PROPAGATION CHANNEL MODELLING AND TIME SERIES SYNTHESIZERS FOR THE SIMULATION OF SATELLITE COMMUNICATION SYSTEMS

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ABSTRACT

The concept of Fade Mitigation Technique (FMT) has been highlighted for the Fixed Satellite Service since the use of high frequency (Ka, Q/V or EHF-band) is foreseen in the near future. At low frequency bands (C to Ku), propagation through the troposphere is considered only through the implementation of a static margin into the system, which at Ku-band is approximately the rain attenuation exceeded for the percentage of time corresponding to the availability requirement. At Ka and Q/V-bands, other propagation effects have to be taken into account (gas and cloud attenuation, scintillation), and as impairments are stronger, the typical service availability objectives can not be obtained anymore if the system is designed in the same way. Fade Mitigation Technique have to be considered and have to be introduced into the system through the design of a control loop, which aims at mitigating a propagation event in real time, by adapting some systems parameters : transmitted power, coding, modulation. The dynamics of the channel is therefore a key element to be taken into account directly into the definition of FMT control loop, for instance by numerical simulation using experimental time series of propagation impairments. However these experimental data are not always available to system designers, and in addition exist only for specific locations, frequencies and elevations. An alternative is to use time series synthesisers, where the inputs are characteristics of the link, and the outputs represent every kind of temporal and spectral characteristics of the channel (short term signal variations, long term primary and secondary statistics, …).

The aim of this paper is to present recent developments in terms of propagation time series synthesisers. In the first part, the initial requirements related to propagation time series and to the dynamics of the propagation channel for system performance simulation are listed, focussing on the requested inputs and on the expected outputs of time series synthesisers. In the second part, a list of time series generators that have been presented so far in the literature is given with their basic principles. In the third part, two methodologies used to compare and validate the time series synthesisers are mentioned (long-term and event-based analyses). A large testing activity has been conducted using an experimental database collected during the ITALSAT and OLYMPUS campaign. The results of this analysis give very promising confidence for using some of these channel models for the simulation and design of future satellite systems.

REQUIREMENTS ON CHANNEL MODELS

The implementation of Fade Mitigation Technique (FMT) leads to a specific design of adaptive systems, with several functions to be implemented : detection of the fade level, prediction of the attenuation a short time ahead, decision making and activation of a FMT mode. FMTs are introduced through the design of a control loop, which should track the signal variations, especially the slow component (attenuation), and possibly the envelope of fast fluctuations. The dynamics of the propagation channel is a key element to be taken into account into the definition of FMT control loops and can be simply described in terms of fade slope, fade duration or spectral characteristics. Fade slope and fade duration can help to optimise internal parameters of the FMT control loops (response time, internal margins or guard time). Spectral characteristics are important in order to filter out quick variations of the signal due to scintillation.

Previous studies [1] [2] have demonstrated that the introduction of experimental propagation time series into the simulation of the performance of the physical layer allows FMT control loops to be better optimised. Up to now, experimental data have been used for this purpose, but they are not always available. This data exists only for specific locations, frequencies and elevations. An alternative for running systems simulation is to use global channel models, taking into account all characteristics of the link. These channel models can be called time series synthesisers from which every kind of temporal, spectral and statistical characteristics of the propagation channel can be represented.

The synthesisers should allow time series of rain attenuation and scintillation to be generated, because rain attenuation is the main propagation effect limiting air interface performance at frequencies higher than 10 GHz and scintillation can result in erratic behaviour of FMT control loops. On the other hand, it would be valuable to generate other effects such as clear sky attenuation effects especially for systems operating at Q/V band.

As far as input parameters are concerned, any possible configuration between an Earth station and a geostationary satellite must be taken into account : geometry of the link (elevation angle, satellite and Earth station positions), radiowave characteristics (frequency and polarisation), climatic conditions introduced from radio-climatological

parameters available for all over the world (maps from ITU-R recommendations, or generated from ECMWF data or other meteorological offices). This last requirement is very important, because channel models must be flexible and compact enough to be generalised and extended to conditions different to those where measurements were carried out.
As far as model outputs are concerned, a great flexibility is needed in order to be able to synthesise both short-term and long-term time series. Short-term time series correspond to the generation of "event-on-demand" specified by its maximum attenuation and/or its total duration. This functionality is important for testing the behaviour of a FMT control loop with fade events that correspond to FMT activation thresholds, for evaluating switching rate between specific FMT modes or for assessing signalling issues. Long-term time series are useful to infer statistical distributions (availability, switching rate, throughput, etc.) for instance on a monthly basis to analyse the impact of the seasonal variability on the optimisation of control loop internal margins. Event-on-demand may also be selected with the appropriate algorithm from a long-term time series. Whatever the duration, the sampling rate has to be adjustable, for example between 0.1 Hz and 100 Hz. Indeed, depending on the system simulation to be carried out, the granularity of the propagation channel description could be different. For instance for analysing the behaviour of the control loop around a given FMT activation threshold, a fast sampling rate is required ; on the other hand, for performing a network simulation to test the allocation of the satellite resource, a low sampling rate may be sufficient.

AVAILABLE CHANNEL MODELS

Here below is given a list of channel models that have been presented so far in the litterature :

- ONERA-CNES spectral model [3]
- Portsmouth University spectral model [4]
- ONERA-Van de Kamp two-samples model [5]
- DLR channel model [6]
- ETRI channel model [7]
- ONERA N-State Markov chain model [8]
- Portsmouth University N-state model [9]
- Politecnico di Milano Earth-space propagation data derived model [10]
- Politecnico di Milano Synthetic Storm Technique [11]
- Rain-rate generator [12]
- University of Bath numerical weather prediction model data based model [13]

It is not possible here to describe the details of their formulation but the information can be found in the references mentioned above. Different approaches are considered in these various models : Spectral models, Markov chain or Markov process models, Propagation Database oriented models, models for rain rate time series (semi-physical, Markov, or numerical weather prediction model data based model) that can then be transformed into rain attenuation time series. Note that for some of the channel models, specific methods have to be used for retrieving, from experimental measurements, internal parameters that are necessary for running the generator.

METHODOLOGY FOR TESTING THE VALIDITY OF CHANNEL MODELS

Two methodologies have been followed to test the time series synthesisers against experimental data : a long-term testing activity and an event-based testing activity. The experimental databases used to perform the tests are 7 years of data collected during the ITALSAT campaign in Spino d'Adda (Italy) at 19, 40 and 50 GHz between 1994 and 2000, and 2 years of data collected during the OLYMPUS campaign in Louvain-la-Neuve and Lessive (Belgium) at 12.5, 20 and 30 GHz in 1990 and 1992.
The long-term testing activity methodology consists in generating 10 datasets with each time series synthesiser, each of these 10 datasets corresponding to a total duration of 1 year. The interest to generate 10 datasets is to get an idea of the dispersion of the results obtained with each of the time series synthesisers. Once these 10 datasets have been generated, testing activity is performed in terms of first order statistics (rain attenuation distributions) and second order statistics (fade slope and fade duration). The testing variable used for rain attenuation is the one given in Recommendation ITU-R P.311, whereas the testing variables for fade slope and fade duration are given in [14].
The event-based testing methodology has been developed to validate the physical soundness of rain attenuation events synthesisers and to compare them [15]. It is based on the analysis of a set of feature parameters of each individual event : maximum and mean attenuation, maximum and mean attenuation slope, total attenuation duration, spectrum characteristics, etc… It consists in carrying out a Principal Component Analysis (PCA) which aims at identifying relations between parameters and then in using the Mahalanobis distance as a criterion to perform the comparison. First of all, a matrix of correlation coefficients where each raw corresponds to a rain attenuation event and each column

represents a specific characteristic parameters of attenuation events is computed. Afterwards, the Mahalanobis distance between each synthesised and each experimental attenuation event is calculated and the Cumulative Distribution Functions (CDF) of Mahalanobis distances are generated. Finally, the error between synthesised and experimental CDFs of Mahalanobis distances is computed.

EXAMPLES OF LONG-TERM VALIDATION

In the framework of an ESA study [16], an intensive testing activity of the channel models has been conducted. A first series of comparisons between CDF of attenuation obtained from synthesised and experimental time series are presented in Fig. 1. Very good agreements are obtained with Spectral (SPL), Two-samples (TSM), DLR and Italsat data-based (PMI) models. It must be added also that the yearly dispersion is for all the channel models similar to the experimental dispersion.

Comparisons between CDF of 1-s attenuation slope obtained from synthesised and experimental time series are presented in Fig. 2 for an exceeded attenuation threshold of 10 dB. For this threshold, the shape of the experimental curve is very well approximated by SPL, TSM and PMI models. Generally, for low percentages of time, the time series synthesisers seem to underestimate the attenuation slope. The dispersion obtained with the time series synthesisers is generally similar or lower than the one obtained with the experimental data.

For fade duration, examples of comparisons between distributions of the relative number of fades are presented in Fig. 3 for an exceeded attenuation threshold of 10 dB. SPL, TSM and PMI models as well as the Synthetic Storm Technique (SST) perform very well. The dispersion obtained with all the time series synthesisers is similar as the one obtained with the experimental data.

EXAMPLES OF EVENT-BASED VALIDATION

Preliminary results concerning the event-based testing activity are given in this section where the synthetic CDFs of Mahalanobis distances are compared with the experimental one only in the reliable percentage range [8.10^{-1} ; 100]. Fig. 4 shows the experimental CDF and the ones obtained with SPL, TSM, PMI and SST models.

The PMI and SPL channel models exhibit quite good agreement with the experimental CDF in the low Mahalanobis distances range. The TSM model CDF has the same global shape as the experimental one, but a significant offset exists between them. This can mean that the diversity of the events produced by the TSM model can be quite similar to the experimental one, but the characteristics poorly modelled by the TSM create this significant offset. Finally, the SST model CDF appears to be significantly far from the experimental one. This could be ascribed to the method used to get to 1 second-sampled time series from 10 seconds sampled rain gauge time series that can alter considerably parameters related to fade dynamic.

CONCLUSION

In this paper, recent research activity concerning the development of time series synthetizers of the propagation channel for Earth-Space propagation at Ka-band and above has been presented. These channel models are necessary for the simulation of adaptive satellite communications systems using FMT. A set of channel models has been developed with consolidated theoretical basis. Methodologies have been designed for long term testing of channel models, and for short term or event-based testing of channel models. Some comparisons of synthesised time series against measured data collected during the OLYMPUS and the ITALSAT propagation experiments have been presented, which have shown good agreement between the distributions obtained from the synthesis of time series and the experimental distributions.

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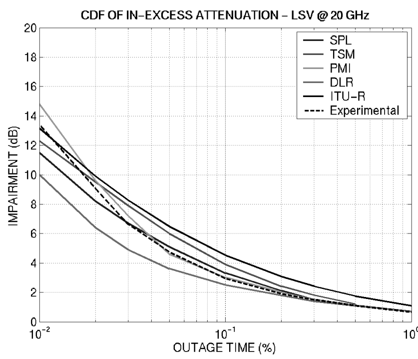

Fig. 1: Comparison between CDF of rain attenuation obtained from synthesised data and from OLYMPUS experimental data in Lessive at 20 GHz

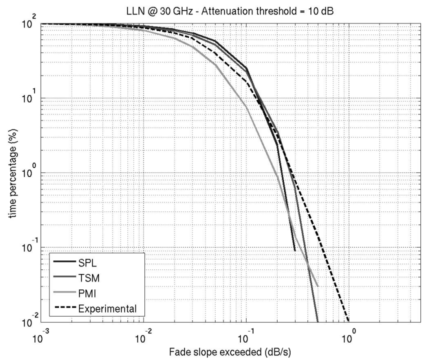

Fig. 3: Comparison between CDF of 1 s attenuation slope obtained from synthesised data and from OLYMPUS experimental data in Lessive at 30 GHz

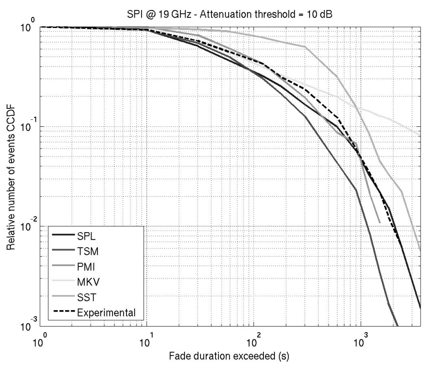

Fig. 2: Comparison between distributions of the relative number of fades relative to their duration, obtained from synthesised data and from ITALSAT experimental data in Spino d’Adda at 19 GHz

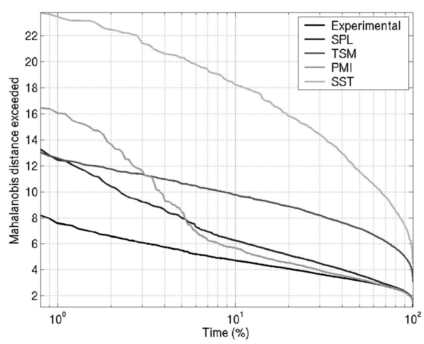

Fig. 4: CDFs of Mahalanobis distances of the experimental and synthetic rain events