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# Characterisation and Channel Modelling for Satellite Communication Systems

Asad Mehmood and Abbas Mohammed  
*Blekinge Institute of Technology  
Sweden*

## 1. Introduction

The high quality of service, low cost and high spectral efficiency are of particular interest for wireless communication systems. Fundamental to these features has been much enhanced understanding of radio propagation channels for wireless communication systems. In order to provide global coverage of broadband multimedia and internet-based services with a high signal quality to diverse users, seamless integration of terrestrial and satellites networks are expected to play a vital role in the upcoming era of mobile communications. The diverse nature of propagation environments has great impact on the design, real-time operation and performance assessment of highly reconfigurable hybrid (satellite-terrestrial) radio systems providing voice, text and multimedia services operating at radio frequencies ranging from 100 MHz to 100 GHz and optical frequencies. Therefore, a perfect knowledge and modelling of the propagation channel is necessary for the performance assessment of these systems. The frame work for most of the recent developments in satellite communications includes satellite land mobile and fixed communications, satellite navigation and earth observation systems and the state-of-art propagation models and evaluation tools for these systems.

The organization of the chapter is as follows: Section 2 describes the multipath propagation impairments in land mobile satellite (LMS) communications. In Section 3, the probability distributions that characterize different impairments on radio waves are discussed. Section 4 provides an overview of statistical channel models including single-state, multi-state and frequency selective channel models for LMS communications. The chapter ends with concluding remarks.

## 2. Propagation Impairments Effecting Satellite Communication Links

The use of satellite communication systems for modern broadband wireless services involves propagation environments for radio signals different from that in conventional terrestrial radio systems. The radio waves propagating between a satellite and an earth station experience different kinds of propagation impairments: the effects of the ionosphere, the troposphere and the local fading effects as shown in Fig. 1. The combined effect of these

impairments on a satellite-earth link can cause random fluctuations in amplitude, phase, angles of arrivals, de-polarization of electromagnetic waves and shadowing which result in degradation of the signal quality and increase in the error rates of the communication links.

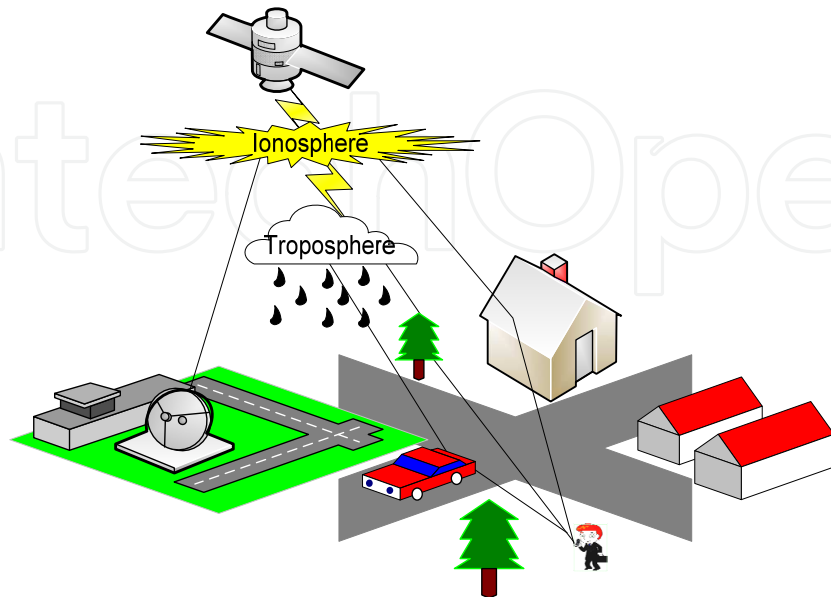


Fig. 1. The land-Mobile-Satellite Communication System

## 2.1 Ionospheric Effects

The effects of the ionosphere (an ionized section of the space extending from a height of 30 km to 1000 km) have adverse impact on the performance of earth-satellite radio propagation links. These effects cause various impairments phenomena such as scintillation, polarization rotation, refraction, group delays and dispersion etc, on the radio signals. The scintillation and polarization rotation effects are of foremost concern for satellite communications.

Ionospheric scintillations are variations in the amplitude level, phase and angle of arrival of the received radio waves. They are caused by the small irregularities in the refractive index of the atmosphere owing to rapid variations in the local electron density. The main effect of scintillation is fading that strongly depends on the irregularities or inhomogeneities of the ionosphere (Ratcliffe, 1973; Blaunstein, 1995; Saunders & Zavala, 2007). Scintillation effects are significant in two zones: at high altitudes (E and F layers of ionosphere) and the other is  $\pm 20^\circ$  around the earth's magnetic equator. The effects of scintillation decrease with increase in operating frequency. It has been observed in various studies that at the operating frequency of 4 GHz ionospheric scintillations can result in fades of several dBs and duration between 1 to 10 seconds. The details about ionospheric scintillation can be found in International Telecommunication Union Recommendations (ITU-R, 2009a).

The orthogonal polarization (linear or circular) is used in satellite communication systems to increase the spectral efficiency without increasing the bandwidth requirements. This technique, however, has limitations due to depolarization of electromagnetic waves propagating through the atmosphere. When linearly polarized waves pass through the

ionosphere, the free electrons present in the ionosphere due to ionization interact with these waves under the influence of the earth's magnetic field in a similar way as the magnetic field of a motor acts on a current carrying conductor. This results in rotation of the plane of polarization of electromagnetic waves, recognized as Faraday rotation. The magnitude of Faraday rotation is proportional to the length of the path through the ionosphere, the geomagnetic field strength and the electron density, and inversely proportional to the square of the operating frequency. The polarization rotation is significant for small percentages of time at frequencies 1 GHz or less. The effect of Faraday rotation is much lower at higher frequencies even in the regions of strong ionospheric impairments and low elevation angles, e.g., at frequency of 10 GHz, Faraday rotation remains below  $1^\circ$  and can be ignored (ITU, 2002). Cross-polarization can also be caused by the antenna systems at each side of the link. The effects of depolarization are investigated by two methods: cross-polarization discrimination (XPD) and polarization isolation. The details can be found in (Roddy, 2006; Saunders & Zavala, 2007).

## 2.2 Tropospheric Effects

The troposphere is the non-ionized lower portion of the earth's atmosphere covering altitudes from the ground surface up to a height of about 15 km of the atmosphere. The impairments of this region on radio propagations include hydrometeors, e.g., clouds, rain, snow, fog as well as moisture in atmosphere, gradient of temperature and sporadic structures of wind streams both in horizontal and vertical directions. The effects imparted by these impairments on radio signals are rain attenuation, depolarization, scintillation, refraction, absorption, etc. The radio waves are degraded by these effects to varying degrees as a function of geographic location, frequency and elevation angle with specific characteristics. The tropospheric effects in LMS communication links become significant when the operating frequency is greater than 1 GHz.

One of the major causes of attenuation for LMS communication links operating at frequency bands greater than 10 GHz (e.g., Ku-Band) is rain on the transmission paths in tropospheric region. The rain attenuation in the received signal amplitude is due to absorption and scattering of the radio waves energy by raindrops. The attenuation is measured as a function of rainfall rate and increases with increase in the operating frequency, rainfall rate and low elevation angles (Ippolito, 2008). The rainfall rate is the rate at which rain would accrue in a rain gauge placed in a specific region on the ground (e.g., at base station). The procedure to calculate attenuation statistics due to rainfall along a satellite-earth link for frequencies up to 30 GHz consists of estimating the attenuation that exceeds 0.001% of the time from the rainfall rate that exceeds at the same percentage of time and has been detailed in ITU-R recommendations (ITU-R, 2007).

The LMS channel utilization can be augmented without increasing the transmission bandwidth by the use of orthogonally polarized transmissions (linear or circular). The polarization of radio waves can be altered by raindrops or ice particles in the transmission path in such a way that power is transferred from the desired component to the undesired component, resulting in interference between two orthogonally polarized channels. The shape of small raindrops is spherical due to surface tension forces, but large raindrops adopt shape of spheroids (having flat base) produced by aerodynamic forces acting in upward

direction on the raindrops. When a linearly polarized wave passes through raindrops of non-spherical structure, the vertical component of radio wave parallel to minor axis of raindrops experiences less attenuation than that the horizontal component. As a result, there will be a difference in the amount of attenuation and phase shift experienced by each of the wave components. These differences cause depolarization of radio waves in the LMS links and are illustrated as differential attenuation and differential phase shift. Rain and ice depolarization have significant impacts on satellite-earth radio links for frequency bands above 12 GHz, especially for systems employing independent dual orthogonally polarized channels in the same frequency band in order to increase the capacity. The method of predicting the long-term depolarization statistics has been described in ITU-R recommendations (ITU-R, 2007).

A radio wave propagating through satellite-earth communication link will experience reduction in the received signal's amplitude level due to attenuation by different gases (oxygen, nitrogen, hydrogen, etc.) present in the atmosphere. The amount of fading due to gases is characterized mainly by altitude above sea level, frequency, temperature, pressure and water vapour concentration. The principal cause of signal attenuation due to atmospheric gases is molecular absorption. The absorption of radio waves occurs due to conversion of radio wave energy to thermal energy at some specific resonant frequency of the particles (quantum-level change in the rotational energy of the gas molecules). Among different gases only water vapours and oxygen have resonant frequencies in the band of interest up to 100 GHz. The attenuation due to atmospheric gases is normally neglected at frequency bands below 10 GHz. A procedure to find out the effects of gaseous attenuation on LMS links has been discussed in ITU-R recommendations (ITU-R, 2009b).

Scintillations (rapid variations in the received signal level, phase and angle-of-arrival) occur due to inhomogeneities in the refractive index of atmosphere and influence low margin satellite systems. The tropospheric scintillations can be severe at low elevation angles and frequency bands above 10 GHz. Multipath effects can be observed for small percentages of time at very low elevation angles ( $\leq 4^\circ$ ) due to large scale scintillation effects resulting in signal attenuation greater than 10 dB.

### 2.3 Local Effects

In addition to the ionospheric and the tropospheric attenuation effects, radio waves suffer from energy loss due to complex and varying propagation environments on the terrain. An earth station is surrounded by different obstacles (buildings, trees, vegetation etc) of varying heights, dimensions and of different densities. These obstructions cause different multipath propagation phenomena: diffraction due to bending of the signal around edges of buildings, dispersion or scattering by the interaction with objects of uneven shapes or surfaces, specular reflection of the waves from objects with dimensions greater than the wavelength of the radio waves, absorption through foliage etc. In addition, the movement of mobile station on earth over short distances on the order of few wavelengths or over short time durations on the order of few seconds results in rapid changes in the signal strength due to changes in phases (Doppler Effect). All these effects result in loss of the signal energy and degrade the performance and reliability of LMS communications links. A detailed

discussion about local effects on LMS communication links can be found in (Goldhirsh & Vogel, 1998; Blaunstein & Christodoulou, 2007).

### 3. Probability Distribution Functions for Different Types of Fading

The performance of satellite-earth communication links depends on the operating frequency, geographical location, climate, elevation angle to the satellite etc. The link reliability of a satellite-based communication system decreases with the increase in operating frequency and at low elevation angles. In addition, the random and unpredictable nature of propagation environments increases complexity and uncertainty in the characterization of transmission impairments on the LMS communication links. Therefore, it is suitable to describe these phenomena in stochastic manner in order to assess the performance of LMS communication systems over fading channels. Various precise and elegant statistical distributions exist in the literature that can be used to characterize fading effects in different propagation environments (Simon & Alouini, 2000; Corraza, 2007). In general signal fading is decomposed as large scale path loss, a medium slowly varying component following lognormal distribution and small scale fading in terms of Rayleigh or Rice distributions depending on the existence of the LOS path between the transmitter and the receiver. In this section, we give a brief overview of standard statistical distributions used to model different fading effects on the LMS communication links.

#### 3.1 Rayleigh Distribution

In case of heavily built-up areas (Urban Environments) the transmitted signal arrives at the receiver through different multipath propagation mechanisms (section 2.3). The resultant signal at the receiver is taken as the summation of diffuse multipath components characterized by time-varying attenuations, different delays and phase shifts. When the number of paths increase the sum approaches to complex Gaussian random variable having independent real and imaginary parts with zero mean and equal variance. The amplitude of the composite signal follows Rayleigh distribution and the phases of individual components are uniformly distributed in the interval 0 to  $2\pi$ . The received signal (real part) can be written as:

$$R_{Ray} = \sum_{i=1}^n a_i(t) \cos(\omega_c t + \theta_i(t)) \quad i = 0, 1, 2, \dots, n \quad (1)$$

where  $a_i(t)$  is the amplitude,  $\theta_i(t)$  is the phase of the  $i^{th}$  multipath component and  $\omega_c$  represents the angular frequency of the carrier. The corresponding probability density function (pdf) of the received signal's envelope is expressed in the following mathematical form:

$$P_{Ray}(r) = \frac{r}{\sigma^2} \exp(-r^2 / 2\sigma^2) \quad r \geq 0 \quad (2)$$

where  $\sigma$  denotes the standard deviation and ' $r$ ' represents envelop of the received signal.



### 3.2 Rician Distribution

In propagation scenarios when a LOS component is present between the transmitter and the receiver, the signal arriving at the receiver is expressed as the sum of one dominant vector and large number of independently fading uncorrelated multipath components with amplitudes of the order of magnitude and phases uniformly distributed in the interval  $(0, 2\pi)$ . The received signal is characterized by Rice distribution and is given as follows:

$$R_{Rice} = C + \sum_{i=1}^n a_i(t) \cos(\omega_c t + \theta_i(t)) \quad i = 0, 1, 2, \dots, n \quad (3)$$

where constant 'C' represents the magnitude of the LOS signal between the transmitter and the receiver. Other parameters are the same as described for Rayleigh distribution. The pdf of the envelope of the received signal is illustrated in the following mathematical form:

$$P_{Rice}(r) = \frac{r}{\sigma^2} \exp\left[-\frac{(r^2 + C^2)}{2\sigma^2}\right] I_0\left(\frac{rC}{\sigma^2}\right) \quad (4)$$

where  $I_0$  represents the modified Bessel function of first kind and zero order, and  $C^2/2$  is the mean power of the LOS component. If there is no direct path between the transmitter and the receiver (i.e.,  $C = 0$ ) the above equation reduces to Rayleigh distribution. The ratio of the average specular power (direct path) to the average fading power (multipath) over specular paths is known as Rician factor ( $a^2/2\sigma^2$ ) and is expressed in dBs.

### 3.3 Log-Normal Distribution

In addition to signal power loss due to hindrance of objects of large dimensions (buildings, hills, etc), vegetation and foliage is another significant factor that cause scattering and absorption of radio waves by trees with irregular pattern of branches and leaves with different densities. As a result the power of the received signal varies about the mean power predicted by the path loss. This type of variation in the received signal power is called shadowing and is usually formulated as log-normally distributed over the ensemble of typical locals. Shadowing creates holes in coverage areas and results in poor coverage and poor carrier-to-interference ratio (CIR) in different places. The pdf of the received signal's envelope affected by shadowing follows lognormal distribution that can be written in the following mathematical form:

$$P_{\log normal}(r) = \frac{1}{\sqrt{2\pi}\sigma r} \exp\left[-\frac{1}{2}\left(\frac{(\ln r - \mu)^2}{\sigma^2}\right)\right] \quad r \geq 0 \quad (5)$$

where  $\mu$  and  $\sigma$  are mean and standard deviation of the shadowed component of the received signal, respectively.

### 3.4 Nakagami Distribution

As discussed in (Saunders & Zavala, 2007), the random fluctuations in the radio signal propagating through the LMS communication channels can be categorized into two types of fading: multipath fading and shadowing. The composite shadow fading (line-of-sight and multiplicative shadowing) can be modelled by lognormal distribution. The application of lognormal distribution to characterize shadowing effects results in complicated expressions for the first and second order statistics and also the performance evaluation of communication systems such as interference analysis and bit error rates become difficult. An alternative to lognormal distribution is Nakagami distribution which can produce simple statistical models with the same performance. The pdf of the received signal envelope following Nakagami distribution is given by,

$$P_r(r) = \frac{2}{\Gamma(m)} \left( \frac{m}{2\sigma^2} \right)^m r^{2m-1} \exp\left( \frac{-mr^2}{2\sigma^2} \right) \quad r \geq 0 \quad (6)$$

where  $\Gamma(\cdot)$  represents the Gamma function,  $2\sigma^2 = E(r^2)$  is the average power of the LOS component and  $m \geq \frac{1}{2}$  is the Nakagami- $m$  parameter which varies between  $\frac{1}{2}$  to  $\infty$ . When  $m$  increases the number of Gaussian random variables contributions increases and the probability of deep fades in the corresponding pdf function decreases. Non-zero finite small and large values of  $m$  correspond to urban and open areas, respectively. The intermediate values of  $m$  correspond to rural and suburban areas.

### 3.5 Suzuki Distribution

The Suzuki process is characterized as the product of Rayleigh distributed process and lognormal process (Pätzold et al., 1998). Consider a Rayleigh distributed random variable  $\alpha$  with pdf  $P_\alpha(r)$  and another random variable  $\beta$  following lognormal distribution with pdf  $P_\beta(r)$ . Let  $\xi$  be a random variable defined by the product of these two independent variables ( $\xi = \alpha \cdot \beta$ ). The pdf  $P_\xi(r)$  of  $\xi$  can be written as follows:

$$P_\xi(r) = \frac{r}{\sqrt{2\pi}\sigma_0^2\sigma_\mu} \int_0^\infty \frac{1}{r^3} \cdot \exp\left( \frac{-r^2}{2\sigma_0^2} \right) \cdot \exp\left( -\frac{1}{2} \left( \frac{\ln r - m_\mu}{\sigma_\mu} \right)^2 \right) dr \quad r \geq 0 \quad (7)$$

This type of distribution can be used to represent propagation scenarios when LOS component is absent in the received signal.

## 4. Statistical Channel Models for Land-Mobile-Satellite Communications

The influence of radio channel is a critical issue for the design, real-time operation and performance assessment of LMS communication systems providing voice, text and multimedia services operating at radio frequencies ranging from 100 MHz to 100 GHz and optical frequencies. Thus, a good and accurate understanding of radio propagation channel



is of paramount significance in the design and implementation of satellite-based communication systems.

The radio propagation channels can be developed using different approaches, e.g., physical or deterministic techniques based on measured impulse responses and ray-tracing algorithms which are complex and time consuming and statistical approach in which input data and computational efforts are simple. The modelling of propagation effects on the LMS communication links becomes highly complex and unpredictable owing to diverse nature of radio propagation paths. Consequently statistical methods and analysis are generally the most favourable approaches for the characterization of transmission impairments and modelling of the LMS communication links.

The available statistical models for narrowband LMS channels can be characterized into two categories: single state and multi-state models (Abdi et al., 2003). The single state models are described by single statistical distributions and are valid for fixed satellite scenarios where the channel statistics remain constant over the areas of interest. The multi-state or mixture models are used to demonstrate non-stationary conditions where channel statistics vary significantly over large areas for particular time intervals in nonuniform environments. In this section, channel models developed for satellites based on statistical methods are discussed.

#### 4.1 Single-State Models

**Loo Model:** The Loo model is one of the most primitive statistical LMS channel model with applications for rural environments specifically with shadowing due to roadside trees. In this model the shadowing attenuation affecting the LOS signal due to foliage is characterized by log-normal pdf and the diffuse multipath components are described by Rayleigh pdf. The model illustrates the statistics of the channel in terms of probability density and cumulative distribution functions under the assumption that foliage not only attenuates but also scatters radio waves as well. The resulting complex signal envelope is the sum of correlated lognormal and Rayleigh processes. The pdf of the received signal envelope is given by (Loo, 1985; Loo & Butterworth, 1998).

$$P(r) = \begin{cases} \frac{1}{r\sqrt{2\pi}d_0} \exp\left[-\frac{(\ln r - \mu)^2}{2d_0}\right] & \text{for } r \gg \sqrt{b_0} \\ \frac{r}{b_0} \exp\left(-\frac{r^2}{2b_0}\right) & \text{for } r \ll \sqrt{b_0} \end{cases} \quad (8)$$

where  $\mu$  and  $\sqrt{d_0}$  are the mean and standard deviation, respectively. The parameter  $b_0$  denotes the average scattered power due to multipath effects. Note that if attenuation due to shadowing (lognormal distribution) is kept constant then the pdf in (8) simply yields in Rician distribution. This model has been verified experimentally by conducting measurements in rural areas with elevation angles up to  $30^\circ$  (Loo et al., 1998).

**Corraza-Vatalaro Model:** In this model, a combination of Rice and lognormal distribution is used to model effects of shadowing on both the LOS and diffuse components (Corazza & Vatalaro, 1994). The model is suitable for non-geostationary satellite channels such as medium-earth orbit (MEO) and low-earth orbit (LEO) channels and can be applied to different environments (e.g., urban, suburban, rural) by simply adjusting the model parameters. The pdf of the received signal envelop can be written as:

$$P_{(r)}(r) = \int_0^{\infty} p(r/S) p_S(s) ds \quad (9)$$

where  $p(r/S)$  denotes conditional pdf following Rice distribution conditioned on shadowing  $S$  (Corazza et al., 1994)

$$P(r/S) = 2(K+1) \frac{r}{S^2} \exp\left[-(K+1) \frac{r^2}{S^2} - K\right] I_0\left(2 \frac{r}{S} \sqrt{K(K+1)}\right) \quad r \geq 0 \quad (10)$$

where  $K$  is Rician factor (section 3.2) and  $I_0$  is zero order modified Bessel function of first kind. The pdf of lognormal of shadowing  $S$ , is given by:

$$P_S(S) = \frac{1}{\sqrt{2\pi h\sigma S}} \exp\left\{-\frac{1}{2} \left(\frac{\ln S - \mu}{h\sigma}\right)^2\right\} \quad S \geq 0 \quad (11)$$

where  $h = \ln(10)/20$ ,  $\mu$  and  $(h\sigma)^2$  are mean and variance of the associated normal variance, respectively. The received signal envelop can be interpreted as the product of two independent processes (lognormal and Rice) with cumulative distribution function in the following form (Corraza & Vatalaro, 1994):

$$P_r(r_0) = P(r < r_0) = \int_0^{r_0} \int_0^{\infty} \frac{P_S(S)}{S} P_r\left(\frac{r}{S}\right) dr dS = 1 - E_S\left\{Q\left(\sqrt{2K}, \frac{r_0}{S} \sqrt{2(K+1)}\right)\right\} \quad (12)$$

where  $E(\cdot)$  denotes the average with respect to  $S$  and  $Q$  is Marcum  $Q$ -function.

The model is appropriate for different propagation conditions and has been verified using experimental data with wide range of elevation angles as compared to Loo's model.

**Extended-Suzuki Model:** A statistical channel model for terrestrial communications characterized by Rayleigh and lognormal process is known as Suzuki model (Suzuki, 1977). This model is suitable for modelling random variations of the signal in different types of urban environments. An extension to this model, for frequency non-selective satellite communication channels, is presented in (Pätzold et al., 1998) by considering that for most of the time a LOS component is present in the received signal. The extended Suzuki process is the product of Rice and lognormal probability distribution functions where inphase and quadrature components of Rice process are allowed to be mutually correlated and the LOS

component is frequency shifted due to Doppler shift. The pdf of the extended Suzuki process can be written as (Pätzold et al., 1998):

$$P_{\xi}(r) = \int_{-\infty}^{\infty} \frac{1}{|y|} P_{\alpha\beta}\left(\frac{r}{y}, y\right) dy \quad (13)$$

where  $P_{\alpha\beta}(x, y)$  denotes the joint pdf of the independent Rician and lognormal processes  $\alpha(t)$  and  $\beta(t)$ , and  $x = r/y$  where  $y$  is variable of integration. The pdfs of Rice and lognormal processes can be used in (13) to obtain the following pdf:

$$P_{\xi}(r) = \frac{r}{\sqrt{2\pi}\psi_0\sigma} \int_0^{\infty} \frac{1}{y^3} \exp\left\{-\left[\frac{\left(\left(\frac{r}{y}\right)^2 + p^2\right)}{2\psi_0}\right]\right\} I_0\left(\frac{rp}{y\psi_0}\right) \cdot \exp\left[-\frac{(\ln y - m)^2}{2\sigma^2}\right] dy \quad r \geq 0 \quad (14)$$

where  $\psi_0$  is the mean value of random variable  $x$ ,  $m$  and  $\mu$  are the mean and standard deviation of random variable  $y$  and  $p$  denotes LOS component.

The model was verified experimentally with operating frequency of 870 MHz at an elevation angle  $15^\circ$  in rural area with 35% trees coverage. Two scenarios were selected: a lightly shadowed scenario and a heavily shadowed scenario with dense trees coverage. The cumulative distribution functions of the measurement data were in good agreement with those obtained from analytical extended Suzuki model.

**Xie-Fang Model:** This model (Xie & Fang, 2000), based on propagation scattering theory, deals with the statistical modelling of propagation characteristics in LEO and MEO satellites communication systems. In these satellites communication systems a mobile user or a satellite can move during communication sessions and as a result the received signals may fluctuate from time to time. The quality-of-service (QoS) degrades owing to random fluctuations in the received signal level caused by different propagation impairments in the LMS communication links (section 2). In order to efficiently design a satellite communication system, these propagation effects need to be explored. This channel model deals with the statistical characterization of such propagation channels.

In satellite communications operating at low elevation angles, the use of small antennas as well as movement of the receiver or the transmitter introduces the probability of path blockage and multipath scattering components which result in random fluctuations in the received signal causing various fading phenomena. In this model fading is characterized as two independent random processes: short-term (small scale) fading and long-term fading. The long term fading is modelled by lognormal distribution and the small scale fading is characterized by a more general form of Rician distribution. It is assumed, based on scattering theory of electromagnetic waves, that the amplitudes and phases of the scattering components which cause small scale fading due to superposition are correlated. The total electric field is the sum of multipath signals arriving at the receiver (Beckman et al., 1987):

$$E_{tot} = E \exp(j\psi) = \sum_{i=1}^n A_i \exp(j\phi_i) \quad (15)$$

where  $n$  denotes the number of paths,  $A_i$  and  $\phi_i$  represent the amplitude and phase of the  $i^{th}$  path component, respectively. The pdf of the received signal envelope can be obtained as follows (Xie & Fang, 2000):

$$P_r(r) = \frac{r}{\sqrt{S_1 S_2}} \exp \left[ -\frac{S_1 r^2 + S_2 \alpha^2 + S_1 \beta^2}{2 S_1 S_2} \right] \times \frac{1}{2\pi} \int_0^{2\pi} \exp \left[ \frac{2 S_2 \alpha r \cos \theta + 2 S_1 \beta r \sin \theta + (S_1 - S_2) r^2 \cos^2 \theta}{2 S_1 S_2} \right] d\theta \quad (16)$$

and the pdf of the received signal power envelope is given by:

$$P_p(W) = \frac{1}{2\sqrt{S_1 S_2}} \exp \left[ -\frac{S_2 W + S_1 \alpha^2 + S_2 \beta^2}{2 S_1 S_2} \right] \times \frac{1}{2\pi} \int_0^{2\pi} \exp \left[ \frac{2 S_2 \alpha \sqrt{W} \cos \theta + 2 S_1 \beta \sqrt{W} \sin \theta + (S_1 - S_2) W \cos^2 \theta}{2 S_1 S_2} \right] d\theta \quad (17)$$

where the parameters  $S_1$ ,  $S_2$ ,  $\alpha$ , and  $\beta$  denote the variances and means of the Gaussian distributed real and imaginary parts of the received signal envelope ' $r$ ', respectively, and ' $W$ ' represents the power of the received signal.

This statistical LMS channel model concludes that the received signal from a satellite can be expressed as the product of two independent random processes. The channel model is more general in the sense that it can provide a good fit to experimental data and better characterization of the propagation environments as compared to previously developed statistical channel models.

**Abdi Model:** This channel model (Abdi et al., 2003) is convenient for performance predictions of narrowband and wideband satellite communication systems. In this model the amplitude of the shadowed LOS signal is characterized by Nakagami distribution (section 3.4) and the multipath component of the total signal envelope is characterized by Rayleigh distribution. The advantage of this model is that it results in mathematically precise closed form expressions of the channel first order statistics such as signal envelop pdf, moment generating functions of the instantaneous power and the second order channel statistics such as average fade durations and level crossing rates (Abdi et al., 2003). According to this model the low pass equivalent of the shadowed Rician signal's complex envelope can as:

$$R(t) = A(t) \exp[j\phi(t)] + Z(t) \exp[j\phi(t)] \quad (18)$$

where  $A(t)$  and  $Z(t)$  are independent stationary random processes representing the amplitudes of the scattered and LOS components, respectively. The independent stationary random process,  $\phi(t)$ , uniformly distributed over  $(0, 2\pi)$  denotes the phase of scattered components and  $\varphi(t)$  is the deterministic phase of LOS component. The pdf of the received signal envelop for the first order statistics of the model can be written as (Abdi et al., 2003):

$$P_r(r) = \left( \frac{2b_0 m}{2b_0 m + \Omega} \right)^m \cdot \frac{r}{b_0} \exp\left(-\frac{r^2}{2b_0}\right) \cdot {}_1F_1\left(m, 1, \frac{\Omega r^2}{2b_0(2b_0 m + \Omega)}\right) \quad r \geq 0 \quad (19)$$

where  $2b_0$  is the average power of the multipath component,  $\Omega$  is the average power of the LOS component and  ${}_1F_1(\cdot)$  is the confluent hypergeometric function.

The channel model's first order and second order statistics compared with different available data sets, demonstrate the appropriateness of the model in characterizing various channel conditions over satellite communication links. This model illustrates similar agreements with the experimental data as the Loo's model and is suitable for the numerical and analytical performance predictions of narrowband and wideband LMS communication systems with different types of encoded/decoded modulations.

## 4.2 Multi-state Models

In the case of nonstationary conditions when terminals (either satellite or mobile terminal) move in a large area of a nonuniform environment, the received signal statistics may change significantly over the observation interval. Therefore, propagation characteristics of such environments are appropriately characterized by the so-called multi-state models.

Markov models are very popular because they are computationally efficient, analytically tractable with well established theory and have been successfully applied to characterize fading channels, to evaluate capacity of fading channels and in the design of optimum error correcting coding techniques (Tranter et al., 2003). Markov models are characterized in terms of state probability and state probability transition matrices. In multi-state channel models, each state is characterized by an underlying Markov process in terms of one of the single state models discussed in the previous section.

**Lutz Model:** Lutz's model (Lutz et al., 1991) is two-state (good state and bad state) statistical model based on data obtained from measurement campaigns in different parts of Europe at elevation angles between  $13^\circ$  to  $43^\circ$  and is appropriate for the characterization of radio wave propagation in urban and suburban areas. The good state represents LOS condition in which the received signal follows Rician distribution with Rice factor  $K$  which depends on the operating frequency and the satellite elevation angle. The bad state models the signal amplitude to be Rayleigh distributed with mean power  $S_0 = \sigma^2$  which fluctuates with time. Another important parameter of this model is time share of shadowing 'A'. Therefore, pdf of the received signal power can be written as follows (Lutz et al., 1991):

$$p(S) = (1 - A) \cdot p_{Rice}(S) + A \int_0^{\infty} p_{Ray}(S/S_0) p_{LN}(S_0) dS_0 \quad (20)$$

The values of the parameters  $A$ ,  $K$ , means, variances and the associated probabilities have been derived from measured data for different satellite elevations, antennas and environments using curve fitting procedures. The details can be found in (Lutz et al., 1991). Transitions between two states are described by first order Markov chain where transition from one state to the next depends only on the current state. For two-state Lutz' model, the probabilities  $P_{ij}$  ( $i, j = g, b$ ) represent transitions from state  $i$  to state  $j$  according to good or bad state as shown in Fig. 2.

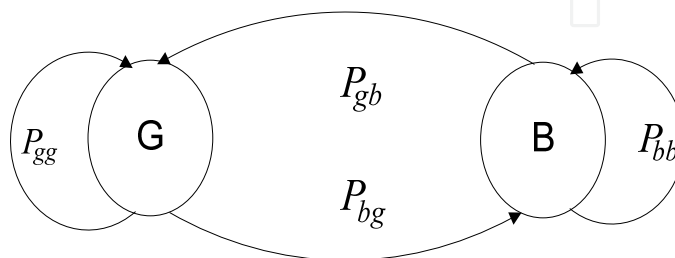


Fig. 2. Lutz's Two-state LMS channel model.

The transition probabilities can be determined in terms of the average distances  $D_g$  and  $D_b$  in meters over which the system remains in the good and bad states, respectively.

$$P_{gb} = vR/D_g \quad P_{bg} = vR/D_b \quad (21)$$

where  $v$  is the mobile speed in meters per second,  $R$  is the transmission data rate in bits per second. As the sum of probabilities in any state is equal to unity, thus  $P_{gg} = 1 - P_{gb}$  and  $P_{bb} = 1 - P_{bg}$ . The time share of shadowing can be obtained as:

$$A = \frac{D_b}{D_b + D_g} \quad (22)$$

The parameter  $A$  in this model is independent of data rate and mobile speed. For different channel models, the time share of shadowing is obtained according to available propagation conditions and parameters. For example in (Saunders & Evans, 1996) time share of shadowing is calculated by considering buildings height distributions and street width etc.

**Three-State Model:** This statistical channel model (Karasawa et al., 1997), based on three states, namely clear or LOS state, the shadowing state and the blocked state, provides the analysis of availability improvement in non-geostationary LMS communication systems. The clear state is characterized by Rice distribution, the shadowing state is described by



Loo's pdf and the blocked state is illustrated by Rayleigh fading as shown in Fig. 3(a), where  $a_1$  denotes the LOS component,  $a_2$  represents shadowing effects caused by trees and  $a_3$  represents blockage (perfect shadowing). Similarly, multipath contributions in the form of coherently reflected waves from the ground are denoted by  $b_1$  and incoherently scattered components from the land obstructions are represented by  $b_2$ . The pdf of the received signal envelop is weighted linear combination of these distributions:

$$P_R(r) = MP_{Rice}(r) + LP_{Loo}(r) + NP_{Rayleigh}(r) \quad (23)$$

where  $M$ ,  $L$ , and  $N$  are the time share of shadowing of Rice, Loo and Rayleigh distributions, respectively. The distribution parameters for the model were found by means of the data obtained from measurements using "INMARSAT" satellite and other available data sets. The model was validated by comparing the theoretical cumulative distributions with those obtained from measurement data. The state transitions characteristics of the model were obtained using Markov model as shown in Fig. 3(b). The state occurrence probability functions  $P_A$ ,  $P_B$  and  $P_C$  (where  $P_A + P_B + P_C = 1$ ) can be computed as follows (Karasawa et al., 1997):

$$P_A = (90 - \theta)^2 / a \quad (24)$$

where  $\theta$  is the elevation angle of satellite ( $10^\circ \leq \theta \leq 90^\circ$ ) and 'a' is a constant with values:

$$a = \begin{cases} 7.0 \times 10^3 & \text{for urban areas} \\ 1.66 \times 10^4 & \text{for suburban areas} \end{cases}$$

$$P_B = \begin{cases} P_C / 4 & \text{for urban areas} \\ 4P_C & \text{for suburban areas} \end{cases} \quad (25)$$

In order to characterize the state duration statistics such as the average distances or time spans during which a particular state tends to persist, a model capable of providing time-variant features is essential. A Markov process suitable for this purpose is expressed as three-state model as shown in Fig. 3(b) (Karasawa et al., 1997). In this model short-term fluctuations in the received signal are represented by specific pdfs within the states and long-term fading is described by the transitions between the states. This model is also suitable for the performance assessment of satellite diversity.

A significant aspect of the LMS systems is that a single satellite is not adequate for achieving the desired coverage reliability with a high signal quality. Thus, it is desirable that different satellite constellations should be employed which can improve the system availability and signal quality by means of satellite diversity. If a link with one of the satellites is interrupted by shadowing, an alternative satellite should be available to help reduce the outage probability. This channel model also provides analysis for the improvement of the signal quality and service availability by means of satellite diversity where at least two satellites in LEO/MEO orbit, illuminate the coverage area simultaneously in urban and suburban environments.

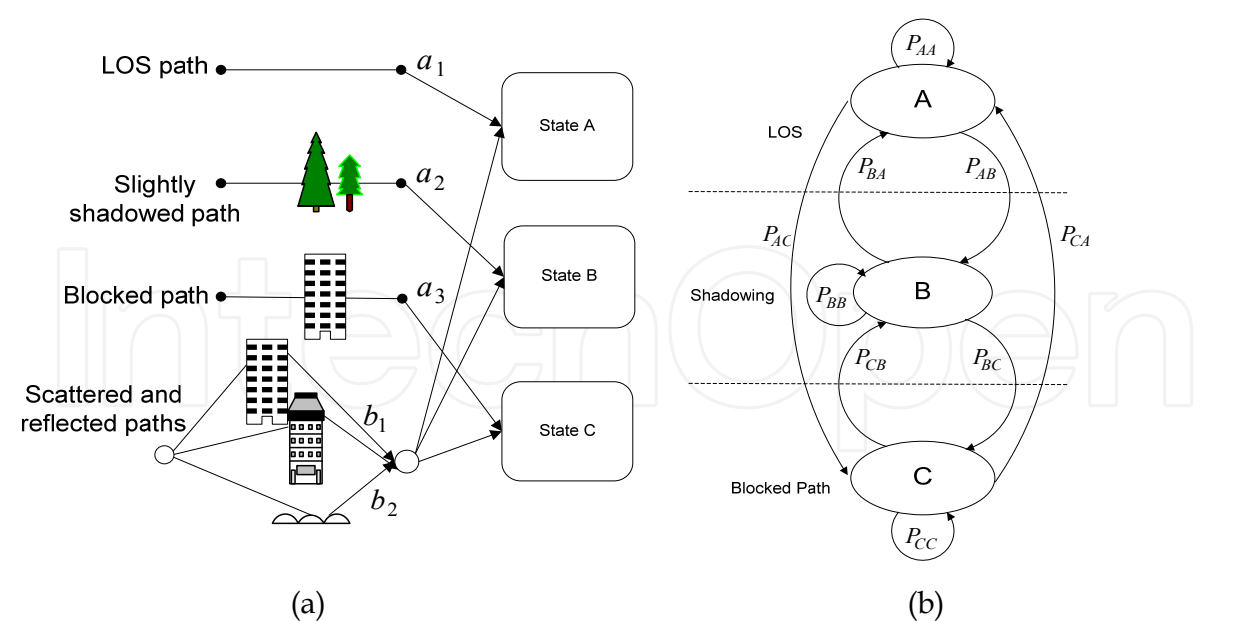


Fig. 3. Three-sate LMS channel model (a) Propagation impairments (b) Markov model.

**Five-State Model:** This channel model is based on Markov modelling approach in which two-state and three-state models are extended to five-state model under different time share of shadowing (Ming et al., 2008). The model is basically a composition of Gilbert-Elliot channel model and the three-state Markov channel model in which shadowing effects are split into three states: ‘good’ state represents low shadowing, ‘not good not bad’ state characterizes moderate shadowing and ‘bad state’ describes heavy or complete shadowing as shown in Fig. 4 (Ming et al., 2008). The ‘good’ state has two sub-states: clear LOS without shadowing and LOS state with low shadowing. Similarly, the ‘bad’ state has two sub-states: heavily shadowed areas or completely shadowed or blocked areas. A state transition can occur when the receiver is in low or high shadowing areas for a period of time. The transitions can take place from low and high shadowing conditions to moderate shadowing conditions but cannot occur directly between low and high shadowing environments.

For different shadowing effects, the statistical signal level characteristics in terms of the pdf are described as: low shadowing follows Rice distribution, moderate shadowing is represented by Loo’s pdf and high shadowing conditions are described by Rayleigh-lognormal distribution. The pdf of the received signal power is a weighted linear combination of these distributions:

$$P(s) = X_1P_{Rice1}(s) + X_2P_{Rice2}(s) + X_3P_{Loo}(s) + X_4P_{Ray\_L1}(s) + X_5P_{Ray\_L2}(s) \tag{26}$$

where  $X_i$  ( $i = 1,...,5$ ) are time share of shadowing of the states  $S_i$  ( $i = 1,...,5$ ), respectively.

The state probability and state transition probability matrices are determined using the time series of the measured data. The channel model has been validated using available measured data sets and different statistical parameters are obtained using curve fitting procedures. The channel statistics like the cumulative distribution function, the level crossing rate, the average fade duration, and the bit error rate are computed which show a

good agreement with the statistics of the data obtained from measurements. The channel model is appropriate for urban and suburban areas.

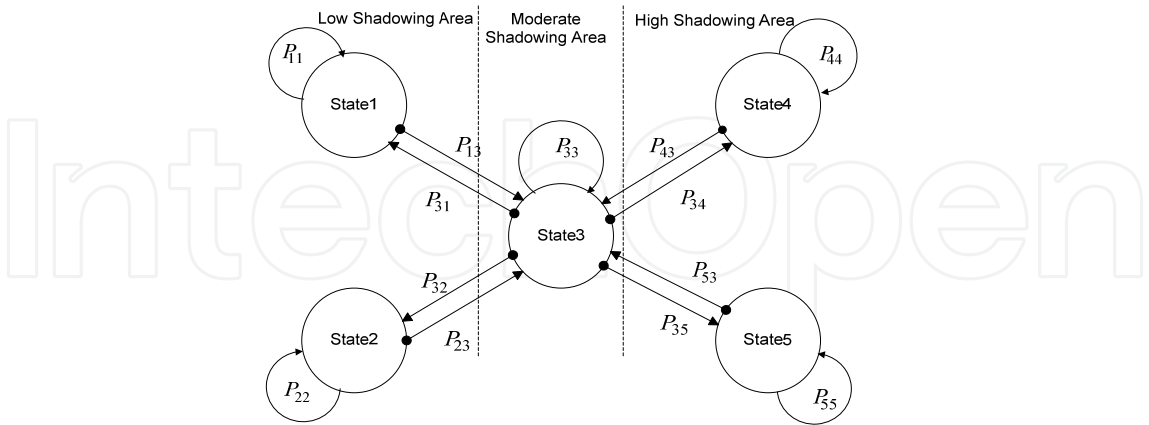


Fig. 4. Five-state Markov channel model for LMS communications.

**Modelling Frequency Selective LMS Channel:** The LMS propagation channel effects depend on the propagation impairments (section 2), geographical location, elevation angles and operating frequency band. Extensive measurements are needed for the characterization of LMS fading caused by different propagation impairments. When components of a signal travelling through different paths arrive at the receiver with delays significantly larger as compared to the bit or symbol duration, the signal will undergo significant amount of distortion across the information bandwidth, it results in frequency selective fading or wideband fading (e.g., in the case of broadband services or spread spectrum). The impulse response of a wideband channel model (also known as tapped-delay line model) under wide sense stationary uncorrelated scattering (WSSUS) assumption can be written as:

$$h(t, \tau) = \sum_{i=1}^N a_i(t) \delta[t - \tau_i(t)] \exp[j(2\pi f_{d,i}(t) + \theta_i(t))] \tag{27}$$

where  $a_i(t)$ ,  $\tau_i(t)$ ,  $f_{d,i}$  and  $\theta_i(t)$  are the amplitude, delay, Doppler shift and phase of the  $i^{th}$  component of the received signal, respectively, and  $\delta(t)$  denotes the Dirac delta function.

A tapped-delay line model that describes the wideband characteristics of LMS communication link has been given in (Jahn, 2001). The parameters for this model are extracted using extensive measurement data at L-band for different applications, scenarios and environments. In order to adopt the channel for LMS communications, the channel impulse response is divided into three components: the direct path, near echoes and far echoes as shown in Fig. 5 (Jahn, 2001). The delays  $\tau_i$  ( $i = 1, 2, \dots, N$ ) of the taps are taken with respect to the delay of the direct path. The power of all taps is normalized to the power of the direct path. The amplitude distributions of the echoes follow Rice or Rayleigh distribution (section 3) depending on the presence of LOS or non-LOS situations,

respectively. The number  $N^n$  of near echoes in the locality of the receiver follows Poisson distribution with parameter  $\lambda$  (*i.e.*,  $f_{\text{Poisson}}(N) = (\lambda^N / N!) e^{-\lambda}$ ) and the corresponding delays  $\tau_i$  ( $i = 1, 2, \dots, N$ ) characterizing near echoes follow exponential distribution with parameter  $b$  (*i.e.*,  $f_{\text{exp}}(\tau_i^n) = (e^{-\tau_i^n / b} / b)$ ). The power of the taps decay exponentially. The far echoes  $N^f = N - N^n - 1$ , which are few in numbers are characterized by Poisson distribution. The amplitude distributions of the far echoes are described by Rayleigh distribution. The description of different regions of the wideband LMS channel impulse response can be found in (Jahn, 2001). Another physical-statistical channel model that deals with the frequency selectivity of LMS channels is found in (Parks et al., 1996). This model consists of two cascaded processes. The first one deals with propagation effects from satellite to earth and the second process illustrates the terrestrial propagation impairments.

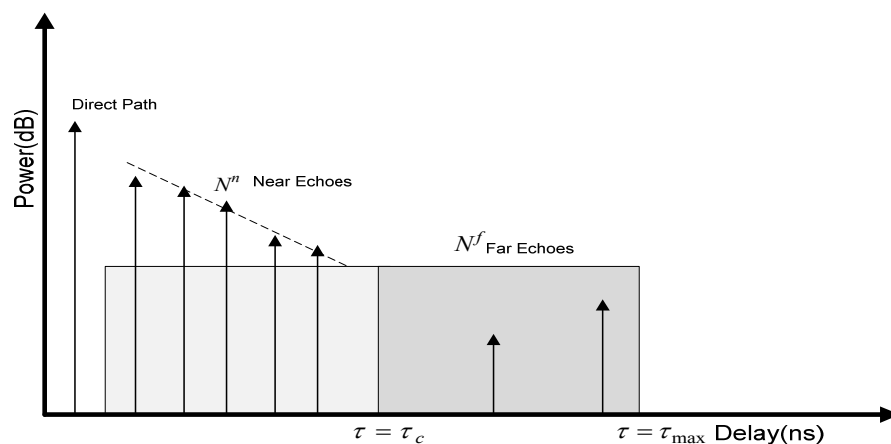


Fig. 5. Wideband LMS channel impulse response with different regions.

## 5. Conclusions

This chapter provides an overview of propagation impairments on LMS communication links, probability distributions describing these fading effects and channel models developed using these probability distributions. Proper knowledge of propagation impairments and channel models is necessary for the design and performance assessment of advanced transceiver techniques employed to establish reliable communication links in LMS communication systems. The main focus lies on highlighting which are the effects and the relevant propagation models need to be considered for LMS communication links in order to accurately estimate the propagation impairments. The performance of LMS communication systems depend on different factors including operating frequency, elevation angles, geographic location, climate etc. Different approaches can be used to find the effects of these factors on LMS communication links such as physical-statistical channel models which are more accurate but require long simulation times and are complex. On the other hand statistical methods are simple and require less computational efforts. In addition, due to diverse nature of propagation environments, it is appropriate to use stochastic approaches for the performance assessment of LMS communication links.

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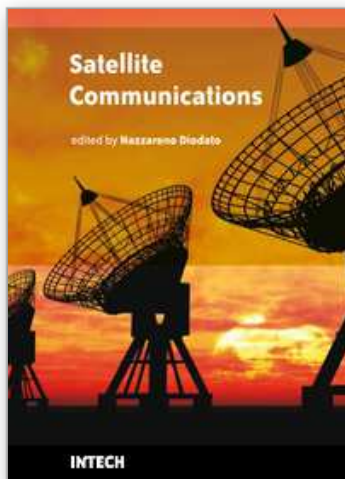
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