COST Action 272

"Packet-Oriented Service Delivery via Satellite"

Review and trends on channel modelling and mitigation techniques for GEO and non-GEO system design

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1. INTRODUCTION

A number of broadband multimedia satellite systems (access and/or core networks) are being designed to provide data rates well above 2 Mb operating at high frequencies (see Figure 1). For such high frequencies the classical procedure of relying upon long-term and per-link or monthly/yearly basis by evaluating link margins (for a given availability: 95 or 97%) provides too high values at Ka (20/30 GHz) or V band (40/50 GHz).

It is then necessary to optimize the system as a whole, taking into account the fade countermeasure and the diversity schemes. This requires a new prediction methodology and the development of adequate channel models to be easily incorporated to the system model.

In this document we present the state of the art of channel modeling for satellite systems and its use for system performance evaluation.

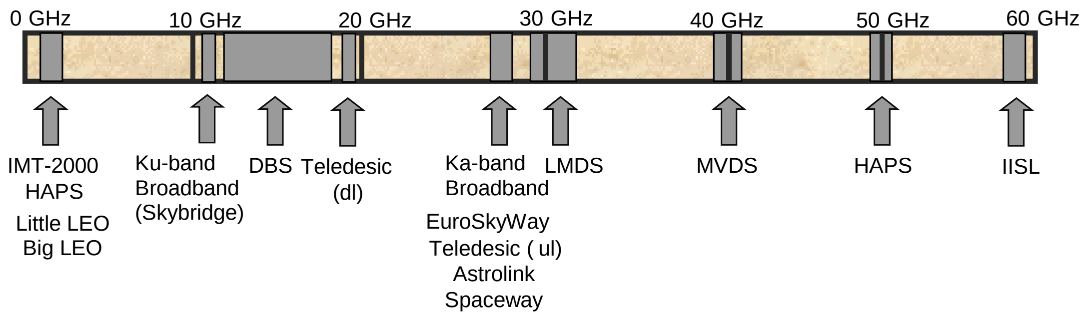

Figure 1. *Simplified spectrum map of deployed and future wireless systems.*

2. TROPOSPHERIC PROPAGATION IMPAIRMENTS IN A RADIO SYSTEM

2.1 MODELS

Different atmospheric phenomena must be considered particularly for low fade margin satellite communication systems at Ku band and above. The principal impairments in an Earth-to-satellite link are attenuation due to atmospheric gases (oxygen and water vapor), clouds and precipitation, and scintillation due to tropospheric turbulence.

Gas Attenuation: Oxygen and water vapor are the main atmospheric gases affecting signal at centimeter and millimeter waves. Oxygen concentration is almost constant during the day and during the year and slightly varies over the globe. The oxygen specific attenuation depends on frequency (see Figure 1), ground temperature and atmospheric pressure. The amount of water vapor is highly variable being a function of temperature and of atmospheric conditions and its main effect is measured in a broadened band around the H_2O absorption line at 22.2 GHz (see Figure 2). The attenuation due to water vapor exhibits noticeable daily, seasonal and geographical variations. Models to compute attenuation are:

- **Liebe's model** [1]: requires vertical profiles of temperature, humidity and pressure that are not usually available.
- **ITU-R P.676-4 Recommendation** [2] indicates how to calculate yearly averaged gaseous attenuation at zenith. The zenith attenuation can then be scaled in elevation for all methods by a cosecant law,
- **Salonen et Al** [3] propose a model to calculate oxygen and water vapor attenuation

Cloud Attenuation. Clouds consist of suspended water droplets of size smaller than the wavelength for frequencies up to V band. Clouds attenuation is highly variable, depending on the presence or not of clouds along the link and on their liquid water content. Models to compute attenuation are:

- **ITU-R Recommendation P.840-2** [4] indicates how to calculate clouds attenuation as a function of the integrated reduced liquid water content, the frequency, the elevation angle and the dielectric constant of the water.
- **Dissanayake et Al** model [5] calculates, instead, the cloud attenuation distribution due to four cloud types using their average properties (vertical and horizontal extent and water content) and their cover percentage.

Rain Attenuation. The specific attenuation of rain depends on the temperature, size distribution, terminal velocity and shape of the raindrops.

Best performing models on rain attenuation at frequencies up to 50 GHz are: Australian [6] Bryant [7] EXCELL [8] ITU-R Rec. P.618-6 [9] and Misme-Waldteufel [10] methods appear to be the best methods according to the test run in the frame of European Community research project COST255 [11]. When measured distributions of rain intensity are not available, the global map of the parameters of the rain intensity prediction model by Baptista and Salonen, recommended by ITU-R [12] can be used, without substantial degradation of the performance of rain attenuation models.

Models on spatial diversity predicting diversity gain, i.e. the difference between the single-site and joint attenuations at the same probability level are: EXCELL [13] and Hodge [14] (among others).

Models on second order statistics or distributions of fade intervals are: Paraboni and Riva [15] (among others)

Tropospheric Scintillation is due to small-scale refractive index inhomogeneities induced by atmospheric turbulence along the propagation path. It results in rapid fluctuations of the received signal amplitude that affect earth-space links above about 10 GHz. A good approximation is that scintillation amplitude follows a Gaussian distribution (strictly speaking the amplitude distribution is not symmetrical) and that the standard deviation of scintillation calculated over few minutes is a random variable with log-normal or gamma distribution. The most important parameter to be predicted is then the standard deviation of scintillation. Many models are now available to predict yearly averaged standard deviation of scintillation:

- **ITU-R Rec. 618-6** (9) model performs well below 15 GHz
- **Van de Kamp** (17) model is especially adequate for high frequency links.

2.2. COMBINATION OF TROPOSPHERIC EFFECTS

Several statistical rules can be used for combination of the different effects. Equiprobability summing method assumes that the different effects are fully correlated and adds their respective attenuation levels for equal probabilities. This method may be used for worst-case approximation. Otherwise, if two fade phenomena can be assumed as not correlated, their statistical distributions can be combined by the convolution of their probability density functions. Finally, if two phenomena can be regarded as disjoint, their statistical distributions of attenuation can be combined by adding the probabilities (i.e. exceeding time) at the same attenuation level. Disjoint summing is hence recommended, if it is possible to calculate disjoint distributions. Another possible method for combining two attenuation distributions is to use the root of the quadratic sum of their attenuation at the same probability level. It is easy to see that this method gives smaller values for total attenuation than the equiprobability summing. **The ITU-R Rec. 618-6** (9) suggests an equiprobability summing for clouds and rain.

2.3. APPLICATION TO SYSTEM DESIGN

A number of examples of the reviewed models application to system design are given in [18]. For example, for a satellite link between a hub at Portsmouth, UK and a VSAT at Spino d'Adda, Italy, the long-term statistical properties are calculated. A regenerative repeater is assumed operating at 14 GHz uplink and 12 GHz downlink with an asymmetrical configuration (outbound link is of a broader bandwidth than the inbound).

Exceedance of quality objectives	Up-link	Down-link
Availability margins		
Outbound	6 h	361 h
Inbound	365 h	7 h
Quality objectives margins		
Outbound	2.9 min	2.7 min
Inbound	3.0 min	2.7 min

Table 1. Power margins for Asymmetrical Ku band regenerative repeater data comm. system

Power margin (dB)	Up-link	Down-link
Availability		
Outbound	2.2	0.3
Inbound	0.4	1.8
Quality		
Outbound	13	13
Inbound	18	11

Table 2. Outage duration composed of intervals longer than 3 minutes

Table 3. Radio system characteristics in relation to the propagation fading

Radio System Characteristics	Options / Choices	Comments / Application	Atmospheric Propagation Impact on System Design
Transmission Technology	Analogue	Obsolete	Graceful deterioration
	Digital	End-to-end quality	Good/bad threshold effect
Spacecraft Orbits	Geostationary (GEO)	High free space loss	May become prohibitive for very high frequencies
	Low Earth Orbit (LEO)	Earth terminal tracking	Frequency dependent effects
	High Altitude Platform (HAP)	Terrestrial by ITU-R?	Most of the effects are still relevant
Links	Fixed	GEO, HAP	Atmospheric propagation only
	Mobile (inc. variable angle)	GEO, LEO, HAP	Local effects have to be taken in account as well
Frequency Band	Up to and Ku	mature	Most cases solved with a margin
	Ka	Current	Simple countermeasures
	V and beyond	Imminent	Complex countermeasures
Satellite Payload	Transparent Transponder	Mature	Uplink impairments affect downlink quality; joint statistics
	Regenerative Transponder	Imminent	Separation of uplink and downlink effects
Basic Multi-user Support	TDMA	These configuration characteristics and their combinations and derivatives will play part in terms of implementation of complex fade countermeasures and their algorithms for future systems.	
	FDMA		
	CDMA		
Multiple Access	Demand Assignment		
	Random		
Network Topology	Star		
	Mesh		
Traffic Symmetry	Asymmetrical	Likely to dominate in the future	Propagation characteristics at two sites may bear different importance
	Symmetrical	For very large users only?	Propagation characteristics at the sites are of equal importance
Bandwidth	Narrow-band	Current; future return links	Flat fading, atmospheric impairments dominate
	Broad-band	Imminent requirement	Local effects may become dominant.
Statistical Availability	High	Business, mission critical	Fade mitigation must be in place.
	Low	Consumer, light users	Fade mitigation on a lower scale
Temporal Availability	Time of day	Broadcast	Trade-off between lost revenue risk and system complexity/cost
	Maximum outage duration	Traffic delivery mode dependent	For real-time delivery this may be the most critical parameter
Traffic Delivery Mode	Real time	Live Entertainment, business/markets	Complex countermeasures will be required
	Near-real time	Pay per view retrieval, browsing/shopping	With careful design simple FCMs will be good enough
	Non real time	Data	Simple or no countermeasures

Implementing power margins to achieve statistical availability is usually not a problem. Design constrains in those cases come from the requirements on the maximum duration of outage intervals. In the considered system, the outage intervals should not be longer than 3 minutes. Using the model referred to in the previous section for the prediction of fade duration, it is possible to check if fades that exceed power margins in Table 1 for 5% of the time last longer than 3 minutes as it is shown in Table 2. From Table 2 it appears that margins chosen according to availability objectives do not allow the fulfillment of the quality objectives. With larger margins, those shown on the bottom of Table 1, for example, quality objectives can be achieved as shown in the bottom of Table 2. Those margins may not be always feasible with the present technologies in which case some fade mitigation would have to take place even at the Ku band. At higher frequencies, it will be a definitive requirement.

3. PROPAGATION IMPAIRMENTS DUE TO NEAR ENVIRONMENT

3.1 MODELS

Classical terrestrial land mobile modelling artificially separates slow and fast variations due to shadowing and multipath respectively and model them independently. Conversely in LMS systems the usual approach is to model both effects together. The reason is that terrestrial propagation rarely exhibits LOS conditions and the environment from the base station contributes as a whole to both slow and fast variations. However direct signal is usually present when transmitters are located above the earth due to the higher elevations and for the same reason impairments of the signal are mainly caused only by the near environment (see Figure 2). To account for the combined effect of shadowing and multipath effects, a **empirical-statistical** approach to channel modelling uses combinations of distributions while the possible scenarios are classified into a limited number of categories: open area, suburban area, tree shadowed, urban area, etc.. It is then understood that while a mere combination of Rayleigh (fast variations) and lognormal (slow variations) have been suggested for the terrestrial case [10], for the satellite scenario a number of models have been proposed from which we can mention the following:

- **Statistical Single-state**
  - **Loo** model [19] assumes that the received signal follows a Rice distribution (direct signal + multipath) where the multipath power is constant and the direct signal is locally log-normally distributed
  - **Corazza&Vatalaro** [20] model assumes that the received signal follows a Rice distribution where both direct signal and multipath are locally log-normally distributed. In [21] an extension of the model is given that assumes an additional diffuse Rayleigh component
  - **Hwang** [22] model assumes that the received signal follows a Rice distribution where both direct signal and multipath follow independent log-normal distribution

- **Vogel&Akturan** [23][24] model defines path states probabilities for clear (C), shadowed (S) and blocked (B) conditions. Rice distribution is then applied to the clear state and Loo model for the shadowed and blocked conditions. The derived urban three-state model is therefore

$$f_r(r,\alpha) = C(\alpha) f_{Rice}(r) + S(\alpha) f_{Loo}(r) + B(\alpha) f_{Loo}(r) \quad (1)$$

  where r is the received signal and α is the elevation angle. Rice and Loo distribution parameters are extracted from measurements and the values (%) of C, S and B are estimated from fisheye pictures. A comparison is presented in [25].

- **Statistical Multi-sate**
  - **Lutz** [26] proposes a two-state ("good" and "bad") Markov model where transitions and state probabilities are also computed from measurements. Signal is modeled as Rice in the good state and as Rayleigh+Lognormal in the bad state
  - A number of three-state Markov channel models are proposed in [27][28][29] suggesting different statistical distributions for each state of the signal. Typically, each state will last a few meters along the traveled route. In [19] a minimum state length or state frame with a length of 3 to 5 m was obtained from the analysis of a large experimental data carried out at S-Band. For GEO satellites, relatively low elevation angles are found especially for the northern latitudes while lower orbits provide higher elevation angles, thus making it possible to overcome, in part, the shadowing. This dependency with elevation must be also included in the channel model. In [27] a different Markov chain is proposed for each satellite elevation (with a given granularity) and the appropriate chain is triggered by the satellite movement as it is shown in Figure 2.
- **Physical-statistical**: this approach integrates the statistical ease-of-use and low computational requirements of empirical-statistical models with the physical insight of deterministic models. To achieve that they propose parameterization of built-up areas by statistical distribution of the building heights.
- **Physical:** these models are site-specific and combine high frequency methods for calculating diffracted field amplitudes models with topographical/morphological information and ray-tracing acceleration techniques similar to those used for digital image rendering. The most popular method is the Geometrical Theory of Diffraction (GTD); and the Uniform Theory of Diffraction (UTD) which is an extension of GTD to remove the discontinuities at the boundaries of reflection and shadowing for perfectly conducting wedges.

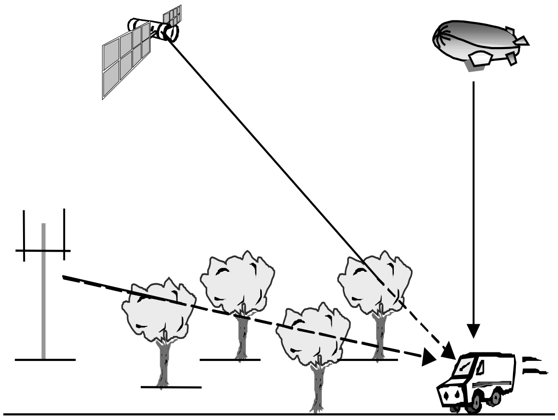

Figure 2. *Low elevation propagation of mobile terrestrial versus high elevation of LMS and HAPS*

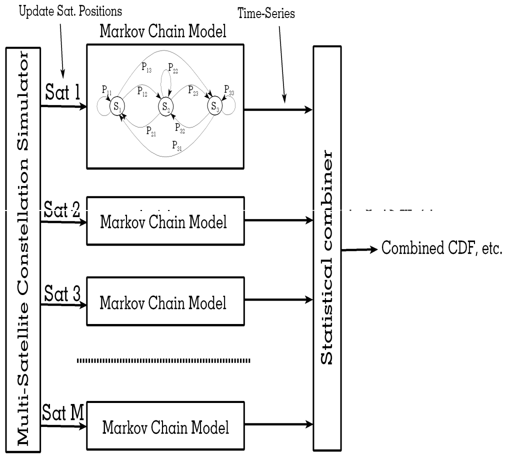

Figure 3. *Land Mobile Multisatellite channel model based on a set of 3-state Markov chains*

Most of the models mentioned so far are “generative models” meaning they can provide **time-series** of the complex envelope of the received signal. In the case of the **narrowband** channel such time-series will multiply the transmitted signal thus reproducing the channel fading and Doppler shift phenomena. When **wideband** conditions occur, the term time-series would refer to the complex variations in the different taps in a **tapped-delay-line** channel model. The narrowband channel case is the most likely condition found in practice in the LMS channel.

3.2. MITIGATION TECHINQUES AND SYSTEM PERFORMANCE

Time-series of channel parameters characterizing narrowband and wideband behavior of the channel can be directly used to provide physical-layer outputs as well as availability figures. Following, some aspects on Power Control on CDMA systems and availability are briefly described.

5.1 Power Control

Power control techniques (PC) used by CDMA based systems by which a closed loop dialogue is set up between transmitter and receiver in order to dynamically compensate fades, can smooth away slow variations but not fast variations when mobile speed is high. In CDMA systems PC techniques are also critical to solve the near-far effect so that the received $E_b/(N_0+I_0)$ from all users is similar at the gateway. In satellite systems these techniques perform poorer than in terrestrial due to the higher delays and power limitations in the user terminal. In [30] a study is presented on the power control performance in a satellite scenario. The followed steps are: 1º generation of the received timeseries of signal amplitude for a given environment, mobile speed and time sampling, 2º simulation of PC algorithm operation upon the received signal timeseries. Figure 3 shows an example of obtained power controlled channel timeseries for an urban environment. The target level has been set to a normalized value of 0 dB, the elevation is in the range of 45º-65º, the mobile speed is 15 m/s, the time resolution was set to 10 ms which is coincident with a CDMA frame length. It can be seen how the drastic signal variations are eliminated by the PC although fast variations are still present. It is also shown how these remaining variations can be fitted to a lognormal distribution.

Figure 5 shows the BER cumulative distribution function for a suburban environment after applying PC as described above. The required $E_b/(N_o+I_o)$ is the ideal for coded QPSK and therefore 50% of the time BER is less than the target 10^{-2} since the target value is the mean of the lognormal variations, it can be observed that the probability decreases as N increases.

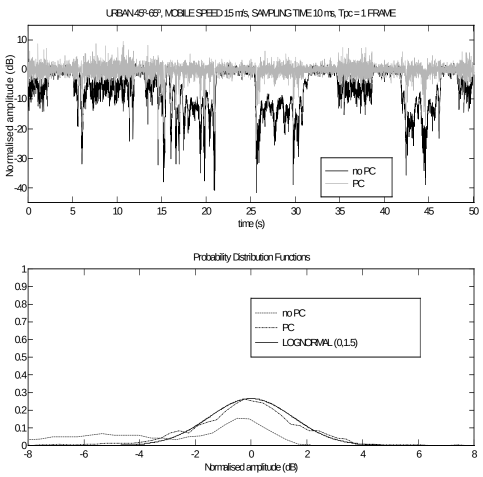

Figure 4. *Example of power control performance at S Band (urban, 45º-65º elevation,15 m/s).*

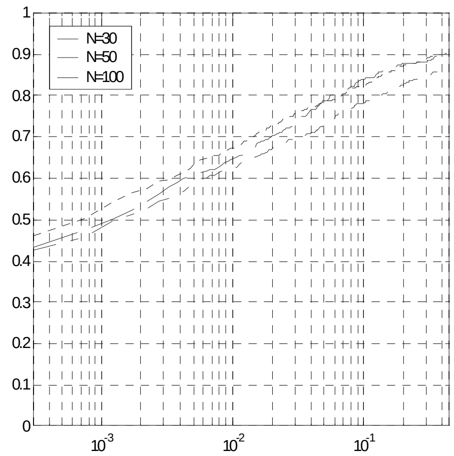

Figure 5*. Effect of number of users and required Eb/(No+Io) on BER statistics for coded QPSK (K=9,1/3) and users at 15 m/s*

5.2 Availability

To evaluate the availability improvement achieved with multi-satellite diversity, existing single-satellite propagation models need to be enhanced by incorporating information accounting for the partial cross-correlation of blockage effects found in the various links between the user terminal and the satellites in the constellation. A number of studies [31][32][33] have been published where the evaluation of the shadowing probability is performed by means of street **masking functions** indicating the azimuths and elevations for which a link can or cannot be completed for a given user terminal position. These functions were worked out by means of photogrametric studies or by ray-tracing (geometrical considerations).

Some of the models described in the previous section make it possible the calculation of masking functions which can be applied to **simplified scenarios** to produce a limited number of masking functions and hence making it possible to produce fast, approximate assessments of the combined availability in different multi-satellite configurations. Further, an urban scenario with a given masking angle (MKA) can be assumed to be made up of a combination of a small number of typical configurations (**basic/constitutive scenarios**), namely, street canyons, street crossings, T-junctions and single walls, each with a given occurrence probability. A **path-mixture** vector can be defined, in this case stating, for a given built-up area, the probabilities of encountering each of the constitutive scenarios $\vec{M}(w_{\mathrm{scy}}, w_{\mathrm{scr}}, w_{\mathrm{T-j}}, w_{\mathrm{sw}})$, with $\sum w_i = 1$. If the multi-satellite availability probabilities are calculated for those four (or more) constitutive scenarios, the overall availability could be roughly estimated as the weighted sum of the availabilities in each scenario. To illustrate this procedure the availability of a Globalstar-like system with switched diversity in a dense urban area with a (MKA) of approximately 63º is calculated. The user terminal is assumed to be located in Barcelona (Spain). A stepping interval, ΔT, of 1 minute and an observation period T_{obs}=2 h (close to the constellation period) are considered. Figure 6 shows the availability with time for the four basic scenarios. Each point in the curves is a street orientation averaged value.

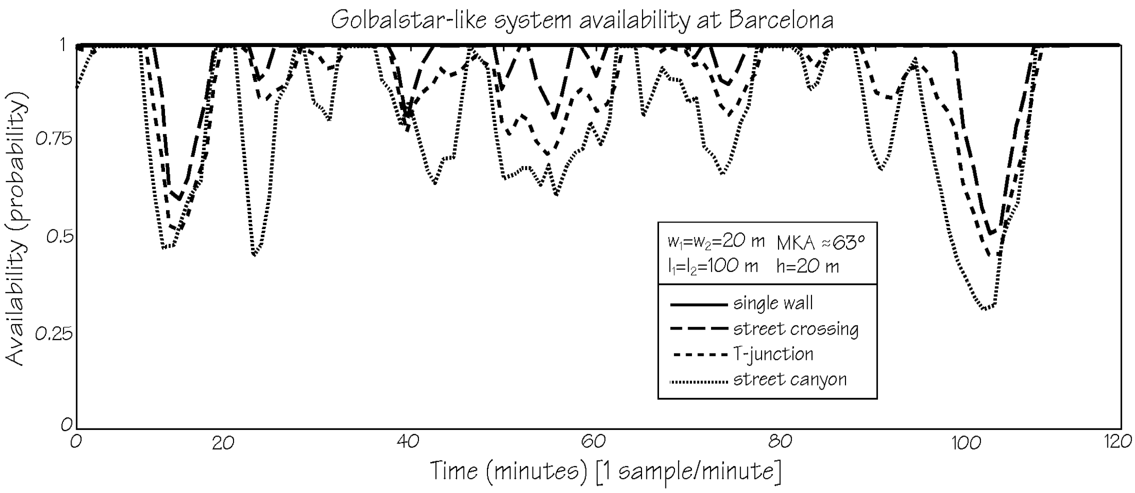

Figure 6. *Availability of a Globalstar-like system with switched diversity.*

REFERENCES

[1] Liebe H.J., “Modelling attenuation and phase of radio waves in air at frequencies below 1000 GHz”, *Radio Science*, Vol. 16, No. 6, 1981, pp. 1183-1199

[2] ITU-R, “Attenuation by atmospheric gases”, *ITU-R P Series Recommendations – Radiowave Propagation*, Rec. ITU-R P.676-4, Geneva, 1999.

[3] Salonen E., S. Karhu, S. Uppala and R. Hyvönen, “Study of improved propagation predictions”, Final report ESTEC contract 9455/91/NL/LC(SC), 1994.

[4] ITU-R, “Attenuation due to clouds and fog”, *ITU-R P Series Recommendations – Radiowave Propagation*, Rec. ITU-R P.840-2, Geneva, 1997.

[5] Dissanayake A., Allnutt J. and Haidara F., “A prediction model that combines rain attenuation and other propagation impairments along earth-satellite paths”, *IEEE Trans. on Ant. and Prop.*, Vol. 45, No. 10, pp. 1546-1558, 1997

[6] Flavin R.K., “Satellite link rain attenuation in Brisbane and a proposed new model for Australia”, Telstra Research Laboratories, Report N. 8375, 1996.

[7] Bryant G.H., Adimula I., Riva C. and Brussaard G., “Rain Attenuation Statistics from Rain Cell Diameters and Heights”, submitted to *Int. J. of Sat. Comm.*, 1999.

[8] Capsoni C., Fedi F. and Paraboni A., “A comprehensive meteorologically oriented methodology for the prediction of wave propagation parameters in telecommunication applications beyond 10 GHz”, *Ra. Sci*., Vol. 22, No. 3, pp. 387-393, 1987.

[9] ITU-R, “Propagation data and prediction methods required for the design of earth-space telecommunication systems”, *ITU-R P Series Recommendations - Radiowave Propagatio*n, Rec. ITU-R P.618-6, Geneva, 1999.

[10] Misme P. and Waldteufel P., “A model for attenuation by precipitation on a microwave earth-space link”, *Ra. Sci*., Vol.15, p. 655, 1980.

[11] Riva C. (Editor), “Testing of Prediction Models”, COST 255 Final Report “Radiowave propagation modelling for SatCom services at Ku-band and above”, Chapter 2.6, to be published in 2001.

[12] ITU-R, “Characteristics of precipitation for propagation modelling”, *ITU-R P Series Recommendations –Radiowave Propagatio*n, Rec. ITU-R P.837-2, Geneva, 1998.

[13] Bosisio A.V. and Riva C., “A novel method for the statistical prediction of rain attenuation in site diversity systems: theory and comparative testing against experimental data”, *Int. J. of Sat. Comm*., Vol 16, pp. 47-52, 1998.

[14] Hodge D.B., “An improved model for diversity gain on earth-space propagation paths”, *Ra. Sci*., Vol. 17, No. 6, pp. 1393-1399, 1982.

[15] Paraboni A. and Riva C., “A new method for the prediction of fade duration statistics in satellite links beyond 10 GHz”, *Int. J. of Sat. Comm*., Vol. 12, pp. 387-394, 1994.

[16] Fišer O. (Editor), “Rain Attenuation”, COST 255 Final Report “Radiowave propagation modelling for SatCom services at Ku-band and above”, Chapter 2.2, to be published in 2001.

[17] Van de Kamp M.M.J.L., “Asymmetrical signal level distribution due to tropospheric scintillation”, *Electron. Let*t., Vol. 34, No. 11, pp. 1145-1146, 1998.

[18] C. Riva, M. Filip and B.C. Grémont, “Propagation in the design and planning of radio systems”, HF Journal, issue on Radiowave Propagation, Nº 1 2000

[19] Loo C., ’A statistical model for land mobile satellite link’. IEEE Transactions on Vehicular Technology. Vol. VT-34, No.3, August 1985

[20] Corazza G.E. and Vatalaro F., ’A statistical model for land mobile satellite channels and its application to non-geostationary orbit systems’. IEEE Trans. on Vehicular Technology, Vol. 43, pp. 738-742, August 1994

[21] Vatalaro F., ‘Generalised Rice-Lognormal channel model for wireless communications’, Electronic Letters, Vol. 31, Nº 22, pp. 1899-1900, Oct. 1995.

[22] Hawng S.H., Kim K.J., Ahn J, Whang K.C., ‘A channel model for nongeostationary Orbiting satellite systems’, IEEE International Vehicular Technology Conference, May 1997

[23] Akturan R., Vogel W., 1996, “Photogrammetric Mobile Satellite Service Prediction”, Electronic Letters, Vol. 31, No. 3, pp. 165-166.

[24] Goldhirsh J. And Vogel W., ‘Handbook of Propagation effects for Vehicular and Personal Mobile Satellite Systems’, Overview of Experimental and Modeling Results’, available at http://www.utexas.edu/research/mopro/

[25] Pérez-Fontán F, Vázquez-Castro M.A, Enjamio C. and Pita J., ’Comparison of synthetically generated time-series based on three different statistical models for the LMS channel’, 19th AIAA International Communications Satellite Systems Conference and Exhibit, 7-20 April 2001

[26] Lutz E., Dippold D.M., Dolainsky F., Papke W., ‘The land mobile satellite communications channel - Recording, statistics and channel model’, IEEE Trans. on Vehicular Technology, Vol. 40, pp. 375-386, 1991

[27] Pérez-Fontán F, Vázquez-Castro M.A, Buonomo S., Baptista P. and Arbesser-Rastburg, ‘S-Band LMS propagation channel behaviour for different environments, degrees of shadowing and elevation angles. IEEE Tans. Broadcasting, Vol. 44, No. 1, pp 40-76, March 98

[28] Barts R.M., and W.L.Stutzman, ‘Modelling and simulation of mobile satellite propagation’, IEEE Trans. on Antennas and Propagation Vol.40, No.4, April 1992

[29] Karasawa Y., Kimura K. and Minamisoto K., ’Analysis of availability improvement in LMSS by means of satellite diversity based on three-state propagation channel model’, IEEE Trans. on Vehicular Technology, Vol. 46, No. 4, Nov. 1997, pp 1047-1056

[30] Vázquez-Castro M.A. and Pérez-Fontán F., ‘DS-CDMA satellite performance analysis with imperfect power control and diversity. link and system level interface’, 19th AIAA International Communications Satellite Systems Conference and Exhibit, 7-20 April 2001

[31] R. Akturan, W. J. Vogel, ‘Path diversity for LEO satellite PCS in urban environment’, IEEE trans. on Antennas and Propagation, Vol. 45., No. 7, July 1997, pp 1107-1116

[32] F. Dosiere, G. Maral, ‘Shadowing process models for mobile and personal satellite systems’, IEEE Globecom 1995, pp 536-540.

[33] C. Meenan, M. Parks, R. Tafazolli, B. Evans, ‘Availability of 1st generation personal communication network service in urban environments’, IEEE Vehicular Technology conference, VTC'98, pp 1471-1475