A Multistate Markov Channel Modelling of
Vegetation Dynamics at 40 GHz
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Abstract—In this paper, a Markov model intended to model the time-variant vegetation effects at 40GHz, is proposed. A narrowband fast fading channel model is evaluated and results are presented for side scattering regions around an isolated tree, when exposed to relatively high wind speeds. The adopted methodology differs from the traditional one, in that, the Markov model is not applied entirely to the complete set of samples of the measured signal, but instead, is applied to segments of the measured signal. By doing so, a number of simulated time series or segments will be obtained. Additionally, the concatenation of these segments will result into a simulated time series in relatively good agreement with the measured fading signal. The proposed model provides a flexible tool for obtaining predictive channel dynamic data for specific vegetation scenarios, obviating the need to perform expensive and time consuming measurements.

Index Terms—Markov model, multistate Markov, channel dynamics, wind effects, vegetation, trees.

I. INTRODUCTION

This paper concentrates on improving a generic propagation model [1] developed for the OFCOM (UK) aimed at more accurate prediction and quantification of the effects of vegetation media in radio system planning. This work has contributed to the recent recommendation ITU-R P.833-5 [1], in which the Radiative Energy Transfer (RET) theory has sought to model the re-radiated energy from vegetation media in terms of the absorption and scatter propagation modes only. While existing propagation models generally provide predictions of mean signal strength, radio designers require dynamic fading models for use in conjunction with the basic mean signal level calculation. In this paper, the modelling of dynamic variations on the channel due to movement of leaves and branches in the wind, for co-polarised radio signals at 40 GHz, is presented.

II. VEGETATION STATISTICAL MODEL

Statistical representations of the time varying signals emanated from vegetation volumes are a pre-requisite for radio planners to determine appropriate signal fade margins.

The received signal can be classified into two types of signal: shadowing and unshadowing. The proposed model approaches the multiplicative processes of a propagation channel as shadowing. The shadowed signal consists of a shadowed direct component and the diffuse scattering component, both emanated from random scattering media, e.g. vegetation volumes. These combined at the receiver end, may produce considerable interference patterns which may be time variant, particularly in the presence of wind. The shadowing direct component represents both the scattering and absorption propagation mechanisms present in vegetation media, which may be predicted qualitatively from Energy Transfer (RET) theory [1].

Hence, the probability density function of the envelope of the signal is assumed to have a Lognormal distribution, with an appropriate set of parameters extracted from the measurement data, as reported in [2]. Lognormal distribution is used to model the shadowed radio propagation. Its origin is based on the theory of random variables, where variables are arranged by a multiplicative process [3]. Lognormal probability density function is defined as [3]

\[
p(r) = \frac{20 \log e}{\sqrt{2\pi}} \exp \left[ -\frac{(20 \log r - \mu dB)^2}{2\sigma^2 dB} \right] \quad r > 0
\]

where \( r \) is the signals envelope amplitude and \( \mu \) and \( \sigma \) are the mean value and standard deviation of \( \ln(r) \), respectively. To this extent, a Multistate Markov Channel model is proposed as a means of predicting the fast fading present in complex random media as in vegetation, under the influence of wind dynamics.

III. MULTISTATE MARKOV CHANNEL MODEL

The study of Markov chains with a Finite Space emerges from early work of Gilbert and Elliot [4]. The Gilbert-Elliot model assumes the propagation channel to be in either good or bad state. Wang and Moayeri [5] generalised this model into a finite-state Markov channel model, or in other words, a multistate Markov channel model, in which the number of states exceeds two.

A. Markov Model Theory

If the state space is finite, let \( \mathbf{S} = \{s_0, s_1, \ldots, s_M \} \) denote a
finite set of states and \(\{S_n\}, n=0,1,\ldots,M-1\), be a constant Markov process. The concept of a first-order Markov model is that if a process is in state \(S_0\) at time \(n\), then the probability that it moves to state \(S_t\) at time \(n+1\) depends only on the current state and does not depend on the time \(n\) [4, 5], as depicted in Fig. 1a.

![Diagram of (a) Irreducible Markov and (b) Adopted Markov models.](image)

The switching process between states is described by a transition probability matrix. Since the constant Markov process has the property of stationary transitions [4], the transition probability is independent of time index \(n\) and can be written as [4, 5]

\[
t_{i,j} = \Pr(S[n+1] = s_j | S[n] = s_i), 0 \leq i, j \leq M-1
\]  

(3)

where \(\Pr(\cdot)\) denotes the probability that a particular event occurs, that is, if the discrete-time Markov chain \(S_n\) is currently in state \(i\) at time index \(n\), then it moves to state \(j\) at time index \(n+1\) with a transition probability \(t_{i,j}\). With this definition, one can define a \(J\times J\) transition probability matrix, with its elements as in (3):

\[
T_{S[n-1], S[n]} = \begin{bmatrix}
t_{0,0} & t_{0,1} & \cdots & t_{0,J-1} \\
t_{1,0} & t_{1,1} & \cdots & t_{1,J-1} \\
\vdots & \vdots & \ddots & \vdots \\
t_{J-1,0} & t_{J-1,1} & \cdots & t_{J-1,J-1}
\end{bmatrix}
\]

(4)

Additionally, the initial state probability of state \(i\) at any permissible index \(n\) without any state information at other time indices can also be defined as [4, 5]

\[
w_j = \Pr(S[n] = s_j), 0 \leq j \leq M-1.
\]

(5)

Note that both the transition probability matrix and initial probability vector must satisfy the following constraints [4, 5]:

\[
\sum_{j=0}^{M-1} \Pr(S[n+1] = s_j) = 1
\]

(6)

\[
\sum_{j=0}^{M-1} \Pr(S[n] = s_j) = 1
\]

(7)

B. Adopted Methodology

Let \(S[n]\) define a discrete-time Markov chain process related to the shadowing component only. Switching among different signal thresholds can be represented by a multistate Markov stochastic process [4]. Thus, each state condition will be defined by a range of signal thresholds.

Additionally, the adopted Markov chain is said to be non-irreducible. That is, its state space is a non-communicating class, which means it’s not possible to get to any state from any state. More specifically, the adopted Markov model does not allow self-loop transitions, where \(i=j\), which differs from the definition of the traditional (irreducible) Markov model, as can be seen in Fig. 1b and represented in (8):

\[
\Pr(S[n+1] = s_j | S[n] = s_i) = 0, 0 \leq i \leq M-1.
\]

(8)

This will enhance the ability of the proposed model, to model effectively rapid signal variations which may occur in vegetative channel under the influence of wind dynamics. In order to extract the model input parameters, measurement data was collected from specific measurements performed on a single tree inside an anechoic chamber at 40 GHz. Consequently, processing of experimental data assumed the following steps [4]:

A. The received signal obtained at a sampling rate of 8 kHz was divided into small blocks of 500 samples each and consequently into 16 measured signal blocks, as shown in Fig. 2.

![Measured signal time series division into 16 signal blocks.](image)

The following processing sequence was then applied to each of the measured signal blocks:

1. Within the range of possible signal levels, discrete thresholds for Lognormal states were defined;
2. The signal time series was processed frame-by-frame, i.e. signal was divided into small frames, as seen in Fig.3. Each frame includes 10 measured fading samples;

![Signal block division into signal frame-by-frame.](image)

3. Each frame was assigned to a corresponding state and the signal was classified using the thresholds defined in step 1), as follows:
If the frame mean value is in between the state delimiting signal power values, then the frame belongs to that respective state. This result into M separate signals, as shown in Fig.4;

![Fig. 4 Channel state records.](image)

4. Lognormal mean and standard deviation values for all frames, are calculated. These are averaged out for each state to yield the input model parameters to the Lognormal distribution, as shown in Fig.5;

5. The state probabilities and the state transition probabilities are computed, as follows:

\[
P(i) = \frac{N_i}{N_f} \quad (10)
\]

\[
P(i, j) = \frac{N_{ij}}{N_i} \quad (11)
\]

where \(N_i\) is the number of frames in state \(i\), \(N_f\) is the total number of frames and \(N_{ij}\) is the number of transitions from state \(i\) to \(j\);

6. The simulated time series using the initial probability array, transition matrix and Lognormal averaged state parameters calculated in step 4), were generated, as depicted in Fig.5;

![Fig. 5 Diagram of the Markov model simulator.](image)

B. Finally, all the generated simulated time series for each of the signal blocks were concatenated and a 8000 samples signal was therefore obtained.

IV. MEASUREMENT SCENARIO

Specific radio measurements have been performed on one downscaled tree, i.e. Schefflera species, inside an anechoic chamber to characterise the time-varying re-radiated signals from trees, when illuminated by radiowaves at 40 GHz. The experiment geometry adopted is shown in Fig. 6.

The time-varying of the signal envelope at the receiver was recorded over a period of 1s at a sampling rate of 8 kHz. This measurement scenario was intended to allow the characterisation and modelling of the temporal variations of the received scatter signals due to wind dynamics. Further details of the measurement equipment and geometry are presented in [2].

![Fig. 6. Measurement geometry.](image)

V. MODEL VALIDATION

Although measurements were done for several scenarios, including different wind speeds, wind incidences and receiver scattering angles [2], the proposed model validation is presented only for the scenario where wind was generated from position A, high wind speed and \(\phi=90^\circ\) (where the received scattered signal is mainly diffused). These scenario parameters were chosen because they represent the worst case scenario [2].

The proposed multistate Markov model assumes sixteen 4 x 4 state transition matrices, given in the Appendix. The number of signal blocks used in this model can be adapted to yield the closest possible agreement between simulated and measured data. The increase of these, will allow the proposed model to best model the fast variations of the channel, particularly when the canopy is under the influence of high speed wind. The number of 16 signal blocks is the result of a trade off between data and the number of resulting transition matrices.

The proposed model performance was evaluated by comparing first and second order statistics. These were obtained in terms of Probability Density Function (PDF) and the Cumulative Distribution (CDF), in addition to the secondary statistics, Average Fade Duration (AFD), in which examples are presented in Fig. 8. Furthermore both a Kolmogorov-Smirnov test was applied to CDF and Root-Mean-Square (rms) error was calculated to PDF, in order to assess the similarity between the resulting statistics from fading measured signal and that obtained from the simulated time series.

The Kolmogorov-Smirnov test applied resulted in 96% resemblance between measured and simulated data. The Root-Mean-Square error in terms of PDF was 0.0179. From a close analysis of Fig. 8, one can observe a relatively overall good agreement between measured and simulated signal statistics. The PDF, CDF and AFD statistics were shown to be in good agreement with the measured data. Additionally, the proposed multistate Markov model is able...
to simulate time series in good agreement with measured time series, as seen in Fig. 7. Hence, this model is an important and accurate tool to simulate vegetation channel dynamics at 40 GHz.

VI. CONCLUSION

This paper presents a Markov model to simulate the dynamic effects in foliage due to wind movement at 40 GHz. The narrowband fast fading channel model is proposed as a means of simulating the time varying propagation channel for high wind speeds, providing statistical estimates in relatively good agreement with measurement data, thus providing a flexible tool for obtaining data for specific vegetation path geometries.

REFERENCES


APPENDIX A – TRANSITION MATRICES