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Land Mobile Satellite Dual Polarized MIMO Channel along Roadside Trees: Modeling and Performance Evaluation

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Abstract—We present a novel physical-statistical, generative model for the land mobile satellite (LMS), dual polarized, multiple-input-multiple-output (MIMO) channel along tree sided roads. Said model is parameterized by means of a physical model based on the Multiple Scattering Theory (MST) which accounts for the signal attenuation and scattering by trees. Moreover, Finite-Difference Time-Domain (FDTD) electromagnetic computations were performed to characterize the scattering pattern of an isolated tree, and to calculate the MIMO shadowing correlation matrix required by the model, and not provided by MST. This modeling framework also encompasses the single-input-multiple-output (SIMO)/space diversity case. To illustrate the capabilities of the developed model, time series were generated and used in system performance calculations. The obtained results give an insight into the advantages of dual polarized MIMO and SIMO/space diversity techniques in these very frequent scenarios, and may help service providers in evaluating the technical feasibility of such systems.

Index Terms—LMS MIMO, diversity, signal fading, vegetation.

I. INTRODUCTION

The true broadcast nature of satellite-based mobile communication systems offers great advantages for delivering multicast and broadcast services to both populated and isolated areas. However, due to the high path loss, limited satellite power, and other impairments, current land mobile satellite (LMS) systems show lower capacities and availabilities than those of terrestrial systems [1]. Their performance can be increased using multiple-input-multiple-output (MIMO) techniques, and may help service providers in evaluating the technical feasibility of such systems.

Attenuation and fading due to vegetation depends on a range of factors such as tree type, whether the trees are in-leaf or out-of-leaf, whether the trees are dry or wet, the frequency band, the path length through foliage, etc. [2]. A single-input-single-output (SISO), roadside tree LMS channel model which takes into account the signal fading caused by position-dependent tree scattered fields and by swaying tree components due to wind was reported in [3] and [4]. Fade mitigation techniques (FMTs) such as MIMO might be used to counteract the signal fading caused by vegetation. Availability of realistic channel time series and detailed knowledge of their correlation properties are needed for performing accurate simulations [5]. Several studies on terrestrial MIMO systems can be found in the literature, while studies on LMS MIMO are rather limited, among them are [1], [6]–[9].

In this paper, we present a novel physical-statistical, generative channel model for the roadside tree, LMS, dual polarized MIMO channel which includes as a special case the single-input-multiple-output (SIMO) case. Figure 1 shows the considered propagation scenario where a mobile terminal receives partially correlated co- and cross-polar, right and left hand circular polarized (RLHCP) tree scattered fields from both sides of the road. The wanted model requires parameterization; this is achieved by means of a physical model based on the Multiple Scattering Theory (MST) [10]–[12]. This technique is used to estimate the signal attenuation and scattering by a single tree. MST assumes a uniform distribution of scatterers in both azimuth [0, 2π] and elevation (0, π/2) [3], [4], [13]. This assumption makes it impossible to quantify spatial effects such as the cross-correlation of the shadowing affecting the direct signal reaching the receive antennas. To overcome this, Finite-Difference Time-Domain (FDTD) electromagnetic computations were performed to accurately calculate the MIMO shadowing correlation matrix. In addition, calculated tree scattering patterns are also shown which coincide with results obtained using MST.

To show the potential of the proposed physical-statistical, generative model, examples of performance evaluation for SISO, SIMO and MIMO configurations were carried out using synthesized time series. The results give an insight into the advantages of polarization MIMO and SIMO/space diversity techniques, and may be used in assessing the technical feasibility of LMS systems in roadside tree scenarios.

The paper begins in Section II by presenting the FDTD
Two scenarios were investigated: the far-field scattering pattern and the total field in a straight line along the y-axis behind the tree (see the dashed line in Fig. 2). Two runs of the FDTD tool were performed, one with a vertical and the other with a horizontal polarized incident wave. These were then combined to yield circularly polarized signals. A Gaussian pulse was used as the source field. A near-to-far-field transformation was performed to calculate the far-field scattering pattern.

Figs. 3 and 4 show the normalized far-field scattering pattern of the co- and cross-polar components of the RHCP and LHCP signals at 2 GHz, respectively. The results are obtained by rotating the observation point $360^\circ$ around the tree as shown in Fig. 2, where zero deg. represents the line-of-sight (LOS) path between the satellite and the mobile terminal (through the tree). We can observe that the scattering patterns of the co-polar components have a forward lobe with an isotropic background, the same as with MST, as reported in [3] and [4], or the Radiative Energy Transfer, RET, as reported in [16].

Fig. 5 shows the total received field along a straight line parallel to the y-axis behind the tree for the co- and cross-polar components of the RHCP and LHCP signals. The points at the start (before 0 m) and at the end of the straight line (after 2.64 m) are not blocked (LOS conditions) toward the source while the rest are shadowed by the tree (the tree is located between 0 to 2.64 m along y-axis). The fields along the straight line are passed through a running average filter (with ten point window size) for calculating the large-scale fading (shadowing) effects caused by the tree, see Fig. 6.

As we move along the positive y-axis direction, we can observe from Fig. 6 the change of state due to tree shadowing i.e., LOS-shadowing-LOS. Table I shows the MIMO shadowing (large scale fading) correlation matrix, $R_p$, calculated using the mentioned filtered FDTD series at 2 GHz. In Table I, R/R refers to the co-polar signal from a RHCP transmit antenna to a RHCP receive antenna, R/L refers to the cross-polar signal from a RHCP transmit antenna to a LHCP receive antenna, and so on.

Note that the FDTD results presented in this section are only applicable when the tree is in leaf. There exist many very different tree configurations and the shadowing cross-correlation may vary dramatically from tree to tree. This is an issue which requires further investigation, to be carried out at a later time, the main aim of this paper being the description of the physical-statistical model discussed next and how such model can be parameterized.

![Diagram of the propagation scenario for the LMS dual polarized MIMO: a mobile terminal receives correlated co- and cross-polar (R/LHCP) tree attenuated and scattered fields from both sides of the road.](image)
Fig. 2. FDTD computation zones and boundary conditions. Cell size of 1 cm and total cells of 56461383 are used.

Fig. 3. Scattering patterns of the co- and cross-polar components of the RHCP signal at 2 GHz.

III. PHYSICAL-STATISTICAL, GENERATIVE ROADSIDE TREE LMS DUAL POLARIZED MIMO CHANNEL MODEL

Here a family of physical-statistical, generative models for LMS roadside tree environments is presented, starting with the SISO model and going on to present the SIMO and, finally the MIMO models.

Physical-statistical models are deemed more accurate than purely statistical ones as they take into account the geometry of the link(s), while they rely on physical (electromagnetic-based) methods for calculating the needed model parameters. The underlying assumption made in this family of models is that the received signal is composed of the direct component which may be subjected to shadowing and accompanied by so-called coherent component fluctuations, and the multipath

Fig. 4. Scattering patterns of the co- and cross-polar components of the LHCP signal at 2 GHz.

Fig. 5. Time series of the co- and cross-polar components of the RHCP and LHCP signal at 2 GHz.

Fig. 6. Shadowing time series of the co- and cross-polar components of the RHCP and LHCP signal at 2 GHz.
component due to diffuse scattering, i.e., a Ricean channel. Thus we implement a statistical random number generator fitting a Rice distribution whose parameters are changing as the terminal travels through a propagation environment described in terms of simple, canonical volumetric forms representing trees. Also time variations are taken into account, as mentioned earlier, especially for stationary terminals.

The two Rice distribution parameters (direct signal amplitude and multipath power) are calculated using MST: the direct signal is affected by the specific attenuation of the tree canopy provided by MST once the geometrical path through the canopy is worked out for the different terminal route positions. The second component, the multipath power, is also parameterized by means of MST which provides the average coherent and incoherent scattered powers, these are mapped to the relevant Rice distribution parameter, also taking into account the possible paths through and off the tree canopies on both sides of the street.

At least two alternatives are possible for generating locally Ricean time series: one is using a point-scatterer approach (used in the current SISO and SIMO implementations) and the other is by filtering complex random Gaussian series. The latter option has been selected for implementing the MIMO channel.

A. LMS SISO channel model

A SISO model/simulator was reported by the authors in [3] and [4]. The model uses MST as described in [10]–[13] with modifications to account for slant paths and circular polarization. In the model, the tree canopy is modeled as a vertically oriented cylindrical volume, V, in a rectangular coordinate system defined by the orthonormal vectors, x, y and z. The canopy volume contains randomly distributed and oriented leaves and branches. Leaves are modeled as thin lossy dielectric disks, branches as finite lossy dielectric cylinders and the trunk as a finite lossy dielectric cylinder, see Fig. 7.

The SISO model generates the position-dependent signal fading by calculating the total coherent (the sum of coherently scattered and free-space field) and incoherent tree scattered fields. The phase variations in the scattered signal are accounted for using a point-scatterer approach, where the contribution from each tree is assumed to originate from a point in the center of the canopy from which the distance dependent phase variations for the various route sampling points are calculated.

In addition, the signal fading due to wind swaying is accounted for by modeling the tree components as masses attached to springs. The position-dependent fading and the signal fading due to tree swaying are then combined to give the overall signal fading caused by vegetation. The model is applicable for different polarizations and elevation angles, and was validated in terms of first and second order statistics using measurements at 2 GHz, see [3] and [4] for more details.

B. SIMO receiver space diversity

The previously described SISO channel model can easily be extended to the SIMO/space diversity case. The model is again based on the physical-statistical tree model (see Fig. 7) reported in [3] and [4] and MST. The considered propagation scenario is shown in Fig. 8: two antennas with the same polarization separated by a given distance are receiving tree attenuated and scattered co-polar signals from each side of the road. The fades at each antenna element, h_{total}(t), are generated by taking into account the tree scattered fields from each side of the road as well as the LOS field, given by

\[
\begin{align*}
    h_{\text{side1}}(t) &= \sum_{m=1}^{S_1} \sum_{n=1}^{N} A_{\text{diff1},mn}(t) \frac{\exp\{j(\phi_{mn} + kd_{mn}(t))\}}{d_{mn}(t)} \\
    &+ A_{\text{coh1},mn}(t) \frac{\exp\{j(\phi_{mn} + kd_{mn}(t))\}}{d_{m}(t)} \\
    &+ A_{\text{LOS},mn}(t) \frac{\exp\{j(\phi_{mn} + kd_{mn}(t))\}}{d_{m}(t)} \\
    h_{\text{side2}}(t) &= \sum_{n=1}^{N} \sum_{w=1}^{S_2} A_{\text{diff2},mn}(t) \frac{\exp\{j(\phi_{wn} + kd_{wn}(t))\}}{d_{wn}(t)} \\
    h_{\text{total}}(t) &= h_{\text{side1}}(t) + h_{\text{side2}}(t)
\end{align*}
\]

where S_1 and S_2 are the number of trees on each side of the road, N is the total number of scatterers in a single tree and k is the wavenumber. Note here how the overall scattered signal from one single tree has now been split into N components, provided that the link budget of the scattered power and the MST constraints are preserved. This shows a possible way toward a wideband model. Parameters A_{\text{diff}}(t) and A_{\text{diff2}}(t) are the amplitudes of the incoherent scattered components from side one (satellite side) and side two (opposite side) of the road, respectively. Parameters A_{\text{coh}}(t) and A_{\text{LOS}}(t) are the amplitudes of the coherent scattered field (side one) and the LOS field, respectively. The coherent and incoherent scattered fields can be estimated from the physical-statistical tree model reported in [3] and [4]. Parameters \phi and d(t) are the initial phase and path length of each signal component, respectively.
The coherent and incoherent scattered fields as well as the LOS field are received from one side of the road, see (1), while only the incoherent scattered fields are received from the other side of the road, see (2). These are combined to produce the signal received at each antenna position, see (3) and Fig. 8.

The resulting simulated correlation coefficient versus antenna separation distance for the small scale fading (absolute values) is shown in Fig. 9 (for two co-polar RHCP antennas). As expected, we can observe that the correlation coefficient decreases with increasing antenna separation distance. The resulting simulated correlation coefficient was also fitted to the square of the zero order Bessel function of the first kind, $(J_0(2\pi d/\lambda))^2$ where $d$ is the relative separation distance and $\lambda$ is the wavelength, see the dashed line in Fig. 9. It can be seen that the fit between the two curves is quite good. Thus, a model based on the zero-th order Bessel function of the first kind could be used to model the correlation coefficient of the small scale fading in roadside tree LMS SIMO/space diversity channel. Fig. 10 shows examples of simulated received signal time series on the two antennas (RHCP co-polar antennas) for a separation distance of one wavelength. It can be seen that the time series have similar large scale fading characteristics but relatively decorrelated small scale fading due to the separation distance between the two antennas.

C. LMS dual polarized MIMO channel model

The SISO channel model discussed in Section III-A can be extended to the MIMO case by taking into account the correlation between the co- and cross-polar channels. Table I gives the MIMO correlation matrix for the large scale fading obtained using FDTD. The correlation matrix for the small scale fading (multipath), $R_s$, can be found by assuming independent multipath fading on the MIMO channels as reported in [1] and [17]. As previously indicated, the underlying assumption is a set of locally Ricean processes whose parameters are slowly-variant along the traveled route. The slow fading correlation properties are then imposed on the direct signal component of the Rice process and the fast variation correlation properties are imposed on the multipath component.

The proposed model for the roadside tree LMS dual polarized MIMO channel is presented in Fig. 11. In the model, the correlated processes which are the inputs to the shadowing filter (see Fig. 11) are given by

$$I(t) = C_l n_l(t)$$

where $I(t) = [l_1(t) \ldots l_4(t)]^T$ are partially correlated processes. $n_l(t) = [n_{1l}(t) \ldots n_{4l}(t)]^T$ are independent real-valued white Gaussian processes with zero mean and unit variance. $C_l$ is the Cholesky decomposition of $R_l$.

The complex white Gaussian processes, $n_{si}(t)$, for $i = 1 \ldots 4$ are filtered (according to [18]) for Doppler spectrum shaping ($H_{di}(z)$ is the Doppler filter), see Fig. 11. The resulting time series are then multiplied by the standard deviation of the non-coherent component of each channel, $\sigma_i(t)$ (estimated by means of MST [3] and [4]), to produce the small scale fading. Similarly, the partially correlated processes, $l_i(t)$, are
low-pass filtered by a shadowing filter with transfer function given by [19]
\[ H_s(z) = \sqrt{1 - b^2} \]
with
\[ b = \exp \left( - \frac{d_{st}}{L_{corr}} \right) \]
where \( d_{st} \) is the sampling distance and \( L_{corr} \) is the correlation distance. Note that shadowing is only applied to the coherent part [19]. \( H_s(z) \) can slightly differ between the co- and cross-polar shadowing channels [1]. Thus, the filtering step can modify the correlation coefficient between two channels. To deal with this effect, \( \mathbf{R}_t \) can be weighted by a correction coefficient prior to taking its Cholesky factorization [17]. The correction coefficient is given by [17]
\[ C_{ correct} = \frac{1 - b_{co} c_{cross}}{\sqrt{1 - b_{co}^2} \sqrt{1 - c_{cross}^2}} \]
where \( b_{co} \) and \( c_{cross} \) are the filter coefficients for the co- and cross-polar channels as defined in (6). The outputs of the shadowing filter are first weighted by the total coherent component parameter, \( \sigma_i(t) \), and then added to the attenuated direct signal, \( q_i(t) \) (which are estimated using MST [3] and [4]). The time series are then converted to linear scale (i.e., to lognormal distributed time series) to obtain the large scale fading. The small and large scale fading processes of each channel are summed and weighted by \( v_i(t) \) (estimated from the physical-statistical tree model reported in [3] and [4]) to account for the signal fading caused by wind swaying. Finally, the Doppler shift of the direct signal component is accounted for by multiplying each channel by \( \exp(j\phi_i) \), where \( \phi_i \) is the phase corresponding to the traveled distance. \( \exp(j\phi_i) \) is the Doppler shift of the direct signal component. \( h_i(t) \) is a correlated complex signal envelope of the LMS dual polarized MIMO channel.

IV. PERFORMANCE EVALUATION

A. Channel capacity

For a narrowband MIMO system with \( N_t \) transmit and \( M_r \) receiver antennas, the receive signal is expressed as
\[ \mathbf{r} = \mathbf{H} \mathbf{a} + \mathbf{n} \]
Fig. 12. Simulated partially correlated $2 \times 2$ dual polarized MIMO channel time series. Simulation parameters are given in Table II.

**TABLE II**

**SYSTEM SIMULATION PARAMETERS**

<table>
<thead>
<tr>
<th>Type</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>Frequency</td>
<td>2 GHz</td>
</tr>
<tr>
<td></td>
<td>Elevation angle</td>
<td>30°</td>
</tr>
<tr>
<td></td>
<td>Azimuth angle</td>
<td>60°</td>
</tr>
<tr>
<td></td>
<td>Speed of the mobile terminal</td>
<td>10 m/s</td>
</tr>
<tr>
<td></td>
<td>Signal-to-noise ratio</td>
<td>20 dB</td>
</tr>
<tr>
<td>Tree</td>
<td>Canopy height</td>
<td>10 m</td>
</tr>
<tr>
<td></td>
<td>Trunk height</td>
<td>10 m</td>
</tr>
<tr>
<td></td>
<td>Canopy radius</td>
<td>5 m</td>
</tr>
<tr>
<td></td>
<td>Trunk radius</td>
<td>0.4 m</td>
</tr>
<tr>
<td></td>
<td>Number of trees in each side of the road</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Spacing between tree trunks</td>
<td>11 m</td>
</tr>
<tr>
<td></td>
<td>Number of scatterers in a tree</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Width of the road</td>
<td>10 m</td>
</tr>
<tr>
<td>Wind</td>
<td>Mean wind speed</td>
<td>2 m/s</td>
</tr>
</tbody>
</table>

Table II. As expected, we can observe the increase in capacity achieved with MIMO compared to the SISO case.

### B. Link diversity

Diversity improves link availability. The amount of diversity gain/improvement obtained depends on the degree of correlation between the various parallel links which, in turn, depends on the propagation environment. For the dual polarized MIMO case, the instantaneous signal-to-noise ratio at the output of the maximum-ratio-combiner (MRC) is given by [21]–[23]

$$
\gamma = \gamma_{\lambda_{\text{max}}} (11)
$$

where $\lambda_{\text{max}}$ is the largest eigenvalue of $\mathbf{HH}^H$ for $N_t \geq M_r$ (or $\mathbf{H}^H \mathbf{H}$ for $N_t \leq M_r$). For SIMO case

$$
\gamma = \tau \left( |h_1|^2 + |h_2|^2 \right) (12)
$$

where $h_1$ and $h_2$ are the complex envelopes of the SIMO channel.

Fig. 14 presents the CDFs of the received signal for the LMS roadside tree scenario for SISO, SIMO/space diversity (for two co-polar RHCP antennas, one wavelength apart) and dual polarized MIMO diversity with MRC. We can observe the significant diversity gain achieved with dual polarized MIMO and SIMO/space diversity compared to the SISO case. It can also be seen that the best performance is achieved with dual polarized MIMO diversity. This is because, firstly, the cross-polar components are not lost and contribute to increase the sum of signal-to-noise ratios at the output of the MRC. Secondly, we can observe from Fig. 12 that the cross-polar components are especially useful when the link is shadowed by the roadside trees. At these positions, the levels of the co- and cross-polar components are comparable (see Fig. 12) which results in significant diversity gains.
In this paper we studied the LMS dual polarized MIMO channel along roadside tree areas. A novel physical-statistical, generative tree model based on multiple scattering theory was proposed for calculating the attenuation and scattering effects. FDTD electromagnetic computations were performed to characterize the tree scattering pattern and to calculate the shadowing cross-correlation matrix of the dual polarized MIMO channel. Generally, the use of FDTD has advantages in obtaining an accurate solution of electromagnetic interaction with arbitrary objects, however, it also has limitations in terms of the size of the computation volume relative to the wavelength, which is directly related to the required simulation time. This means that performing FDTD simulations over large computation areas/volumes may not be feasible, even using parallel computing.

In addition, a channel model/simulator for the SIMO receiver space diversity was also presented using the physical-statistical tree model, thus extending the SISO model in [3] and [4]. The physical-statistical approaches discussed are more effective for simulating large scenarios compared to complex physical models, and more accurate than merely empirical or statistical models.

In addition, performance analyses of the LMS SISO, dual polarized MIMO and SIMO space diversity configurations were carried out. Compared to the SISO case, significant increases in performance were observed for the dual polarized MIMO and SIMO space diversity cases. The results obtained can be used to evaluate the technical feasibility of LMS systems in roadside tree scenarios. They also give an insight into the kinds of system performance analyses which could be carried out using the models developed in this paper.

In general, the proposed channel models can be used to carry out different system level analyses such as capacity, bit-error-rate, etc. Future work includes validating the developed LMS dual polarized MIMO and SIMO space diversity channel models using measurements, as well as carrying out further comparisons between MST and FDTD results.

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