Digital modelling of fade and interfade duration on high frequency radio links and its application in time series synthesis

Collection of PhD Theses

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Introduction

At the department of Broadband Infocommunications and Electromagnetic Theory (BME-HVT) since 1997 is operating a measurement system that serves the investigation of the precipitation affected radio links in the 13-80 GHz frequency range. The data collecting system is expanding continuously; it measures and stores the received power and several meteorological properties. In the past 10 years has been huge amount of data collected, which is the base of propagation research, modelling and investigations.
These measurement data is particularly applicable to study the high frequency radio links, determine their statistical properties and in such modelling processes where long time measurement data are necessary.
The meteorological data are also well usable during the research work as the fading events on the terrestrial links caused mainly by the precipitation, particularly the rain that can cause remarkable attenuation on the radio links.
The main theme of my dissertation is creating digital fade and interfade duration models, based on the measurement data, in order to determine their distribution and develop time series synthesisers based on them.
Beside of the terrestrial links I created also fade and interfade duration model for a Land Mobile Satellite (LMS) radio channel with multipath propagation and shadowing. Time series generation methods based on these models were also investigated.
Furthermore, I dealt with the fog attenuation in the V band (40-75 GHz), I developed a measurement device for the fog density and worked out the calibration process of the equipment, based on the V-band measurements.

Overview of literature

In order to study the propagation effects on precipitation affected radio channel, I refer to [1]; the statistical properties of the multipath propagation effects can be found in [3]. The latest calculation methods and parameters are collected in the ITU (International Telecommunication Union) recommendations.
The ITU-R P.530 [6] gives the calculation methods for terrestrial, the ITU-R P.618 [7] for the fixed satellite connections to determine the attenuation. These methods are applicable - besides of the other attenuation effects - to calculate the long-term distributions of the rain attenuation. The applied expressions are mainly empirical and are more or less applicable to express the local geological differences. The summary of the EU COST 235 [34] programme was also an important source for me to study the propagation of millimetre band radio waves.
The dynamics of the fading is summarized in ITU-R P.1623 [10] recommendation for the earth-space channel.
The description of digital channel models and times series generators can be found in [32], showing generative and descriptive methods. A summary of digital satellite communication is [35]. The SatNEx (Satellite Communications Network of Excellence) FP7 program, where BME-HVT was also participant, published a handbook [4] with the summary of several European research institutes in radio propagation.
During the investigation of the attenuation time series stationarity I referred mainly to [12] and [16]-[20]. The calculations with the structure-function are implemented for attenuation time series based on [21]. The fade and interfade duration processes, as renewal processes are studied by [13]-[14] and using the definition of the variation coefficients, described in [22]. The theory of Markov processes and Markov chains are summarized first of all by [13] and [23]. The Markov

models for channel modelling are published at first in [29]-[31], they served as base for my further research work.

Main objectives

ITU-R as the main organization for the development of radio frequency design standards gives recommendation only for calculations the fade duration distributions the earth-space channel. There are standards neither for the terrestrial nor for LMS links. The interfade duration calculation methods are completely missing. It was the motivation for me to develop digital modelling processes for fade and interfade duration. Before selecting the appropriate model type, the analysis of the measured attenuation time series was necessary. Therefore, I analyzed the stationarity, the renewal property and the Markov order as it is summarized in the first thesis group.
Afterwards I found the discrete time and discrete state, first order Fritchman's Markov chain as an appropriate model for the distributions of fade and interfade duration. The second thesis group deals with the model parameterization and determination of the equations to describe the threshold dependency of model parameters. Additionally, I developed a method to join the separate fade and interfade duration models.
The equations describing the threshold dependency of the fade and interfade duration model parameters are applicable to generate synthetic attenuation time series. This is the theme of the third thesis group where I show three different methods.
It is an important issue now the increasing of the capacity the microwave feeder networks. In the V-W band, the attenuation due to clouds and fog becomes more important. I developed an optical measurement device in order to determine directly the Liquid Water Content (LWC) in the air, and I will show the calibration process of the device, based on the V band attenuation measurements. This is the last chapter in the dissertation.

Research methodology

- I overviewed the literature of the fading processes, its digital modelling methods and the time series generators (journals, books, IEEE Explore).
- With analytical methods has been tested the weak stationarity of terrestrial and LMS attenuation time series, the digital fade and interfade duration processes as renewal processes and the Markov order of the fading process.
- I simulated the digital fade and interfade duration processes, generated by different types of Markov chain models and tested their renewal properties.
- I parameterized Markov models with regression methods and the general calculations of the model parameters were expressed.
- The models tested by comparing their first and second order statistics with real measurements. The synthetic time series generation methods are tested with long-term simulations.
- Computer based data processing, database handling and visualization; development of a measurement device for extreme working environment were the practical part of my work.

New scientific results

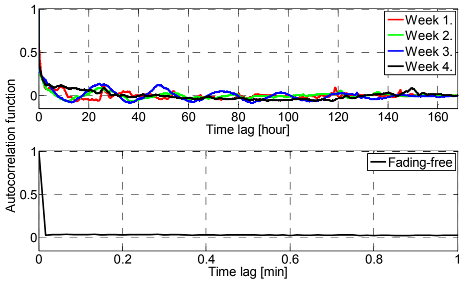
Thesis group 1: *Examination the attenuation time series of faded radio channels*

I examined the fading processes of the rain-faded terrestrial and the multipath propagation LMS channel in order to select the most appropriate model for fade and interfade duration.

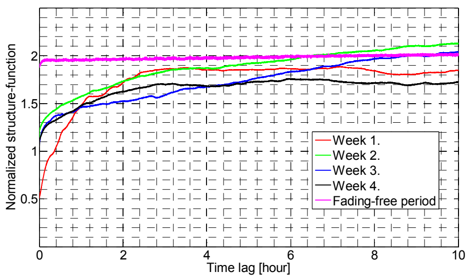
As first step, I investigated the stationarity of attenuation time series of terrestrial and LMS radio channels by the autocorrelation function, the expected value and the structure function. Afterwards the relation with the renewal processes was tested by the variation coefficients. I studied the processes generated by Markov chains and determined their renewal properties. The thesis group is closed finally by the calculation of the Markov order of the discrete state fading processes.

Thesis 1.1: I studied with different methods the stationarity the attenuation time series of millimetre band rain faded and multipath propagation LMS radio channels. I stated that the investigated fading process is a weakly stationary process. Further investigations shows that the separation of fade and non-fade parts could improve the modelling method and this confirms the applicability of combined Markov models. [S1] [S2] [S7] [S40]

The attenuation on different type of faded channels is changing randomly. If we want to model it with a stochastic model, the model parameters could be determined from the original process, if its statistical properties are time-independent. In my work, I studied the weak stationarity of attenuation time series, based on LMS and terrestrial data. The autocorrelation function is an appropriate tool to determine the time delay where the samples of the measurement data are already independent. This value is in case of rain fading several hours, while for fading free periods are shorter. This calculation provide the duration for moving average calculations to determine the time dependency of the expected value. The results are evaluated with the Wald-Wolfowitz runs test, which investigates the randomness of the samples comparing to the median. Based on this test the expected value was not time independent, but as the number of runs was very low comparing to the number of N^+ and N^-, I tested the weak stationarity also with the Kolmogorov's structure function.



Autocorrelation function of attenuation time series, HU11



Structure-function of attenuation time series, HU11

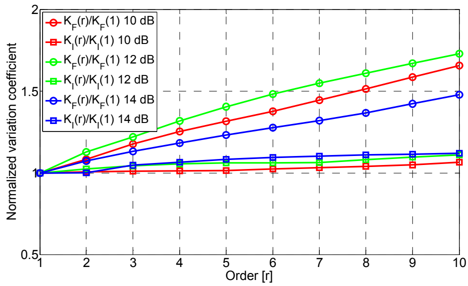
The τ time shift dependent structure function, $D_r(\tau)$ of an $r(t)$ stochastic process is the next expected value: $D_r(\tau)=E\{[r(t+\tau)-r(t)]^2\}$.

By normalizing it with the value of the $R_r(0)$ autocorrelation function in $\tau=0$, $D'_r(\tau)=D_r(\tau)/R_r(0)$ is converging to value 2 in case of weakly stationary processes. This proves the weak stationarity of the investigated attenuation time series. The setting time of the autocorrelation function helps to evaluate the structure function. The method was applicable both for the LMS and for the terrestrial links. As in case of all investigated time series the structure function was converging to 2, together with the result of the autocorrelation function, the weak stationarity of the attenuation time series was proved.

Further investigations of the fading-free and faded periods are showing that they structure function is converging much faster to the value 2, therefore the validity of the combined Markov models are also demonstrated. The combined models are separately modelling the macroscopic and the microscopic structure of the fading process.

Thesis 1.2: I introduced the digital fade and digital interfade duration processes (DFD and DIFD), and the derived multiple DFD and DIFD processes. I investigated the measured data both for the LMS and for terrestrial radio channels regarding their renewal properties. I declared that the multiple DFP process is not renewal for each channels, but the multiple DIFD process is renewal. [S23] [S24]

In this thesis, I created the abstraction of the fading process, that is a binary process at the given threshold level. These processes called as digital fade and interfade duration processes. I defined also the multiple digital fade and interfade duration processes (high order processes), and investigated their renewal properties. The calculations has done by the variation coefficients, that is given according to its definition, as the normalized variance of the original process, applying the variance of a BSC channel with equal event probability, $p=Pr(e_i=1)$ as a normalization factor.



Normalized DFD and DIFD variation coefficients (LMS, town)

If the normalized variation coefficients of the DFD or DIFD processes are increasing or decreasing by the order, the process is positively or negatively correlated, not renewal process. An order-independent constant shows that the process is renewal.

According to my calculations, the multiple DFD process is neither for LMS, nor for terrestrial channel are renewal, and they are positively correlated. The multiple DIFD processes are renewal for both channels. The digital modelling of fade and interfade duration processes are solved with generative type Markov chains, according to my work in the second thesis group. In order to select the most appropriate model type, the investigation of the renewal properties of different Markov models was necessary, as it will be shown in the next thesis.

Thesis 1.3: I investigated with simulation several different Markov chain types in order to determine that their generated multiple DFD and DIFD processes are renewal or not. This process helped to select the Fritchman's model as the most appropriate Markov chain for fade and interfade duration modelling. [S23] [S24]

The Gilbert, Gilbert-Elliott and the general Fritchman's Markov models were simulated and tested to decide if their generated multiple DFD and DIFD processes are renewal or not. According to the results, I selected the Fritchman's model, because:

• The renewal property of the Fritchman's model is similar to the multiple DFD and DIFD processes in the measured LMS and terrestrial radio channels.
• The Fritchman's model is widely used in the modelling of burst type error processes in radio channels, and this process is very similar to the DFD and DIFD processes.
• Both the Gilbert and the Gilbert-Elliott model can be transformed to Fritchman's model, as they are its simplified versions.

Thesis 1.4: I calculated the Markov order of the rain faded and the multipath propagation LMS channel attenuation processes. I stated that the processes are low order processes in each case. This proves that first order Markov chains are applicable to synthesize attenuation time series. [S19] [S22]

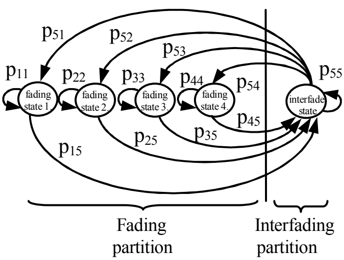
A further aspect of the model selection is the Markov order of the simulated process. To determine the order Bartlett and Hoel [24]-[25] suggested a Chi-square probe to decide if a given sample sequence can be considered as a Markov chain with order *r*. I proved that the attenuation process during the fading events on LMS and rain faded terrestrial radio channels are first order Markov processes, similar to the fading-free periods with scintillation. According to the results of the first thesis group, I apply first order, Fritchman's type Markov chain to model the fade and interfade duration.

Thesis group 2: *Markov modelling of fade and interfade duration*

In my work related to the second thesis group the fade and interfade duration modelling will be shown by applying the Fritchman's Markov model, selected by the stationarity, renewability and Markov order investigations performed in the previous chapters.

It will be proved that the Fritchman's Markov chain is applicable to model the distribution of fade and interfade duration. The threshold dependency of the model parameters and its equations are also given, that are applicable to synthesize attenuation time series. The joint modelling of the fade and interfade duration will be also demonstrated by applying a new model type.

Thesis 2.1: It has been proved, that the Fritchman's partitioned Markov chain is applicable to model the distribution of fade and interfade duration for rain fading and multipath propagation radio channels. I expressed the analytical equations the threshold dependency of the model parameters. This allows calculating the distributions for any threshold level, allowing the attenuation time series synthesis, based on these models. [S8] [S9] [S33] [S34] [S37] [S38] [S39]



According to the investigations in the first thesis group, I selected the Fritchman's first order, discrete state and discrete time Markov chain to model the distribution of fade and interfade duration. The model is a 4/1 state partitioned Markov chain, where the state probability can be analytically expressed, giving the complementary cumulative distribution of fade and interfade duration.
The model parameters can be determined with gradient method from the complementary distributions of the measured fade and interfade durations.

This method is based on the linear regression of the distribution functions, where the elements of the Markov chain transition matrix can be calculated from the parameters of the regression lines.
I investigated also the dependency of model parameters on the threshold level, applied during the calculation the fade and interfade duration. I stated that a $p(K)=aK^{C}+b$ type exponential equation is applicable to express the threshold dependency. I determined both for LMS and for terrestrial links the a, b and c constants. This results a general, threshold dependent model what can be used also to generate synthetic attenuation time series.

Thesis 2.2: I worked out a new method to join the fade and interfade duration models, which will be capable to model both distributions with a single architecture. The new model has been tested by comparing the measured and simulated fade and interfade duration statistics. [S35] [S36]

This thesis deals with a method to join the fade and interfade duration models. The result is a 4/4 Fritchman's model which correctly represents both type of second order statistics. I applied a weighting method by the stationary distribution of the separate models in order to determine the final model parameters. The measured and calculated distributions are in good correlation; therefore the precision of the joint model has been proved.

Thesis group 3: *Generating synthetic time series by applying Markov models*

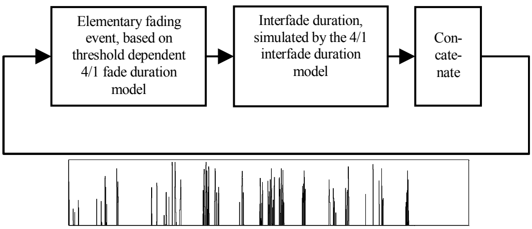
This thesis group deals with time series generation methods by applying the fade and interfade duration models introduced in the previous theses.

I worked out three different methods to generate synthetic time series:

- Applying clearly the fade and the interfade duration models.
- A combined method, with a two state fade/non-fade model and the threshold dependent fade duration model.
- A modelling method based on the measured wind speed and direction, by simulating the rain cell movement.

Thesis 3.1: I worked out an attenuation time series generator, based on the threshold dependent fade and interfade duration models. A new method will be also shown to generate the elementary fade events from the threshold dependent fade duration model. [S27] [S31] [S32]

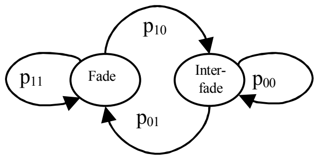
As the distribution functions of fade and interfade duration can be modelled at desired threshold level according to the results in the second thesis group, this allows the generation of attenuation time series, too. During this process at first I generate an elementary fading event, which is according to my definition that part of the attenuation time series, where the consecutive A_i attenuation values, comparing to the A_M fading free values, are monotonically increasing and after arriving to a maximum level, are monotonically decreasing.



Synthetic time series

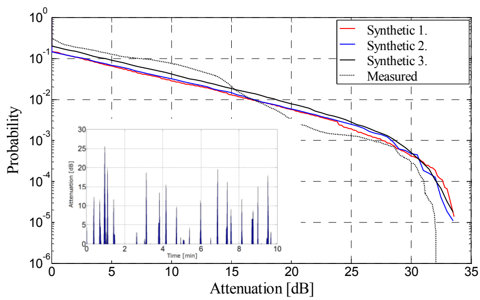
To simulate the delay between two consecutive elementary fading events I applied the interfade duration model. By chaining the elementary fading events and the fading free periods, an attenuation time series can be generated and its distribution is in good correlation with the measured time series.

Thesis 3.2: I worked out an attenuation time series generator, based on the two state fade/non-fade model and on the Markov model the fade duration. A new method will be shown to determine the model parameters of the two state model from the fade duration model. [S27] [S30]



2 state model

The method of the 3.1 thesis has been developed to synthesize the fade/non-fade periods with a two state Markov chain and the so defined fading periods are filled with elementary fade events. This method represents more realistic the burst property of the fading process, than the first one.
The parameters of the two state model will be determined with a new method, based on the fade duration Markov model. The two state model is determined with two parameters; the Z_F fading probability, that can be determined from the complementary fade duration model, and the p_{10} transition probability what can be expressed analytically from the Fritchman's model. Afterwards the transition probabilities of the two state model can be calculated and the model produce a binary fade/non-fade sequence.
In the figure at right the distribution of three different realizations of LMS attenuation time series can be seen, compared with the measured one with the same length.
A sample time series with 10-minute length is also depicted.

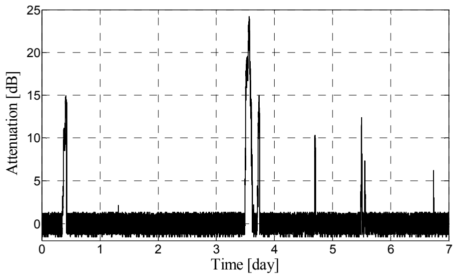


CCDF of synthetic and measured LMS time series with 10 min. sample

Thesis 3.3: I have been proved that the scintillation can be successfully modelled with a hidden Markov chain, parameterized from filtered Gaussian white noise with the Baum-Welch algorithm. It has been shown, that the superimposed synthetic time series and scintillation decrease the error of the synthetic time series at the lower attenuation range. [S2] [S29]

The previously demonstrated processes were not simulated the fast variation of the attenuation, called as scintillation, that is caused by the turbulences in the air. In order to simulate this effect I proposed a hidden Markov model, parameterized with the Baum-Welch (BWA) algorithm [41]. To determine the model parameters a fourth order Butterworth filter with 0.1 Hz cut-off frequency has been applied and filtered a Gaussian white noise was generated as the input of the BWA. The similarity of power spectral density the original and the synthesized scintillation time series proved the applicability of this method.

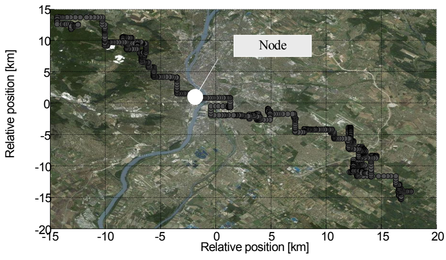
The synthesized scintillation time series can be superimposed to the attenuation time series, generated either with the method described in thesis 3.1 or with the method outlined in thesis 3.2. The attenuation distribution of synthetic time series with scintillation has better correlation with the measured time series especially at lower levels.



Time series with scintillation, terrestrial connection

Thesis 3.4: I worked out an attenuation time series generator based on the Markov modelling the movement of rain cells over a two dimensional plane. A method will be shown to parameterize the models from the measured wind speed and direction statistics. It will be shown that the rain cell parameters can be determined from the fade duration model and from the measured rain intensity distribution. This method was tested with good results on converged radio link topology where the local differences between the radio links can be modelled with small error. I proved that the attenuation time series can be transformed to radio links with different physical parameters, therefore the time series generation methods becomes universally applicable. [S4] [S6] [S17] [S20] [S25] [S28]

This thesis deals with time series generation for terrestrial point-to-point radio links by simulating the movement of the rain cells. The speed and direction of the movement are separately modelled with discrete time, discrete state Markov chains, parameterized on measured meteorological data.



Simulated rain cell movement

The profile of the rain cells are modelled with the EXCELL model [33], developed at the University of Milano, while the cell sizes comes from the fade duration and the wind speed, the peak rain intensity from the measured annual rain intensity statistics. The simulation generates long-term statistics of the attenuation by running several rain cells over the simulation area. The path attenuation is the integral of the point rainfall rates:

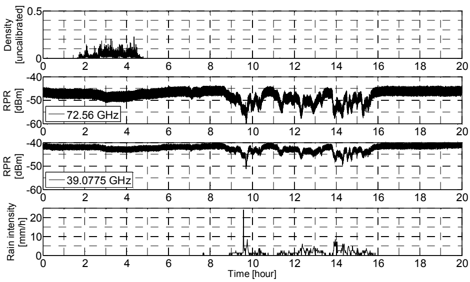
$$A_L = \int_0^L k R_n^{\alpha}(x_n, y_n) dl$$

This is the function of point rainfall rate, frequency, polarization; all of them are known during the simulation. As the cell sizes and moving speed is based on annual statistics, the resulting attenuation time series follows with small error the measured link characteristics. This method is particularly applicable in star topology to express the local differences on radio links with common end but different direction, length and frequency.

An application based on research work

A close research connecting to the theme of the dissertation is the investigations in the V-W radio band (40-110 GHz). In this band the effect of the fog, its attenuation on the microwave links is notable, therefore I dealt with the development of a fog density measurement device. My results in this field are applicable not only for the modelling the radio frequency range, but in case of Free Space Optical (FSO) connections.

The growing bandwidth requirements in the feeder networks are shifting the frequency ranges towards the V-W band. Therefore, a new meteorological parameter, the effect of the fog becomes more important and it should be take into account during the propagation calculations. The detection and quantitatively measurement of the fog density can not be solved with conventional meteorological devices. The present weather detectors are detecting the fog but they do not provide sufficient information for attenuation calculations. Therefore, I developed an optical device in order to detect and measure the fog density. This device is applicable to improve the attenuation models in V-W bands and for FSO.



Fog density, received power at 72.56 and 39.07 GHz, and rain intensity

The attenuation due to cloud and fog is described in the ITU-R P.840 [39] recommendation. At the department in 2009 a 72.56 GHz terrestrial link was integrated to the measurement system, allowing to calculate and test the fog attenuation on that link. I worked out the calibration process of the fog density measurement device, based on the V-band attenuation measurements in order to be able the direct liquid water content measurement with the device.

The sensor is capable to distinguish the fog and the rain events. For the calibration, to convert the measured data to LWC [mg/m^3], served the 72.59 GHz connection as reference. The applicability of the device has been proved by comparison of measured and predicted fog attenuation values. [S3] [S5] [S10] [S14] [S15] [S16] [S18] [S26]

Research benefits and further research directions

My results have been published in the framework of several local and international projects, in reports or summary books of the common research work.

I would like to highlight the next cooperation: Broadwan, (Broadband services for everyone over fixed wireless access networks, 2003-2006), SatNEx, (European Satellite Communications Network of Excellence, 2004-2009), MARCH, (Multilink Architecture for Multiplay Services, 2008-), Gigabit, (Gigabit radio link networks, 2009-), and the cooperation with Pannon since more than 10 years.

A COST IC0802 (Propagation Tools and Data for Integrated Telecommunication, Navigation and Earth Observation Systems) program started in 2008 and will be ended in 2012. In this project, I participate as an active member of the workgroup the terrestrial microwave and optical propagation. The main goal of this cooperation is to develop new standards or improve the old ones for

the ITU-R. In this framework my research results will be applicable in the V and FSO band simulations and modelling.
A further international cooperation can be foreseen with the University of Northumbria (Newcastle, UK), to perform measurements in their fog chamber and improve my density measurement device.
We have a good cooperation with the Technical University of Graz (TUG), where the Optical Communication Laboratory applies my fog density device to collect measurement data in order to improve their FSO attenuation models. Several common publications are already available.
In the education at our university I was consulted several thesis, diploma and TDK works. I lead also a laboratory practice on channel modelling especially for students of electrical engineering.

Own publications

Book chapter

[S1] L. Csurgai-Horvath, F. Cornet, F. Lacoste, C. Riva, A. Martelucci, G. Blarzino, L. Castanet, L. Feral, N. Jeannin, J. Lemorton: "Atmospheric effects: Space Variations of Rain Attenuation In: Laurent Castanet (ed.) Influence of the Variability of the Propagation Channel on Mobile, Fixed Multimedia and Optical Satellite Communications", Shaker, 2008. Chapter 2.4.
[S2] L. Csurgai-Horváth, J. Bitó: "An Investigation of the Applicability of Fade Duration Markov Model in Attenuation Time Series Synthesis for Multipath Fading Channel", In: Frigyes István (ed.) Advances in mobile and wireless communications – views of the 16th IST Mobile and Wireless Communication Summit. Springer, 2008. pp. 165-184.

Journal

[S3] M. S. Awan, L. Csurgai-Horvath, S. S. Muhammad, E. Leitgeb, F. Nadeem, M. S. Khan: "Characterization of Fog and Snow Attenuations for Free-Space Optical Propagation", Journal of Communications, Vol. 4., No. 8. , pp. 533-545, 2009.
[S4] B. Héder, L. Csurgai-Horváth, J. Bitó: "Adaptive Terminal to Base Station Assignment in BFWA Systems", IEEE Communications Letters, Vol. 13., Issue 8., pp. 588-590, 2009.
[S5] M. S. Awan, R. Nebuloni, C. Capsoni, L. Csurgai-Horváth, S. S. Muhammad, E. Leitgeb, F. Nadeem, M. S. Khan: "Prediction of Drop Size Distribution Parameters for Optical Wireless Communications through Moderate Continental Fog", International Journal of Satellite Communications and Networking (elfogadva)
[S6] Csurgai-Horváth László: "Rain Attenuation Time Series Synthesis with Simulated Rain Cell Movement", Periodica Polytechnica-Electrical Engineering, (elfogadva)
[S7] Csurgai-Horváth László, Bitó János: "Rain attenuation time series synthesis with combined Markov models for microwave terrestrial links", International Journal of Mobile Network Design and Innovation, Vol. 2. No. 3/4, pp. 216-222, 2007.
[S8] Csurgai-Horváth László, Bitó János: "Multipath Propagation Fade Duration Modeling of Land Mobile Satellite Radio Channel", Journal On Communications, (Híradástechnika, selected papers in English), Vol. LXII/7, pp. 22-26, 2007.
[S9] Csurgai-Horváth László, Bitó János: "Fading időtartam modellezés műholdas földi mozgó rádiócsatornán", Híradástechnika, Vol. LXII/3, pp. 19-23, 2007.

Project report

[S10] L. Babits, T. Tanem, T. Tjelta, I. Frigyes, T. O. Breivik, J. Bitó and L. Csurgai: "Gigabit radio link potential role in Telenor's and Pannon's networks", Research Note, 2009. (belső használatra)
[S11] L. Csurgai-Horváth, J. Bitó: "Activities at BME for millimeter band terrestrial radio connections and FSO", COST IC0802 MCM2 meeting, 04-06 November, Toulouse, France, 2009.
[S12] L. Csurgai-Horváth, J. Bitó: "A simple fog density measurement device and its application in attenuation calculation", COST IC0802 MCM3 meeting, 26-28 April, Athens, Greece, 2010.
[S13] I. Frigyes, L. Csurgai-Horváth: "Gbit/sec wireless via Free-Space Optics and E-band radio", COST IC0802 MCM3 meeting, 26-28 April, Athens, Greece, 2010.

Conference paper

[S14] L. Csurgai-Horváth, János Bitó: ”Fog attenuation on V band terrestrial radio and a low-cost measurement setup”, Future Network & Mobile Summit 2010, 16 - 18 June 2010, Florence, Italy (elfogadva)

[S15] I. Frigyes, L. Csurgai-Horvath: “Free-Space optics and E-band radio: Complementary techniques for Gbit/sec Wireless”, IEEE Wireless Communications and Networking Conference 2010, Sydney, Australia, 18/Apr/2010-21/Apr/2010, paper #01-03-03.

[S16] I. Frigyes, L. Csurgai-Horvath: “From Gigabit to Multi-Gigabit: mm Waves in Mobile Networks’ Backhaul”, IEEE Globecom 2009, International Workshop on Multi-Gigabit MM-Wave and Tera-Hz Wireless Systems, Hawaii, USA, 30/Nov/2009-04/Dec/2009, paper #2.

[S17] László Csurgai-Horváth, János Bitó: “First and second order statistics of synthetic rain attenuation time series”, ICT Mobil Summit 2009, Santander, Spain, 10/Jun/2009-12/Jun/2009. paper #101.

[S18] M. S. Awan, L. Csurgai Horvath, E. Leitgeb, R. Nebuloni, P. Brandl, F. Nadeem: “Transmission of high data rate optical signals in fog and snow conditions”, Wireless VITAE, Aalborg, Denmark, 17/ May/2009-20/May/2009, pp. 702-706.

[S19] László Csurgai-Horváth, János Bitó: “Testing the Markov Property of Rain Fading on Millimeter Band Terrestrial Radio Link”, EUCAP 2009, Berlin, Germany, 23/Mar/2009-27/Mar/2009. pp. 2901-2905.

[S20] L. Castanet, L. Csurgai-Horváth, F. Lacoste, C. Riva, U. Fiebig, A. Martelucci, A. D. Panagopoulos, T. Javornik, N. Jeannin, E. Leitgeb, P. Thompson, V. Pastoriza: “Channel modelling activities related to atmospheric effects in the SatNEx project”, EUCAP 2009, Berlin, Germany, 23/Mar/2009-27/Mar/2009, pp. 1697-1701.

[S21] Csurgai-Horváth László, Héder Balázs, Bitó János, Frigyes István: “Applicability of the 50-90 GHz frequency bands in feeder networks”, EUCAP 2009, Berlin, Germany, 23/Mar/2009-27/Mar/2009, pp. 336-340.

[S22] Csurgai-Horváth László, Bitó János: “Testing the Markov Property of the Multipath Fading Process”, International Workshop on Satellite and Space Communications 2008, Toulouse, France, 01/Oct/2008-03/Oct/2008, pp. 97-101.

[S23] Csurgai-Horváth László, Bitó János: “Renewal Properties of Rain Fade and Interfade Duration on Radio Links”, ICT Mobil Summit 2008, Stockholm, Sweden, 10/Jun/2008-12/Jun/2008, paper #70.

[S24] Csurgai-Horváth László, Bitó János: “Renewal Properties of Fade and Interfade Duration on Land Mobile Satellite Channel”, ASMS 2008. Bologna, Italy, 26/Aug/2008-28/Aug/2008, CD proceedings.

[S25] Csurgai-Horváth László, Bitó János: “Modeling of Coherent Rain Cells Movement Affecting Terrestrial Radio Links”, 2nd JA 2310 SatNEx Workshop. München, Germany, 17/Apr/2008-18/Apr/2008, paper #15.

[S26] Babits László, Csurgai-Horváth László, Héder Balázs, Bitó János, Frigyes István: ”Az 50-90 GHz frekvenciasávok alkalmazása ellátó hálózatokban”, 16. Távközlési és Informatikai Hálózatok Szeminárium és Kiállítás. Zalakaros, Magyarország, 15/Oct/2008-17/Oct/2008, pp. 94-103.

[S27] L. Csurgai-Horváth, B. Héder, J. Bitó: “Markov Models for Radio Links and Their Application in Attenuation Time Series Synthesis”, First JA 2310 SatNEx Workshop. Toulouse, France, 05/Feb/2007-08/Feb/2007. (csak előadás)

[S28] Csurgai-Horváth László, Bitó János: “Spatial Markov Model of Fade Duration on Terrestrial Radio Links”, 2nd European Conference on Antennas and Propagation: EuCAP 2007, Edinburgh, UK, 11/Nov/2007-16/Nov/2007, pp. 593-594.

[S29] Csurgai-Horváth László, Bitó János: "Scintillation Time Series Synthesis for Satellite Links with Hidden Markov Model", 2007 International Workshop on Satellite and Space Communications, Salzburg, Austria, 12/Sep/2007-14/Sep/2007, pp. 22-25.
[S30] Csurgai-Horváth László, Bitó János, Hercz János: "Rain Attenuation Time Series Synthesis with Combined Two-State and Hidden Markov Models for Microwave Terrestrial Links", 12th Microcoll Conference. Budapest, Hungary, 14/May/2007-16/May/2007, pp. 113-116.
[S31] Csurgai-Horváth László, Bitó János: "Attenuation Time Series Synthesis for Land Mobile Satellite Links", 16th IST Mobile and Wireless Communications Summit, Budapest, Hungary, 01/Jul/2007-05/Jul/2007, paper #292.
[S32] Csurgai-Horváth László, Bitó János: "Attenuation Time Series Generator with Markov Model of Fade and Interfade Durations", Loughboroug Antennas and Propagation Conference, Loughborough, UK, 02/Apr/2007-03/Apr/2007, pp. 105-108.
[S33] Singliar R, Din J, Csurgai L, Tharek AR, Horváth P, Bitó J: "Comparison of 38 GHz Rain Fade Dynamics between Malaysia and Hungary“, 15th IST Mobile and Wireless Summit. Myconos, Görögország, 04/Jun/2006-08/Jun/2006, paper #851.
[S34] Héder B, Csurgai-Horváth L, Bitó J: "Markov Modeling of First and Second Order Statistics of Land Mobile Satellite Fading", Broadband Europe Conference (BBEurope'06). Geneva, Switzerland, 11/Dec/2006-14/Dec/2006, www.bbeurope.org
[S35] Csurgai-Horváth László, Bitó János: "Land Mobile Propagation Fade Duration Modeling by Markov Chains", 2006 International Workshop on Satellite and Space Communications, Madrid, Spain, 14/Sep/2006-15/Sep/2006, pp. 242-246.
[S36] Csurgai-Horváth László, Bitó János: "Joint Modeling of Fade and Interfade Duration on Radio Connections Applying Markov Chain", The European Conference on Antennas and Propagation EuCAP 2006, Nice, France, 06/Nov/2006-10/Nov/2006, paper #350086.
[S37] Csurgai-Horváth László, Bitó János: "Fade Duration Modeling of Terrestrial Links Applying Markov Chain", Loughboroug Antennas and Propagation Conference,Loughborough, UK, 11/Apr/2006-12/Apr/2006, pp. 457-460.
[S38] Csurgai-Horváth László, Bitó János: "Fade Duration Modeling of Satellite Links Applying Markov Chain", 3rd Advanced Satellite Mobile Systems Conference. Herrsching am Ammersee, Germany, 29/May/2006-31/May/2006, pp. 76-83.
[S39] Csurgai-Horváth László, Bitó János: "Fade Duration Modeling with Partitioned Markov Model", ESA Wave Propagation Workshop 2005: Propagation Modelling and Measurements for SatCom and SatNav Systems, Nordwijk, Netherland, 23/Nov/2005-25/Nov/2005, paper #34.
[S40] Singliar R, Héder B, Csurgai-Horváth L, Fiebig U C, Perez-Fontan F, Bitó J: "Comparison of Rain Attenuation Models of Satellite Communication Channels Based on Measured Point Rain Intensity", IADAT-tcn International Conference on Telecommunications and Computer Networks (IADAT-tcn'04), San Sebastian, Spain, 01/Dec/2004-03/Dec/2004, pp. 161-165.

Bibliography for theses

[1] M.P.M. Hall, L.W. Barclay and M.T. Hewitt: "Propagation of Radiowaves", Institution of Electrical Engineers, 1996.
[2] L. Boithias: "Radio Wave Propagation", McGraw-Hill, 1987.
[3] J. Proakis: "Digital Communications", McGraw-Hill, 1989.
[4] Laurent Castanet (Ed.): "Spatial Variations of Propagation Impairments" in: "Influence of the Variability of the Propagation Channel on Mobile, Fixed Multimedia and Optical Satellite Communications", The SatNEx E-book, Shaker Publishing, Germany, 2008.
[5] ITU-R Rec. P.372-10: "Radio noise", ITU, 2009.
[6] ITU-R Rec. P.530-13: "Propagation data and prediction methods required for the design of terrestrial line-of-sight systems", ITU, 2009.
[7] ITU-R Rec. P.618-10: "Propagation data and prediction methods required for the design of Earth-space telecommunication systems", ITU, 2009.
[8] ITU-R Rec. P.837-5: "Characteristics of precipitation for propagation modelling", ITU, 2007.
[9] ITU-R Rec. P.838-3: "Specific attenuation model for rain for use in prediction methods", ITU, 2005.
[10] ITU-R Rec. P.1623-1: "Prediction method of fade dynamics on Earth-space paths", ITU, 2003-2005.
[11] E. Lutz, D. Cygan, M. Dippold, F. Dolainsky, W. Papke : "The Land Mobile Satellite Communication Channel-Recording, Statistics, and Channel Model", IEEE VT-40, 1991, pp. 375-386.
[12] A. Papoulis: "Probability, Random Variables and Stochastic Processes", McGraw-Hill, 3rd edition, 2001.
[13] L. Kleinrock: "Queueing Systems. Volume 1: Theory", 1st edition, Wiley, 1975.
[14] Györfi L., Győri S., Pintér M.: "Tömegkiszolgálás informatikai rendszerekben", Műegyetemi Kiadó, 2005.
[15] L. Breiman: "Probability", Society for Industrial Mathematics, Reprint edition 1992.
[16] H. von Storch, F. W. Zwiers: "Statistical Analysis in Climate Research", Cambridge University Press, 2003.
[17] Bendat J, Piersol A.: "Random data: Analysis and measurement procedures", New York, John Wiley & Sons, 1971.
[18] Box, G.E.P., G.M. Jenkins, and G.C. Reinsel: "Time Series Analysis: Forecasting and Control", Third edition, Prentice Hall, 1994.
[19] Hamilton, J.D.: "Time Series Analysis", Princeton University Press, 1994.
[20] O.D. Anderson (ed.): "Time Series Analysis: Theory and Practice 1.", North-Holland, 1982.
[21] R. H. Clarke: "A statistical theory of mobile radio reception", Bell Syst. Tech. J., vol. 47, 1968, pp. 957–1000.
[22] J.-P.A. Adoul: "Error Intervals and Cluster Density in Channel Modeling", IEEE Trans. Inform. Theory, vol. IT-20, Jan. 1974, pp. 125-129.
[23] D. Isaacson, R. Madsen: "Markov Chains Theory and Applications", J. Wiley, 1976.
[24] M.S. Bartlett: "The Frequency Goodness of Fit Test for Probability Chains", Cambridge Philosophical Proceedings, 1951, vol. 47, pp. 86-94.
[25] P. G. Hoel: "A Test for Markoff Chains", Biometrika, vol. 41, 1954, pp. 430-433.
[26] Erwin Kreyszig: "Advanced Engineering Mathematics", Wiley, 1993.
[27] T.W. Anderson, L.A. Goodman: "Statistical Inference about Markov Chains", Ann. Math Statistics, Vol. 28, Nr. 1., 1957, pp. 89-110.

[28] V. I. Tatarskii: “Wave Propagation in a Turbulent Medium”, McGraw-Hill, New York, 1961.
[29] E.N.Gilbert: “Capacity of a Burst-Noise Channel”, Bell Syst. Tech. J., vol. 39, Sep.1960, pp. 1253-1265.
[30] E.O.Elliott: “Estimates of Error Rates for Codes on Burst-Noise Channel”, Bell Syst. Tech. J. vol 42, 1963, pp. 1977-1997.
[31] B. D. Fritchman: “A binary channel characterization using partitioned Markov chains”, IEEE Trans. Inform. Theory, vol. 13, Apr. 1967, pp. 221-227.
[32] L. Kanal, A. Sastry: “Models for Channels with Memory and Their Applications to Error Control”, Proceedings of the IEEE, vol. 66. no.7, July 1978, pp. 724-744.
[33] C. Capsoni, F. Fedi, C. Magistroni, A. Paraboni, A. Pawlina: “Data and theory for a new model of the horizontal structure of rain cells for propagation applications”, Radio Sci., Vol. 22/3, 1987, pp. 395-404.
[34] COST 235: “Radiowave propagation effects on next generation fixed-services terrestrial telecommunications systems”, Technical report, European Commission, EUR 16992 EN, Final Report, 1996.
[35] Giovanni E. Corazza (Ed.): “Digital Satellite Communications”, Springer, 2007.
[36] COST 255: “Radiowave propagation modelling for SatCom services at Ku-band and above”, Final Report, ESA, Noordwijk, 2002.
[37] COST 280: “Propagation Impairment Mitigation for Millimetre Wave Radio Systems”, http://www.cost280.rl.ac.uk
[38] ITU-R P.676-8 Recommendation: “Attenuation of atmospheric gases”, ITU, Geneve, Switzerland, 2009.
[39] ITU-R P.840-4 Recommendation: “Attenuation due to clouds and fog”, ITU, Geneve, Switzerland, 2009.
[40] ITU-R P.833-6 Recommendation: “Attenuation in vegetation”, ITU, Geneve, Switzerland, 1992-2007.
[41] L. R. Rabiner: “A Tutorial on Hidden Markov Models and Selected Applications in Speech Recognition”, Proceedings of the IEEE, vol. 77, no. 8, Feb. 1989.

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