A Brief Survey of Channel Models for Land Mobile Satellite Communication

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***Abstract*—The last review of the modeling of the land mobile satellite channel was done by Karaliopoulos and Pavlidou in 1999. Since then a lot of work has been done to model the land mobile satellite channel. In this paper an up-to-date review of the modeling of the land mobile satellite channel is presented. We look at the various physical characteristics that influence communications in the land mobile satellite channel and then look at the different types of models derived for the land mobile satellite channel and review different models for each type of modeling.**

***Index Terms*—communication channel modelling, fading channels, land mobile satellite channels, satellite communications**

I. INTRODUCTION

CURRENT research into land mobile satellite (LMS) communications channels in the TeleNet research group pointed out that the review of LMS channel modeling is outdated. The last review was done by Karaliopoulos and Pavlidou in 1999 [1]. Since then a lot of work has been done in this area and in this paper we present an up-to-date review of the work done to model the LMS channel. This review will assist us in selecting an appropriate channel model for a satellite modem communication system we are working on.

Satellite communication has found its place in practice and is implemented in numerous applications. Some of the more common implementations are Global Positioning Systems, satellite television and marine communications. The research field has attracted much attention due to the practical implementations for satellite communication. LMS communications forms an integral part of the satellite communications field and is therefore also an active research field. The LMS channel is a complex communications channel with many factors influencing the channel. A detailed discussion on the physical characteristics that influence the LMS channel can be found in [2]. We will now briefly look at the physical properties of the LMS channel and examine the impact the various factors have on a signal as it propagates from a transmitter to a receiver.

The most basic losses that will occur in a radio propagation system are losses due to free-space attenuation. These losses will have an impact on the signal strength of the line-of-sight (LoS) component in a radio propagation system.

In the local surroundings of a transmitter or receiver a signal will experience losses due to shadowing or blocking of the LoS component and also due to multipath effects, these multipath effects are the result of propagation mechanisms such as reflection, diffraction and scattering. Shadowing will only influence the amplitude of the signal, while diffraction, scattering and reflection can influene both phase and amplitude of the received signal. These effects can also result in a time delay in the received signal.

Besides the losses due to the local surroundings, other losses experienced on earth are losses due to weather effects. These effects can sometimes be negligible, but as the frequency of a system increases, the influence of weather effects, such as rain, also increases on the system [3]. For LMS systems operating from especially the Ku-band upwards, weather effects can have an impact on the received signal strength.

A signal can also experience losses while propagating through the earth's atmosphere. These losses are due to particles in the atmosphere that can absorb or reflect a signal.

Other effects that can impact a signal are factors such as Faraday rotation and time-dispersion. Faraday rotation is explained in [4]. For the majority of LMS channel models only free-space losses, shadowing and multi-path effects are taken into account, as these effects have the biggest impact on the received signal.

Communication channel modeling is a powerful tool to facilitate the design of communication systems. These models make it possible to simulate a communication system to observe the impact of physical characteristics on the channel. In this paper we will take a look at a few models available in the literature. In order to examine these models we will group them into four groups and examine each of these groups. The four groups are:

- Analytical models
- Empirical models
- Statistical models
- Hybrid models

In the next four sections we will discuss each of these groups of models.

II. ANALYTICAL MODELS

Until recently not much effort was made to derive analytical models specifically for the LMS channel, but analytical models for terrestrial radio propagation have been developed since the 1960's. According to [5], Ossana was the first to propose an analytical model for radio propagation. Shortly after Ossana's

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model, Gilbert [6] proposed and compared three analytical models and then Clarke [7] created his model based on one of Gilbert's models. A review of analytical models for terrestrial radio propagation are given in [5] for the interested reader.

Recently analytical models for the LMS channel were derived by making use of ray-tracing techniques. Ray-tracing techniques were originally developed to determine the path of a wave or particle when moving through a system. Ray-tracing is based on a branch of physics called ray theory. When used to model electromagnetic waves, the waves are approximated by narrow beams. These techniques can accurately model the propagation path of a wave if the objects that interact with the wave have much greater dimensions than the wave length of the wave. However interference and diffraction of a wave can not be modeled by ray-tracing. We will now examine ray-tracing based models for the LMS channel:

Dottling [8] proposed a ray-tracing based model for the LMS channel. The aim of this model was to create a model that would be able to model all the various aspects that impact the LMS channel and also be versatile enough to cover the whole frequency range of LMS communication. The resulting model consists of the following five main components:

- Orbit generator: Predicts the position of the satellite.
- Surroundings generator: A detailed description of the receiver's surroundings.
- 2D ray tracing model: A two-dimensional prediction of the propagation path.
- 3D scattering model: A detailed model to describe scattering over the geographical area.
- Stochastic model: This model modifies the ray tracing results to compensate for non-deterministic effects.

This model addresses numerous complex characteristics of the LMS channel and makes use of detailed representations of the real world in an effort to describe the LMS channel. A further extension to this model is presented in [9], where the ray-tracing model is extended to a 3D ray-tracing model. According to [9] the 3D ray-tracing model improves the model notably.

Another ray-tracing based model, proposed by Sofos [10], was created with the aim to be simple and computationally efficient. The model consists of 18 rays to model the propagation of the signal.

In this section a discussion of the analytical models for the LMS channel were given. From this it can be seen that the advantage of analytical models are that they can describe a channel accurately and are also adaptable to different environments due to the underlying physical properties taken into account when deriving an analytical model. The disadvantages are that analytical models can be computationally intensive due to the complexity of the model. Another disadvantage is that the LMS channel's properties are not always known and must be approximated. These approximations can lead to inaccuracies in analytical models.

III. EMPIRICAL MODELS

Empirical models are models that are derived by studying measurements made in a LMS communication system. A model is then created by fitting a certain curve or curves to the measured data. This method has been used for terrestrial radio propagation models such as the Okumura model [11] and the Hata model [12]. Some of the first models developed for the LMS channel were derived in this way. A detailed review of empirical models can be found in [1] and [13]. We will now briefly look at some empirical models by classifying them into two groups and discussing each group. The two groups are:

- Vegetative attenuation models
- Link budget calculation models

A. Vegetative attenuation models

Vegetative attenuation models only calculate the losses a of radio signal when propagating through tree cover and is therefore not a complete LMS channel model on their own, but is often incorporated into a LMS channel model for rural and suburban environments. A few important models derived for vegetative attenuation are:

- Modified Exponential Decay model [14]
- International Radio Consultative Committee (CCIR) model [15]
- Barts-Stutzman model [16]
- Goldhirsh and Vogel model [17]

B. Link-budget calculation models

Link-budget calculation models were developed to fascilitate the design of communication systems by helping the designer to get an approximation of the losses a communication system will experience. A few link-budget models for the LMS channel will now be discussed.

1) CCIR model

The CCIR [18] model for link-budget calculation is derived from a measurement campaign with NASA's ATS-6 satellite. From the measurement campaign two equations were derived. These equation were designed to give a margin that will guarantee a functional link for 90% of the time. The two equations given below are for urban and suburban/rural areas respectively:

$$\begin{aligned} M = 1.78 + 1.92 \cdot f - 0.052 \cdot \theta + \\ K \cdot (7.6 + 0.053 \cdot f + 0.04 \cdot \theta) \end{aligned} \quad (1)$$

$$\begin{aligned} M = 12.5 + 0.17 \cdot f - 0.17 \cdot \theta + \\ K \cdot (6.4 - 1.19 \cdot f - 0.05 \cdot \theta) \end{aligned} \quad (2)$$

The symbols for the above equations are defined as follow: M is the link-margin in decibels, f is the frequency in megahertz and θ is the elevation angle in degrees. K is a value that correspondes to the percentage of locations where the link will be functional for 90% of the time. Typical K values are: $K(50\%) = 0$; $K(90\%) = 1.3$; $K(95\%) = 1.65$; $K(99\%) = 2.35$

2) Empirical Roadside Shadowing Model

The Empirical Roadside Shadowing (ERS) model was proposed by Goldhirsh and Vogel [19] after a measurement campaign using the INMARSAT MARECS-B2 geostationary satellite. This model was designed specifically for 1500MHz operating frequency. The model derived is described with the following equations:

$$M = -A \cdot ln(P) + B \quad (3)$$

with

$$A = -0.002 \cdot \theta^2 + 0.0975\theta + 3.44 \tag{4}$$

and

$$B = -0.443 \cdot \theta + 34.76 \tag{5}$$

where M is the link-budget in decibels, P is the outage probability and A and B are factors depending on the elevation angle(θ).

3) Modified Emprical Roadside Shadowing Model

This model was proposed by the European Space Agency (ESA) and is a modification of the ERS model [20]. This model is derived for a frequency of 1300MHz and is valid for elevation angles from 20° to 80°. The model is described by the following equations:

$$M = -A \cdot ln(P) + B \tag{6}$$

with

$$A = 1.117 \cdot 10^-4 \cdot \theta^2 - 0.0701 \cdot \theta + 6.1304 \tag{7}$$

and

$$B = 0.0032 \cdot \theta^2 - 0.6612 \cdot \theta + 37.8581 \tag{8}$$

where M is the link-budget in decibels, P is the outage probability and A and B are factors depending on the elevation angle (θ).

4) Combined Empirical Fading Model

The Combined Empirical Fading Model (CEFM) is another model that is derived from the ERS model. The CEFM works for more than one frequency; 1300MHz and 2450MHz are acceptable. The equations for this model are given as:

$$M = A \cdot ln(P) + B \tag{9}$$

with

$$A = 0.002 \cdot \theta^2 - 0.15 \cdot \theta - 0.7 - 0.2 \cdot f \tag{10}$$

and

$$B = 27.2 + 1.5f - 0.33 \cdot \theta \tag{11}$$

where M is the link-budget in decibels, P is the outage probability, A and B are factors depending on the elevation angle (θ) and f is the frequency in gigahertz.

5) Urban Environment Model for High Elevation Angles

This model was proposed by Kanatas [21] and was specifically designed for high elevation angles. This model is valid for elevation angles of 60°, 70° and 80°. The equations for this model is:

$$M = -A \cdot ln(P) + B \tag{12}$$

with

$$A = -0.4074 \cdot \theta^2 + 5.5219 \cdot \theta + 180.487 \tag{13}$$

and

$$B = -0.10454 \cdot \theta^2 + 13.259 \cdot \theta + 395.364 \tag{14}$$

where M is the link-budget in decibels, P is the outage probability and A and B are factors depending on the elevation angle (θ). This model is valid for P from 5% to 30%.

Empirical models have the advantage that they are computationally simple and can produce reasonably good approximations very quickly. The main disadvantage for empirical models is that they are not related to the physical characteristics of the channel and therefore does not handle changes to the environment well.

IV. STATISTICAL MODELS

Statistical models for terrestrial propagation have been derived as early as the 1960's with Clarke's model [7] and is therefore a well defined method that has been studied in-depth for a long time. Important contributions to statistical modelling for communication systems is Suzuki [22] with his mixed distribution model and the Gilbert-Elliot [23] multi-state model. The first statistical model for the LMS channel was developed by Loo [24] in 1985. Statistical models can be grouped into two groups and each of these two groups will now be discussed.

A. Fading distributions

These types of models are derived for non-selective fading in LMS channels. Loo's model was the first model specifically for the LMS channel, but Suzuki's model was the first model of this type and was derived for terrestrial propagation. A few of these models will now be discussed:

1) Loo's model

Loo [24] derived his model in 1985 and based the model on measurements taken in a rural area. Loo assumed that the line-of sight (LoS) component suffers from foliage attenuation and is lognormally distributed, while the multipath component's attenuation is Rayleigh distributed. The model is described as follows: Let the received signal be:

$$r \exp(j\theta) = z \exp(j\phi_0) + w \exp(j\phi) \tag{15}$$

with z lognormally distributed, w Rayleigh distributed and ϕ and ϕ_0 uniformly distributed between 0 and 2π. The probability density function (pdf) for r is:

$$\begin{aligned} p(r) = r/b_0\sqrt{2\pi d_0} \int_0^\infty & 1/z \exp[-(\ln z - \mu)^2/2d_0 - \\ & (r^2 + z^2)/2b_0] I_0(rz/b_0) dz \end{aligned} \tag{16}$$

with μ and $\sqrt{d_0}$ the mean and standard deviation of the lognormal pdf, b_0 the average scattered power due to the multipath and I_0 the Bessel function of zero'th order. When z in (15) is kept constant, (16) transforms into a Ricean pdf, this is for when multipath fading occurs, but there is no shadowing on the LoS component. If w is equal to 0 in (15), (16) transforms into a lognormal pdf. This happens when no multipath fading occurs, but shadowing is present in the LoS component. When there is no LoS component present ($z = 0$), (16) transforms into a Rayleigh pdf. The Loo model is a versatile model that can represent each of the above mentioned cases.

2) *Rice-Lognormal models*

The Rice-lognormal (RLN) model was first presented by Corazza [25] and then generalised by Vatalaro [26] later on. The model differs from Loo's model in the way the received signal is interpreted. For Loo's model the received signal is seen as the sum of two independant process, while for the RLN model the shadowing and multipath components are both incorporated in one process. The received signal is expressed as:

$$r = RSe^{j\theta} \tag{17}$$

with R a Ricean pdf and S a lognormal pdf. The RLN model is discussed in detail in [25]. In this paper we are going to look at the Generalised Rice Lognormal (GLRN) model proposed by Vatalaro [26]. The GLRN model is the RLN model with multipath components with constant power added to the received signal. The new equation for the received signal will then be:

$$r = RSe^{j\theta} + x_1 + jy_1 \tag{18}$$

x_1 and y_1 are Gaussian zero-mean random processes with equal variance. The pdf for the envelope of the GLRN model is given as:

$$p(r) = \int_0^\infty p(r|S)p(S)dS \tag{19}$$

with

$$\begin{aligned} p(r|S) = \frac{2r\xi(K+1)}{1+\xi S^2} \exp\left[-\xi\frac{KS^2+(K+1)r^2}{1+\xi S^2}\right] \\ \cdot I_0\left[2rS\frac{\xi\sqrt{K(K+1)}}{1+\xi S^2}\right] \end{aligned} \tag{20}$$

and

$$p(S) = \frac{1}{\sqrt{2\pi} h\sigma_s S} \exp\left[-\frac{1}{2}\left(\frac{\ln S - h\mu_S}{h\sigma_S}\right)^2\right] \tag{21}$$

For the above equations the symbols are defined as:

a and σ^2 are the Ricean parameters, μ_s and σ_s are the lognormal mean and variance, σ_1^2 is the Gaussian random process' variance, $h = (\ln 10)/20)$, S the lognormally distributed variable, r the received signal, $K = \frac{a^2}{2\sigma^2}$ and $\xi = \frac{\sigma^2}{\sigma_1^2}$.

Another Rice-lognormal based fading model is found in [27], based on Suzuki's model for urban radio propagation. The received signal is modelled by the product of correlated Ricean and lognormal processes. The model is quite a complex model and the full description of the model can be found in the reference above.

3) *Hwang model*

Hwang [28] proposed another mixture distribution model with Ricean and lognormal distributions, but he made the assumption that the shadowing experienced by the direct and multipath components are independant and is not correlated in any way, expressing the received signal as:

$$r = A_c S_1 e^{j\phi} + RS_2 e^{j(\theta+\phi)} \tag{22}$$

where A_c is a constant, S_1 and S_2 are lognormally distributed and R is Rice distributed. The pdf for this model is:

$$\begin{aligned} p(r) = \int_0^\infty \int_0^\infty \frac{r}{\sigma^2 S_2^2} \exp\left[-\frac{r^2 + A_c^2 S_1^2}{2\sigma^2 S_2^2}\right] I_0\left(\frac{A_c r S_1}{S_2^2 \sigma^2}\right) \cdot \\ \frac{1}{2\pi S_1 S_2 d_1 d_2} \exp\left[-\left(\frac{(\ln S_1 - \mu_1)^2}{2d_1^2} + \frac{(\ln S_2 - \mu_2)^2}{2d_2^2}\right)\right] \cdot \\ dS_1 dS_2 \end{aligned} \tag{23}$$

For the above pdf the symbols are defined as: S_1 and S_2 are the lognormally distributed variables, σ is the Ricean parameter, d_1,d_2, μ_1 and μ_2 are the lognormal variances and means. A_c is a constant factor of the LoS component and r is the received signal. This model is very flexible and can approximate multiple other models including Loo and RLN, but has the disadvantage of having a complex pdf.

4) *Cavdar's model*

Another fading model is proposed in [29]. For this model the LMS channel is divided into three categories: unshadowed region, obstructed region and vegetatively shadowed region. The unshadowed region is represented by Ricean distributions, the obstructed region is represented by Rayleigh distributions and the vegetatively shadowed region is represented by lognormal-Rayleigh distributions. Each category of the model has it's own pdf and the overall pdf for the model is equal to the weighted sum of each of the categories' pdfs. The overall pdf for this model is defined as:

$$G(F) = B_1 \cdot G_1(F) + B_2 \cdot G_2(F) + B_3 \cdot G_3(F)$$

where $G(F)$ is the overall pdf, $G_1(F)$, $G_2(F)$, and $G_3(F)$ is each individual category's pdf and B_1, B_2 and B_3 is the weight of each category's contribution to the overall pdf.

B. State-orientated modelling

Gilbert's model [23] was the first multi-state model for a communications channel and the multi-state models derived for the LMS channel are based on Gilbert's model. For these models Markov chains are used to choose between different states of the channel. For the LMS channel these states are usually connected to different fading distributions such lognormal, Ricean, Rayleigh or even a mixture distributions as discussed in the previous section. Various multi-state models for the LMS channel will now be discussed:

1) *Two-state model*

Lutz [30] derived a two-state Markov chain for the LMS channel from the Gilbert-Elliot model. Similar to Gilbert's model, Lutz's model had a "good" and a "bad" state. His two states were defined as a state where the LoS component is unobstructed and no shadowing is present and a state where severe shadowing is present. For the "good" state the received signal envelope is Ricean distribution and for the "bad" state the envelope is modeled as a Rayleigh distribution. The model is seen as the base for state-orientated models for the LMS channel.

Briso's model [31] is another two-state model for the LMS channel with one state for when the LoS component is available and one state where the LoS component is not available. The LoS state is modelled by the sum of uncorrelated lognormal and Rayleigh distributions, while the non-LoS state is represented by a Ricean or Rayleigh distribution.

2) Three-state models

Fontan [32], Karasawa [33] and Gillespie [34] derived three-state Markov models for the LMS channel. For all three models the three states are defined as:

- LoS component is present ("good state")
- moderate fading ("intermediate state")
- severe fading conditions, no LoS component ("bad state")

The models differs on how each state influences the received signal. Fontan described all three states with Loo's model [24], while Karasawa described the "good" state with a Ricean distribution, the "intermediate" state with Loo's model and the "bad" state with a Rayleigh distribution.

3) M-state models

In this section we look at multi-state models with more than three states. Wakana [35], Dongya [36] and Ming [37] proposed five, six and five-state Markov chains respectively. Their models are all based on the Gilbert-Elliot model with two main states namely "good" or "bad". They then created sub-states for each of the main states to create higher resolution models. All three of them used Rayleigh distribution for their fading("bad") states and Ricean statistics for their non-fading("good") states. The differences in their models comes in with the number of sub-states selected for each main state and in the transition matrices for their models. Detailed description of each of these models can be found in the references.

Another state-orientated model was proposed by Csurgai-Horvath [38]. The model was derived to be extendable to include multiple fade states. The model also has one interfade state. The only transitions allowable for the model are from a fade state to the interfade state and from the interfade state to a fade state. Each fade state would have a different fade duration and the fade durations for the LMS channel could be modelled in this way.

4) Multi-level multi-state models

Multi-level multi-state Markov chain models are essentially made-up of seperate Markov chains and the results of each of the chains are combined. Such a model is proposed by [39]. The model proposed here has two levels; a shadowing and a fading level. Each of these two levels are extendable to as many states as desired. The shadowing Markov chain uses lognormal distributions, while the fading chain uses Rayleigh distributions. The different states in each level use different parameters for their distributions to represent variations in fading and shadowing. Each of the two levels returns a value generated by their respective Markov chains and these two values are multiplied to generate an attenuation value for the signal strength.

V. HYBRID MODELS

A. Roadside Vegetation Attenuation Model

This model was proposed by Sofos [40] to simulate the attenuation due to trees in rural areas. The model was derived from measurements made at relatively low elevation angles ($10° - 40°$). The model is a combination of an empirical model and a statistical model. The MED model in [14] is modified to include a Gaussian random process. The model is described by the following equation:

$$F(dB) = 0.3A + 0.7rand(2A, A-2) \tag{24}$$

A is the value obtained from the MED model and the random process is a Gaussian random process with $\epsilon = 2A$ and $\sigma = A - 2$. This model introduces a method to combine a deterministic model and a statistical model, but has the disadvantage that the model strongly depends on the measured data used.

B. High Resolution Satellite-to-Indoor channel model

The model discussed [41] is a high resolution model with a deterministic part and a statistical part and is therefore a highly detailed and complex model. The deterministic model consists of five main components: scenario description, ray-tracing and polarization tracking, electromagnetic modeling, generation of results and model validation and fine-tuning. The idea of the model is to perform each of the above steps for a scenario and then validate and fine-tune the results to fit the measured results. This process is then repeated for a wide range of scenarios, so that parameters can be determined and extracted and be used for statistical models. Statistical models are easier to use, if the parameters of the model are correctly identified.

C. A Deterministic-statistical model

This model, proposed by Li [42], combines statistical modeling and deterministic ray-tracing to model the LMS channel. The ray-tracing part of the model is done by making use of the Ergospace ray-tracing package. The model is defined by handling shadowing and fast-fading seperately. For the shadowing part of the model two possible cases exist: the LoS case and the non-LoS case. For the LoS case the attenuation is modeled by the normal free-space attenuation equation and for the non-LoS case the shadowing is determined by ray-tracing. For the fast-fading part of the model both LoS and non-LoS is modeled by using Nakagami statistical distributions. The parameters for the Nakagami distributions are determined by making use of ray-tracing. This is another model that demonstrates the use of a combination of modeling techniques in an effort to accurately model the LMS channel.

VI. CONCLUSION

From this paper we see that a great variety of methods have been presented to model the LMS channel. It is important to see that different models are developed for different applications. Some models were derived for specific operating frequencies or for specific elevation angles, while other models were developed for versatility. In some cases a model was derived to be as accurate as possible, while other models were designed to be easy to use. The usefulness of statistical models often depends on the measured data available. We conclude that the application determines the choice and effectiveness of a model.

In our future work we will select a channel model that will be used to model a satellite modem communication system. The knowledge gathered from this review will assist us in the process of selecting an appropriate model that will best fit our application.

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