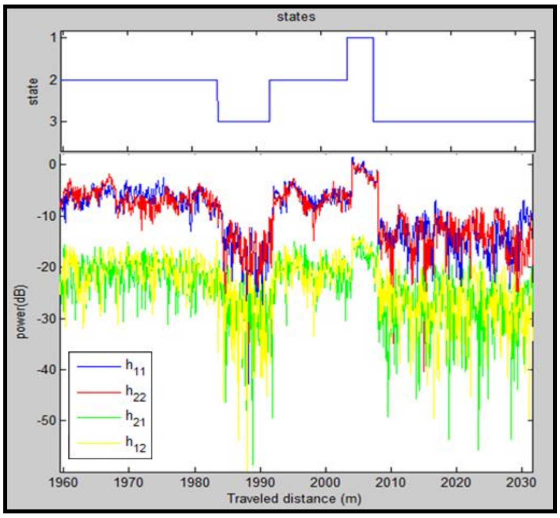

Figure 10. Normalized average fades duration and level of crossing rate 0f the simulated signal.

V. Conclusions

This paper presented a statistical channel model for simulating LEO dual-polarized MIMO-LMS channel and introduces detailed block diagrams and procedures for this simulation. All the values and the filters used in this model can easily be modified for further tuning to adapt the model to simulate different satellite scenarios, environmental conditions and Antenna types, this simulation can be useful in designing the dual-polarized MIMO systems over LMS and on investigating its gain.

VI. References

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