

SITE DIVERSITY MODELLING OF RAIN ATTENUATION FOR SATELLITE COMMUNICATION SYSTEMS

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Doctoral Dissertation
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PROSTORSKO RAZNOLIKO MODELIRANJE
SLABLJENJA ZARADI DEŽJA V SATELITSKIH
KOMUNIKACIJSKIH SISTEMIH

Doktorska disertacija

Supervisor: Prof. Dr. Gorazd Kandus

Ljubljana, Slovenia, May 2017

To my beloved family. . .

Acknowledgments

It is my pleasure to express my special appreciations and thanks to many people, who so generously supported and guided me during the work on the thesis.

First and foremost, I would like to express my deepest gratitude to my supervisor, Dr Gorazd Kandus for his continued support, guidance, encouragement, insightful advising and patience for all these years. He was willing to help every time and for every way in all the stages of this work, which would have been impossible to accomplish without him.

Furthermore, I am deeply indebted to Dr Andrej Vilhar for his constant faith in my work. As a good friend, he was always willing to help and give his best suggestions and experiences about the problem research and writing the thesis.

I would like to recognize the valuable contributions from Dr Andrej Hrovat during this research work. I especially acknowledge him for his comments, suggestions and corrections during the last intensive writing period of the thesis.

I want to also thank Urban Kuhar for his enormous technical support in the experimental measurement campaign which was useful for my research.

I greatly appreciate the extraordinary cooperative work with Dr Charilaos Kourogiorgas and Dr Athanasios Panagopoulos from National Technical University of Athens. I am especially grateful to Dr Charilaos Kourogiorgas as a key person during my research for his continual willingness to discuss and help with the research ideas and solutions in this field and also during the writing of the thesis.

My special thanks go to Dr Michael Schönhuber from Joanneum Research Institute in Graz, for enabling us to have a measurement station in their Institute premises, necessary for the evaluation of my research.

I am also truly grateful to my committee members, Dr Aleš Švigelj, Dr Tomaž Javornik and Dr Erich Leitgeb, for their reading of the manuscript, and for their insightful suggestions and comments on my thesis.

I sincerely appreciate my group of co-authors and collaborators from several countries, and my colleagues from the Jožef Stefan Institute for each valuable contribution to this work.

I am very specially indebted to Dr Mihael Mohorčič, head of the Department of Communication Systems at JSI, for enabling me to have a proper environment for research and financial support. I also appreciate that he gave me the opportunity to present our work at international conferences where I became acquainted with the latest research and well known scientists.

I gratefully acknowledge the funding received during the three years from Slovene Human Resources Development and Scholarship Fund, which enabled me to undertake my PhD.

Last, but not least, I would like to dedicate this thesis to my family, my wife and my daughter. Words cannot express how grateful I am to my wife for her support, patience, and the long conversations that motivated me to strive toward finalizing the PhD. My smart daughter with her kindness and joy was a strong reason for a good mood after every hard-working day. Thank you to all!

Abstract

The thesis presents novel models for prediction of rain attenuation statistics induced on Earth-satellite multiple-site diversity systems using copula functions. Site diversity systems are adopted for the compensation of severe rain attenuation and therefore increase the system availability. Therefore, the models proposed can be used for the accurate and reliable design of site diversity systems operating at high frequencies, thus enabling high data rates in Earth-satellite communications.

The first proposed model is based on the Gaussian copula and joint statistics of rain attenuation are calculated taking into account the rain attenuation statistics for particular Earth-satellite slant paths and the separation distance between the Earth stations. The proposed model outperforms the existing ITU-R P.618 model for two-site diversity and the model based on the Clayton copula. The model can be used in multisite diversity with an arbitrary number of sites, which was not adequately supported from state of the art models. In order to improve the accuracy, a further prediction model based on the Gaussian copula is proposed, which takes into account not only the separation distance but also two other geometric characteristics of the site diversity system, namely the baseline orientation angle and the elevation angle. The total error performance comparison shows that the second model performs better than the first one for two- and three-site diversity configurations. The only disadvantage of the Gaussian-based copula models is the calculation complexity.

Considering that generally the Archimedean copulas are simpler and after extensive analysis of several families, we found that the hyperbolic cosecant copula is appropriate for the prediction of joint statistics of rain attenuation. Two multisite prediction models are proposed one that takes into account only the distance between the stations, and another that also includes the dependency on the baseline and elevation angles.

The error performance between the four models compared to experimental data has been investigated using the database of 56 two-site diversity experiments from different regions of the world and 11 three-site diversity experiments from Europe and the USA. From the results, it was found that for two-site diversity systems, the proposed models perform notably better than the ITU-R model, and slightly better than the Clayton model. Gaussian models have the smallest error in general. However, for a specific subset of experiments depending on region or different conditions, the behaviour of every model is different considering the error statistics. More particularly, the Gaussian model, which account only for the distance, performs the best for European experiments in two- and three-site diversity cases. For two-site experiments located in the USA, Canada and Japan and three-site experiments in the USA the hyperbolic cosecant copula-based model which accounts for the dependency on distance, elevation and the baseline angle shows the best performance. The Gaussian model which takes into account distance, elevation and baseline angles in two-site diversity systems outperforms the other models notably when the distance is larger than 10 km and baseline angles are above 45°.

Povzetek

V disertaciji so predstavljeni novi modeli za napovedovanje statistike slabljenja signala zaradi dežja v zemeljsko-satelitskih prostorsko raznolikih komunikacijskih sistemih. Modeli so zasnovani na osnovi funkcij kopula. Namen prostorsko raznolikih sistemov je blaženje močnih slabljenj signala zaradi dežja in posledično povečevanje razpoložljivosti sistema. Predlagane modele uporabljamo za natančnejše načrtovanje zanesljivih prostorsko raznolikih zemeljsko-satelitskih komunikacijah sistemov, ki delujejo na visokih frekvencah in omogočajo visoke hitrosti prenosa podatkov.

Prvi predlagani model temelji na Gaussovi funkciji kopula. Skupno statistiko slabljenja zaradi dežja smo izračunali z upoštevanjem izmerjenih statistik slabljenja zaradi dežja posameznih nagnjenih zemeljsko-satelitskih povezav ter razdalj med zemeljskimi postajami. Predlagani model prekaša obstoječi model ITU-R P.618 za prostorsko raznoliki sistem z dvema postajama in model, ki temelji na Claytonovi funkciji kopula. Model lahko uporabljamo tudi za prostorsko raznolike sisteme s poljubnim številom zemeljskih postaj, ki jih drugi sodobnejši modeli ne podpirajo ustrezno. Da bi izboljšali natančnost, smo predlagali tudi nadgradnjo modela, temelječega na Gaussovi funkciji kopula, ki poleg razdalje med postajami upošteva dodatni dve geometrijski značilnosti prostorsko raznolikega sistema, in sicer položajni in elevacijski kot posamezne postaje. Primerjava skupne napake obeh modelov kaže, da za prostorsko raznolike sisteme z dvema in tremi postajami drugi model v večini primerov prekaša prvega. Edina slabost modelov na osnovi Gaussove funkcije kopula je računska zahtevnost.

Glede na to, da so Arhimedove funkcije kopula v splošnem enostavnejše, smo po obsežni analizi funkcij Arhimedove družine ugotovili, da se hiperbolična kosekantna funkcija kopula izkaže kot najprimernejša za napovedovanje skupne statistike slabljenja zaradi dežja. Predlagali smo dva več-prostorska modela napovedovanja, pri čemer prvi upošteva le razdaljo med postajami, drugi pa upošteva tudi položajni in elevacijski kot.

Napako napovedovanja štirih modelov smo ocenili na podlagi primerjave z merjenimi podatki 56 eksperimentov s prostorsko raznolikimi sistemi z dvema postajama v različnih območjih po svetu in 11 eksperimentov s prostorsko raznolikimi sistemi s tremi postajami v Evropi in ZDA. Ugotovili smo, da predlagani modeli za prostorsko raznolike sisteme z dvema postajama dajejo precej boljše rezultate kot ITU-R model in nekoliko boljše rezultate kot model na osnovi Claytonove funkcije kopula. Gaussovi modeli imajo v splošnem najmanjšo napako. Za različne podmnožice poskusov se statistične napake različnih modelov med seboj razlikujejo. Gaussov model, ki upošteva le razdaljo, je najprimernejši za prostorsko raznolike sisteme z dvema in tremi postajami, ki se nahajajo v Evropi. Za prostorsko raznolike sisteme z dvema postajama v ZDA, Kanadi in na Japonskem in za prostorsko raznolike sisteme s tremi postajami v ZDA pa je model na osnovi hiperbolične kosekantne kopula funkcije, ki upošteva odvisnost od razdalje ter elevacijskega in položajnega kota, najprimernejši. Gaussov model, ki upošteva razdaljo ter elevacijski in položajni kot, pa je boljši od vseh ostalih modelov v primeru prostorsko raznolikih sistemov z dvema postajama, kjer je razdalja med postajama večja kot 10 km in položajni kot nad 45° .

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Abbreviations

AC	... Adaptive Coding
AM	... Adaptive Modulation
AZ/EL	... Azimuth/Elevation
C/I	... Carrier to Interface
CCDF	... Complementary Cumulative Distribution Function
CDF	... Cumulative Distribution Function
DRR	... Data Rate Reduction
DSD	... Drop Size Distribution
EIRP	... Effective Isotropic Radiated Power
ESA	... European Space Agency
FMT	... Fade Mitigation Technique
FNAC	... Fully Nested Archimedean Copula
FSR	... Frequency Scaling Ratio
FSS	... Fixed Satellite Services
HAC	... Hierarchical Archimedean Copula
HPBW	... Half Power Beam Width
HTS	... High Throughput Satellite
IFSR	... Instantaneous Frequency Scaling Ratio
JSI	... Jožef Stefan Institute
LHCP	... Left Hand Circular Polarization
LNB	... Low Noise Block
MPM	... Millimeter wave Propagation Model
OBBS	... On-Board Beam Shaping
OD	... Orbital Diversity
OIC	... Orthogonal Iris Coupler
OMT	... Orthogonal Mode Transducer
PNAC	... Partially Nested Archimedean Copula
PSK	... Phase Shift Keying
QAM	... Quadrature Amplitude Modulation
RHCP	... Right Hand Circular Polarization
SatProSi	... Satellite Propagation Slovenia
SD	... Site Diversity
SMOC	... Stochastic Model of Clouds
TD	... Time Diversity
TLE	... Two Line Element
ULPC	... Up-Link Power Control
USRP	... Universal Software Radio Peripheral
XPD	... Cross-Polar Discrimination

Symbols

$A(p)$	... attenuation at percentage level p
$A_i(t)$	... attenuation time series in the i -th site
$A_{joint}(t)$	... joint attenuation time series
$A_{m,i}(p)$	... measured joint attenuation of i -th experiment at percentage level p
$A_{p,i}(p)$	... predicted joint attenuation of i -th experiment at percentage level p
A_{th}	... attenuation threshold
A_ψ	... slant path attenuation
b	... baseline orientation angle
C	... copula function
$CPL(t)$	... co-polar signal
d	... distance between Earth stations
f	... operating frequency
F_i	... i -th marginal distribution
h_R	... mean annual rain height above mean sea level
h_s	... height above mean sea level of the Earth station
K_{th}	... selected factor
N_{wet}	... refractive index
R	... rain rate
r_R	... slant path length with rain
u_i	... i -th CDF
Δt	... time difference
δt_{detect}	... control loop detection time
δt_{FMT}	... FMT execution time
$\varepsilon_i(p)$	... error for the i -th experiment at percentage level p
ε_{mean}	... mean value of error
ε_{rms}	... rms value of error
ε_{std}	... standard deviation of error
$\zeta(t)$	... attenuation slope
θ_{ij}	... ij -th hyperbolic cosecant copula parameter
ρ_{ij}	... ij -th Gaussian copula parameters
Σ	... symmetric matrix of Gaussian copula
Φ	... CDF of the marginal standard Gaussian distribution
φ	... Archimedean generator of copula
ψ	... elevation angle

Chapter 1

Introduction

The demand for broadband services with high data rates can be met by adequate development and deployment of telecommunication infrastructures. Terrestrial connections in the form of wireline, wireless and optical links can be efficiently supplemented by satellite communications. Especially for the services provided in specific geographical areas such as rural, insular, and maritime or mountain areas, satellite links may provide the most practical, economically efficient and sometimes even the only viable solution. In urban areas, terrestrial communications will remain dominant, however coexistence with satellite communications could be interesting even in this case. Satellite communication systems may also provide trunking services to terrestrial mobile systems and can be used for the traffic and signalling offload for the fifth generation mobile communication systems.

Apart from current applications supported by satellite communication systems, new applications are being developed and introduced, such as ubiquitous ultra-fast broadband internet access (e.g. on-board planes), health related applications and various Earth observation based services. In order to meet the high data rate demands, a concept called “terabit per second satellite” or the High Throughput Satellite (HTS) has been introduced [1]. For such high data rates, high bandwidths are required and consequently wide frequency bands need to be allocated. Since the conventional frequency bands at Ku-band (12-18 GHz) [2] and below are already congested, higher bands have to be employed, for example at Ka-band (20-40 GHz), Q/V-band (40-75 GHz) or even W-band (75-110 GHz) [3]. Satellite communication of such high data rate systems at Ka-band are Ka-Sat, SES Astra, Yahsat and ViaSat-1 [4, 5]. In order to support such high capacity systems, operating at the Terabit/s rates, feeders (links between a Gateway and the satellite) at Q/V-band have been studied [6].

However, wireless communications at high frequency bands are sensitive to atmospheric impairments. The propagated electromagnetic waves are highly affected by tropospheric phenomena such as rain, clouds and fog, atmospheric gases and turbulence. The listed phenomena impact the signal differently. Among them, heavy rain causes the most severe signal degradation. The impact of the tropospheric effects can be reduced by using Fade Mitigation Techniques (FMTs). Site diversity proves to be a very efficient FMT for counteraction of the rain attenuation on the feeder links and the direct-to-user links [7]. Modelling the tropospheric impact on the signal is indispensable for the design and implementation of the next generation satellite communication systems. In particular for the design of the site diversity system, the performance of the system needs to be evaluated in terms of joint rain attenuation probability statistics. There is an ongoing pursuit for the new models, with the goal to improve their reliability and usability. The models are typically based on data obtained from experimental Earth-satellite

measurement campaigns. Most of the propagation models are developed for usage in the Ku- and Ka-bands, which is a consequence of the fact that most of the propagation campaigns took place at these bands. The research trend in the field pushes the limits further through several new measurement campaigns throughout the world, investigating the propagation impairments at higher Ka-, Q/V- and W-bands. The Department of Communication Systems at Jožef Stefan Institute has recently established a network of measurement stations at Ka- and at Q-band. The site diversity performance is investigated through the measurements at Ka-band at four locations. Based on the obtained measurements as well as on the available databases, we have proposed new models for site diversity performance evaluation.

1.1 The Need for Site Diversity Modelling

A site diversity system consists of two or more ground stations which communicate with the same satellite. The stations are interconnected by terrestrial links and are separated geographically by a few kilometres in order to benefit from the spatial decorrelation characteristic of intense rainfalls. Since rainfall cells appear with limited horizontal extension, the probability of simultaneous high rain attenuation in all slant paths is lower than the probability of the rain attenuation at each individual Earth-satellite link. The rain attenuation of the whole system is reduced by choosing the ground station with the lowest detected attenuation at any instant of time. The method is especially useful for the feeder links, but it can work theoretically in any scenario where the connection from a ground station to the destination ground point is implemented by terrestrial links.

For the successful design of a site diversity system, the prediction of simultaneous attenuation probabilities is needed. For example, the Complementary Cumulative Distribution Function (CCDF) of joint rain attenuation gives the information about the foreseen outage of the site diversity system. It helps system engineers calculate in advance the system performance for a given geometry or vice versa, the system geometry can be planned by selecting proper separation distances and system angles in such a way that desired system performance is achieved. Various models have been proposed in the past for the prediction of site diversity performance. In this thesis, we propose four new models for the prediction of joint rain attenuation statistics in multisite diversity systems.

1.2 Motivation and Hypothesis

Applicability of the existing models is generally limited. For example, they can be used just for the analysis of a system with two sites and typically they account only for the distance between the stations as the geometrical parameter. The error performance of some models is poor. Our work has been driven by these motives: to find the prediction model with a good error performance, with no limitation in terms of number of stations, with an easy mathematical applicability and with the possibility to expand the input parameters such that the geometry can be described more precisely (the baseline orientation angle and the elevation angle in addition to the distance).

The hypothesis of the presented dissertation is that our goals can be achieved by using the theory of copula functions. The motivation is additionally strengthened by the recent employment of copula functions in satellite propagation modelling: (i) for the prediction of joint exceedance probability of rain attenuation for two-site diversity systems based on two families of Archimedean copula [8] and for the rain attenuation time series synthesis based on Gaussian copula [9, 10]. Most of the models in the

literature are either really complex to implement such as the Multi-Excell model [11], or these are based on specific distributions for modelling rain attenuation statistics. Compared to the other models, modelling through copulas is simpler since the specific distribution of rain attenuation is not needed and also lower number of parameters is required.

1.3 Contributions

In order to achieve the goals set by our study, we took into consideration several different copula functions. We have analysed their adequacy by testing them on the measured data, obtained from a number of previously conducted experiments. The analysis shows that the appropriate functions are the Gaussian copula and the hyperbolic cosecant copula, which are subsequently studied further in the thesis. Four new models are proposed for two-site or multisite diversity prediction.

The results presented in the thesis are expected to contribute to the improvement of the system design and to the further research of modelling the next generation higher frequency satellite links. The main contributions are as follows:

- Two novel multisite diversity prediction models based on Gaussian copula
 - considering the distances between the stations,
 - considering the distances, baseline angles and elevation angles.
- Two novel multisite diversity prediction models based on hyperbolic cosecant copula
 - considering the distances between the stations,
 - considering the distances, baseline angles and elevation angles.
- Improved error performance is achieved compared to the ITU-R model and to the state-of-the-art models.

Further contributions that are also of high importance to the researchers working in the area include the following:

- Model extension for multiple-site system based on the HAC structure.
- The proposed expressions for parameters of the copulas.
- Measurement results from our site diversity experimental configurations.

1.4 Organization of the Dissertation

Chapter 2 provides a review of the main propagation impairment effects and their modelling in slant paths. It introduces the main concepts necessary for the system design, such as attenuation, fade dynamics, frequency scaling and site diversity. It is shown that the rain attenuation is the main impairment component in the total attenuation. The general concept of site diversity is presented and more details are given about the existing prediction models.

In chapter 3, Fade Mitigation Techniques are introduced. A comparison is made between the different techniques to counteract the propagation impairment. The site diversity is pointed out as a technique with the best performance against heavy rain attenuations.

Chapter 4 introduces the history of Earth-satellite measurement campaigns with the emphasis on our own experiments. We introduce our ground propagation terminals, site diversity configurations, data processing methodology and statistical analysis of attenuation and fade dynamics. Data analysis for four-channel receiver is given in terms of first order statistics, second order statistics and some example Cross-Polar Discrimination (XPD) results. Site diversity is analysed in terms of CCDFs of attenuation and equiprobable diversity gains for different ground station combinations. These results are then further used in chapter 5, dealing with prediction models.

In chapter 5, four models for prediction of joint attenuation statistics are proposed and analysed. In addition to our own experimental data, those available from measurement databases are used for evaluation. A comprehensive comparison with the other models is made in terms of their error performance.

Finally, chapter 6 concludes the thesis by highlighting the main findings and pointing out the directions for future work.

Chapter 2

Propagation Impairments Modelling in Earth-Satellite Links

In order to increase the capacity of satellite communication systems and consequently to fulfil the demands for high data rates, the frequency bands higher than Ku-band have to be utilized. Nowadays numerous commercial satellite communication systems operate at Ka-band while in the near future some of them will operate in the higher Q/V, W bands. However, as the frequency is increased, the atmospheric phenomena degrade propagated electromagnetic waves on Earth-satellite links more heavily and they must be considered in the system design. Precipitation (mainly rain), oxygen, water vapour, clouds and fog cause attenuation of the signal power, tropospheric turbulence causes fast fluctuations of the signal amplitude known as scintillation and precipitation (mainly ice and rain) causes signal depolarization. However, among mentioned atmospheric phenomena, rain is the most dominant fading mechanism.

A power margin must be taken into account at the system design phase. However, the use of only a high static power margin for the compensation of attenuation leads to the inefficient use of the resources on ground and space segments. Therefore, FMTs must be introduced. In order to design and evaluate the characteristics of the systems with the mentioned concepts, it is important to know, especially for the design of fixed fade margins, the first order statistics such as CCDF of total attenuation. Fade dynamics, namely fade and inter-fade duration and fade slope are particularly important for design of the FMTs. In case of dual polarization systems, the distribution of depolarization and cross-polarization are needed. Moreover, where the attenuation from the higher frequency in uplink is estimated from measured attenuation in lower frequency in downlink the frequency scaling is needed. Modelling of joint CCDF of rain attenuation, especially in site diversity systems, is necessary for designing the site diversity system configuration with certain marginal gain and for evaluating the performance of an existing site diversity system configuration.

2.1 Atmospheric Effects and First Order Statistics Modelling

The main atmospheric effects such as attenuation of the signal power caused by rain, atmospheric gases, clouds and fogs, melting layer and scintillation of the signal amplitude due to tropospheric turbulences are described in this section. Moreover, modelling of first order statistics of these effects, which are important for the system design, are shown.

2.1.1 Rain attenuation

The effect of rain attenuation is the most dominant impairment on the transmission path in Earth-satellite communications operating at frequencies above 10 GHz. The rain drops scatter and absorb the electromagnetic wave energy, resulting in signal attenuation which degrades the availability and performance of the telecommunication link. Therefore, rain attenuation must be considered in the design of the satellite telecommunication systems. The rain attenuation on the slant paths can be accurately measured by satellite beacon signals. However, the propagation measurements are carried out only at particular places in the world and at certain frequencies and elevation angles. Because the measurements are not available at every location, the rain attenuation prediction modelling methods are required for system margin calculation.

The research on determination of the radio wave attenuation caused by rain was begun in the middle of the twentieth century [12]. The first empirical procedure for calculating the rain attenuation at centimetre wavelengths based on extensive sets of terrestrial measurements has been given in [13]. The methods from early studies have been changed and improved, in particular the ability to calculate the attenuation on slant path Earth-satellite communication links. Several attenuation models have been proposed which can be used for system margin calculation. The most common expression for the calculation of specific attenuation α is the power law equation expressed as a function of the rain rate R and the frequency and the temperature dependent constants a and b [14]:

$$\alpha = aR^b \left(\frac{dB}{km} \right) \quad (2.1)$$

If path length r_R is known, the total attenuation A_ψ on the slant path, shown in Figure 2.1, with elevation angle ψ can be calculated as:

$$A_\psi = \int_0^{r_R} \alpha(x) dx \quad (2.2)$$

where the path length r_R is defined as:

$$r_R = \frac{h_R - h_s}{\sin \psi} \quad (2.3)$$

where h_s is height above mean sea level of the Earth station in kilometres, and h_R the mean annual rain height above mean sea level in kilometres that may be obtained from the 0°C isotherm. The main challenge in the estimation of the slant path attenuation A_ψ is determination of the extent of the path length r_R and rain rate profile along that path. Significant research was accomplished by the determination of techniques and models by characterizing the slant path from measured surface rain rate and 0° C izoterm height [12]. Considering that rain fall rate can be modelled as random variable, the rain attenuation induced on the slant path and its impact on Earth-satellite links must be calculated statistically.

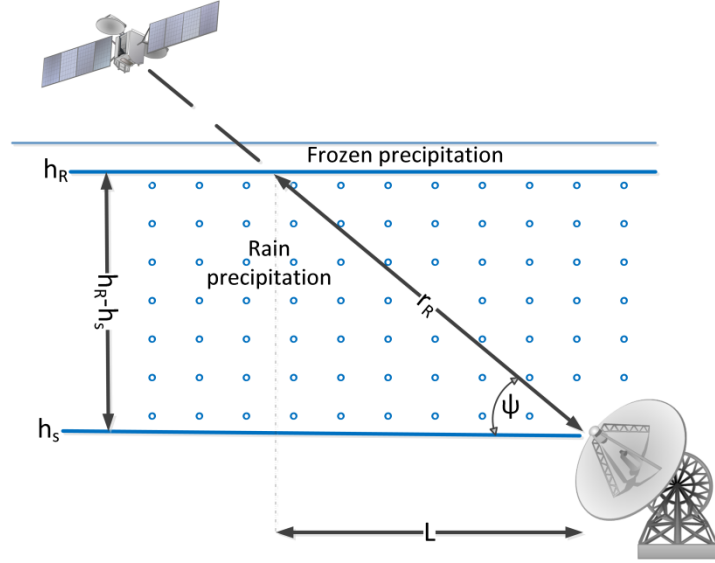


Figure 2.1: Earth-satellite slant path.

Usually long term attenuation data for a given path link are presented in the form of exceedance probability, i.e., the CCDF of rain attenuation on an annual, seasonal or monthly basis. The yearly CCDF presents the percentage of the time within a year for which the rain attenuation exceeds a given attenuation. Therefore, to achieve the desired link performance, the outage and availability can be calculated and rain margins have to be taken into account in system design.

Several prediction models for the prediction of CCDFs exist and most of them require a long-term statistics of the rain rate during an average year at the site of the Earth station, which can be obtained either from measurements or from ITU-R rain rate maps. In order to calculate the induced rain attenuation some of the prediction methods use surface rain rate R at the receiver location as a statistical variable and exploits the relationship (2.1) and additionally define an effective path length parameter as a function of rain rate $L(R)$ [12].

Several models for predicting the exceedance probability of rain attenuation exist and are classified as semi-physical, empirical and statistical models [3]. Semi-physical models are based on the concept of rain cells. Several methods have been developed and tested with the available data of the signal attenuation statistics. Some of them are widely used and are mentioned hereafter. The model in [15] predicts the CCDF of rain attenuation based on the assumption of a double concentric rain cell having external diameter of 33 km. The internal cylinder rain cell diameter and the rain rate in the concentric external rain cell are supposed to be a function of rain intensity. The input parameters of the method are the point rain fall rate distribution of an average year at the site where the Earth station is located, the elevation angle, the rain height h_R , the parameters a and b for specific attenuation in (2.1), and the latitude and the altitude of the Earth station. The model in [16] is based on the concept of effective rain cell and variable rain cell height, while the model in [17] is based on the assumption of exponential shape of rain cells and horizontal distribution of rain rate inside the rain cell. Taking into account the probability of rain occurrence, the specific radius of the cell and its maximum value,

and known distribution of rain rate, the CCDF of rain rate for stratiform and convective rain can be computed.

The most known empirical model for rain attenuation prediction in slant paths is the ITU-R model given in Recommendation P.618-12, paragraph 2.2.1.1 [18]. It computes the slant path length r_R below the rain height from Eq. (2.3) for elevation angle $\psi \geq 5^\circ$, while for low elevation angles $\psi < 5^\circ$ the Earth curvature is taken into account. Figure 2.2 presents an example of prediction of the CCDF of rain attenuation for an average year, performed with ITU-R model for an Earth station located in European region at 40° elevation angle at four frequencies; 10 GHz, 20 GHz, 30 GHz and 40 GHz. The curves show that the rain attenuation at higher operating frequencies is higher.

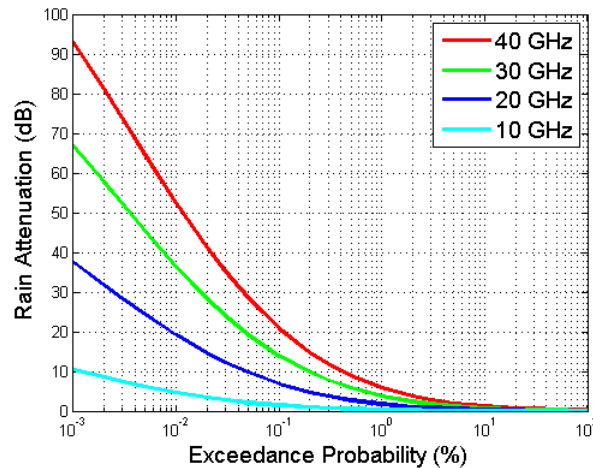


Figure 2.2: CCDF of rain attenuation at different frequencies.

The rain rate and rain attenuation are in statistical models assumed to have a specific probability distribution. A typical statistical model is the model proposed in [19], where it is assumed that rain rate and rain attenuation follow a lognormal distribution. It is widely known in literature that the most accepted models for describing point rainfall rate statistics are the lognormal and gamma distributions. The lognormal model provides a good approximation in regions with low rainfall rates, while the gamma model is more accurate in regions with high rainfall rates. On the other hand, the Weibull distribution provides a very good approximation for both high and low rainfall and attenuation values. The Weibull distribution was selected to represent the CCDF of rain attenuation in [20]. A simple prediction model for single site attenuation was derived using an appropriate regression fitting analysis. In [21] modelling of CCDF is performed assuming that single-site rain attenuation has the Inverse Gaussian distribution and evaluation was given by fitting to the experimental data.

2.1.2 Gaseous attenuation

Gaseous molecules present in the atmosphere may absorb energy from radio wave propagating in the transmission path thereby causing attenuation and adding atmospheric noise to the signal. There are several gaseous components in the atmosphere, but only oxygen and water vapour significantly contribute to the signal degradation. The oxygen and water vapour have resonance frequencies in the bands interesting for space communications. Oxygen has several near absorption lines from 57-64 GHz, preventing the use of this band for satellite communication and one absorption line at 118.74 GHz. Water vapour has one absorption line at 22.3 GHz and two other at high frequencies;

183.3 GHz and 323.8 GHz [12]. Several models for the prediction of specific attenuation and total attenuation caused from gaseous absorption exist.

In [22], the procedure for the calculation of total gaseous attenuation based on regression analysis from direct measurements of oxygen and water vapour on local surface is provided. The Millimetre-wave Propagation Model (MPM) developed by Liebe [23, 24, 25], is the most accurate model for calculating gaseous attenuation. In the model the atmosphere is divided in two homogeneous layers with specific attenuation corresponding to oxygen and water vapour, respectively. The total gaseous attenuation is the sum of path attenuations for each layer. Moreover the total attenuation due to oxygen and water vapour is estimated using the values of the specific attenuation of each component in the ground and equivalent height of oxygen and water vapour. The specific attenuations of gases at ground level can be calculated only from surface meteorological measurements, while the statistics of equivalent height can be calculated by using the Liebe's model and radiosonde data [26]. ITU-R proposes two versions in two annexes for prediction of attenuation by atmospheric gases in Recommendation P.676 [27]. Both versions require vertical profiles of pressure, temperature and water vapour density which can be obtained from ITU-R P.835 [28]. The second model is less complicated. It uses approximation algorithms and the surface metrological data and maps of integrated water vapour content for various time percentages obtained from ITU-R P.836 [29]. The method gives the total gaseous attenuation for zenith paths and for elevation angles from 5° up to 90° . For elevation angles from 0° up to 5° the first annex must be used.

2.1.3 Cloud attenuation

The clouds and fog are composed of small droplets of liquid water with size much less than the wavelength of the transmitted signals. The signal attenuation results mainly from absorption by the cloud or fog droplets. Although the precipitation attenuation is generally most severe, the frequent presence of clouds causes attenuation for a large proportion of the time and becomes more severe at higher operating frequencies. Therefore, the cloud attenuation must be accurately quantified for the reliable design of low margin satellite communication systems at high frequencies. The cloud attenuation depends on the particle size and density distribution, temperature, index of refraction, frequency and cloud extent. Under conditions without precipitation, clouds below the zero degree isotherms have a composition similar to fog [30].

Due to the small size of droplets, the attenuation caused by clouds can be determined using the Rayleigh model of electromagnetic wave scattering. The cloud attenuation modelling using this approach requires the assessment of cloud vertical profiles which can be obtained from radiosonde measurements. Therefore, the estimation of the cloud attenuation depends mainly on accuracy of the radiosonde data. The Rayleigh model can be used as a reference model for testing of other models [26]. In the existing literature, there are various prediction models for cloud attenuation at frequencies above 10 GHz. The cloud attenuation methods based on meteorological quantities using regression fitting analysis have been presented in [30, 31]. The Salonen [32] method calculates the cloud attenuation at a given elevation angle and over the frequency range from 10 GHz to 60 GHz for any location on Earth. The model depends on the frequency, temperature and total liquid water content. The model in [33] is based on average cloud properties of four cloud types and on the assumption that the statistical distribution of cloud attenuation follows a lognormal probability function. In [34] the Stochastic Model of Clouds (SMOC) to synthesize 3D spatially correlated cloud fields has been proposed based on radar data. Another method for calculation of cloud attenuation for Earth-space systems operating in the 20-200 GHz frequency range has been proposed in [35]. The

method presented in ITU-R P.840 [36] has adopted the Salonen [32] method and can be used for calculation of attenuation due to fog and clouds.

In Figure 2.3 an example of the CCDF of cloud attenuation according to ITU-R model for an Earth-satellite link on European region for several frequencies from 10 GHz up to 50 GHz at elevation angle 36° is depicted. The attenuation increases by increasing frequency, but even for low percentages it is very low. For lower elevation angles and for tropical regions the attenuation is higher.

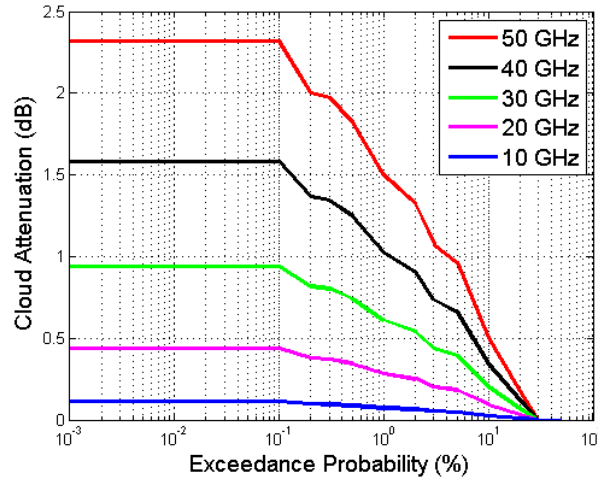


Figure 2.3: CCDF of cloud attenuation at European climate.

2.1.4 Melting layer attenuation

The melting layer is a stratified region of the atmosphere which appears around the effective rain height, just below the 0° isotherm level, where snow and ice melt and cause liquid droplet precipitation. Stratiform precipitation usually starts with ice clouds comprised of ice crystals [26]. Large and low density structures, like snowflakes, aggregate during the fall of the ice crystals. Due to collisions of cooled water drops even higher density particles (hailstones) can be created [37, 38]. The melting process usually starts at around 0° isotherm and is completed a few hundred metres below. From there on only the rain drops are present, whereas above the melting layer a mixture of ice structures with different sizes and densities are present [26]. Regarding the attenuation and depolarization the melting layer has different properties than the rain layer. Therefore in slant path propagation attenuation an additional attenuation which is the difference between attenuation due to the melting layer and that due to the same thickness of the resulting rain has to be considered. Especially in the case of light rain and low elevation angle link, the contribution of the melting layer in total slant path attenuation is significant [39].

The knowledge of the melting layer also has an impact on the determination of rain height [40]. The globally used model for calculation of rain attenuation, ITU-R P.618, assumes constant rain height and takes into account the thickness of the melting layer into the effective path length. The rain height is derived from yearly averaged zero degree isotherm height. However, it was found that the rain height is not invariant with time since significant variations with the rain rate were observed [41]. Results from experiment [40] in tropical regions suggest a possible modification in the rain attenuation

model taking into account the melting layer height variation with the season and rain rate.

Modelling of propagation characteristics in the melting layer began with identification of the structure and shapes of the melting particles. Observations in [37, 38] show that melting particles are found in complex conditions in different shapes and at different events in different concentrations. Examples of models of melting layer characteristics assuming that melting particles have spherical shape can be found in [39, 42, 43].

2.1.5 Tropospheric scintillation

Tropospheric scintillation is a fast fluctuation of signal amplitude and phase due to turbulent irregularities in temperature, humidity, and pressure, which cause small-scale variations of the refractive index. The associated refractive index variations (in clear air, cloud, and rain) along the propagation path continuously focus and defocus the wave front at the antenna aperture. The amplitude and phase wave front disturbances are translated in random fades and enhancements in the signal level, and their amplitude increases by increasing frequency [44].

Therefore, in the system design phase the prediction of the scintillation in the satellite link in terms of annual statistical distribution of signal's fades and enhancements is needed. While fade distribution gives the required scintillation margin, the distribution of enhancements is important particularly in multicarrier satellite transponders, where a large amplitude enhancement of one carrier could significantly decrease the Carrier to Interface (C/I) ratio of the other carriers [45].

The tropospheric scintillation increases with temperature and humidity as well as with total water content of the heavy clouds. Therefore, higher intensity scintillation is observed during hot seasons, during wet days and during the period of the day with the highest temperature. The scintillation is more distinctive in warm tropical and equatorial areas than in dry regions. Moreover, the scintillation intensity increases with the increasing frequency and decreasing elevation angle and aperture of receiving antenna [26]. Higher aperture of antenna averages the scintillation across the different paths and consequently minimizes the value.

Scintillation fade plays an important role in the low fade margin systems operating at frequencies higher than 10 GHz and elevation angles lower than 15° since it may cause similar attenuation as rain, especially for time percentages larger than 1%. Knowledge of dynamic characteristics of scintillation is also important for the design of up-link power control, antenna tracking systems and the systems which require compensation techniques [46]. For high availability systems at elevation angles higher than 15°, the scintillation fades are significantly lower compared to rain attenuations and can be neglected in the link budgets calculations. At 10 GHz and at elevation angles below 5° scintillation amplitudes exceeding 15 dB have been observed [47].

Several models for prediction of scintillation effects can be found in literature. The Karasawa model [48] predicts the standard deviation of the signal fluctuations due to scintillation and is given as a function of elevation angle, frequency, effective antenna diameter and refractive index N_{wet} . Additionally, expressions for the long-term distribution of amplitude deviation as signal enhancement and signal fade, expressed also as a function of the predicted long-term standard deviation are included in the model.

The step by step procedure for the scintillation fade depth $A(p)$ prediction, exceeded for $p\%$ of the time is given in ITU-R P.618 [18]. The fade depth distribution is adopted from the Karasawa model for signal fade. In Figure 2.4 the predicted CCDF of the scintillation fade depth according to ITU-R P.618 for two Earth-satellite links located in tropical and temperate region operating at 20 GHz frequency and at 40° elevation is

depicted. Due to high elevation angles both regions experience low fade depths, although slightly higher ones are observed for the tropical link.

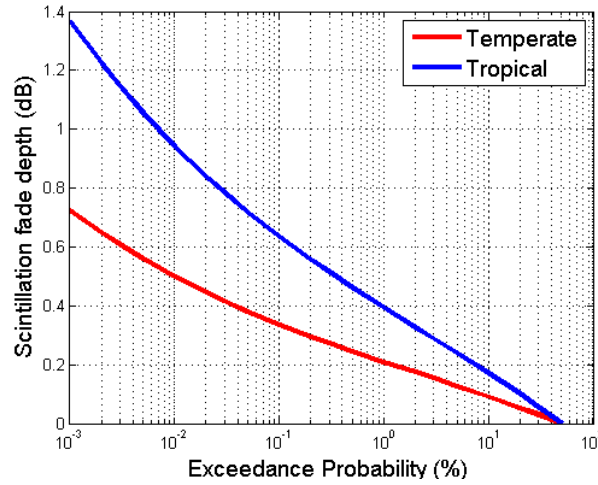


Figure 2.4: CCDFs of scintillation fade depth.

The Otung model [45] is similar to the ITU-R model but uses a different expression for the standard deviation of the scintillation. Another model that predicts long term distribution of the fades and enhancements of the signals due to scintillation is described in [46]. The method that predicts long-term statistical distribution of tropospheric scintillation on satellite links from radiosonde based on a rigorous statistical approach is described in [49].

2.1.6 Depolarization

In order to double the system capacity, the frequency reuse communication systems employ the same frequency band and dual polarization. The orthogonal polarization in one frequency band may be either linear or circular. The limitation of such a system is the isolation between the polarizations. The atmospheric effects in the transmission path may cause the transfer of the energy of the electromagnetic wave from one polarization to another resulting in interference or cross-talk between two channels. Vertical polarized wave may interfere with horizontal wave or the Right Hand Circular Polarization (RHCP) wave with Left Hand Circular Polarization (LHCP) wave and vice versa [50]. The ionospheric effect such as Faraday rotation can be neglected for operating frequency above 10 GHz. The depolarization is caused by anisotropic propagation path effects such as non-spherical hydrometeors (primarily rain and ice). The depolarization induced by rain is produced by different attenuation and phase shift caused by non-spherical rain drops and inclined falling direction usually caused by wind. The depolarization due to ice crystals on Earth-space slant paths has been observed by satellite beacon measurements. The strong depolarization accompanied by very low co-polarized attenuation and abrupt changes in the XPD has been observed to coincide with lightning discharge in the area of the slant path. Usually the ice crystals have the shape of needles and plates and their axes can be abruptly aligned by lightning discharge which reflects in an increased cross-polarized signal while the co-polarized signal is almost unaffected.

The depolarization is measured in terms of cross-polar discrimination at the receiver part, considering that the transmitter transmits only one (desired) polarization. For linearly polarized waves the XPD in decibels is defined as the difference between the

signal power of the co-polarized (desired) direction and the power of the induced signal into the orthogonal cross-polarized (undesired) direction. Generally, for frequencies higher than 10 GHz, the XPD for vertically polarized transmission is higher compared to horizontally polarized transmission at the same attenuation level. The depolarization is stronger on circular polarization compared to horizontal polarization which results in lower XPD. A prediction method for long term statistical calculation of the XPD from rain attenuation statistics is provided by Recommendation ITU-R P.618 [18].

2.1.7 Total attenuation

The influence of several attenuation components and their correlation must be identified in order to calculate the exceedance probability of the total signal attenuation. For systems operating at high frequencies and low elevation angles, with low margins and low required availability, in addition to rain attenuation, all attenuation components must be taken into account. The total attenuation represents the combined attenuation from rain, gas, clouds and scintillation. In order to obtain the CCDFs of total attenuation, different methods for predicting CCDFs of combined attenuation of the components exist [33, 51, 52]. For statistical prediction, the CCDF of combined attenuation, considering that tropospheric effects are totally correlated, can be calculated according to equiprobable summation, where the total attenuation at $p\%$ is calculated as a sum of attenuation of each component at $p\%$. If the effects are not correlated, the root-sum-square of the components is used in the models.

The ITU-R recommended a method for predicting CCDF of the total attenuation in ITU-R P.618 [18]. According to this method, the total attenuation for a given probability, $A_T(p)$, is given by:

$$A_T(p) = A_G(p) + \sqrt{(A_R(p) + A_C(p))^2 + A_S^2(p)} \quad (2.4)$$

where the $A_T(p)$, $A_G(p)$, $A_R(p)$, $A_C(p)$ and $A_S(p)$ are the total attenuation, gaseous attenuation, the rain and cloud attenuation, and the scintillation fade depth at the same probability $p\%$. The rain $A_R(p)$ and cloud $A_C(p)$ are considering as dependent between each other and the combined attenuation of both effects is calculated as a summation. Since the attenuation from rain and cloud $A_R(p) + A_C(p)$ is considered independent to the scintillation fade $A_S(p)$, the root-sum-square of the two components is used. Finally, the attenuation due to atmospheric gases $A_G(p)$ is combined using equiprobable summing. Figure 2.5 gives an example of CCDFs of total attenuation and attenuation components, i.e., rain attenuation, gaseous attenuation, cloud attenuation and scintillation fade depths predicted by ITU-R for an Earth station in Ljubljana with the elevation angle 36° and frequency 20 GHz. For most percentages the CCDFs of rain attenuation and total attenuation are quite close to each other which confirms that the rain attenuation is the most important component of the total attenuation.

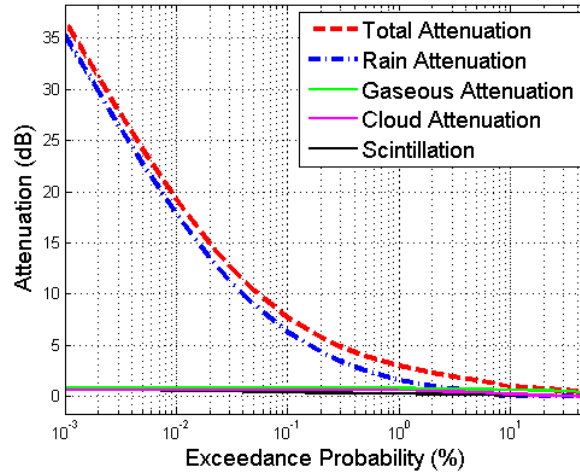


Figure 2.5: CCDFs of rain and total attenuation.

2.2 Fade Dynamics on Earth-space Slant Paths

In order to optimize satellite system capacity and achieve the desired quality in the design of telecommunication systems, FMTs and resource sharing techniques are required. The aforementioned techniques depend on the dynamic characteristics of fading due to atmospheric propagation. Therefore, information on fade slope, fade duration and inter-fade duration statistics for a given attenuation level need to be known.

2.2.1 Fade and inter-fade duration

Fade duration is defined as the time interval between two consecutive crossings above the same attenuation threshold while the inter-fade duration is defined as the time interval between two consecutive crossings under the same attenuation threshold [53]. Fade duration is considered as an important parameter for satellite system design, operation and control. It gives information for outage periods or unavailability of the system or link, whereas inter-fade duration can be used for calculation of availability or periods of time when the system or link is operative. Moreover, in order to reallocate the system resources to other users during the outage time it is important to have an insight into the statistical time duration of an event when a group of users is in outage. Fade duration is important for FMT design defining the statistical duration that the system needs to be in the compensation configuration by FMT before the system is back to its normal mode. Results from fade duration analysis can be presented as [54]:

- statistics of the number of fade events in which attenuation is above a given attenuation threshold and longer than a given duration,
- statistics of the total duration of fade events higher than a given attenuation threshold and longer than a given fade duration,
- directly the statistics of fade duration with respect to the fraction of time during which fade intensity is above a given attenuation threshold.

Several models have been developed and are available for prediction of fade duration statistics such as the Goldhirsh model [55], the Saffai-Jazi model [56], and the Matriciani model [57]. The Paraboni-Riva model [58] was adopted by ITU-R P.1623 [53]. The model enables the calculation of the fade duration statistics as a combined effect of attenuation

and scintillation on the slant path. The model is valid for the duration longer than 1 s, the frequencies from 11 GHz up to 50 GHz and the elevation angles from 6° to 60°. Statistical distribution is independent of location and climatic parameters, but dependent on rain rate and therefore on the attenuation level, frequency and elevation angle [54]. Although several models for fade duration statistics exist, there is no available model for inter-fade duration.

2.2.2 Fade slope

Fade slope dynamic is important for satellite systems in which the FMT have to be implemented. Fade slope is defined as the rate of the attenuation change during certain time interval. Knowledge of the fade slope is important for determining the required tracking speed of FMT, useful in the design of the control loop that can follow the signal variation, but also to enable the short-term prediction of the propagation conditions. In both cases the knowledge of the slow varying component of the signal from the rain attenuation is needed. The fast fluctuation of the signal caused by troposphere scintillation is unpredictable since the autocorrelation function decreases very rapidly with the time and consequently the scintillation component is completely uncorrelated after only two seconds [54]. To calculate the slope of the attenuation component from measured time series, it is necessary to remove the scintillation component by filtering. The experimental results show that scintillation can be filtered out adequately by using low pass filter with 3 dB gain and cut-off frequency of 0.02 Hz. Once the rapid fluctuations have been removed, fade slopes are calculated for each attenuation threshold. Attenuation slope $\zeta(t)$ corresponds to the rate of change of the attenuation $A(t)$:

$$\zeta(t) = \frac{A\left(t + \frac{1}{2}\Delta t\right) - A\left(t - \frac{1}{2}\Delta t\right)}{\Delta t} \left(\frac{dB}{s}\right) \quad (2.5)$$

Several fade slope prediction models based on the filtering data and derived from Eq. (2.5) have been published. A well-known Van de Kamp model which calculates fade slope statistics [59] has been approved by ITU-R as Recommendation ITU-R P.1623 [53].

2.3 Frequency Scaling

It was observed from several measurement campaigns that characteristics of the propagation at different operating frequencies exhibit certain similarities. Therefore, to estimate the magnitude of the propagation effect (attenuation, scintillation and depolarization) from the known magnitude at lower frequency, the frequency scaling method has been developed. This technique provides information of the propagation effects in order to design the system operating at the high frequency bands such as Ka- and V-band from the measurements and knowledge of the characteristics of the system operating at lower frequency bands, e.g., Ku-band. Moreover, the frequency scaling is also needed for the design of the FMT control loop, and FMTs such as power control and site diversity, where the attenuation at higher frequency in uplink is estimated from downlink measured attenuation. By investigating the frequency scaling variations during a rain event, frequency scaling can also provide valuable information about the drop size distribution (DSD) [54].

There are two kinds of frequency scaling considered in literature, namely (i) the long-term frequency scaling based on comparison of cumulative distributions of the propagation effects for the same exceedance probability and (ii) instantaneous frequency

scaling which compares the ratio of the instantaneous attenuation at two distinct frequencies. The instantaneous frequency scaling ratio can exhibit strong variation especially during convective rain and is caused by the dynamic variation of the DSD during such an event. It is possible that a scatter plot of attenuation at a given frequency as a function of attenuation at another frequency during the duration of the same rain event show a hysteresis. For the same reason, the long-term frequency scaling ratio for different attenuation values also exhibit changes. Based on the variations that show the instantaneous frequency ratio, attenuation-dependent frequency scaling ratio must be considered as proposed in ITU-R P.618 [18]. The long term prediction models of the frequency scaling ratio (FSR) are generally based on the following expression:

$$FSR(p) = \frac{A_2(p)}{A_1(p)} = \frac{g(f_2)}{g(f_1)} \quad (2.6)$$

where f_1 is the lower frequency and f_2 is the higher frequency, p is time percentage of exceedance probability. The function $g(f)$ is an empirical function which may depend just on the frequency or also on attenuation and polarization, depending on the used method. The methods in [60] and [61] assume that FSR depends only on the frequency, whereas in ITU-R P.618 model long-term FSR depends on frequency and attenuation.

Considering that modelling of the instantaneous frequency scaling is needed e.g., activation of a fade countermeasure in the uplink relies on the short term prediction of attenuation, based on attenuation measured on the downlink, several instantaneous FSR (ISFR) models have been proposed. The propagation experiments have shown that ISFR of rain attenuation is a stochastic quantity and several authors treated the modelling of ISFR statistically by mean and standard deviation [61, 62].

2.4 Modelling of Site Diversity Performance

Heavy rainfalls are localized events horizontally spread within a few kilometres which usually cause high attenuation on the Earth-satellite slant paths. Often the heavy rain cell has a central convective cell with high rain rate surrounded by wider area with exponentially decreasing rain rate intensity. Site diversity systems consist of two or more spatially separated Earth stations which communicate with the same satellite. Site diversity principle is based on the fact that the fade at different spatially diverse slant paths experience different attenuation. The probability that the rain attenuation occurs simultaneously on two or more routes is lower than the probability of rain attenuation on each individual path. In order to achieve the communication between the satellite and the desired Earth destination, a simple combining technique (selection combining) is used where the Earth station affected by a weaker event fades is used and the communication to the destination is routed through the terrestrial links.

The performance of site diversity is statistically usually expressed by CCDF of joint rain attenuation. Joint attenuation time series express the minimum attenuation among the all Earth-satellite links in any instant of time. The joint CCDF is of great importance because it defines the outage of the site diversity system. Other metrics for describing the performance of the site diversity performance and calculated from CCDFs of attenuation of single terminal and joint CCDFs are diversity gain and improvement factor. The diversity gain is defined as a difference between the path attenuation associated with a single site and multiple-site joint attenuation exceeded for given percentage of the time. The diversity improvement is defined as the ratio of probability associated with a single

site and probability associated with multiple sites at which a given attenuation level is exceeded.

Knowledge of the CCDF of rain attenuation helps the system engineers to build the system with the required performance for a given geometry and performance parameters of the site diversity system. Therefore, various models have been proposed for prediction or calculation of joint CCDF, diversity gain and improvement factor. They can be classified in two general groups as empirical and physical models. The first ones use an empirical relationship, and the parameters have been obtained from fitting the procedure to the experimental data, whereas the physical models are based on the modelling of the rain structure. Examples among the proposed empirical models can be considered:

- Hodge model [63]: calculates the diversity gain for two-site diversity system described through empirical expression as a function of the Earth terminal separation distance, link frequency, elevation angle and baseline orientation angle.
- NTUA prediction model [20]: provides an empirical function for prediction of the diversity gain. The prediction method is proposed based on the Hodge methodology but with greater sensitivity to the distance variation.
- ITU-R P.618-12, paragraph 2.2.4.2 model [18]: is a simple model based on empirical expression adopted from Hodge model [63]. It can be used for prediction of diversity gains for pairs of sites separated less than 20 km.
- Allnut-Rogers model [64]: predicts the diversity gain based only on the meteorological data. In this model it is assumed that rainfall rate at the two sites will be almost completely correlated at 0.3% of the time. In this model there are two different separate features of the diversity gain characteristics as a function of the mean single site attenuation: an initial curved section followed by a straight section almost parallel to the ideal diversity gain. The method takes into account frequency and elevation angle variations.
- Goldhirsh model [65]: is a diversity gain computing model derived from radar data in S-band collected over three years' measurement period at Wallops Islands, Virginia. Using regression analysis, the diversity gain is expressed with good approximation as an exponential function of the distance between stations.

In addition to the empirical models, some of well-known and widely used physical-based models developed for prediction of joint CCDF of rain attenuation are:

- Matricciani model [66]: is an extension of the two-layer model. Simple physical and statistical hypotheses have been assumed in order to calculate the bivariate probability distribution of the diversity system. The conditional probability distributions of attenuations of the single links are supposed to be lognormal and the bivariate probability density function of rain attenuation is considered lognormal, too.
- The EXCELL (EXponential CELL) model [67]: describes the precipitation environment by means of the isolated rain cell population with horizontally exponential profile of the rain inside the rotational symmetry derived from investigation of radar rain maps. Because it considers only a single rain cell at the time which affects the link, the model is suitable for sites with separation distance between 10 km and 20 km. With this model, it is possible to calculate the joint rain attenuation CCDF for unbalanced diversity system.

- Mass model [68]: assumes rain cells are circularly cylindrical and of constant rain rate, and rain cell diameters are lognormally distributed, with the median depending on rain rate. The model calculates the joint distribution of attenuation.
- NTUA physical model [69]: calculates the unbalance joint CCDF of rain attenuation in which single site rain attenuation is assumed lognormal and the joint statistics of rain attenuation follows the joint lognormal distribution.
- Paraboni-Barbaliscia [70] model: predicts the joint CCDF of rain attenuation for balanced and unbalanced system of exceeding attenuation thresholds. The method assumes a lognormal distribution for rain attenuation and provides expressions for spatial correlation functions derived from radar data. The method is extended to prediction of exceedance probability for any multisite diversity system.
- ITU-R P.618-12, paragraph 2.2.4.1 [18] model: to predict the joint attenuation CCDFs for two-site diversity, the Paraboni-Barbaliscia model is adopted. In the ITU-R P.618-12 a step by step procedure to calculate the joint CCDF of rain attenuation is given. The method requires the knowledge of the distance between stations, each single site rain attenuation A_i and probability of occurrence P_i for both stations, and probability of rain for a particular location which can be obtained from ITU-R P.837 [71].
- MultiEXCELL model [11]: calculates the joint CCDF of rain attenuation. The model generates the two-dimensional rain rate fields from the conglomeration of the rain cells assuming that horizontal rain rates have exponentially distributions.

In addition, the recently proposed model in [21] is classified as a physical-mathematical model and can be used for prediction of balanced and unbalanced joint exceedance probability of rain attenuation for dual site diversity systems. The single-site and joint-site rain attenuation are modelled using single and bivariate inverse Gaussian (IG) distribution, respectively. The model requires spatial correlation coefficient, and the expression for rain attenuation correlation from the Paraboni-Barbaliscia model was employed. The performance of the method was validated by using DBSG3 database [72] and compared to the ITU-R P.618-12, paragraph 2.2.4.1 model [18]. Comparison of error performance shows that the proposed model gives better performance than the ITU-R model. Moreover, very recently, two other models based on copula functions have been proposed in [8]. The models for the prediction of joint exceedance probability of rain attenuation for two-site diversity systems are based on two families of Archimedean copulas. The comparison to experimental data shows that the model exhibits better in terms of error performance compared to ITU-R P.618 model. Because both single site rain attenuations do not need to be statistically modelled and because only one parameter is employed to couple the two random variables corresponding to the rain attenuation of each one of the two links, the copula based models are easy to implement.

Chapter 3

Fade Mitigation Techniques (FMTs)

In addition to deterministic free space loss most of the atmospheric phenomena discussed in the previous chapter exhibit also space and time stochastic attenuation. The atmospheric attenuation, especially due to rain, can reach very high attenuation for a small percentage of time during the year. Therefore, in order to ensure minimum outage duration of the service, the high system static margins have to be implemented. However, the technology limitation in designing the system with high static margins on both terrestrial and space segments exists. Moreover, the compensation of high attenuation is needed only for small time percentages and in the system with high static margins, the resources of the systems remain unexploited for most of the operation time which is cost inefficient. In order to have a cost efficient system, which would operate under small static margins even in high atmospheric fade conditions, the Fade Mitigation Techniques (FMTs) are used [73, 74]. Various existing FMTs adapt the link budget to the propagation conditions in real time. These physical layer techniques can be classified in three major categories [7]: 1) Effective Isotropic Radiated Power (EIRP) control techniques, 2) Adaptive transmission techniques and 3) Diversity techniques.

3.1 Fade Mitigation Techniques Principle

For the implementation of the FMT, real time detection and prediction of dynamic behaviour of propagation fades are needed. A control loop will be needed in order to track the propagation channel variations and compensate the impairments with the activation of the FMT when it is needed. The control loop usually consists of three main functions: detection, short-term prediction and decision [75]. The first step includes observing and evaluating whether or not an outage of the system (system margin exceedance) due to detected propagation impairments is going to happen. The detection function has as its objective measuring the depth of the event on the particular link subject to fading. A sufficient detection accuracy can be achieved only by satellite beacon measurements operating in uplink and downlink without frequency scaling for the estimation of the uplink attenuation. Since this method can be very expensive, usually the downlink attenuated signal is measured and the use of instantaneous frequency scaling function between uplink and downlink operating frequencies enables estimation of the uplink fade in real time.

In general, all detection methods will inevitably introduce some amount of error and they all need a certain observation and processing time δt_{detect} . Moreover, the execution of FMT, after the decision is made, requires time δt_{FMT} . Knowing the channel behaviour at the adequate advance time which is the same as the reaction time of the entire control loop (detection delay, filtering delay, decision delay, signalling delay, FMT delay, etc.)

will enable the system to react at the moment the event occurs. To reach this objective, accurate short-term prediction needs a precise knowledge about the dynamics of the propagation channel such as fade slope. There are several short-term prediction models based on fade slope dynamics.

Decision function will decide if the considered link performs according to specifications, and if the fade event appears, then FMT is activated. The FMT activation depending on the used FMT technique includes modifying the system parameters compared to clear sky conditions such as: a) transmitted power on Earth or satellite station or antenna gain for power control FMT; b) coding rate, data rate, spectral efficiency for adaptive code and modulation and c) time, frequency, site for diversity FMTs. When the fade appears, the FMT controller switches to degraded mode and when the propagation conditions are recovered the nominal operating mode is restored [76]. Knowledge of fade dynamics, such as fade and inter-fade duration, are required for the design of the switching controller.

In order to build, design and test the satellite communication system that uses FMT, it is crucial to consider the faded satellite channel model. Since the system must perform satisfactorily on a long term basis, yearly statistical analyses are used.

3.2 Effective Isotropic Radiated Power (EIRP) Control Techniques

The EIRP control FMT types can be considered: Up-link Power Control (ULPC), Down-Link Power Control (DLPC) and On-Board Beam Shaping (OBBS).

In the ULPC, the output power of the Earth station is adjusted to the uplink impairments. Transmitter power is increased to counteract fade or decreased in clear sky conditions to limit the interference and optimize the satellite capacity. The two main drawbacks of ULPC technique are the adjacent channel interference due to increased power, sent to side lobes and adjacent satellite interference. Satellite interference is caused by the increased power which is received from other satellites, positioned close to the target receiver satellite.

In order to reduce the downlink attenuation, the DLPC type which adjusts the on-board channel output power is used. Because of the limited size and weight of the satellite and limited ability to control the satellite operation, the implementation of DLPC is very demanding. Apart from the adjacent channel interference, the DLPC may cause also intermodulation interference. Another drawback of DLCP is intersystem interference with the terrestrial networks.

A geostationary satellite, which covers certain geographic region, provides coverage by spot beams. The spot beam gains can be adjusted according to fading conditions and performed by active antennas. This radiated power control technique is known as On-Board Beam Shaping (OBBS). In order to compensate the rain attenuation, the antenna beam width is reduced, which increases the gain only on the spot beams where the rain is likely to occur [26]. To analyse the evolution of meteorological situations over the desired coverage, short-term weather conditions are needed which can be obtained by satellite images [77]. Based on the meteorological conditions, the static or dynamic optimization of the spot beam can be achieved.

3.3 Adaptive Transmission Techniques

By adaptive transmission techniques the degradation of the signal is reduced by modifying the signal processing method on Earth and satellite stations. These techniques, which may be considered as resource-shared FMTs, could be divided into Adaptive Coding (AC), Adaptive Modulation (AM) and Data Rate Reduction (DRR) [7].

AC consists of implementing a variable coding rate which is matched to the impairments, originating from propagation conditions. The coding is employed for detection and correction of bit errors, by adding redundancy bits to the information signals. By increasing the redundancy, the error probability is decreased, but in order to keep the same data rate, the bandwidth has to be increased. Different coding schemes exist and are used according to the impairment intensity [7]. A technique known as interleaving, proves to be efficient only against short fades, particularly scintillation. When the link is subjected to severe attenuations, complex coding schemes such as concatenated codes and turbo codes must be used.

By AM technique higher system capacity for a given bandwidth can be achieved with spectral efficient modulation schemes, but in clear sky conditions only due to link budget power limitation [73]. The Phase Shift Keying (PSK) modulation is the most common modulation scheme in satellite communications. In order to achieve higher transmit data rates without increasing the frequency bandwidth, the higher order PSK schemes, such as QPSK, 8-PSK, 16-PSK and 64-PSK, are used. The combination of phase and amplitude modulation such as Quadrature Amplitude Modulation (QAM) may also be used. The spectral efficiency of the communication link may be increased by higher order modulation techniques such as M-ary PSK and M-ary QPSK schemes. Considering that the separation between consecutive amplitude and phase states becomes more susceptible to errors under heavy meteorological conditions, lower modulation schemes, such as BSPK and QPSK, have to be employed. Highly efficient modulation schemes such as 16-PSK, 64-PSK or even 256-QAM are used during clear sky conditions [78].

By adaptive transmission technique DRR, the information data rate is decreased at constant Bit Error Rate (BER) and bandwidth. The used data rates are matched to propagation conditions, with reduction introduced according to fade level appearance, and nominal data rates under clear sky conditions.

3.4 Diversity Techniques

Finally the diversity techniques are mostly oriented to counteract high impairments of the signal caused by rain. Therefore diversity techniques are the most efficient techniques for high availability system establishment. Four types of diversity techniques are known, namely: site diversity (SD), orbital (satellite) diversity (OD), frequency diversity (FD) and time diversity (TD). The first two techniques exploit the advantages of spatial structure of the rain fall intensities, while the frequency and time diversity exploit the rain attenuation dependency on the frequency spectrum and time, respectively.

Site diversity is a general notion used for diversity technique systems which consists of two or more ground stations spatially separated and interconnected by terrestrial (e.g., optical, wireless or wireline) links. In Figure 3.1 an example of the three-site diversity configuration geometry is shown. Considering that short term heavy rainfall decorrelates with increasing distance between ground stations [79], the probability of simultaneous deep fades occurring at all stations is lower than employing a single ground station. Therefore, the effect of rain attenuation can be significantly reduced by introducing a site diversity system with appropriate separation distance between the stations, proper

system geometry and by applying a suitable algorithm for finding ground stations with weaker attenuations. The communication is routed to the chosen ground station through a terrestrial link. Assuming that during the year, very strong local events, like convective rains and storms, are short in time, the site diversity with high diversity gains, particularly for low percentages, is an efficient technique. Technically, the SD can be considered in terms of high gains achievements as the most efficient diversity scheme. In Ka-band, typical diversity gains can exceed values above 30 dB. The SD requires at least two Earth stations and the existence of control station and terrestrial links between the stations.

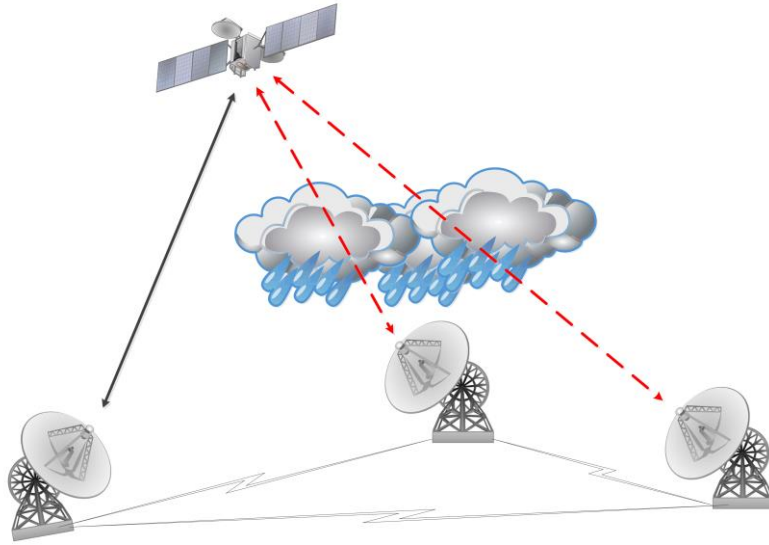


Figure 3.1: Three-site diversity system configuration.

The orbital diversity technique prevents the degradation of quality for the system which consists of only one Earth station that communicates with different satellites. The Earth-satellite link with the least attenuation is selected. In Figure 3.2 the configuration principle of OD, employing two satellites, is depicted. The rerouting strategy can be applied just for FSS (Fixed Satellite Services). The experiments conducting orbital diversity are quite rare especially compared to the number of site diversity experiments. The possible use of the satellite diversity as successful FMT for higher frequency bands has been demonstrated by experiments, described in [80, 81]. Higher diversity gains are obtained for low elevation links. Orbital satellite diversity does not require terrestrial links, while switching and decision operational algorithms are carried out from just a single station. Because the decorrelated fade events can be, in site diversity system, achieved by spatially separated ground stations rather than by increasing the orbital angle between the Earth station and two satellites, the achievable diversity gain is much higher in the site diversity case. In orbital diversity, the antenna pointing from one satellite to other backup satellite is realized with tracking system, or in a case of two satellites, dual beam antenna could be used.

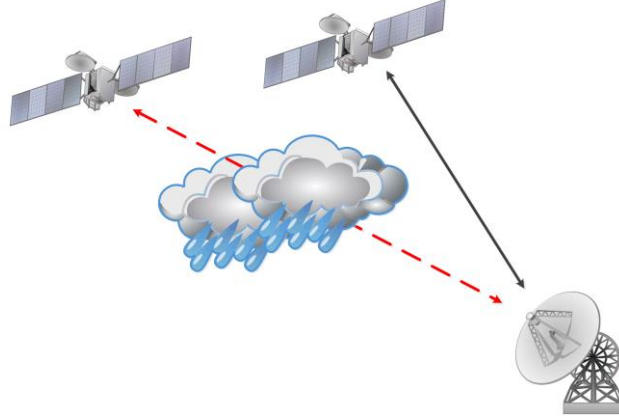


Figure 3.2: Orbital diversity principle.

Frequency diversity is a technique that requires payloads at two different bands on-board, and when a fade occurs the link with the lowest frequency band payload is used, which is less affected to rain compared to the clear sky case, where the highest frequency band is used [82]. The FD technique is very expensive because it requires Earth stations with two terminals to be employed, one for lower bands and the other for higher. Furthermore by using the low frequency band payload the capacity is limited for high data rate services requirements. The sharing of satellite resources must be optimized and thus frequency diversity is only appropriate for very specific communications.

Time diversity can be used as a FMT for the services that do not require transmission of data in real time. Therefore, if the conditions of the propagation channel are degraded due to the event, the data are stored and retransmitted after the end of propagation event. The performance of TD is dependent from fade and interfade duration. Applicability of TD is limited in video on demand, multimedia and data applications.

3.5 Comparison of Fade Mitigation Techniques

The advantages and limitations of the described FMT types are considered in terms of availability range, maximum gain, and technical and cost efficient implementation [26].

The ULPC is a flexible technique and can be implemented for any percentage of time. However, the limitations are ground power range and the repeater gain margin for transparent repeaters [26]. Therefore, the ULPC is only sufficient to mitigate low attenuations due to cloud and weak precipitations, or total attenuations characteristic for high percentages of times while very strong attenuation cannot be completely compensated.

Regarding the DLPC and OBBS techniques, the size of spot beams in Ka- and EHF-band will allow the counteraction of the events over an area of around some hundreds of kilometres. These techniques are more efficient if the size of the apertures of the spot beams is comparable to the size of the rain cell. Therefore, the DLCP and OBBS technique are appropriate mainly for large stratiform rain which appears over large areas, corresponding to annual high time percentages.

The adaptive transmission techniques are interesting if only a few Earth stations experience fading at the same time. Consequently, these techniques are appropriate

especially for local impairments such as heavy clouds and strong precipitation characteristics. They are less effective when fades are highly correlated.

The FD technique can be applied to any percentage of time, but is relatively expensive. When Ka and Ku bands are used for corresponding high and low frequency band payloads, large gains up to 30 dB for low percentages can be achieved. Consequently, an additional limitation of this technique in this case is also the need to use the lower already congested Ku-band.

SD and OD exploit the advantages of atmospheric inhomogeneities by choosing the slant path not affected by impairments, such as heavy rain fall, characteristic for low percentages of time. The main technical limitation of the OD technique is the interruption of the service during the switching between the satellites. For minimizing the interruption, highly sophisticated tracking systems or dual beam antennas in the ground station must be employed. SD ensures the highest diversity gains compared to the other techniques at low percentages of the time and so can be considered the best technical solution against heavy rains specific for low percentages. The main drawback of the SD is expensive implementation, which includes additional Earth stations, terrestrial links and a network control centre for further processing the jointly received signals for switching decisions.

As each FMT is adopted to perform to a specific range of availability and as some of them when used individually achieve inadequate gains, the FMTs can be considered quite complementary. Therefore, by implementing some of the FMTs simultaneously in a combined way will improve the overall efficiency of the mitigation [74].

Chapter 4

Earth-Satellite Propagation Experiments

In order to understand, characterize, and model the tropospheric impairments globally, propagation measurement experiments for high frequency satellite communication systems have been performed for several decades. These efforts enable significant progress in developing new space applications and continuous enhancement of existing satellite services. Earth-satellite propagation measurement has a long history, starting with NASA's ATS-5 (US) spacecraft, launched in 1969, which enabled the propagation measurements at 15.4 GHz. Later on, several experimental communication spacecraft for Earth-satellite propagation measurements at frequencies above 10 GHz have been launched in Europe, Japan, the USA and Canada, such as NASA ATS-6 at 20/30 GHz, CTS at 11.7 GHz, COMSTAR Series at 19/28 GHz, SIRIO at 20/30 GHz, ETS Series at 32/30 GHz (40 GHz in ETS-6), OLYMPUS at 12.5/20/30 GHz, ITALSAT at 18.7/39.6/49.5 GHz, ACTS at 20/27.5 GHz [83]. Recent propagation experiments have been carried out at 20 GHz in Canada with ANIK F2 and in Europe with HotBird 6 and Astra 3B satellites.

Especially two main propagation experiments in Europe using OLYMPUS and ITALSAT F1 satellite allowed collection of relevant propagation data in Ku/Ka- and Q/V-bands. These experiments provide important knowledge on the physical aspects of the radio-wave propagation in slant path. However, some aspects relevant to the design of propagation systems which have not been properly addressed in OLYPMUS and ITALSAT propagation measurements, have been recently pushed into realization through a new Alphasat TDP5 propagation experiment at Ka and Q/V-bands. Alphasat (Inmarsat-4A F4) is a commercial satellite located at 25.0°E and operated by Inmarsat. In cooperation with the European Space Agency (ESA) it carries (among others) the so-called Aldo Paraboni Technology Demonstration Payload 5 (TDP #5) with two fully redundant beacons in the Ka- and Q-bands (19.701 GHz and 39.402 GHz). It provides the European coverage that enables collection of relevant data for Earth-satellite propagation experiments in different locations across Europe [84].

Results from several measurement campaigns performed in different countries over the globe from different satellites are available and can be used for impairments modelling and research. Most of the experiments are oriented to single site configuration propagation [85, 86, 87, 88, 89, 90, 91, 92].

In order to investigate fade mitigation characteristics of site diversity and accurately evaluate and model its performance, several diversity experiments have been performed. Most of the site diversity experiments include two ground stations. Examples of two-site diversity experiments can be found in [93, 94, 95]. A small number of experiments with

three or more stations have been performed. Two examples of three-site diversity experiments are given in [96, 97].

The DBSG3 database includes the statistical data of rain attenuation for many two-site diversity experiments. The database includes the experiments from several countries or regions in the world that are performed with the limited site diversity link configurations such as elevation angle, baseline angle, operational frequency, etc. Therefore, increasing the number of measurement experiments in different regions and with different characteristics is needed.

The experimental setups including several stations capable of measuring beacon signals from Astra 3B and Alphasat satellites have been established also in Slovenia in the scope of ESA projects. In particular, through the beacon signal measurements from Astra 3B satellite at four locations, the site diversity performance is investigated. In this chapter statistical analysis of the attenuation data are given.

4.1 Ground Propagation Experimental Terminals Established by JSI in Slovenia and Austria

The first measuring setup at the Jozef Stefan Institute (JSI), Ljubljana, began with a beacon receiver, based on Software Defined Radio (SDR) that received 19.701 GHz signal from Eutelsat Hot Bird 13A satellite, located in the geostationary orbit at 13°E. The signal data were received and recorded on the local computer from June 2012 to July 2013. In the summer of 2013, Eutelsat redeployed Hot Bird 13A satellite to a new location. Therefore, the receiver was repointed to the Astra 3B satellite, which is located at 23.5°E and transmits beacon signal at 20.199 GHz. The second SDR receiver station was successfully installed 40.7 km south-east from Ljubljana, in Lisec, Slovenia, in August 2013, which is also pointed towards the Astra 3B satellite. In February 2014 the third receiver station was installed at the Hilmwarte tower in Graz, Austria. The station measured the beacon signal at 19.7 GHz from Alphasat satellite up to December 2015 when the station was switched to Astra 3B satellite. The measurement network was additionally extended in February 2015 with the fourth Astra 3B beacon receiver installed in Krvavec, Slovenia.

All four Earth stations were installed in the scope of the ESA project Satellite Propagation in Slovenia (SatProSi). The aim of the propagation experiments was to contribute to the European set of signal strength measurements data and to analyse the performance of site diversity as FMT including different combinations of sites. In these experiments, the receivers are continuously measuring and recording the signal strength from Astra 3B satellite.

In the scope of the SatProSi-Alphasat project a four-channel Alphasat beacon receiver with tracking system, measuring co-polar and cross-polar signals at Ka-band (19.7 GHz) and at Q-band (39.4 GHz) was developed and installed at JSI Ljubljana in the summer of 2015. It is located on top of a building which is 70 m away from the existing Astra 3B receiver. With the station, Slovenia started to participate in the European propagation campaign of the Alphasat Aldo Paraboni scientific experiment.

4.1.1 Ka- and Q-band beacon receivers

Four beacon satellite receivers receiving Astra 3B signal at Ka-band are identical, while the four-channel receiver, measuring the beacon signals from Alphasat satellite, is equipped with a custom built low noise block (LNB) and tracking system. In Figure 4.1 the current overall status of JSI beacon receiver network, measuring signals at four

geographical sites is depicted. The Alphasat satellite was launched as a result of a private-public partnership and is a part of the Inmarsat constellation. The scientific Technology Development Payloads are operated by ESA. It is located at 25°E in an inclined geosynchronous orbit. The inclination is increasing with time but does not exceed $\pm 3^\circ$. The beacons are transmitted towards our area with EIRP of 19.5 dBW at Ka-band and 26.5 dBW at Q-band. The average elevation is 36.0° and azimuth is 165.5° .

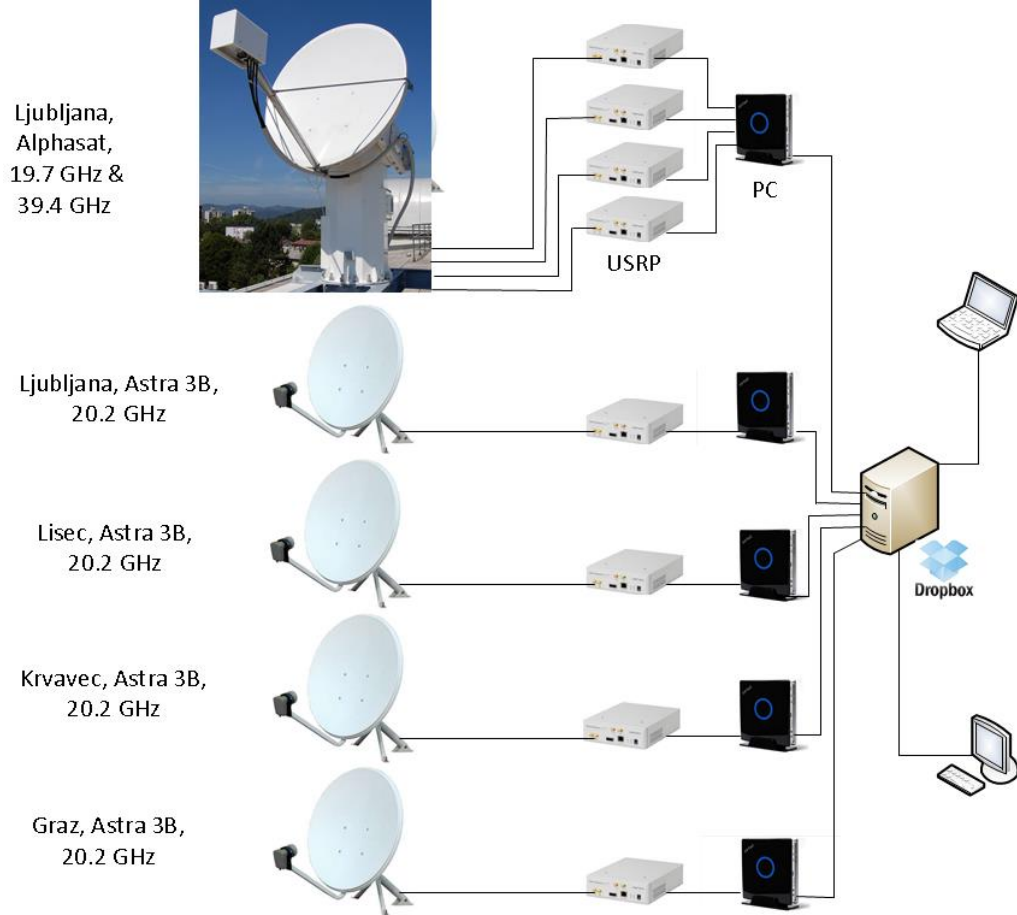


Figure 4.1: Current beacon receiver network.

The Astra 3B satellite is stable in orbit and the receivers can operate without a tracking system. The implemented receiver system is composed of single and four-channel receivers, which consist of RF front-ends and digital detectors, whereas the tracking subsystem is implemented only for four-channel receiver.

All five RF front-ends use an identical 1.2 m offset dish antenna. The nominal antenna gains are 45.8 dBi and 50.8 dBi, with Half Power Beam Width (HPBW) of 0.84° and 0.44° , at Ka-band and Q-band, respectively.

The Alphasat receiver consists of a custom designed 4 port feed and 4 low-noise-converter channels at two bands (19.7 GHz and 39.4 GHz) and two polarizations (co-polar and cross-polar). The dual band dual polarity feed is custom designed, targeting this specific application. The received signal is divided into four-channels by employment of Orthogonal Mode Transducer (OMT) and Orthogonal Iris Coupler (OIC). For best receiver performance, the first and the second down conversion are placed directly after the feed. At the output, the converters provide a standard IF2 in the VHF range (140

MHz). The output signals from the second down conversion are led through coaxial cables to an indoor unit.

The Astra 3B receivers use the Norsat LNB with a local oscillator at 18.25 GHz, which down-converts the received signal to around 1.95 GHz. The signal is then led to an indoor unit where the second down conversion takes place to the IF2 at VHF.

Since the Alphasat orbit is being increasingly inclined over time (up to ± 3 deg.) and the antenna beam is very narrow, especially at Q-band, a precise antenna pointing has been performed. For the precise antenna pointing, the tracking solution uses TLE (Two Line Element) data, which contain the updated information about the satellite orbit. In particular, the system is based on a classical Azimuth/Elevation (AZ/EL) mechanical system with brushless motors and integrated brakes. In addition, adaptive corrections based on received signal strength for fine tuning are performed twice per day. The pointing accuracy of the system is 0.005° . The tracking system is connected into the department local network.

At the indoor unit, the sampling, power estimation and data storage take place. The digital detectors are implemented on PCs in GNU radio application. They employ Universal Software Radio Peripheral (USRP) N200 platforms with BasicRX daughterboards. Altogether eight USRPs are used; four for the Alphasat receiver and one for each Astra 3B receiver.

The signal processing is identical at all 8 receivers. It begins by filtering the data samples with a band-pass filter. Afterwards, the samples are packaged to a vector of 65536 elements and multiplied with a Flat-Top window function. The vectors are converted to a frequency domain, where the signal power is estimated. At each sampling point of time, the value is written in a daily file together with time stamp. Given the sampling rate 400 kSps and FFT size of 16 bit, 6.1 estimated power samples are obtained per second. Finally, the signal power values are stored in the cloud data storage. The digital signal processing architecture is shown in Figure 4.2. Detailed information about the receiver and the SDR application can be found in in [98, 99, 100].



Figure 4.2: Signal processing chain in GNU Radio.

4.1.2 Rain gauge

Most of the existing prediction models of rain attenuation require a long-term statistics of the rain rate at the site of the Earth station.

Rainfall measurements are obtained by a tipping bucket rain gauge Young 52202, equipped with heating and located close to the Astra 3B beacon receiver in Ljubljana. In Lisec, Krvavec and Graz, the rain gauges have not been installed yet. An interface with a microcontroller and an acquisition debounce circuit has been designed to acquire process and store the data. The measured samples are sent to the PC via the RS232 interface. The rain gauge has a catchment area of 200 cm^2 and a measurement resolution of 0.1 mm. The whole assembly installed on the roof at JSI is depicted in Figure 4.3.



Figure 4.3: Tipping bucket rain gauge.

4.1.3 Relative signal power and rain fall rate measurements

In Figure 4.4 the measurements example of relative signal power from Alphasat, for co-polar and cross-polar channels obtained on 16 September 2016, are shown. Relative received power expresses the received signal power level in dB, which varies with time, depending on the intensity of the atmospheric impact. In absolute terms, the value does not have a specific meaning, it only serves as a measure of comparison with some reference level, chosen at the start of observation. In Figure 4.4, the chosen starting reference value is 0 dB for co-polar components. If there are more signals in the graph, the relations among them are also correctly expressed. The parallel rain intensity measurements are obtained by the co-located rain gauge. From the Figure 4.4, a correlation between the rain intensity and signal power is evident.

A light rain started around 8:00 h and continued to 10:00 h. It was preceded by low attenuation caused presumably by rain in the path. From 14:00 h to 19:00 h, a stronger rain event appeared with peak measured rain rate of 28 mm/h around 15:00 h. The respective co-polar attenuations at Ka-band and Q-band amounted to around 12 dB and 38 dB, respectively.

The cross-polar components show stronger fluctuations caused by scintillation, especially at Q-band. The cross-polar discrimination, achieved in practice, is around 12 dB at Ka-band and 27 dB at Q-band.

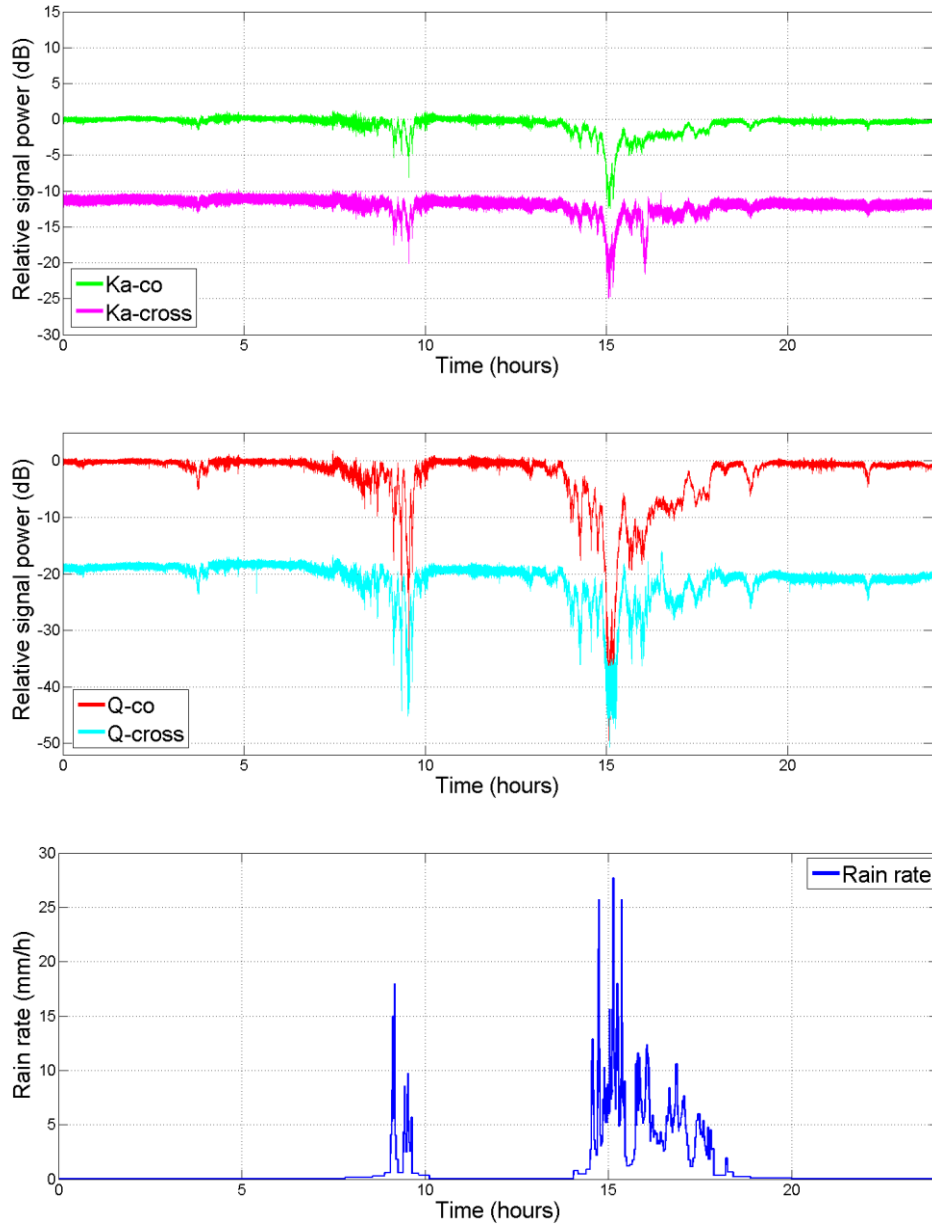


Figure 4.4: Example measurements on a rainy day.

4.2 Site Diversity Experiments at Ka-band

Among four Ka-band stations located in Ljubljana, Lisec, Krvavec and Graz, different possible site diversity experiments were performed. Experimental data for six double-site diversity experiments, four three-site diversity experiments and one four-site diversity experiment, each experiment with at least one year measurement data, were statistically analysed and presented in section 4.5. The main objective of the experiments is to contribute the Ka-band measurements to the global databank which will increase the accuracy of site-diversity models and, in the long-term, to extend the models with different configurations (distances, baseline angles, satellite-diversity, etc.). In addition, the experiments are extensively evaluated by the prediction models in chapter 5.

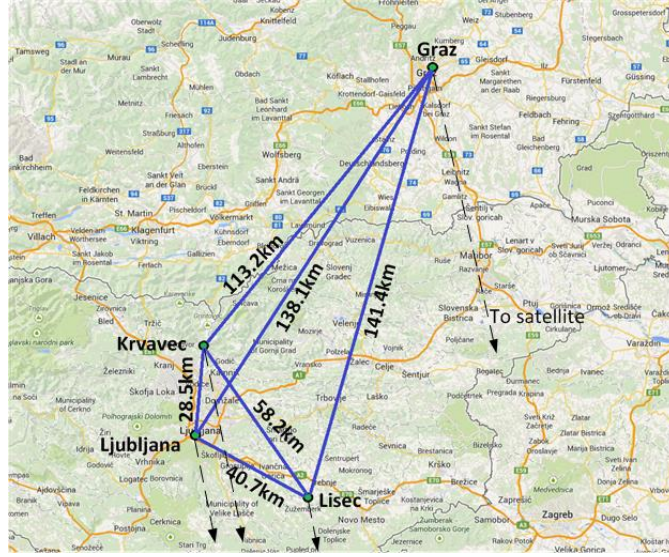


Figure 4.5: Overview of the site diversity system geometry.

The time synchronization between four one-channel Ka-band beacon receivers is performed by GPS receivers. All four stations are receiving vertically polarized 20.199 GHz beacon signal from the Astra 3B satellite. The locations of the stations are shown in Figure 4.5 while the location coordinates, link parameters, inter-site distances and baseline angles are given in Table 4.1 and Table 4.2, respectively. Baseline angle in two-site diversity systems is defined as the angle between the ground projection of the satellite path at the one station and the horizontal line connecting the first and second station. From Table 4.1 it is evident that due to much larger distance between satellite and Earth stations compared to distance among the Earth stations the elevation angles are similar with maximal difference of around 1° . For the same reason, baseline angles are considered equal for both stations in any of the station pairs. However for general site diversity configurations, this approximation is restrictive for the experiments near equatorial zone and for which the satellite longitude is close to the longitude of one Earth station. In these cases the difference in baseline angles at each Earth station of the pair are more prominent.

Table 4.1: Stations locations and link details.

	Ljubljana	Lisec	Krvavec	Graz
Latitude ($^\circ\text{N}$)	46.011	45.865	46.297	47.041
Longitude ($^\circ\text{E}$)	14.487	14.948	14.522	15.465
Azimuth ($^\circ$)	167.6	168.2	168.4	169.1
Elevation ($^\circ$)	36.3	36.5	36.0	35.4

Table 4.2: Distances and baseline angles.

Station 1	Ljubljana	Krvavec	Krvavec	Ljubljana	Lisec	Krvavec
Station 2	Lisec	Ljubljana	Lisec	Graz	Graz	Graz
Distance (km)	40.7	28.5	58.2	138.1	141.4	113.2
Baseline angle ($^\circ$)	50	17	23	47	29	53

4.3 Data Post-Processing Methodology

The relative received signal powers in dB are recorded with the sampling rate of 6.10 Hz. The sampled signals are saved locally in daily files and automatically transferred to a common server. While for each Ka-band receiver one file per day is created and four files, one for each channel, are generated for the four-channel receiver. In order to obtain rain attenuation time series in each slant path, the beacon satellite signals have to be post processed. Moreover, for site diversity analysis the joint attenuation time series are needed.

4.3.1 Single site attenuation time series

At each receiver, time series of attenuation are obtained from the received signal power by three signal post processing steps [98]:

- spike detection,
- visual inspection and update of the validity flags of the beacon data and
- template extraction, where attenuation time series are obtained.

In the beacon signal measurements, samples with the obvious deviation from local average, so-called outliers or spikes may occur. Their detection is performed automatically and they are flagged as doubtful. The method for spike detection is based on moving average based standard deviation, which is calculated continuously by:

$$\varepsilon(t) = \sqrt{\langle CPL(t)^2 \rangle - \langle CPL(t) \rangle^2} \quad (4.1)$$

where the $CPL(t)$ is the beacon level sample within the day in dB and $\langle CPL(t) \rangle$ is the mean value of $CPL(t)$ using 2 minutes moving average filter in dB. The standard deviation serves as a threshold for comparison with actual samples. When the difference between the signal strength and its moving average $|CPL(t) - \langle CPL(t) \rangle|$ is larger than the threshold defined as standard deviation multiplied by a selected factor K_{th} , the sample is recognized as an outlier. Thus, the outliers are samples defined by:

$$|CPL(t) - \langle CPL(t) \rangle| > K_{th} \sqrt{\langle CPL(t)^2 \rangle - \langle CPL(t) \rangle^2} \quad (4.2)$$

The factor K_{th} is usually experimentally assessed and depends from the propagation experiment. An example of detecting spikes using factor $K_{th} = 10$ is depicted in Figure 4.6. In the recorded relative signal power on 16 October 2016 in Lisec two spikes are detected.

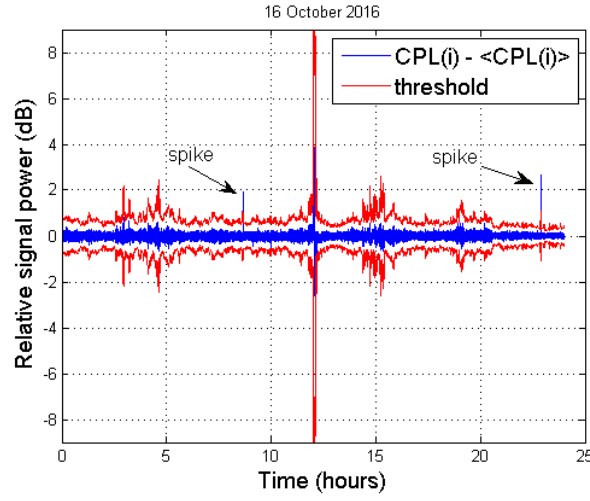


Figure 4.6: Spike detection.

Moreover, in Figure 4.7 the relative signal level with two spikes marked with green colour, which will not be taken into account in the next processing steps, is depicted.

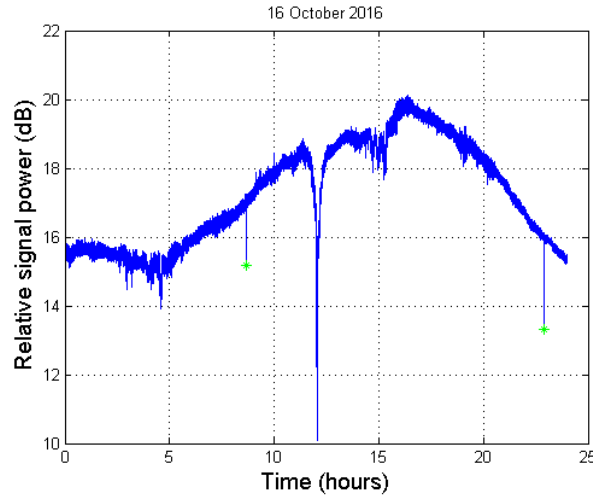


Figure 4.7: Daily relative signal power with two spikes detected.

In order to assure correctness of automatically determined validity flags, the measured values of beacon signal level are inspected visually on a daily basis. In a case of any incorrect spike detection the flags can be changed. Visual inspection is also important in the case of irregular signal behaviour (signal exceeds dynamic range of the receiver, fluctuation, missing samples, etc.) where in the selected time frame the validity flags are changed from valid to invalid and samples are excluded from further analysis. Figure 4.7 shows an example of regular behaviour of measured signal with rain events around 12:00 h while the signal shown in Figure 4.8 is highly attenuated and reached noise floor. In order to exclude false samples from the statistical analysis process these samples are marked.

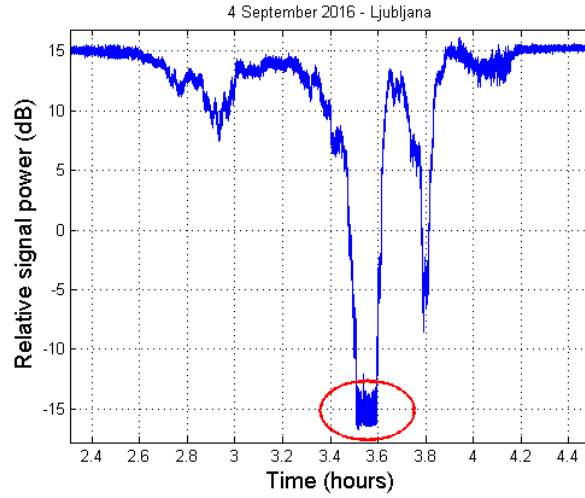


Figure 4.8: Deep fade saturation.

Once the signal data are flagged by automatic spike detection as well as by visual inspection, the next step in the attenuation analysis is the extraction of the daily template and obtaining the attenuation time series. In this step all potential systematic errors, which deteriorate accurate evaluation of atmospheric impairments, are eliminated. The main source of such errors is antenna mispointing due to satellite orbital instabilities, which induce daily signal variation of a few dB as depicted in Figure 4.7, where during the clear sky conditions the signal fluctuates for 0-4 dB. Other possible sources are thermal variations in RF chains and other phenomena such as the wet antenna effect.

Since the radiometer measurements for determining the clear sky reference attenuation are not available, the calculation of total attenuation due to rain, clouds, water vapour and oxygen is not possible. Therefore, only in-excess attenuation, i.e., attenuation due to rain and heavy clouds especially during the rain, can be computed from the received signal. The procedure finds a function which corresponds to system-dependent received signal variations and subtracts it from the beacon signal level. While it is impossible to guarantee the exactness of such a procedure, it is estimated that the systematic error is limited within a margin of maximum 1 dB. Experimental evaluation of the described effects has been performed in [101]. The resulting signal corresponds to the in-excess attenuation due to atmospheric impairments.

To define the template function a moving average of the received beacon signal in clear sky conditions and a proper interpolation for the time intervals with rain events have to be found. The procedure is divided into three steps: (i) determination of events, (ii) finding template function and (iii) subtraction.

In the first step, the events with strong fluctuations are identified and flagged. The second step depends on the form of the beacon signal (i.e. clear sky with no oscillations, rain event presence and oscillating signal) which dictates the selection of the adequate method and template. In the presented analyses the polynomial fitting method is usually used. In the last step, the obtained template function is subtracted from original beacon signal.

In Figure 4.7 the mispointing error due to the inclined orbit variation of the satellite as a periodic signal fluctuation can be observed. Therefore, after the flag samples are removed from the signal, the template extraction starts with the identifying the rain

events which will not be considered in the polynomial fitting. In the Figure 4.9 they are depicted by the red colour.

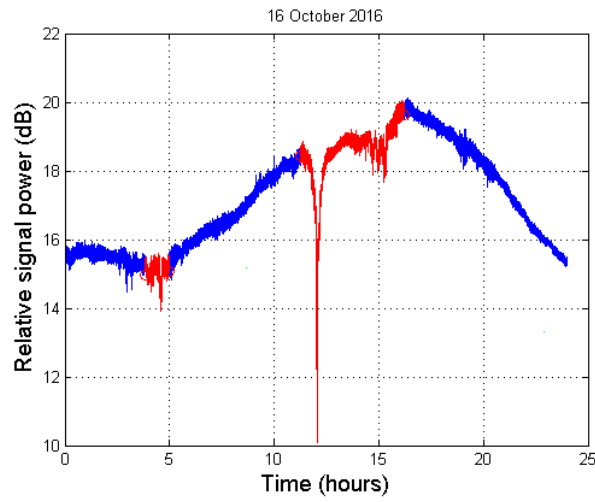


Figure 4.9: Determination of rain event.

In the second step, a polynomial function of 6th order is determined according to the remaining beacon signal intervals (green line in Figure 4.10).

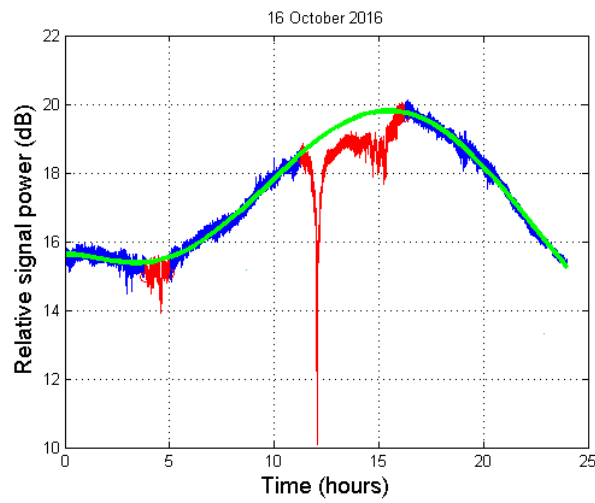


Figure 4.10: Determination of template polynomial function.

Next, the subtraction of the polynomial function from the relative signal function is performed and the relative power of the signal without fluctuation is obtained as shown in Figure 4.11.

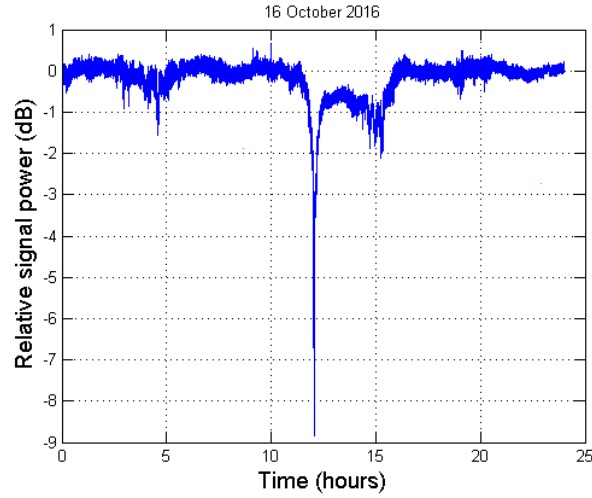


Figure 4.11: Relative signal power after template subtraction.

In the presented example, the mispointing error due to the inclined orbit of the satellite observed as a periodic signal fluctuation is removed. With the polynomial fitting a systematic error of about 4 dB is eliminated. The procedure eliminates the error and without influencing the clear-sky levels and the rain-induced attenuation. Finally the in-excess attenuation is obtained as shown in Figure 4.12. Since the orbit variation of the satellite may differ from day to day, the polynomial functions of different order should be used for each case.

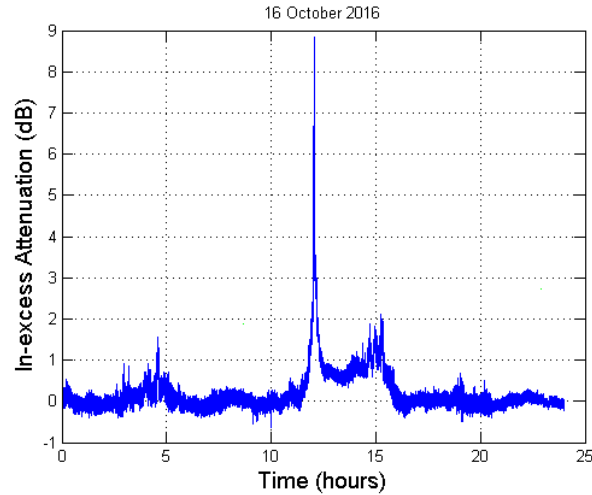


Figure 4.12: Attenuation time series.

The procedure is performed on a daily basis for each station and the attenuation time series are saved in daily files. Due to higher Astra 3B signal variations, a polynomial function of high degree is used. Since the Alphasat receiver is equipped with a tracking system, diurnal signal variations are mostly negligible and hence a constant function or a polynomial function with a low degree is sufficient [102].

4.3.2 Joint rain attenuation time series

The joint rain attenuation time series are obtained from single site rain attenuation time series. After the standard procedure of in-excess attenuation determination for all stations the procedure compares simultaneous samples of the arbitrary number of input attenuations of n stations in the site diversity systems and returns the minimal values of attenuation as:

$$A_{joint}(t) = \min(A_1(t), A_2(t), \dots, A_n(t)) \quad (4.3)$$

The obtained joint attenuation time series for each site diversity configuration is saved in a daily files. In order to calculate time series of joint attenuation the stations must be synchronized. If they are not synchronized, the joint attenuation time series will represent joint attenuation as a minimum value between the attenuations in the stations not just due to site diversity but also due to time diversity.

A typical example of parallel rain attenuation time series obtained on a rainy day (15 May 2015) is shown in Figure 4.13. The graph shows also the joint attenuation time series, representing the minimum attenuation values in three-site diversity mode of the three stations located in Krvavec, Ljubljana and Lisec. During the day the maximum attenuation at Krvavec station reached around 18 dB, while the attenuation in Ljubljana and Lisec did not exceed 9 dB. The maximum joint attenuation for three-site diversity system of 2.5 dB confirms the advantages of three-site diversity systems which benefits from geographical rainfall decorrelation.

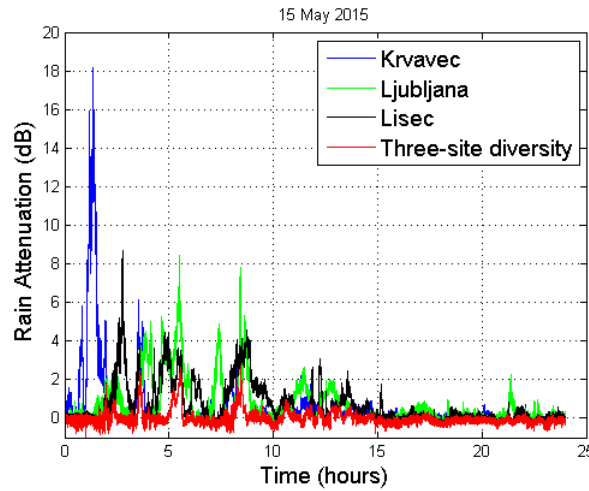


Figure 4.13: Single and joint rain attenuations time series.

Although the principle is straightforward, a few practical issues have to be addressed. The first practical issue is related to the time stamps. Although the four stations are synchronized with the GPS receivers and the values of time stamps are accurate, the samples at four stations may not be recorded at exact real time by the individual computer. In practice, they are shifted by a few milliseconds, as depicted in Figure 4.14 which shows the samples within 2 seconds during a day at Ljubljana, Lisec, Krvavec and joint attenuation samples between three sites. Thus, an algorithm was developed which takes one of the stations for the time reference (Ljubljana in this example) and then performs a comparison of imminent samples in order to calculate the joint attenuation.

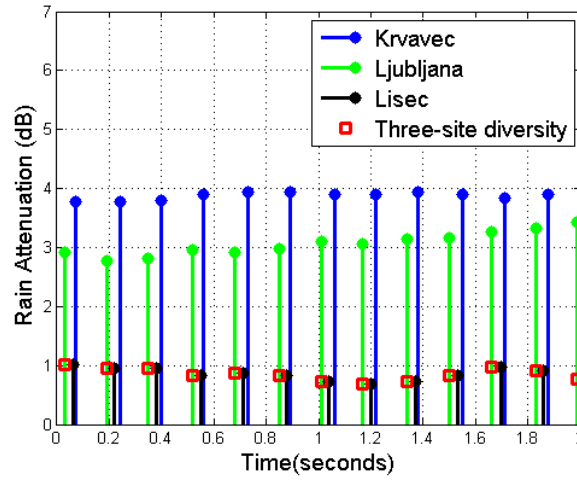


Figure 4.14: Shifted time stamps between samples.

The second issue is related to the missing samples at one of the stations due to possible system malfunction or to the irregular samples which result in undetermined joint attenuation output samples. The joint attenuation time series are calculated for concurrent data. In Figure 4.15 an example of time series for all four stations during 14 October 2016, where Ljubljana and Graz were out of operation for several hours, is shown. At Krvavec and Lisec the samples were recorded for the whole day. In Ljubljana station the data are missing from around 5:42 h in morning till the end of the day, whereas in Graz data are missed from around 13:18 h till the end of the day. Since the concurrent data for two-site diversity configurations between Krvavec and Lisec are on disposal for a whole day, the joint attenuations time series can be determined. Within the time interval between 0 h and 13:18 h the concurrent data are available for Krvavec, Graz and Lisec. Within this interval, the joint attenuation for three-site diversity and for three two-site diversity cases can be determined. Only in the time interval between 0 h to 5:42 h does the concurrent time series from all four stations exist, which enables calculation of four-site diversity joint attenuation and all possible three- and two-site diversity joint attenuations. Thus, for different site diversity configurations we have different availability of joint attenuation time series.

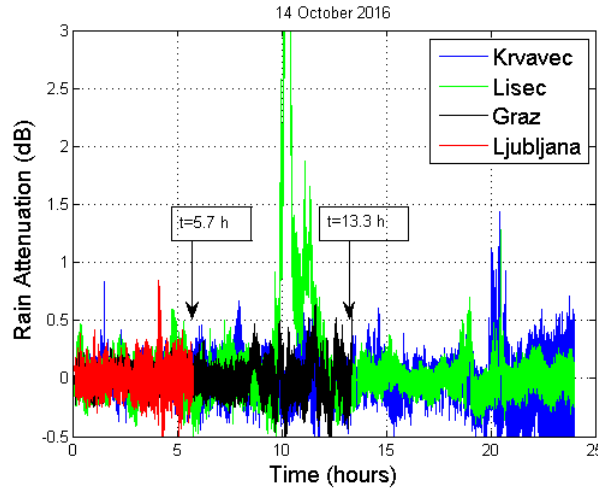


Figure 4.15: Time intervals with missing data in two stations.

4.3.3 Rain gauge data processing

The rain gauge measurements are recorded sequentially as a number of tips, counted on a predefined time period. Data obtained with two sampling rates, 1 minute and 1 second, are stored in two separate sets of files. The longer sampling rate is a standard rate, as defined by Recommendation ITU-R P.837, used to calculate standardized statistics based on 1-min integration time. The shorter rate enables more detailed analyses of the rainfall dynamics.

The procedure starts by converting the number of tips to rain rate expressed in mm/h. Next, it distributes the expressed amount among the former time samples with no tips, which is necessary when the rain intensity is small. If this step is disregarded, low intensity rain measurements are incorrectly presented as sharp and rare bursts of rain. In order to identify possible flaws in the observed signals and to flag them properly, the rain rate files are inspected visually on a daily basis. For the final statistical analysis only valid samples are taken into account [103].

4.3.4 Statistical analysis methodology

The next task of the processing includes the statistical analyses phase in order to calculate first order statistics from the obtained attenuation and joint attenuation time series. Co-polar attenuation analyses consist of long term attenuation and joint attenuation data reading and calculating their CCDF.

To design the efficient FMT systems, in addition to first order statistics the fade dynamics such as fade duration and fade slope of the attenuation and joint attenuation time series are needed.

For the fade duration analysis long term attenuation data are required and relative number of event CCDF and relative fade time CCDF are calculated. Fade slope statistics are calculated by determination of signal dynamics (derivative) and their expression in terms of cumulative distributions [103].

First order statistics of attenuation and fade dynamics for Ka/Q-band Alphasat receiver are analysed and depicted in the section 4.4. In the scope of the thesis, a deep analysis of the first order statistics of attenuations and joint attenuations for every site

diversity experiment configuration are computed and results in terms of CCDFs of joint rain attenuation are depicted in the section 4.5.

Statistical attenuation analyses include long term attenuation time series and joint attenuation time series for one or multiple years of data and computing their CCDF. The minimum of one year of data included in statistical analysis ensures that the data for each season of the year are included. Since the attenuation from year to year may be different, the analysis of multiple years of data provides more accurate statistical representation of the CCDFs. The statistical analyses are performed only by taking into account concurrent data between single and joint attenuation time series for every site diversity configuration and for comparison of different site diversity performances.

The availability of concurrent data in different configurations can be different. In order to compare the performance within the same availability the CCDFs curves of the concurrent data with identical availability are always depicted in the same figure. The curves in different figures corresponding to the same configuration may be slightly different due to different availability of data. The used approach maximizes the use of available data in each different experiment and considers that the comparison is correct only when the concurrent data availability is the same.

4.4 Data Analysis of Four-Channel Receiver

Statistical results of one year of measured attenuation data and rain fall rate data from the rain gauge collected in the time-period between November 2015 and October 2016 are presented in this section. The data availability in this period is 95.55% for the beacon receiver and 94.86% for the rain gauge. System errors may cause loss of data for a few hours or days which significantly affect the total availability. Statistical analysis of the beacon measurements is done to create CCDFs of attenuation, fade dynamics and rain rate. Some plots of cross-polar discrimination analysis are presented.

4.4.1 First order statistics

The seasonally and yearly CCDFs of attenuation measured with the Alphasat station for Ka- and Q-band are depicted in Figure 4.16 and Figure 4.17, respectively. Ljubljana has temperate climate and four distinct seasons. Winters and springs are usually drier than summers and autumns. Thunderstorms appear from May to September and can be quite heavy. Therefore, higher attenuation values are observed in summer and autumn months. The fades are deeper and more frequent at Q-band. Overall, 18.3 dB and 37.1 dB of attenuation were exceeded for 0.01% of the time at Ka-band and at Q-band, respectively.

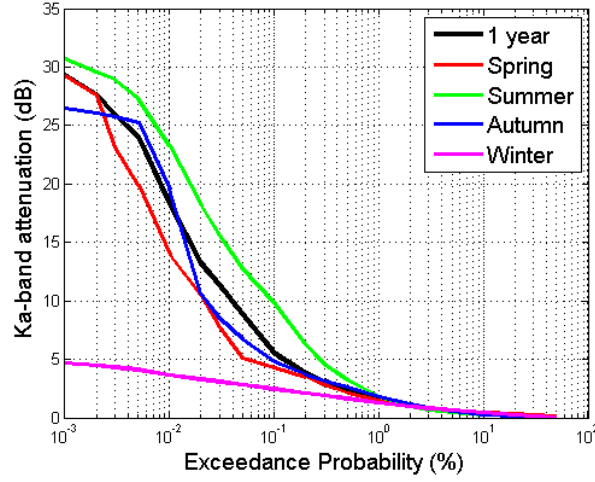


Figure 4.16: Seasonal and yearly CCDFs of attenuation at Ka-band in Ljubljana.

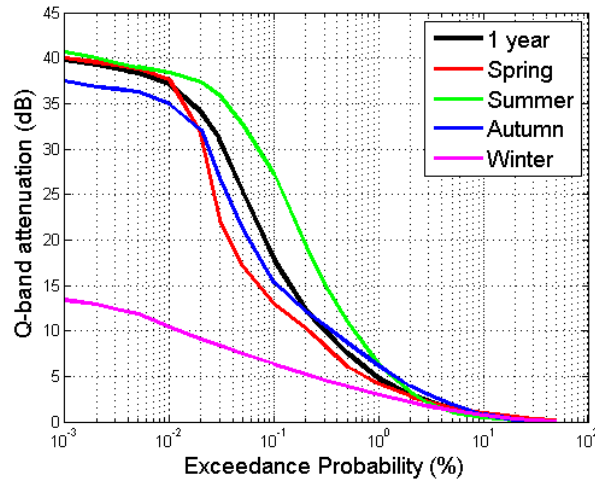


Figure 4.17: Seasonal and yearly CCDFs of attenuation at Q-band in Ljubljana.

The yearly CCDFs of attenuation are further compared to the ITU-R P.618-12 model. Figure 4.18 shows that the distributions match quite well the ITU-R model, especially at Ka-band. Lower measured distribution at Q-band can be partially ascribed to the exceeded receiver margin for about 0.03% of the time. The graph shows also the Q-band CCDF obtained by Ka-band frequency scaling, according to ITU-R P.618-12. Almost a perfect match to the Q-band curve obtained from measurements is achieved, except for the saturated part below the 0.02% exceedance probability.

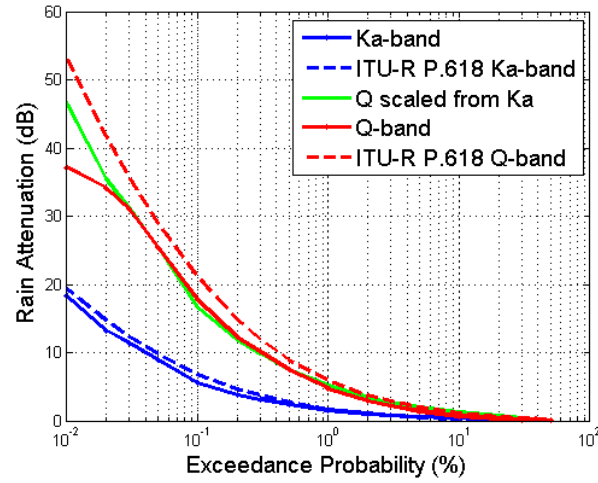


Figure 4.18: CCDFs of attenuation compared to the ITU-R P.618 model.

The Figure 4.19 shows the rain rate distributions. Similar to the signal attenuation, the whole measurement period is compared to the monthly statistics and to the ITU-R P.837 model. Seasonal variations are in line with the expectations, while the modelled values are slightly overestimated.

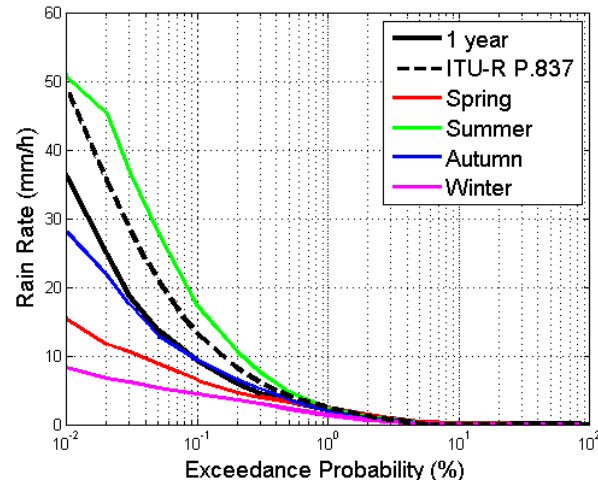


Figure 4.19: CCDFs of rain rate compared to the ITU-R P.837 model.

4.4.2 Second order statistics

Fade duration and fade slope values within the analysed year are calculated and their distributions in terms of CCDF functions are expressed. Before the calculation, the scintillations and rapid variations of rain attenuation were removed from the signal by low-pass filter with the cut-off frequency of 25 mHz. The time interval length for the fade slope was calculated and set to an interval of 2 s.

Figure 4.20 and Figure 4.21 show the CCDFs of relative number of fades and relative fade times exceeding at given attenuation thresholds. According to the Figure 4.20, the relative number of fades does not vary significantly with either the chosen thresholds or

the frequency, whereas for relative fade times, higher differences are observed. As expected, higher fade times are encountered for lower thresholds and for higher carrier frequency.

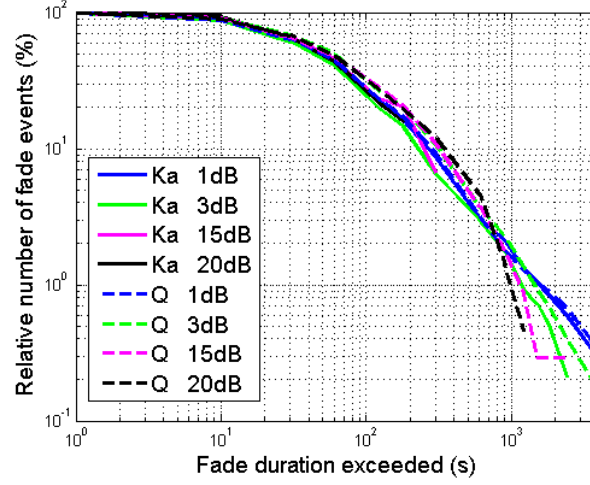


Figure 4.20: Fade duration at Ka- and Q-band.

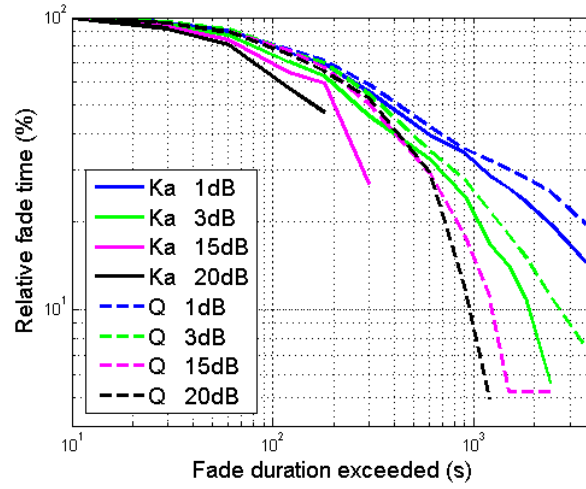


Figure 4.21: Fade duration as relative fade time at Ka- and Q-band.

Figure 4.22 and Figure 4.23 depict the CCDFs of absolute fade slope, presented in linear and in logarithmic scale. The fade slope values increase with the increasing attenuation level. The differences between the bands are not significant.

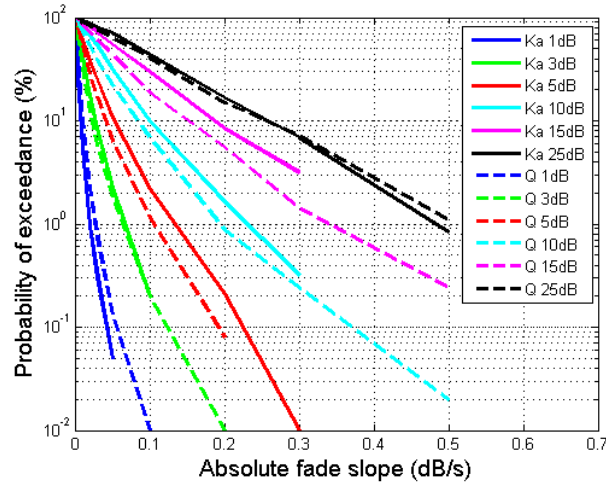


Figure 4.22: Fade slope in linear scale at Ka- and Q-band.

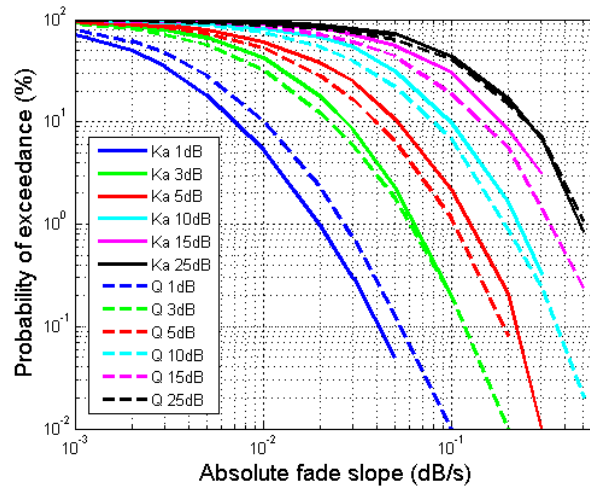


Figure 4.23: Fade slope in logarithmic scale at Ka- and Q-band.

4.4.3 Cross-polar discrimination examples

The XPD results are presented only in terms of raw XPD measurements. Four interesting days with heavy rain are selected, where the attenuation at Q-band exceeds 20 dB. The graphs in Figure 4.24 show the XPD scatter plots as a function of co-polar attenuation for both bands. The behaviour of decreasing XPD with increasing attenuation is expected and well expressed, although it is observed more clearly at Q-band.

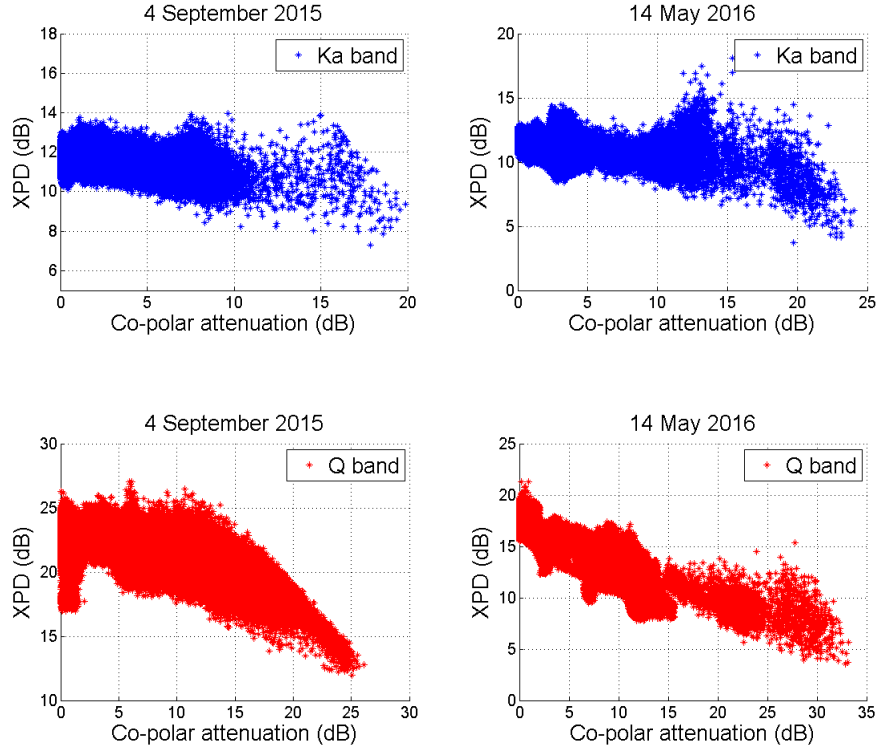


Figure 4.24: XPD examples during two rainy days.

4.5 Statistical Analysis of Site Diversity Performance

In this section the CCDFs of single site attenuation and joint attenuation for different site diversity modes are presented. Moreover, the equiprobable diversity gain is calculated as the difference (in dB) between the attenuation of single site and joint attenuation in diversity system at the fixed probability [63].

The site diversity analyses include data from time synchronized stations in different configurations starting from the middle of March 2014 up to the middle of March 2017. After a few months of operation without synchronization, in the middle of March 2014, the two first stations in Ljubljana and Liseč were time synchronized, while Graz and Krvavec have been synchronized from the beginning of their operation. The site diversity configurations with Graz for which the data from March 2015 to December 2015 are not available are excluded from the analyses. The available data include the attenuation time series from each station receiving Astra 3B signal, except from the middle of March 2014 to the middle of March 2015 when the station in Graz measured signal from Alphasat satellite. Depending on available data for different configurations, we have statistically analysed the attenuation time series considering one-, two- or three-year concurrent data, respectively. Only the site diversity systems comprising the Graz station with one year received data from Alphasat are analysed separately. Four-site diversity statistical analyses include the data collected from January 2016 up to December 2016 from all four stations receiving Astra 3B beacon signal.

4.5.1 Two-site diversity experiments

In this subsection, the statistical analyses of all possible two-site diversity systems are considered. For a two-site diversity system between stations located in Ljubljana and

Lisec, the statistics have been calculated over three years, from 15 March 2014 to 15 March 2017. Single site CCDFs of attenuations for both stations and CCDF of joint attenuations for three years' are depicted in Figure 4.25. The availability of the concurrent three years data is 90%. In addition, in Figure 4.25 the CCDFs of joint attenuation for three different years are depicted separately. It can be observed that the concurrent single site CCDF of rain attenuation between the two stations have similar shapes, which is due to similar climate at both locations of the stations. As expected, the two-site diversity joint CCDFs already provide a significant improvement (lower attenuation values) compared to the corresponding single site CCDFs. The stations are separated by 40.7 km which introduces a good decorrelation of the rain fall. For example, instead of about 34 dB of attenuation exceeded for 0.001% of the time, which is around 5 minutes per year, only 9 dB is exceeded in diversity mode. The joint CCDFs for each year show a low year-to-year variability which can result from the spatial and temporal variations of the rain precipitations and different availability of data from year-to-year. Although the concurrent time series data between single sites and joint time series are equal for all three years of analysed data, the yearly availability can be different.

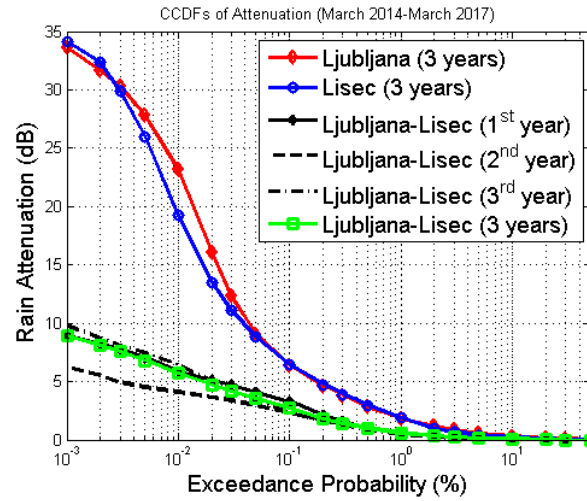


Figure 4.25: Single site and diversity attenuation for Ljubljana and Lisec.

In Figure 4.26 the equiprobable diversity gains achieved on each single site when the system is operating in the diversity configuration are depicted. Diversity gains are obtained from Figure 4.25 by subtracting the red curve (for Ljubljana) and blue curve (for Lisec) from the green curve at the same probability and in Figure 4.26 expressed as a function of single site attenuation. Very large values of diversity gain comparing to the single site attenuations are evident.

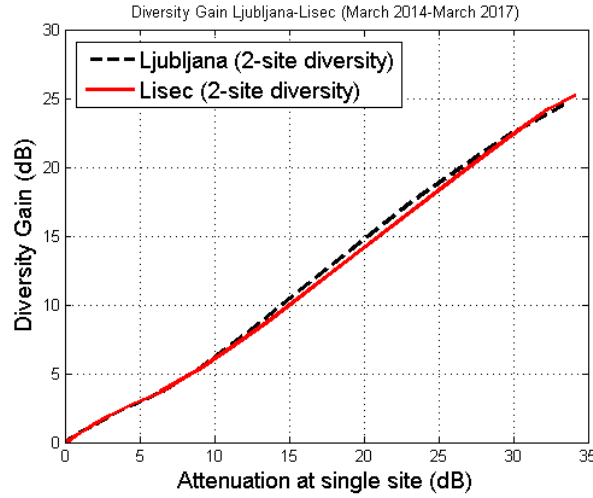


Figure 4.26: Diversity gains for Ljubljana and Lisec.

The statistical results in terms of CCDFs for another site diversity pair separated for 28.5 km in Ljubljana and Krvavec for two years' period data, from March 2015 to March 2017, with the 92% of the concurrent data availability are presented in Figure 4.27 depicting the single and joint CCDFs. The single site CCDFs show lower attenuation values at Krvavec. The CCDF of joint rain attenuation clearly shows the benefit of the two-site diversity. The CCDF of joint attenuation for each year are separately depicted and the variability from year-to-year can be highlighted especially for percentages lower than 0.01%. In Figure 4.28 the equiprobable diversity gains as a function of single site gains achieved by each station operating in the site diversity mode are shown.

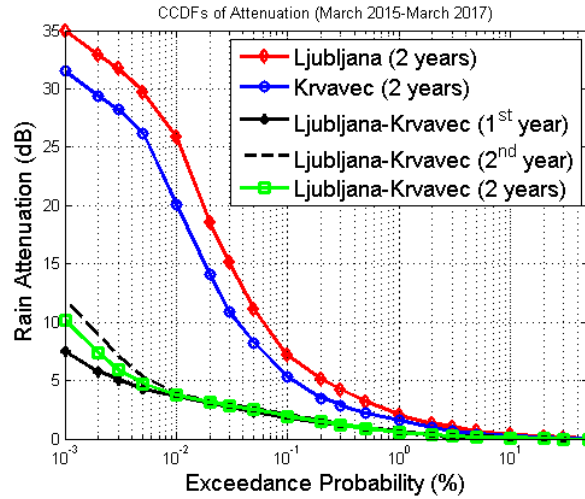


Figure 4.27: Single site and diversity attenuation for Ljubljana and Krvavec.

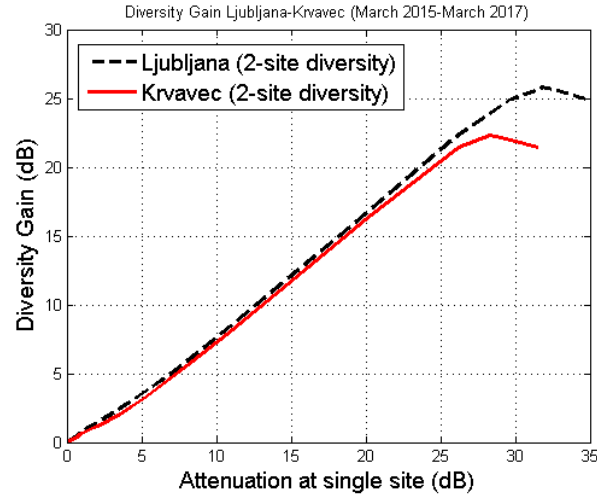


Figure 4.28: Diversity gains for Ljubljana and Krvavec.

The statistical analysis for two-site diversity configuration between the stations located in Liseč and Krvavec are also calculated. The availability of the concurrent two years data is 88%. In Figure 4.29 and Figure 4.30 the CCDFs and diversity gains are depicted, respectively. From the single site CCDF of both stations, it is evident that for the same percentages the attenuation values at Krvavec station are lower. Contrary to the results presented in Figure 4.25 and Figure 4.27, the CCDF of joint attenuation from both years are similar to the total CCDF of the individual years.

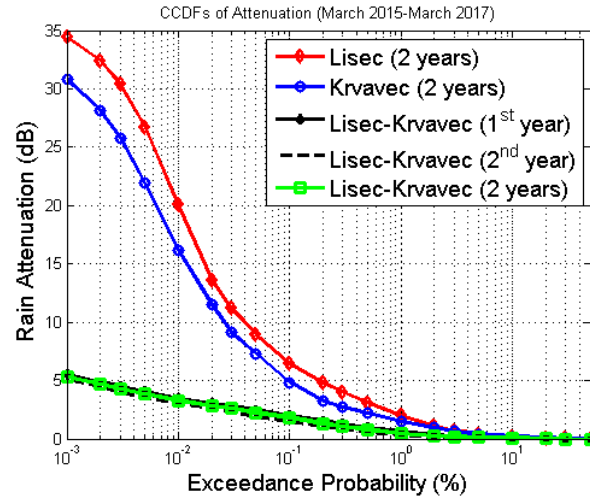


Figure 4.29: Single site and diversity attenuation for Liseč and Krvavec.

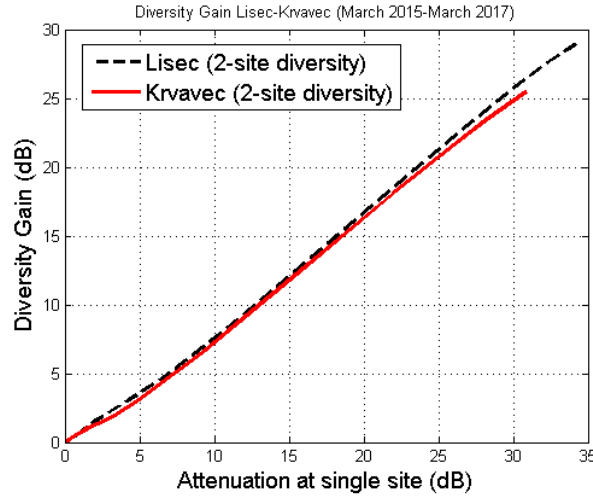


Figure 4.30: Diversity gains for Lisec and Krvavec.

The site diversity configurations with the Graz station are also considered. At the beginning of the operation, from March 2014 to March 2015, the beacon signal from Alphasat was measured at Graz. The only existing operational stations during that period were Lisec and Ljubljana, which measured the signal from Astra 3B satellite. For this period, the statistical analysis of rain attenuation for two-site diversity configurations between Graz and two Slovenian stations are analysed separately. One of the specifics of this analysis is that the beacon signals from different satellites are received, which are positioned close to each other and transmitted in the same band. Nevertheless, the results must be interpreted with these specifics in mind. In December 2015, the station in Graz was repointed to the Astra 3B satellite. Therefore, one year of measurement data from Astra 3B were collected and statistically analysed separately from data measured the previous year. In Figure 4.31 and Figure 4.32 the CCDFs and diversity gains for two different years separately for Ljubljana-Graz diversity configuration are depicted, respectively. Similarly, the CCDFs and diversity gains for diversity system Lisec-Graz are depicted in Figure 4.33 and Figure 4.34, respectively. The first year includes the data from March 2014 to March 2015, when Graz station received a beacon signal from Alphasat while Ljubljana and Lisec received a beacon signal from Astra 3B and the second year includes measurements from January to December 2016, when the Graz station also received the beacon signal from Astra 3B. Between the years, little variation in the statistical analyses can be noted in the single as well as in joint CCDFs. Since the distance between the stations is large, the CCDFs of joint rain attenuation values are low and thus the diversity gains of the system are high.

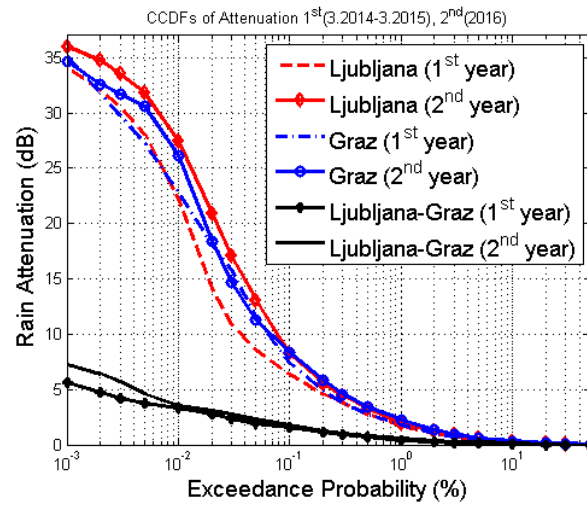


Figure 4.31: Single site and diversity attenuation for Ljubljana and Graz.

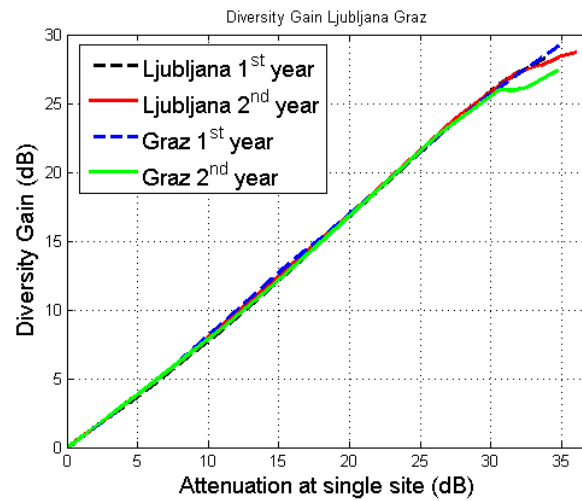


Figure 4.32: Diversity gains for Ljubljana and Graz.

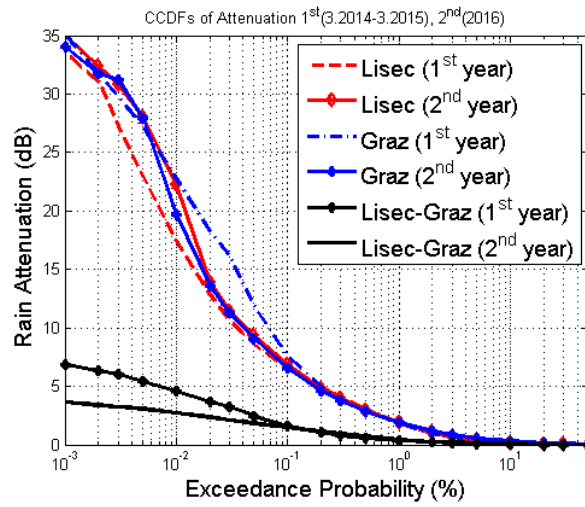


Figure 4.33: Single site and diversity attenuation for Lisec and Graz.

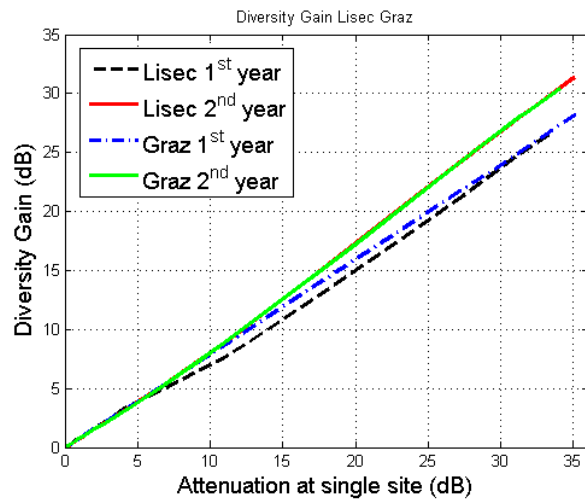


Figure 4.34: Diversity gains for Lisec and Graz.

Finally, Figure 4.35 and Figure 4.36 show the CCDFs of attenuation and diversity gains for the stations at Krvavec and Graz for the period from January to December 2016, respectively, with the 88% of concurrent data availability. In the analysed period the higher attenuation is observed at Graz station.

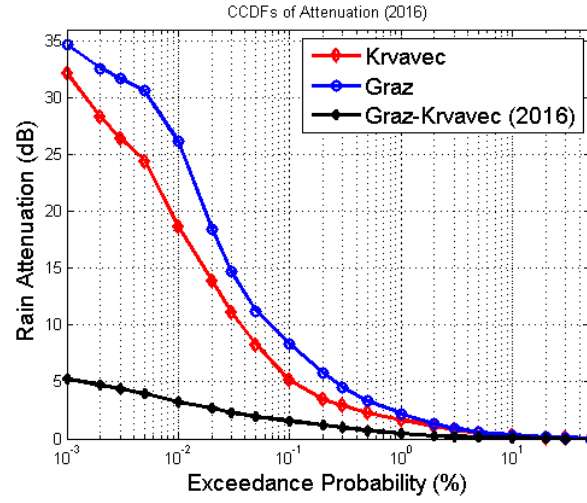


Figure 4.35: Single site and diversity attenuation for Krvavec and Graz.

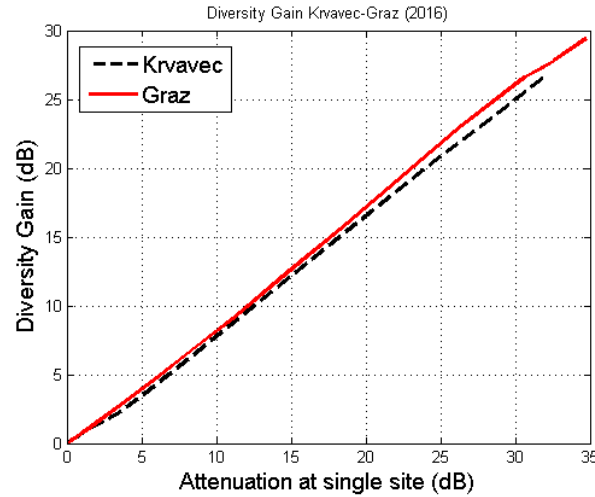


Figure 4.36: Diversity gains for Krvavec and Graz.

4.5.2 Three-site diversity experiments

The two-site diversity joint CCDFs already provide a significant improvement compared to corresponding single-site CCDFs. Further improvements obtained by the three site-diversity system are noted. In this subsection the three-site diversity systems for different station configurations are analysed. The CCDFs are separately calculated considering the availability of the concurrent data for each experimental configuration. Additionally, the equiprobable diversity gains are calculated, which are for three-site configurations defined as the difference between the single site attenuation and joint three-site attenuations at the same probabilities.

Figure 4.37 depicts the single site CCDFs of rain attenuation for stations located in Ljubljana, Lisec and Graz, and joint attenuation CCDFs for two and three-site diversity configurations. The availability of the concurrent attenuation and joint data considered

in statistical analysis from 15 March 2014 to 15 March 2015 is 75 %. The three-site diversity system provides better solution compared to two-site diversity configurations for all percentages. For two-site diversity systems, for 0.001% of the time, the attenuation exceeds 8.93 dB for Ljubljana-Lisec configuration, 6.85 dB for Lisec-Graz configuration and 5.64 dB for Ljubljana-Graz configuration. For the same time percentage in the three-site diversity configuration the attenuation exceeds only 3.71 dB. As a consequence of the separation distance between stations, the two-site diversity systems Ljubljana-Graz and Lisec-Graz perform better compared to configuration Ljubljana-Lisec. As depicted in the map in Figure 4.5, the distance Ljubljana-Lisec (40.7 km) is smaller compared to distances between Ljubljana-Graz (138.1 km) and Lisec-Graz (141.4 km). Nevertheless, the Ljubljana-Graz configuration has a slightly better performance compared to Lisec-Graz even though the distance between the stations is smaller. This may be due to the larger Ljubljana-Graz baseline angle (47°) compared to Lisec-Graz (29°).

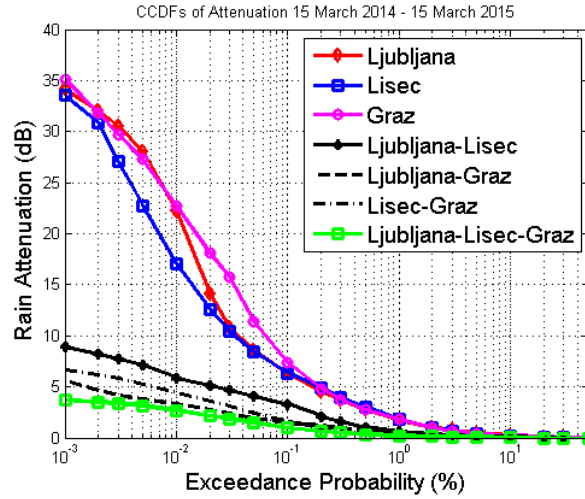


Figure 4.37: Single site and diversity attenuation for Ljubljana, Lisec and Graz.

The representative equiprobable diversity gains achieved at each station for different two- and three-site diversity configurations are depicted in Figure 4.38. The higher diversity gains are reached at stations comprised in three-site diversity configurations. However, quite high diversity gains are evident also when the stations are operating in two-site diversity configurations. Diversity gains in two-site diversity configuration Ljubljana-Lisec are the lowest.

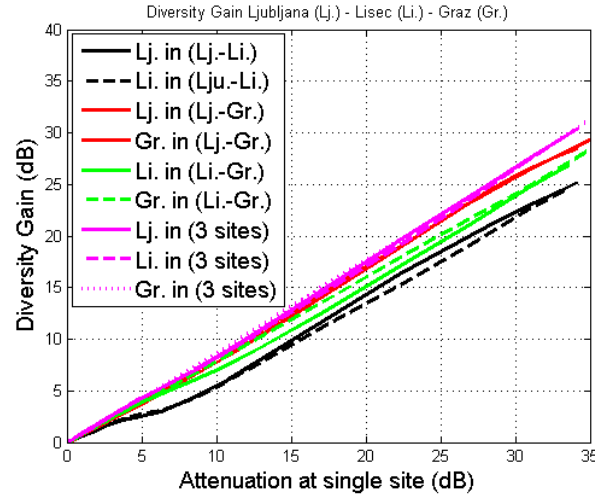


Figure 4.38: Diversity gains for Ljubljana, Lisec, Graz.

CCDFs of joint attenuation for another three-site diversity experiment Ljubljana-Lisec-Krvavec together with the CCDFs of joint attenuation for two-site diversity experiments Ljubljana-Lisec, Ljubljana-Krvavec and Lisec-Krvavec and the CCDFs of rain attenuation for three single sites are shown in Figure 4.39. The availability of the concurrent data within two years' period from 15 March 2015 to 15 March 2017 is 83%. In order to compare the three-site diversity performance from year to year, the CCDFs of joint attenuation separately for both years are additionally presented. The variation of CCDFs of joint attenuation between individual years is small and their comparison to CCDF of two years' data shows minor differences. It is evident that the three-site diversity outperforms all two-site diversity configurations. A close insight into performance can be derived from diversity gains at each station in site diversity configuration as depicted in Figure 4.40.

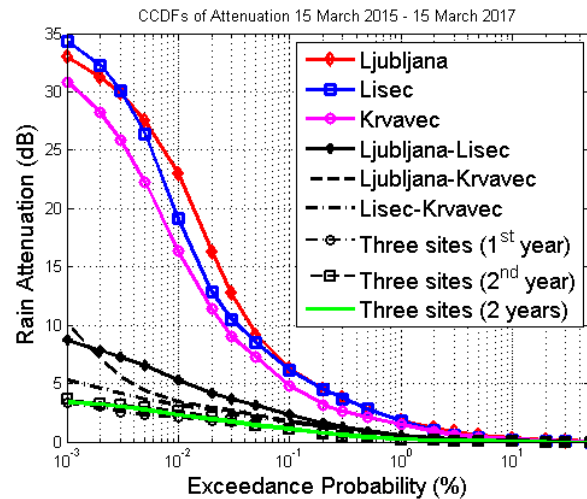


Figure 4.39: Single site and diversity attenuation for Ljubljana, Lisec and Krvavec.

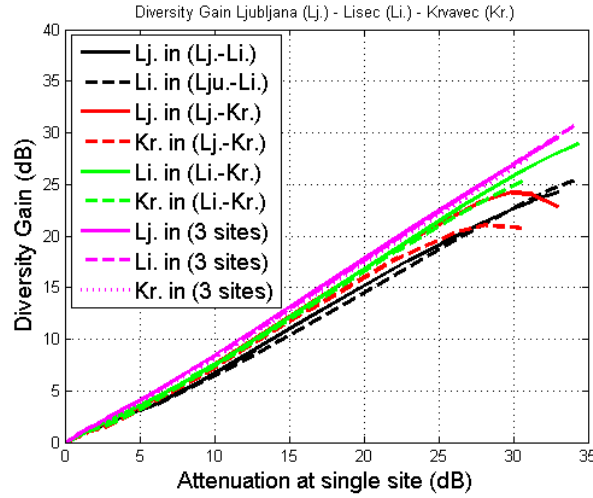


Figure 4.40: Diversity gains for Ljubljana, Lisec, Krvavec.

Lisec-Krvavec configuration, with the largest separation distance of 58.2 km, has the best two-site diversity performance. However, the Ljubljana-Krvavec configuration with station separation of 28.5 km performs better for percentages higher than 0.001% compared to two-site diversity Ljubljana-Lisec where the distance between stations is 40.7 km. The performance in this case may be affected by other factors. The Krvavec is in a mountain zone and as can be noted from CCDF of single sites, the station experienced lower attenuation values which could influence the improvement of site diversity performance. However, for percentages lower than 0.001% Ljubljana-Krvavec configuration performs the worst.

The following figures depict the statistical analysis of one years' data from January 2016 to December 2016 for three-site diversity systems between Graz and stations in Slovenia. Therefore, three experiments are analysed and the results are depicted statistically. For all combinations, the three-site configurations perform better than any two-site configuration.

In Figure 4.41 the three-site diversity experiment Ljubljana-Lisec-Graz presents the lower attenuation values compared to the two-site configurations. However, large distance two-site configurations Ljubljana-Graz and Lisec-Graz perform better than Ljubljana-Lisec two-site system and just slightly worse than the three-site system. The diversity gains achieved at each station operating in different diversity systems are depicted in Figure 4.42. The availability of concurrent data included in the analysis is 86%.

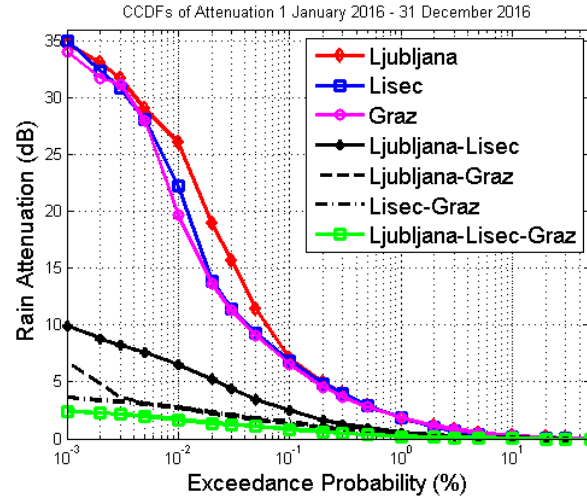


Figure 4.41: Single site and diversity attenuation for Ljubljana, Lisec, Graz.

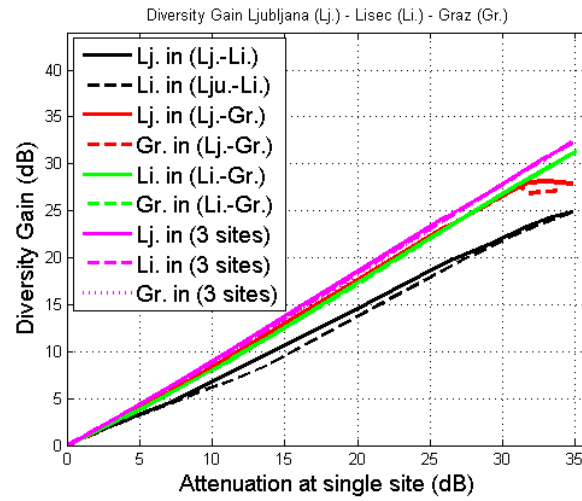


Figure 4.42: Diversity gains for Ljubljana, Lisec, Graz.

Similar conclusions can also be given for the performance of the diversity systems comprised of stations in Ljubljana, Krvavec, and Graz. Results are depicted in Figure 4.43 and Figure 4.44. Again, due to the larger distances between the sites in two-site configurations Ljubljana-Graz and Krvavec-Graz, they both perform better than Ljubljana-Krvavec. The three-site diversity performs the best as usual. The availability of the concurrent data is 82%.

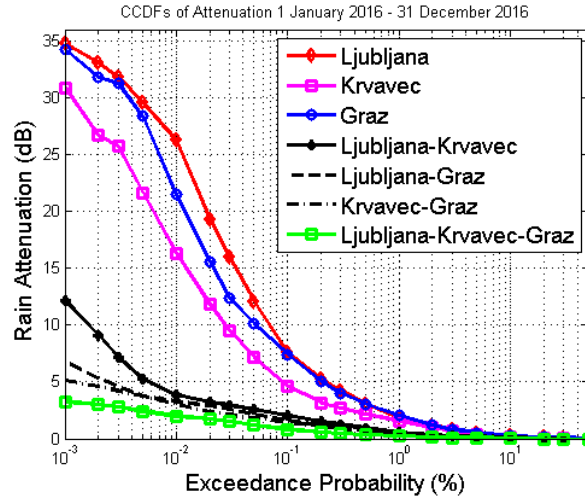


Figure 4.43: Single site and diversity attenuation for Ljubljana, Krvavec, Graz.

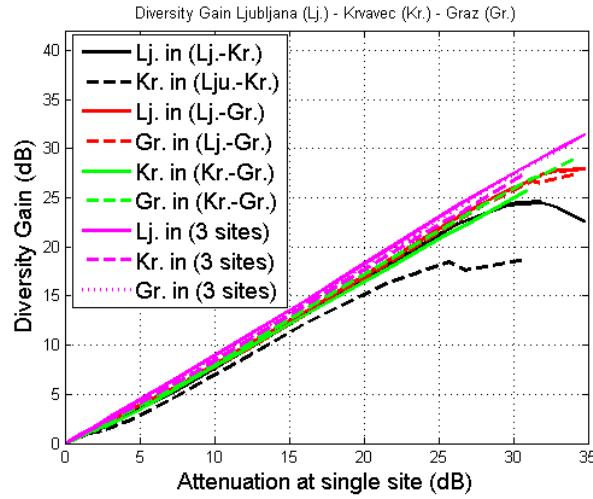


Figure 4.44: Diversity gain for Ljubljana, Krvavec, Graz.

Finally, the CCDFs and diversity gains for site diversity configurations between the stations located in Krvavec, Liseč and Graz are presented in Figure 4.45 and in Figure 4.46, respectively. Considering that two-site diversity systems with stations in Liseč and Krvavec are separated for a quite large distance of 58.2 km, it seems that the rain fall is quickly decorrelated. It can be observed that the performance of the two-site and the three-site diversity configurations are just slightly different. The availability of the concurrent data is 80%.

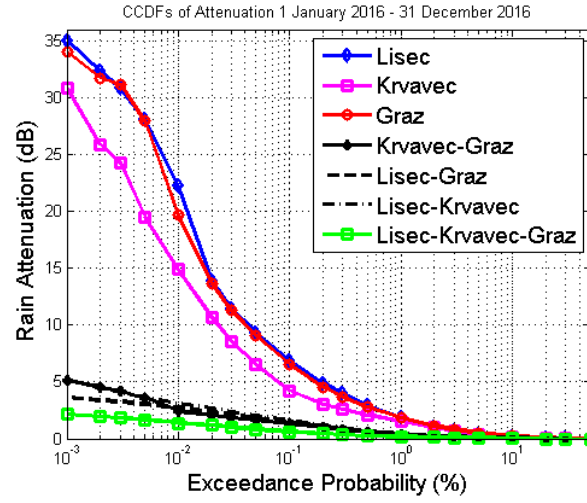


Figure 4.45: Single site and diversity attenuation for Lisec, Krvavec, Graz.

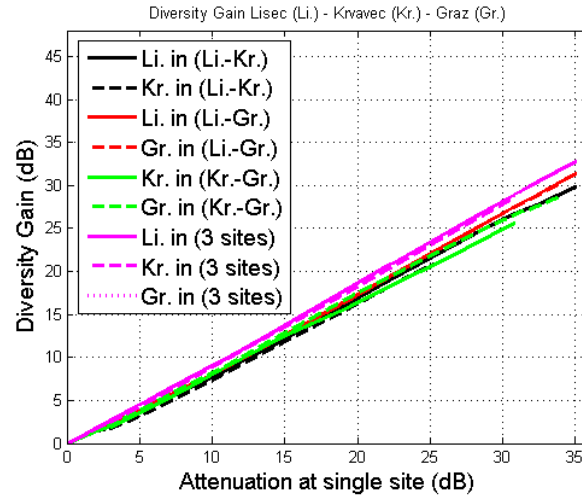


Figure 4.46: Diversity gains for Lisec, Krvavec, Graz.

4.5.3 Four site-diversity experiment

In this subsection, statistical analysis of rain attenuation for the first year of the attenuation data of the on-going four-site diversity experiment is presented. The four stations receive the beacon signal from Astra 3B and the attenuations from January 2016 to December 2016 are analysed. Figure 4.47 depicts the CCDFs of joint attenuation for three and four-site diversity systems with concurrent data availability of 78%. Diversity gains obtained in Ljubljana station for site diversity configurations are depicted in Figure 4.48. The three-site diversity system consisting of three stations located in Ljubljana, Lisec and Krvavec performs the worst. In the three-site diversity systems with the Graz station included, a small difference in the system performance is observed. As expected, the four-site diversity system performs the best. However, the improvement compared to

the three-site configuration with the lowest joint attenuation performance is almost negligible.

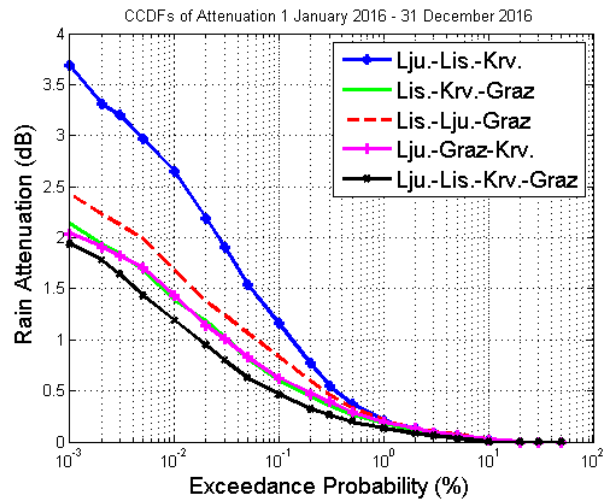


Figure 4.47: Four- and three-site diversity attenuation CCDFs.

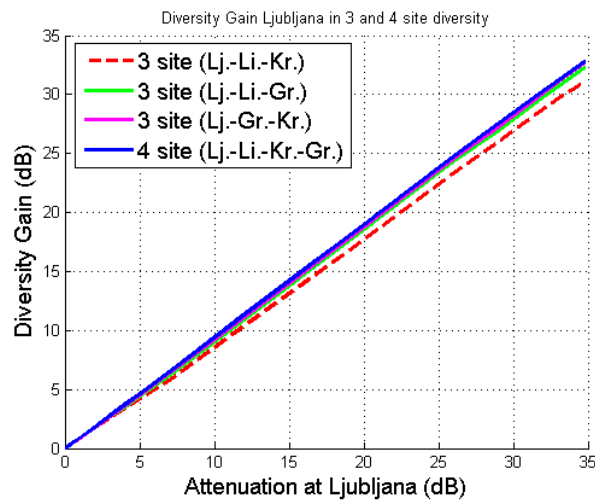


Figure 4.48: Diversity gain in Ljubljana for three- and four-site diversity.

Chapter 5

Multisite Diversity Modelling in Satellite Communications Using Copulas

In this chapter we have proposed the novel models for prediction of joint rain attenuation CCDF induced on Earth-satellite multiple-site diversity systems using copula functions. Based on our measurements as well as on additional large number of experimental data of two-site diversity systems from the available databases, two new models based on Gaussian copula and additional two models based on hyperbolic cosecant copula functions are proposed. In addition to the joint attenuation prediction for two-site diversity systems, the models are extended also for multiple-site systems. For all four models the rain attenuation CCDFs of single sites are required as input parameters. Two of the models consider the distance between the stations, while the two other models in addition to distance consider also the baseline angle and elevation angle as input parameters.

The prediction models are proposed based on the results obtained from fittings of the experimental data joint rain attenuation CCDF from 53 two-site diversity to the theoretical expression of joint CCDFs using copulas, from which the two expressions for copula parameters are proposed as a function of distance and two expressions as a function of distance, baseline angle and elevation angle. The 53 two-site diversity experiments are from temperate zones and contain a range of distances between Earth stations which vary from 1.7 km to 608 km, operating frequency from 11.4 GHz to 30 GHz, baseline orientation from 0° to 90° , and elevation angle from 6° to 83° . The two copula parameters expressions which accounts for the dependency on distance, elevation and baseline angle are valid for experiments for which the elevation angle and baseline angle in both stations are approximately the same. This condition is not restrictive for experiments from temperate region from which the expressions are proposed. However, further analyses are needed for experiments near equatorial zone for which the satellite longitude is close to the longitude of one Earth station. For these conditions the difference in baseline angles in each Earth station of the pair are higher.

Comprehensive tests are conducted comparing the error performance of the proposed models with respect to the previously known Clayton-based copula model and ITU-R model involving the data from large number of the two-site diversity experiments. The performance advantages of our proposed models in terms of less error performance for two-site diversity experiments are depicted. Unlike the dual-site experiments, three-site experiments are very rare and the number of site diversity systems with more than three

stations is not sufficient for evaluation of the models. Since the existing versions of the Clayton and the ITU-R models do not enable multiple-site prediction, error performance comparison include only the prediction performance between the proposed models compared to few accessible experimental data of three-site diversity system and one four-site diversity experiment. It is shown that in general each of the proposed models shows valuable performance for experiment subsets with certain site diversity configuration or subsets from certain region.

5.1 Probability Theory and Copulas

In probability theory, Copulas (from Latin ‘to link’, ‘to couple’) are functions that join multivariate distribution functions to their one-dimensional marginal distributions. According to Sklar's Theorem [104], there exists a unique copula function C , by which n marginal distributions $F_1(x), F_2(x), \dots, F_n(x)$ are combined into an n -dimensional distribution function H :

$$H[x_1, x_1, \dots, x_n] = C(F_1(x_1), F_2(x_2), \dots, F_n(x_n)) \quad (5.1)$$

For the case of n random variables with continual marginal Cumulative Distribution Functions (CDFs), $P[X_i \leq x_i] = F_i(x_i) = u_i$, $i = 1, \dots, n$ defined in the interval $[0, 1]$, the n -dimensional joint CDF is expressed as:

$$P[X_1 \leq x_1, X_2 \leq x_2, \dots, X_n \leq x_n] = C(u_1, u_2, \dots, u_n) \quad (5.2)$$

The joint CCDF for n variables can be calculated from CDFs as [105, 106]:

$$\begin{aligned} P[X_1 \geq x_1, X_2 \geq x_2, \dots, X_n \geq x_n] &= 1 - \sum_{k=1}^n P[X_k \leq x_k] \\ &+ \sum_{k=2}^n \left\{ (-1)^k \sum_{1 \leq i_1 < i_2 < \dots < i_k \leq n} P[X_{i_1} \leq x_{i_1}, X_{i_2} \leq x_{i_2}, \dots, X_{i_k} \leq x_{i_k}] \right\} \end{aligned} \quad (5.3)$$

From (5.2) and (5.3) the joint CCDF can be expressed by using copulas as:

$$\begin{aligned} P[X_1 \geq x_1, X_2 \geq x_2, \dots, X_n \geq x_n] \\ = 1 - \sum_{k=1}^n u_k + \sum_{k=2}^n \left\{ (-1)^k \sum_{1 \leq i_1 < i_2 < \dots < i_k \leq n} C_{i_1, i_2, \dots, i_k}(u_{i_1}, u_{i_2}, \dots, u_{i_k}) \right\} \end{aligned} \quad (5.4)$$

There are several parametric families of copulas such as Archimedean copulas, Student's t copula, and the Gaussian copula. In the thesis applicability of the Gaussian copula and one of most recently proposed member of Archimedean copula, i.e., the hyperbolic copula, are studied for modelling the joint rain attenuation statistics.

5.2 Joint Rain Attenuation Statistics Prediction Method using Gaussian Copula

The proposed prediction model of joint exceedance probability of rain attenuation in Earth-satellite in multisite diversity systems based on the Gaussian copula is based on a number of experimental data of two-site diversity systems with different configurations.

In order to calculate the joint CCDFs of rain attenuation, the CCDFs of single sites and distances between the stations are required. Moreover, the extension of the proposed model which in addition to CCDFs of single sites and distances between the stations, takes into account two additional geometric characteristics of the site diversity system, namely baseline orientation angle and elevation angle, is also presented.

Using (5.4), the joint CCDF of rain attenuation for given attenuation threshold A_{th} is calculated as:

$$P[A_1 \geq A_{th}, A_2 \geq A_{th}, \dots, A_n \geq A_{th}] = 1 - \sum_{k=1}^n u_k + \sum_{k=2}^n \left\{ (-1)^k \sum_{1 \leq i_1 < i_2 < \dots < i_k \leq n} C_{i_1, i_2, \dots, i_k}(u_{i_1}, u_{i_2}, \dots, u_{i_k}) \right\} \quad (5.5)$$

where the Gaussian copula is expressed as:

$$C(u_1, \dots, u_n; \Sigma) = \int_{-\infty}^{\Phi^{-1}(u_1)} \dots \int_{-\infty}^{\Phi^{-1}(u_n)} \frac{e^{-\frac{1}{2}t' \Sigma^{-1} t}}{(2\pi)^{(n/2)} |\Sigma|^{1/2}} dt_n \dots dt_1 \quad (5.6)$$

where Φ is the CDF of the marginal standard Gaussian distribution (zero mean and unity variance) and Σ is a symmetric matrix with $n(n-1)/2$ coefficients ρ_{ij} with diagonals of ones:

$$\Sigma = \begin{pmatrix} 1 & \rho_{12} & \dots & \rho_{1n} \\ \rho_{12} & 1 & \dots & \rho_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{1n} & \rho_{2n} & \dots & 1 \end{pmatrix} \quad (5.7)$$

The multi joint exceedance probability of rain attenuation can be computed if all copula functions in (5.5) are calculated from (5.6), where the input CDFs $u_1, u_2, \dots, u_n$ of single sites attenuation are given and coefficients ρ_{ij} of the matrix Σ are known. Single site CDFs are in our evaluation obtained from experimental data. Two expressions for calculation of the ρ_{ij} have been proposed. The first one is defined as the function of the distance between Earth stations while the second one also takes into account the baseline orientation and elevation angle. In the following subsections, a detailed analysis of the prediction method is given.

5.2.1 Modelling of joint rain attenuation statistics

For a two-site diversity system $n = 2$, the joint exceedance probability of rain attenuation using Gaussian copula can be calculated using the single CDFs of rain attenuation, $u_1 = P[A_1 \leq A_{th}]$ and $u_2 = P[A_2 \leq A_{th}]$, and the bivariate copula function $C(u_1, u_2)$ [107]. Using (5.5), (5.6) and (5.7) the joint CCDF is calculated by:

$$P[A_1 \geq A_{th}, A_2 \geq A_{th}] = 1 - u_1 - u_2 + C(u_1, u_2) \quad (5.8)$$

where the two-variable Gaussian copula is

$$C(u_1, u_2, \rho) = \frac{1}{2\pi\sqrt{1-\rho^2}} \int_{-\infty}^{\Phi^{-1}(u_1)} \int_{-\infty}^{\Phi^{-1}(u_2)} e^{-\frac{t_2^2 - 2\rho t_2 t_1 + t_1^2}{2(1-\rho^2)}} dt_2 dt_1 \quad (5.9)$$

Thus, the Eq. (5.8) takes the form

$$P[A_1 \geq A_{th}, A_2 \geq A_{th}] = 1 - u_1 - u_2 + \frac{1}{2\pi\sqrt{1-\rho^2}} \int_{-\infty}^{\Phi^{-1}(u_1)} \int_{-\infty}^{\Phi^{-1}(u_2)} e^{-\frac{t_2^2 - 2\rho t_2 t_1 + t_1^2}{2(1-\rho^2)}} dt_2 dt_1 \quad (5.10)$$

In order to investigate the performance of the Gaussian copula for modelling the joint statistics of rain attenuation, the joint CCDF of rain attenuation derived from expression (5.10) was fitted to the joint CCDF of experimental data using single site CDFs data u_1 and u_2 . Since the function (5.10) is a nonlinear function, the non-linear least squares regression fitting was used.

In Figure 5.1, the joint CCDF of rain attenuation is shown for two two-site experiments: a) Nittedal and Kjeller, Norway [97] and b) two sites in Slough, Great Britain [72], showing an accurate fitting of the expression given in (5.10) to the data. For the first experiment, the separation distance is equal to 23 km and the operating frequency is equal to 19.68 GHz, while for the second one the distance between the ground stations is 1.7 km and the operating frequency is equal to 11.6 GHz. For the fitting procedure, the single-link CCDFs and joint CCDF of rain attenuation are given as input to Eq. (5.10). The copula parameter ρ is calculated to obtain the best fit. For the Norway experiment, ρ is found to be equal to 0.69, and for the UK experiment $\rho = 0.97$.

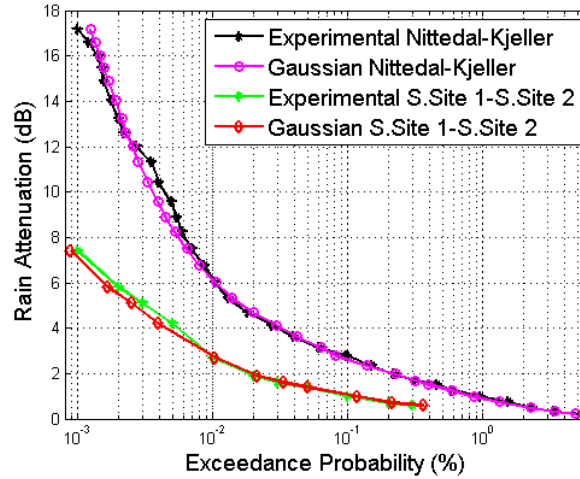


Figure 5.1: Two-site diversity attenuation CCDFs for experiments in Norway and UK.

In order to further investigate the accuracy of joint statistics of rain attenuation modelling with the Gaussian copula, the analysis was extended to 44 experiments' data from DBSG3 [72] and 9 more two-site experiments from [87, 97, 108, 109], which include some large distance configurations. Among all available experiments in the DBSG3, we analysed 44 experiments which are represented with at least five data points. In order to supplement the dataset from DBSG3, an additional 9 experiments represent site diversity systems with large distances. The error metric between the fitted function and the experimental data is calculated using Recommendation ITU-R P.311-15 [110]:

$$\varepsilon_i(p) = \begin{cases} \left(\frac{A_{m,i}(p)}{10}\right)^{0.2} \ln\left(\frac{A_{p,i}(p)}{A_{m,i}(p)}\right), & A_{m,i}(p) < 10dB \\ \ln\left(\frac{A_{p,i}(p)}{A_{m,i}(p)}\right), & A_{m,i}(p) \geq 10dB \end{cases} \quad (5.11)$$

The $\varepsilon_i(p)$ is the error for the i -th experiment at percentage level p , $A_{m,i}(p)$ is measured joint rain attenuation and $A_{p,i}(p)$ is predicted joint rain attenuation. For overall error performance, the calculation (5.11) is repeated for all fifty-three experiments at all available probabilities p . Therefore, for 53 experiments, the mean error is -7.38%, standard deviation of error is 12.86%, and the rms (route mean square) value of error is 14.83%.

Given the small rms error from the fitting procedure, a model for predicting joint statistics of rain attenuation for dual- and multiple-site diversity scenarios is proposed in subsection 5.2.2.

5.2.2 Distance based joint CCDF rain attenuation prediction method

In order to predict a joint CCDF of rain attenuation for a two-site diversity system with an arbitrary pair of sites, the single site distributions u_1 and u_2 need to be known, whereas the dependence parameter ρ of the Gaussian copula needs to be determined. As a result of the fitting procedure explained in subsection 5.2.1, the values of the Gaussian copula parameter ρ are derived. The numerical analysis of ρ parameters obtained from investigated experiments shows that ρ depends mostly on horizontal separation distance between two Earth stations; it tends to decrease as the distance increases. A slightly scattered variation to this main rule may be observed and could be ascribed to other link characteristics such as elevation angle or baseline orientation. First, we chose to model ρ only as a function of parameter with evidently highest impact, i.e., the distance. Using nonlinear regression method, it was found that ρ can be expressed by

$$\rho = Ae^{-\frac{d}{\alpha}} + (1 - A)e^{-\left(\frac{d}{\beta}\right)^2}, \quad d > 0 \quad (5.12)$$

where $A = 0.7447$, $\alpha = 40$, $\beta = 625$, and d is distance expressed in kilometres. The comparison between copula parameters ρ from Eq. (5.12) and from measurements data as a function of distance is for distances up to 60 km depicted in Figure 5.2.

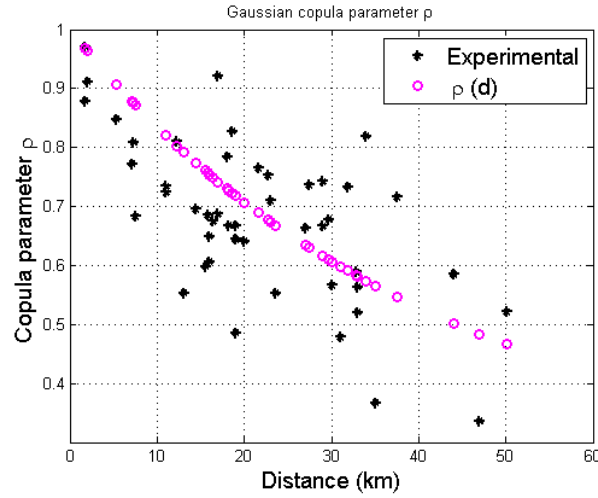


Figure 5.2: Theoretical and experimental copula parameter $\rho(d)$.

Figure 5.3 shows the joint CCDFs of rain attenuation for two experiments obtained from proposed prediction method in comparison to experimental CCDFs. Applying Eq. (5.12), $\rho = 0.74$ is obtained for the first experiment with a distance of 17 km between Earth stations in Kurashiki and Shimotsui in Japan, operating at 12 GHz [72]. In the second experiment, stations are located 601 km apart in Chilbolton and Dundee in UK, operating at frequency 20.7 GHz [13]. For this case, a lower value $\rho = 0.10$ is obtained. For both experiments, a good fitting of prediction model to experimental data can be observed.

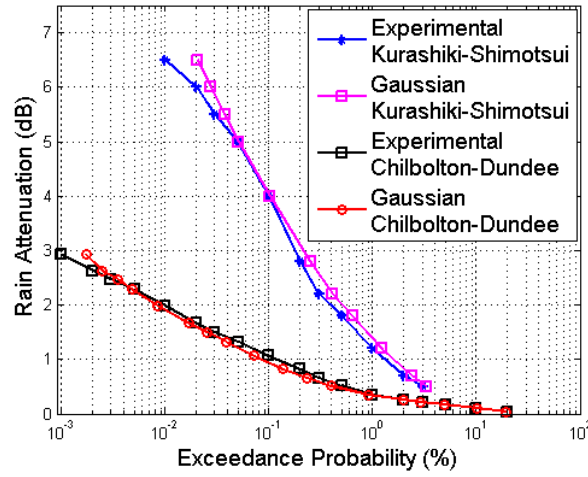


Figure 5.3: Two-site diversity attenuation CCDFs for experiments in Japan and UK.

In case of three-site diversity, the joint CCDF of rain attenuation using Eq. (5.5) is expressed by

$$P[A_1 \geq A_{th}, A_2 \geq A_{th}, A_3 \geq A_{th}] = 1 - u_1 - u_2 - u_3 + \sum_{1 \leq i_1 < i_2 \leq 3} C_{i_1, i_2}(u_{i_1}, u_{i_2}) - \sum_{1 \leq i_1 < i_2 < i_3 \leq 3} C_{i_1, i_2, i_3}(u_{i_1}, u_{i_2}, u_{i_3}) \quad (5.13)$$

The condition $1 \leq i_1 \leq i_2 \leq 3$ implies that i_1 and i_2 form pairs (1, 2), (1, 3) and (2, 3), whereas for $1 \leq i_1 \leq i_2 \leq i_3 \leq 3$, we obtain (1, 2, and 3). Hence, using Eq. (5.13) with the Gaussian copula functions, the joint CCDF takes the form:

$$\begin{aligned}
P[A_1 \geq A_{th}, A_2 \geq A_{th}, A_3 \geq A_{th}] &= 1 - u_1 - u_2 - u_3 + C_{1,2}(u_1, u_2, \rho_{12}) \\
&+ C_{1,3}(u_1, u_3, \rho_{13}) + C_{2,3}(u_2, u_3, \rho_{23}) - C_{1,2,3}(u_1, u_2, u_3, \Sigma) \\
&= 1 - u_1 - u_2 - u_3 \\
&+ \frac{1}{2\pi\sqrt{1-\rho_{12}^2}} \int_{-\infty}^{\Phi^{-1}(u_1)} \int_{-\infty}^{\Phi^{-1}(u_2)} e^{-\frac{t_2^2 - 2\rho_{12}t_2t_1 + t_1^2}{2(1-\rho_{12}^2)}} dt_2 dt_1 \\
&+ \frac{1}{2\pi\sqrt{1-\rho_{13}^2}} \int_{-\infty}^{\Phi^{-1}(u_1)} \int_{-\infty}^{\Phi^{-1}(u_3)} e^{-\frac{t_3^2 - 2\rho_{13}t_3t_1 + t_1^2}{2(1-\rho_{13}^2)}} dt_3 dt_1 \\
&+ \frac{1}{2\pi\sqrt{1-\rho_{23}^2}} \int_{-\infty}^{\Phi^{-1}(u_2)} \int_{-\infty}^{\Phi^{-1}(u_3)} e^{-\frac{t_3^2 - 2\rho_{23}t_3t_2 + t_2^2}{2(1-\rho_{23}^2)}} dt_3 dt_2 \\
&- \int_{-\infty}^{\Phi^{-1}(u_1)} \int_{-\infty}^{\Phi^{-1}(u_2)} \int_{-\infty}^{\Phi^{-1}(u_3)} \frac{e^{-\frac{1}{2}t'\Sigma^{-1}t}}{(2\pi)^{(3/2)}|\Sigma|^{1/2}} dt_1 dt_2 dt_3
\end{aligned} \tag{5.14}$$

where Σ is three dimensional symmetric matrix:

$$\Sigma = \begin{pmatrix} 1 & \rho_{12} & \rho_{13} \\ \rho_{12} & 1 & \rho_{23} \\ \rho_{13} & \rho_{23} & 1 \end{pmatrix} \tag{5.15}$$

For all four Gaussian copula functions $C_{1,2}$, $C_{1,3}$, $C_{2,3}$ and $C_{1,2,3}$ the calculation of three parameters $\rho_{12}(d_{12})$, $\rho_{13}(d_{13})$ and $\rho_{23}(d_{23})$ using Eq. (5.12) is needed. Distances d_{12} , d_{13} , d_{23} represent the distances between stations 1 and 2, 1 and 3 and 2 and 3 respectively.

The CCDFs from experimental and prediction model for our experiment in three-site diversity approach are depicted in Figure 5.4. The experiment consists of two Earth stations around 40 km apart in Ljubljana and Lisec in Slovenia, and the third station located in Graz, Austria, around 140 km away from both Slovenian stations [108]. The presented graph also shows a good performance of the prediction model for the three-site case.

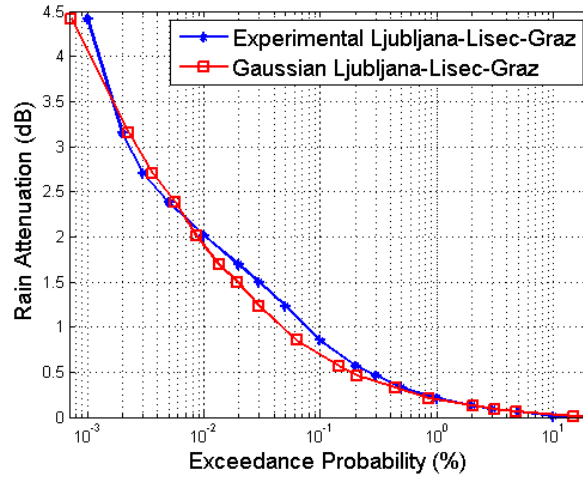


Figure 5.4: Three-site diversity attenuation CCDFs in Slovenia and Austria.

Generally, the prediction method of multisite joint exceedance probability of rain attenuation for n -site diversity system can be done using Eq. (5.5) and Eq. (5.6) and calculating $n(n-1)/2$ correlations ρ_{ij} , i.e., the elements of matrix Σ from Eq. (5.12) using distance d_{ij} between stations i and j for each copula. Single site CDFs $u_i = 1 - P[A_i \geq A_{th}]$ can be derived from CCDFs of experimental data or following Recommendation ITU-R P.618-12, paragraph 2.2.1.1 [18].

5.2.2.1 Comparative tests and error performance of prediction model

The proposed model is validated in terms of error performance. The predicted joint exceedance probability distributions are compared to experimental distributions for all 53 two-site diversity experiments. The errors are computed according to ITU-R P.311 [110] error criteria and expressed as mean errors, standard deviations and rms values. For comparative purposes, the same evaluation is done for the model proposed in ITU-R P.618-12, paragraph 2.2.4.1 [18] and the recent model based on the Clayton copula [8]. The graphs in Figure 5.5, Figure 5.6 and Figure 5.7 show the results for different time percentages of available attenuation data.

Considering that exceedance probability presents the percentage of the time for which the attenuation exceeds a given attenuation, the terms ‘exceedance probability’ is used for signal attenuation representation while ‘time percentage’ term is used for the error performance analyses.

From Figure 5.5 it is evident that lower mean errors are achieved by the proposed Gaussian copula model in comparison to the ITU-R model and the Clayton copula model for almost all time percentages. Furthermore, Figure 5.6 confirms also a better stability of the proposed Gaussian copula model compared to the ITU-R model. In comparison to the Clayton copula model, slightly higher standard deviations of errors are observed for the Gaussian copula model for percentages higher than 0.01%. Finally, Figure 5.7 confirms better rms error performance of the Gaussian copula model for all time percentages in comparison to the ITU-R model. In comparison to the Clayton copula model, slightly worse results are achieved only for time percentages between 0.01% and 0.1%.

In Figure 5.5, Figure 5.6 and Figure 5.7, the error performance is analyzed for each considered time percentage separately. In Table 5.1, the analysis is made for the overall

error performance, taking into account all the available error values, obtained from all 53 experiments for all time percentages. The resulting characteristic rms value of error of the Gaussian copula model is 19.63%, which is significantly lower compared to 39.88% obtained by the ITU-R model and lower than the Clayton copula model rms value of 22.86%.

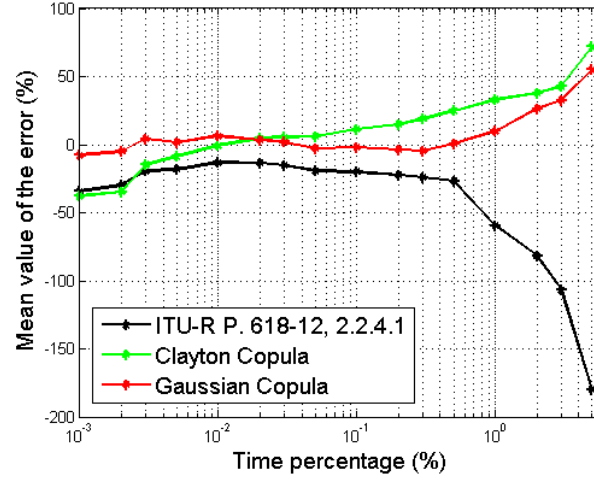


Figure 5.5: Mean value of error for various probabilities for 53 experiments.

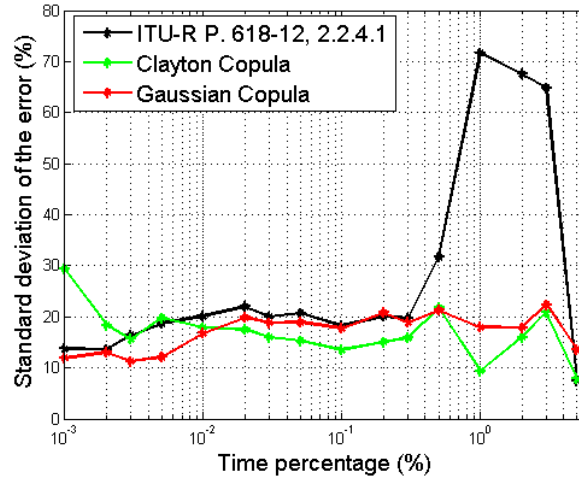


Figure 5.6: Standard deviation of error for various probabilities for 53 experiments.

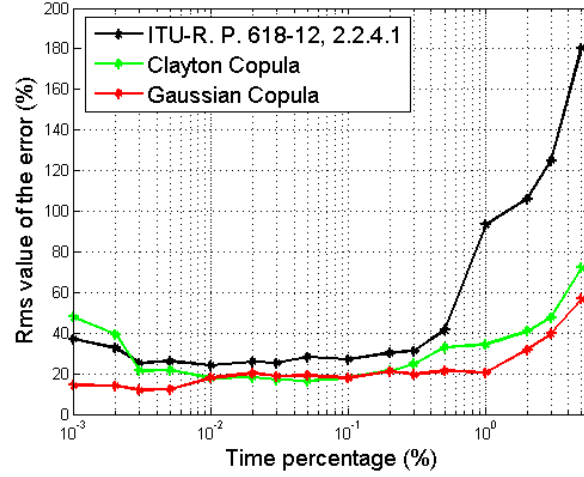


Figure 5.7: Rms value of the error for various probabilities for 53 experiments.

Table 5.1: Total error performance comparison.

Model	$\epsilon_{\text{mean}}(\%)$	$\epsilon_{\text{std}}(\%)$	$\epsilon_{\text{rms}}(\%)$
ITU-R P.618-12	-23.41	32.29	39.88
Clayton	7.46	21.61	22.86
Gaussian	1.87	19.54	19.63

The error of the proposed model for three-site diversity experiments is calculated according to [110]. The experiments used for the error analysis are stated in [108] together with additional two three-site diversity experiments from [97] and [109]. The proposed Gaussian copula model shows low error performance with mean value of error 6.98%, standard deviation 11.50%, and rms error value 13.46%.

5.2.3 Distance, elevation and baseline angle based joint CCDF rain attenuation prediction method

In some experiments, the ρ acquired from data fitting slightly differs from values calculated using expression (5.12). This may be ascribed to the influence of additional characteristics such as elevation angle (ψ) and baseline angle (b) different geographical location of the links, etc. Study of elevation and baseline angles' impact on site diversity system performance can be found in [111, 112]. Advantage of high baseline angle in site diversity performance is shown in early studies in [113]. The Hodge model shows that diversity gain is improved, if baseline and elevation angles have higher values [63].

In order to improve the accuracy of the proposed model based on the Gaussian copula described in subsection 5.2.2, a nonlinear regression fitting for different expressions for ρ parameter was performed. The results suggest that the expression (5.12) could be improved by incorporating elevation angle and baseline angle. Using nonlinear regression method, the ρ as function of distance d (km), elevation angle ψ (degrees) and the baseline angle b (degrees) can be expressed as

$$\rho = Ae^{\left(-\frac{d}{\alpha - Bb - E\psi}\right)} + (1 - A)e^{-\left(\frac{d}{\beta}\right)^2}, \quad b, \psi \leq 90^\circ \quad (5.16)$$

where $A = 0.924$, $B = 0.55$, $\alpha = 118$, $E = 0.70$, $\beta = 900$. Besides the distance, as the most relevant parameter, the introduction of elevation and baseline angles in expression (5.13) is supposed to improve the total error performance.

The comparison between copula parameters ρ from Eq. (5.16) and from measurements data as a function of distance is for distances up to 60 km depicted in Figure 5.8.

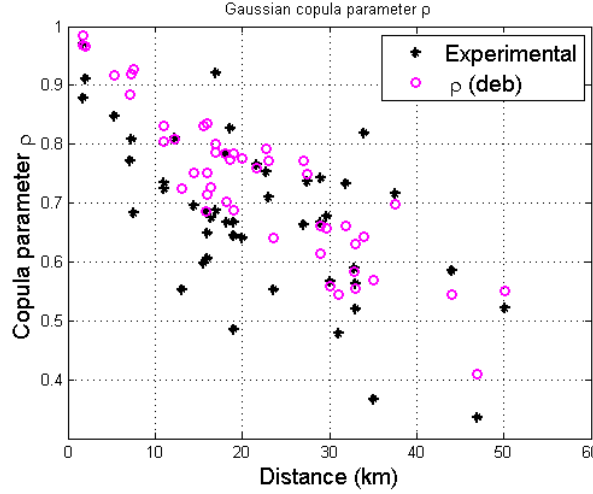


Figure 5.8: Theoretical and experimental copula parameter $\rho(\text{deb})$.

In Figure 5.9 an example of joint CCDFs for two-site diversity is shown, calculated from measurement data and from expression (5.10). Joint CCDF, based on parameter ρ from expression (5.12) is called Gaussian (d) while improved joint CCDF based on parameter ρ from expression (5.16) is called Gaussian (deb). The two Earth stations, which are 21.6 km apart, are located in Beaver Valley and Flesherton in Canada [72]. The operating frequency is 13 GHz, baseline angle is 65° and elevation angle is 15.5° . The copula parameter calculated by Eq. (5.12) is $\rho=0.68$ while the copula parameter in the case of Eq. (5.16) is $\rho=0.75$. Figure 5.9 confirms that the prediction of joint CCDF taking into consideration distance, elevation angle and baseline orientation angle slightly outperforms the approach which considers only distance between the sites.

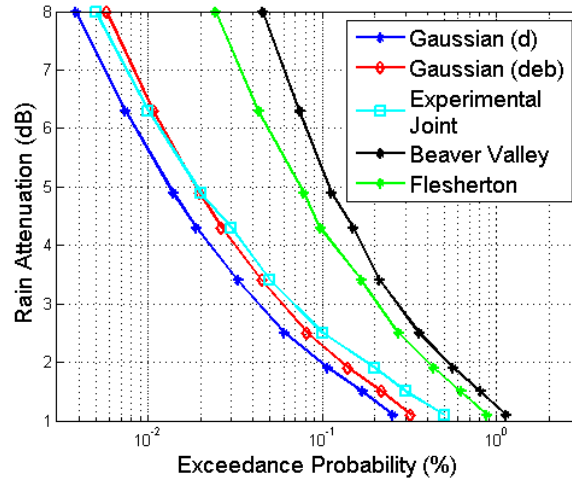


Figure 5.9: Two-site diversity attenuation in Beaver Valley and Flesherton in Canada.

In Figure 5.10 an example of CCDF of joint rain attenuation prediction for three-site diversity system with stations located in Nittedal, Kjeller and Eggemoen in Norway is given. Detailed characteristics of the link configurations are shown in [97]. For both cases the theoretical joint CCDF is calculated by Eq. (5.14) while parameters ρ_{12} , ρ_{13} , ρ_{23} , are calculated by equations (5.12) and (5.16). The single site CDFs (u_1 , u_2 , u_3) for the Nittedal, Kjeller and Eggemoen sites are extracted from measurement data in [97]. Applying reported distances, elevation angles and baseline angles [97], the parameters ρ , calculated by Eq. (5.12) are $\rho_{12} = 0.67$, $\rho_{13} = 0.60$ and $\rho_{23} = 0.46$ while parameter values calculated by Eq. (5.16) are $\rho_{12} = 0.77$, $\rho_{13} = 0.65$ and $\rho_{23} = 0.53$. It can be noticed in Figure 5.10 that applying Eq. (5.16) the accuracy of three-site diversity Gaussian copula model is also slightly improved.

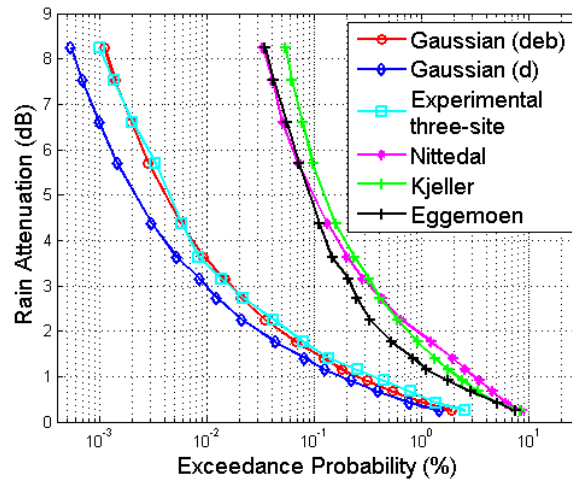


Figure 5.10: Three-site diversity CCDFs of rain attenuation in Norway.

5.2.3.1 Comparative tests and error performance of prediction model

In order to investigate the advantages of the Gaussian (deb) model in terms of error performance, the error statistics of joint rain attenuation statistics were calculated

according to Recommendation ITU-R P.311-15 [110] for joint CCDF called Gaussian (d), joint improved CCDF called Gaussian (deb), and compared to experimental data joint CCDF. The errors are expressed by their mean, standard deviation and rms (root mean square) values for two- and three-site diversity experiments.

5.2.3.1.1 Two-site diversity error performance The predicted joint CCDFs of rain attenuation obtained by Gaussian (d) and Gaussian (deb) model are compared to experimental measurement data CCDFs for fifty-three two-site diversity experiments used also for analysis in subsection 5.2.2. For comparative purposes, the same error analysis is done for the model described in ITU-R P.618-12, paragraph 2.2.4.1 [18]. The error performance in terms of mean value, standard deviation and rms of error for all experiments is depicted in Table 5.2.

Table 5.2: Error performance comparison for 53 experiments.

Model	$\epsilon_{\text{mean}}(\%)$	$\epsilon_{\text{std}}(\%)$	$\epsilon_{\text{rms}}(\%)$
ITU-R P.618-12	-23.79	32.59	39.77
Gaussian (d)	1.96	19.60	19.70
Gaussian (deb)	5.12	17.45	18.19

For total error comparison of the models, the total error performance is calculated taking into account only percentages where the predicted attenuation data from all models and experimental data exists. Therefore, in Table 5.1 and Table 5.2 the values for ITU-R and Gaussian model, which takes into account just the distance between station (Gaussian (d)), are for the same subset of experiments slightly different.

Gaussian copula models perform better compared to ITU-R model. Rms error value of the Gaussian (deb) prediction method is 18.19% which is slightly lower compared to 19.70% achieved by the Gaussian (d). However, after detailed analysis of each experiment, it can be concluded that improved Gaussian prediction method called Gaussian (deb) outperforms Gaussian (d) method for site diversity experiments with baseline angles greater than 45° and distances larger than 10 km. Among investigated experiments, 26 experiments with baseline angles greater than 45° and distance larger than 10 km exist. The total error performance for all the 26 experiments is summarized in Table 5.3. The results clearly show that the proposed Gaussian (deb) method achieves the best error performance in terms of rms error. The rms error for Gaussian (deb) is 16.39%, while for Gaussian (d) is 20.02%.

Table 5.3: Error performance for experiments with $b > 45^\circ$ and $d > 10$ km.

Model	$\epsilon_{\text{mean}}(\%)$	$\epsilon_{\text{std}}(\%)$	$\epsilon_{\text{rms}}(\%)$
ITU-R P.618-12	-22.60	32.28	39.41
Gaussian (d)	1.80	19.94	20.02
Gaussian (deb)	2.80	16.14	16.39

In Figure 5.11, Figure 5.12 and Figure 5.13 the means, standard deviations and rms values of errors for different time percentages are depicted for the 26 experiments. From Figure 5.11 it can be seen that the mean values of error of Gaussian models are similar for almost all percentages. However, Figure 5.12 and Figure 5.13 confirm lower standard

deviation and rms error of Gaussian (deb) for almost all percentages in comparison to the Gaussian (d) method.

The analyses of total error performance for the remaining 27 experiments which do not fulfil stated requirements for baseline angle and distance were performed. It was found that the error performance for both methods is similar. Total rms error value of Gaussian (deb) is 19.88% which is close to 19.41% obtained by Gaussian (d). Therefore the total improvement of this method is ascribed to the experiments with baseline angles larger than 45° and distance larger than 10 km.

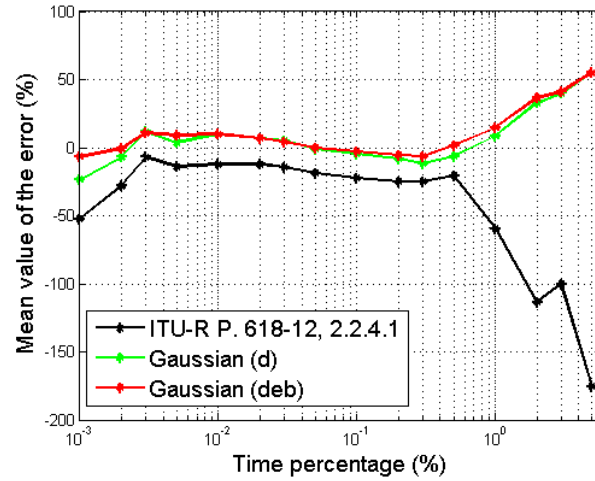


Figure 5.11: Mean value of error for experiments with $b > 45^\circ$ and $d > 10$ km.

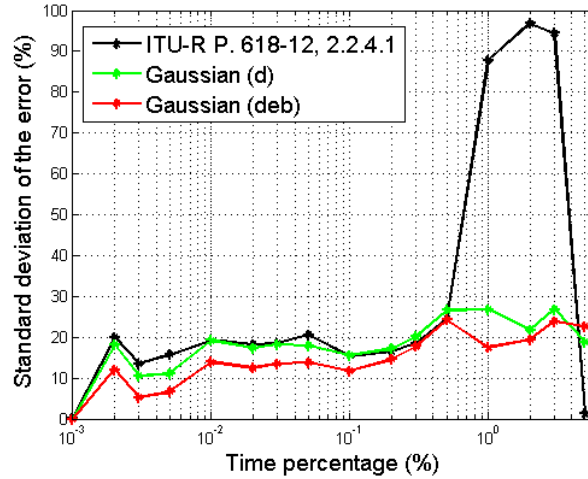


Figure 5.12: Standard deviation of error for experiments with $b > 45^\circ$ and $d > 10$ km.

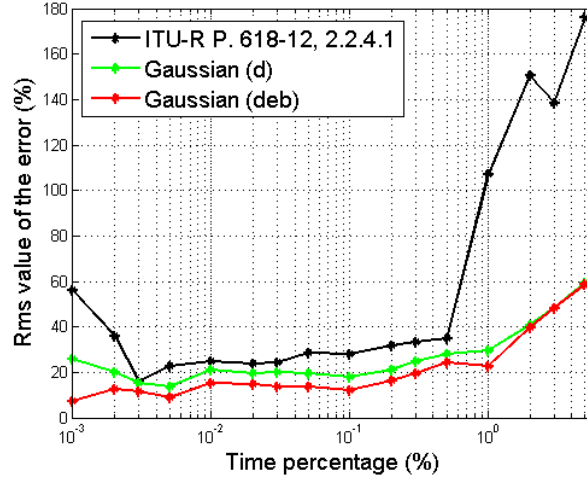


Figure 5.13: Rms value of error for experiments with $b > 45^\circ$ and $d > 10$ km.

5.2.3.1.2 Three-site diversity error performance The Gaussian copula prediction method was also evaluated for three-site diversity systems. Considering that ITU-R does not provide a prediction method for three-site diversity, only an error comparison between Gaussian (d) and Gaussian (deb) is investigated. Since the number of accessible three-site diversity systems experiments is limited, error performance for four experiments published in [96, 97, 108, 109] is calculated. Total error calculation according to ITU-R P.311-15 [110] between experimental data joint CCDF and predicted with the expression (5.14) for both models are shown in Table 5.4. It is evident that Gaussian (deb) has better error performance compared to Gaussian (d).

Table 5.4: Error performance for three-site diversity system.

Model	$\epsilon_{\text{mean}}(\%)$	$\epsilon_{\text{std}}(\%)$	$\epsilon_{\text{rms}}(\%)$
Gaussian (d)	-7.44	11.93	14.06
Gaussian (deb)	-5.58	8.85	10.46

In addition, the error performance for different time percentages of all three-site experiments was investigated. The results in terms of mean, standard deviation and rms values of error for Gaussian (d) and Gaussian (deb) are given in Figure 5.14, Figure 5.15 and Figure 5.16. The statistical values confirm that for most probabilities the error values for Gaussian (deb) are lower compared to Gaussian (d).

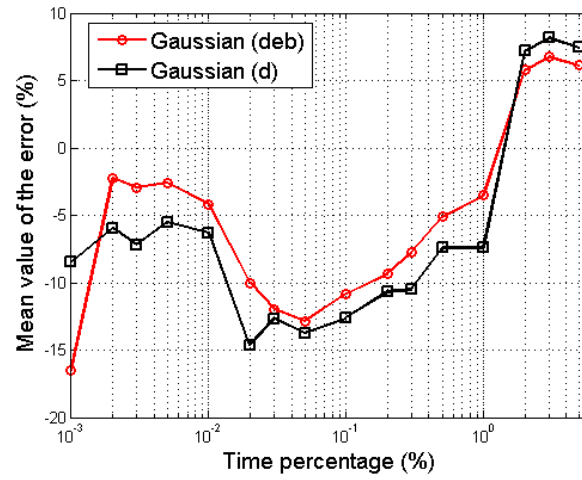


Figure 5.14: Mean value of error for various time percentages.

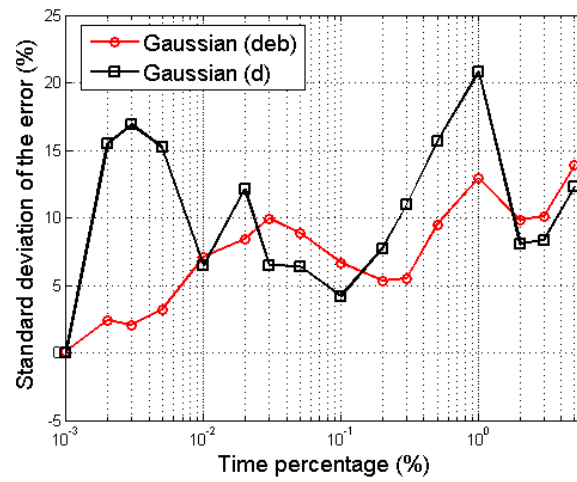


Figure 5.15: Standard deviation of error for various time percentages.

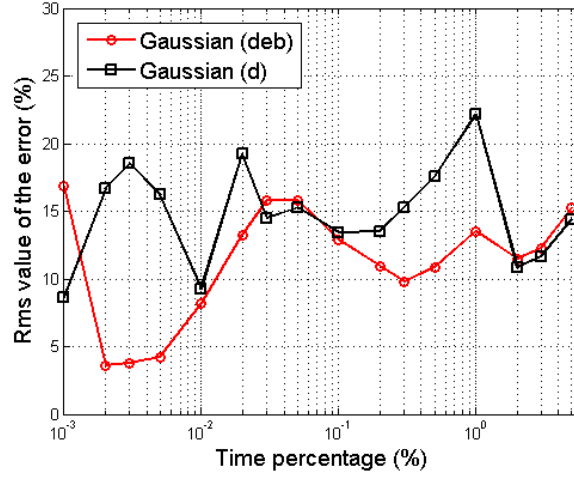


Figure 5.16: Rms value of error for various time percentages.

5.2.4 Discussion of the Gaussian copula prediction models

Proposed method for prediction of joint CCDF of rain attenuation for multisite diversity systems based on the Gaussian copula, called Gaussian (d), is based on the newly defined parameter ρ which is a function of distance. The expression for parameter ρ is proposed based on 53 two-site diversity experiments. Based on extensive comparative tests and error analysis, the proposed method shows considerably better performance on the prediction of joint CCDF of rain attenuation in two-site diversity systems compared to ITU R P.618-12 and better error performance compared to the Clayton-based copula model. An additional advantage of the proposed method is its easy extension to three- and multisite diversity systems which is not supported by the ITU-R model and the Clayton copula model. The evaluation of the Gaussian copula model performance for multisite diversity systems was limited to the comparison of just a few accessible three-site experiment databases, but the results are promising.

Moreover, a modification of the Gaussian (d) method for prediction of joint exceedance probability of rain attenuation for multisite diversity systems based on the Gaussian copula, named Gaussian (deb), is presented. Based on an experiment database, a new expression for the Gaussian copula parameter as a function of distance, baseline and elevation angle is proposed. Evaluation and comparison between Gaussian (d) and improved Gaussian (deb) methods are given for 53 two-site and 4 three-site diversity experiments. Based on comparative tests of the error performance for two-site diversity case, the total rms error value of the Gaussian (deb) method is slightly lower compared to Gaussian (d) method. However, for two-site diversity systems with baseline angle higher than 45° and distance greater than 10 km, the improvement is more evident. The results confirm that the improved method Gaussian (deb) outperforms the Gaussian (d) also for three-site diversity systems. The proposed method gives good results of joint exceedance probability prediction. However, in the future the Gaussian methods should be additionally validated and compared to ITU-R model by a number of new experiments.

5.3 Joint Rain Attenuation Prediction Model based on Hyperbolic Cosecant Copula

Models using the Gaussian copula have achieved better results than ITU-R model or model based on Clayton Archimedean copula. However, the method is implicit and involves multiple integrals. For two-site diversity modelling one double integral has to be solved, while for three-site diversity, three double integrals and one triple integral have to be solved. The number of multiple integrals is increasing by increasing the number of the stations in the site diversity systems. Thus, the computational complexity is the main disadvantage of Gaussian copula method.

The class of Archimedean copulas with a great variety of families is explicitly expressed and as such easier to apply compared to the Gaussian copula. Recently the two-site diversity prediction models based on two families of Archimedean copulas with good prediction results but without extension to multisite have been proposed [8]. The Archimedean copulas include various families and they can be easily constructed. In [104] more than twenty families of Archimedean copulas are reported.

In the first step, we analysed the adequacy of several different existing Archimedean copula families not used before for prediction of the joint rain attenuation CCDFs in two-site diversity cases. The results reveal that an appropriate family for the calculation of joint CCDF of rain attenuation for site diversity systems is the family of Archimedean copula referring as hyperbolic cosecant copula [114]. Therefore, we have proposed a novel model for prediction of joint exceedance probability of rain attenuation for two-site diversity system based on this family of Archimedean copula. The proposed method is based on experimental data of two-site diversity systems with different configurations. In order to calculate the joint CCDFs of rain attenuation, the CCDFs of single sites and distances between the stations are required. In addition, the extension of the proposed model is presented, which takes into account not only CCDFs of single sites and distances between the stations, but also baseline orientation angle and elevation angle. By using the Hierarchical Archimedean Copula (HAC) structure, the proposed methodology is suitable for the prediction of joint rain attenuation CCDF for three- and multiple-site diversity satellite communication systems.

5.3.1 Hierarchical Archimedean Copulas structure using hyperbolic generator function for joint CCDF prediction

Archimedean copulas are a class which is widely used in practical applications. A great number of copula families belonging to this class exist and the number is increasing. Their main advantage is that they can be easily generated. The n dimensional Archimedean copula is expressed as [104]:

$$C(\mathbf{u}; \theta) = \varphi^{[-1]}(\varphi(u_1; \theta) + \varphi(u_2; \theta) + \dots + \varphi(u_n; \theta); \theta) \quad (5.17)$$

where $u \in [0,1]^n$, θ is the parameter and φ is known as Archimedean generator of copula C , whereas the $\varphi^{[-1]}$ is the pseudo inverse function of generator φ , given as

$$\varphi^{[-1]}(t; \theta) = \begin{cases} \varphi^{-1}(t; \theta), & 0 \leq t \leq \varphi(0; \theta) \\ 0, & \varphi(0; \theta) \leq t \leq \infty \end{cases} \quad (5.18)$$

If $\varphi(0) = \infty$, the pseudo inverse describes an ordinary inverse function $\varphi^{[-1]} = \varphi^{-1}$. In this case, the function φ is called a strict generator, and the copula function (5.17) is

called a strict Archimedean copula. In order to be a proper copula generator, the function φ needs to be completely monotone [104].

In general, multivariate Archimedean copulas depend on a single parameter θ which is not always applicable for $n \geq 3$. Therefore, a method for expressing multivariate copulas with $n \geq 3$ has been proposed by using the HAC structure [115]. The HAC represents a multivariate structure, built by nesting different lower-dimensional Archimedean copulas. As an illustration of applying this approach to three-variate copula $C(u_1, u_2, u_3, \theta)$, consider the following example. First, the variables u_1 and u_2 are joined by using the bivariate Archimedean copula $C_1(u_1, u_2, \theta_1)$. The obtained function is then defined as a new variable $v = C_1(u_1, u_2, \theta_1)$, and it is coupled with the variable u_3 by applying Archimedean copula $C_4(v, u_3, \theta_4)$. Thus, the copula $C(u_1, u_2, u_3)$ can be expressed as:

$$\begin{aligned} C(u_1, u_2, u_3, \theta) &= \varphi^{-1}(\varphi(u_1) + \varphi(u_2) + \varphi(u_3)) \\ &= C_4(C_1(u_1, u_2, \theta_1), u_3, \theta_4) = \varphi_4^{-1}(\varphi_4 \circ \varphi_1^{-1}(\varphi_1(u_1) + \varphi_2(u_2)) + \varphi_4(u_3)) \end{aligned} \quad (5.19)$$

Similarly, for multivariate copula of any level, the general HAC is expressed as [116]:

$$\begin{aligned} C(u_1, \dots, u_n, \theta) &= \varphi_{n-1}^{-1}\{\varphi_{n-1} \circ \varphi_{n-2}^{-1}[\dots (\varphi_2 \circ \varphi_1^{-1}(\varphi_1(u_1) + \varphi_2(u_2)) + \varphi_2(u_3)) \\ &\quad + \dots + \varphi_{n-2}^{-1}(u_{n-1})] + \varphi_{n-1}(u_n)\} \end{aligned} \quad (5.20)$$

In order to increase the model's flexibility, different nested strategies can be applied for $n > 3$. In Fully Nested Archimedean Copulas (FNAC), one dimension is added at each next joint level. If copulas of different dimensions are joined, the structure is called Partially Nested Archimedean Copulas (PNAC). A combined structure of FNAC and PNAC can also be used. Note that the Eq. (5.20) represents a general expression of the FNAC structure. Figure 5.17 illustrates the three different strategies for building a HAC structure of a six-variate copula.

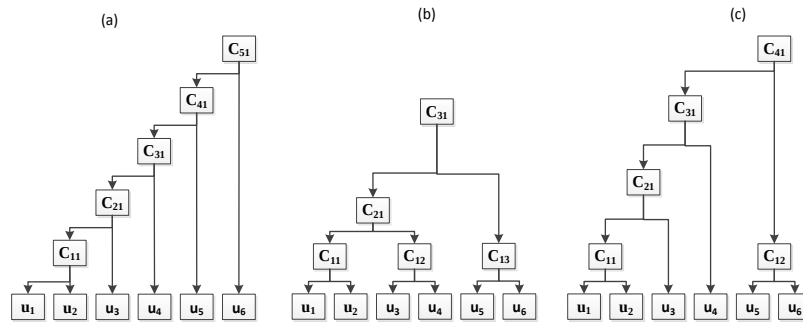


Figure 5.17: HAC structure examples: a) FNAC, b) PNAC and c) mixed.

In multivariate HAC structures, not only the generator functions φ_i , but also their composition functions $\varphi_i \circ \varphi_j$ must be completely monotonic. If all Archimedean copulas in the hierarchy belong to the same Archimedean family, the conditions are fulfilled if the dependence parameters θ_i decreases with the hierarchy level [117], e.g. if $\theta_4 < \theta_1$ in equation (5.19). For the sake of adaptability, it could be beneficial to use different copula families in the HAC structure. This case is also possible but monotonic conditions must be verified separately [118].

In order to predict the joint rain attenuation CCDFs we analysed the adequacy of several different Archimedean copula families not used till now for two-site diversity

prediction performance. The results reveal that an appropriate family for the calculation of joint CCDF of rain attenuation for site diversity systems is the family of Archimedean copulas via the hyperbolic generator [114] which is used in the thesis. For multisite diversity cases, the multivariate copula functions in joint CCDF expression

$$P[A_1 \geq A_{th}, A_2 \geq A_{th}, \dots, A_n \geq A_{th}] = 1 - \sum_{k=1}^n u_k + \sum_{k=2}^n \left\{ (-1)^k \sum_{1 \leq i_1 < i_2 < \dots < i_k \leq n} C_{i_1, i_2, \dots, i_k}(u_{i_1}, u_{i_2}, \dots, u_{i_k}) \right\} \quad (5.21)$$

are expressed with HAC structure, which proves to be an effective solution for site diversity systems with three or more stations. The hyperbolic strict generator is expressed by hyperbolic cosecant function

$$\varphi(t) = \text{csch}(t^\theta) - \text{csch}(1) \quad (5.22)$$

and its inverse function

$$\varphi^{-1}(t) = [\text{acsch}(t + \text{csch}(1))]^{\frac{1}{\theta}} \quad (5.23)$$

where θ is the parameter in the interval $[0, \infty)$ and the hyperbolic cosecant function is

$$\text{csch}(x) = \frac{2}{e^x - e^{-x}} \quad (5.24)$$

5.3.2 Modelling of joint rain attenuation statistics

The joint exceedance probability of rain attenuation for two-site diversity systems is expressed as

$$P[A_1 \geq A_{th}, A_2 \geq A_{th}] = 1 - u_1 - u_2 + C(u_1, u_2) \quad (5.25)$$

where $u_1 = P[A_1 \leq A_{th}]$ and $u_2 = P[A_2 \leq A_{th}]$ represent the single CDFs of rain attenuation, whereas the $C(u_1, u_2)$ is the bivariate copula function, which is defined as

$$C(u_1, u_2) = \varphi^{-1}(\varphi(u_1) + \varphi(u_2)) \quad (5.26)$$

By inserting the strict generator and the inverse function as defined in (5.22) and (5.23), the following expression is obtained [114]:

$$C(u_1, u_2) = [\text{acsch}(\text{csch}(u_1^\theta) + \text{csch}(u_2^\theta) - \text{csch}(1))]^{\frac{1}{\theta}} \quad (5.27)$$

Therefore, dual joint CCDF in Eq. (5.25) takes the form:

$$P[A_1 \geq A_{th}, A_2 \geq A_{th}] = 1 - u_1 - u_2 + [\text{acsch}(\text{csch}(u_1^\theta) + \text{csch}(u_2^\theta) - \text{csch}(1))]^{\frac{1}{\theta}} \quad (5.28)$$

where u_1 and u_2 correspond to CDFs of attenuation of both stations and θ is the parameter which needs to be determined. Considering that satellite propagation experimental data are usually given as CCDFs of rain attenuation $P[A_1 \geq A_{th}]$ and

$P[A_2 \geq A_{th}]$, u_1 and u_2 can be expressed as $u_1 = P[A_1 \leq A_{th}] = 1 - P[A_1 \geq A_{th}]$ and $u_2 = P[A_2 \leq A_{th}] = 1 - P[A_2 \geq A_{th}]$.

In order to investigate the capability of hyperbolic cosecant copula for modelling the joint statistics of rain attenuation, an optimal value of parameter must be determined. Thus, at first investigation stage, the parameter is obtained by fitting the modelled joint CCDF of rain attenuation derived from expression (5.28) to the experimental data joint CCDF. Since (5.28) is a nonlinear function, the non-linear least squares regression fitting is used, taking into account the predefined boundaries $[0, \infty)$. The theoretical joint CCDF is calculated by using single site CDFs u_1 and u_2 and the obtained parameter as an input to expression (5.28).

Two examples of modelling joint CCDF of rain attenuation for two-site systems are presented hereafter, based on the database DBSG3 [72]. The first example is from Austin and Bee Caves in the USA, with operational frequency of 13.6 GHz, the separation distance is equal to 15.8 km, baseline orientation angle is 79° and elevation angles is 52° . Figure 5.18 depicts the rain attenuation CCDFs obtained for this experiment. The measured single links CCDFs and experimental joint CCDF are given as an input to Eq. (5.28). The value of $\theta = 172.82$ is obtained from the fitting procedure. As a result, a very accurate fitting of the hyperbolic copula model to the experimental data is achieved.

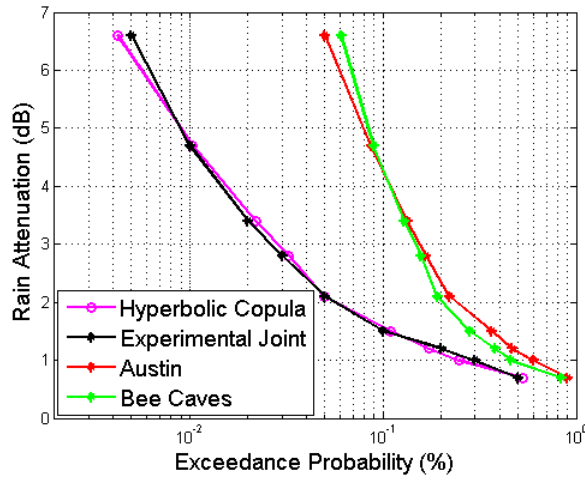


Figure 5.18: Two-site diversity attenuation in Austin and Bee Caves in USA.

Measurements from the stations in Vernet and La Conception in Canada are taken as the second example [72], with rather different configuration parameters. The operating frequency is 13 GHz, the elevation angle is 18° , baseline orientation angle is 65° and the separation distance between the stations is 31.8 km. The experimental and the calculated rain attenuation CCDFs are depicted in Figure 5.19. The copula parameter θ of the experiment is 155.72, which is lower compared to the first experiment. This can be ascribed to different experimental configuration parameters, among which distance is believed to play a crucial role. Note that for a higher distance, a lower θ is obtained.

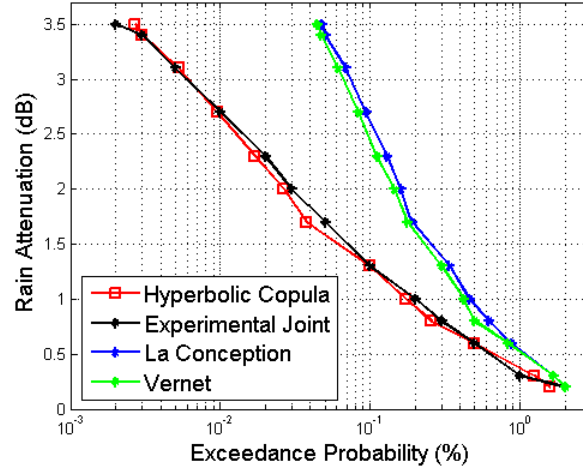


Figure 5.19: Two-site diversity attenuation in Vernet and La Conception in Canada.

The same fitting procedure as described above was repeated for forty-four experiments from DBSG3 [72]. In addition, nine more dual site experiments from [97, 108, 109] are investigated. The parameters θ are extracted for all the 53 analyzed experiments. The errors between theoretical expression (5.28) and experimental joint exceedance probabilities are then calculated according to ITU-R P.311-15 [110]. The mean value, the standard deviation and the rms of the total error are calculated. The resulting total mean value of error is 0.90%, the standard deviation is 13.02% and the rms is 13.05%. A low error performance from the fitting procedure is evident.

Similarly, we analysed several other Archimedean copula families, not used before, for the prediction of the joint rain attenuation CCDFs. The fitting procedure results in a worse error performance compared to the hyperbolic cosecant copula. Therefore, the hyperbolic copula was used for modelling of joint exceedance probability of rain attenuation. In the next subsection, two prediction models of joint rain attenuation statistics for dual and multisite diversity systems are proposed.

5.3.3 Joint CCDF of rain attenuation prediction model

For the prediction of joint exceedance probability of rain attenuation for two-site diversity systems based on expression (5.28), the single site u_1 and u_2 need to be known, while the parameter θ needs to be mathematically determined. Numerical analysis of experimental parameters shows that θ depends primarily on the horizontal separation distance between two Earth stations. In general, θ tends to decrease with increasing distance. Some slight variation of this rule can be observed for experimental pairs with similar distances, which could be ascribed to different geometrical characteristics such as elevation angle and baseline orientation. Other possible causes are different operating frequencies and spatial heterogeneity of rainfalls in different geographical locations. As shown in [119], the weather direction may also play a notable role.

We propose and analyse two versions of the prediction model. First, the parameter θ is modelled only as a function of the separation distance (d). Second, the model is extended by considering the dependency on the elevation angle (ψ) and on the baseline angle (b).

5.3.3.1 Distance based joint CCDF rain attenuation prediction method

Using all the parameters obtained from the fitting process and applying a nonlinear regression method, we found that θ can be expressed as a function of distance:

$$\theta(d) = Ae^{(-\frac{d}{\alpha})} + Be^{-(\frac{d}{\beta})^2} \quad (5.29)$$

where $A = 201$, $\alpha = 49$, $B = 566$, $\beta = 6.8$, and d is horizontal distance expressed in km. The comparison between copula parameters θ from Eq. (5.29) and from measurements data as a function of distance is for distances up to 180 km depicted in Figure 5.20.

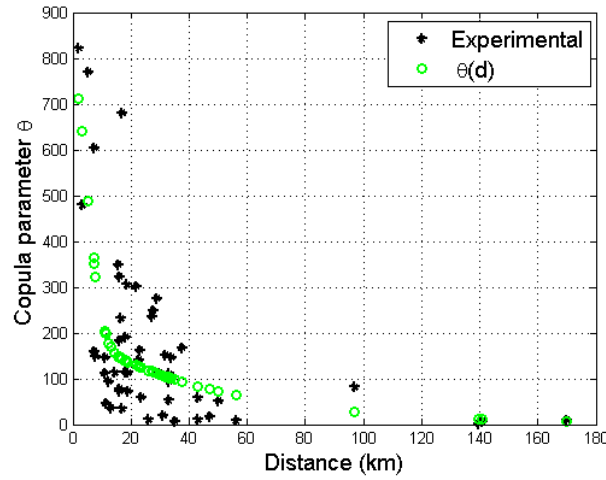


Figure 5.20: Theoretical and experimental copula parameter $\theta(d)$.

An example of the prediction of joint rain attenuation CCDF was performed by using the experimental data from Crawford Hill and Sayreville in the USA [72]. Figure 5.21 depicts the predicted curve in comparison to the experimental joint CCDF and the accompanying measured single site CCDFs.

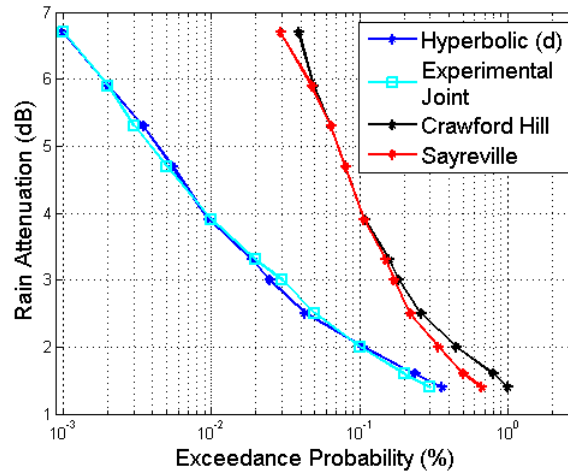


Figure 5.21: CCDFs for a two-site diversity experiment in Crawford Hill and Sayreville.

Equation (5.29) returned $\theta = 102.49$ for the separation distance of 33 km between the Earth stations. The θ parameter was then used as an input for the equation (5.28) in order to express the predicted joint CCDF. As observed from the graph, a very accurate prediction with small error was achieved. This first version of prediction method, depending only on distance (d), is referred to as the Hyperbolic (d).

5.3.3.2 Distance, elevation and baseline angle based joint CCDF rain attenuation prediction method

An assumption was made that the mathematical description of the parameter θ in Eq. (5.29) could be improved further by including additional input configuration variables which increase the accuracy of the model. Therefore, besides the separation distance, the elevation angle and the baseline angle are included. Based on the investigated experiments, we noted that by increasing the baseline orientation angle and the elevation angle, the performance of the site diversity system was improved, which is expressed by a decreased value of θ . Based on the analysis of different expressions using nonlinear regression fitting, we found that parameter θ can be expressed as the following function of the distance, the baseline orientation and the elevation angle:

$$\theta(d, b, \psi) = Ae^{(-\frac{d}{\alpha - \lambda b - \gamma \psi})} + Be^{-(\frac{d}{\beta})^2}, \quad \alpha - \lambda b - \gamma \psi > 0 \quad (5.30)$$

where $A = 340$, $B = 300$, $\alpha = 67$, $\lambda = 0.34$, $\gamma = 0.59$, $\beta = 10$, and d is the distance expressed in km, and b and ψ are the baseline and the elevation angles expressed in degrees, respectively, where b is always lower than 90 degrees. The values of b and ψ must satisfy the condition $\alpha - \lambda b - \gamma \psi > 0$. This condition is not very restrictive, as all of the 53 analysed experiments comply with it. This version of prediction method, which depends on d, b and ψ , is referred to as the Hyperbolic (deb). The comparison between copula parameters θ from Eq. (5.30) and from measurements data as a function of distance is for distances up to 180 km depicted in Figure 5.22.

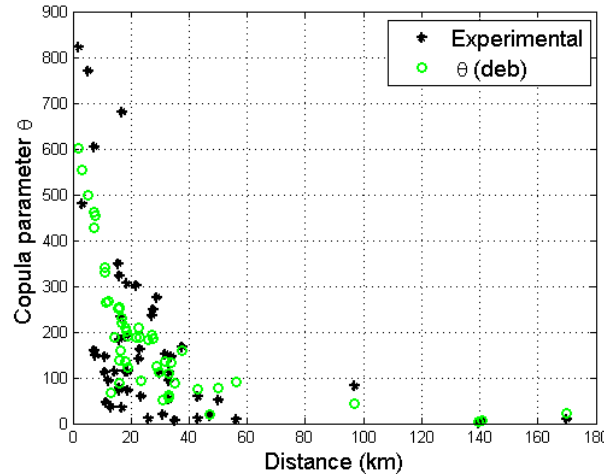


Figure 5.22: Theoretical and experimental copula parameter $\theta(\text{deb})$.

An example of prediction is shown in Figure 5.23. CCDFs for the two-site diversity system in Atlanta and in Cobb County, USA [72] are depicted. The predictions were made using both the Hyperbolic (d) and the Hyperbolic (deb) method. As expected, a

more accurate prediction model was achieved by the Hyperbolic (deb). A comprehensive error performance analysis and comparison of both methods are given in subsection 5.3.4.

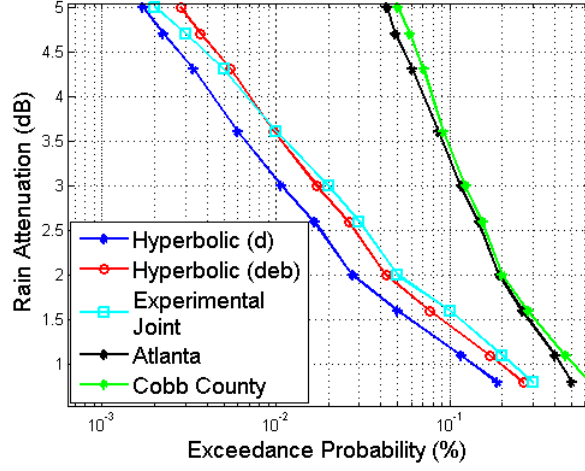


Figure 5.23: Two-site diversity attenuation in Atlanta and Cobb County, USA.

5.3.3.3 Three and multiple site diversity prediction model using HAC

The methodology is extended from the common two-site case to a general case with an arbitrary number of sites. The procedure is first derived for a three-site diversity case and then generalized to an n -site case. By using Eq.(5.21), the joint CCDF of rain attenuation for three-sites can be expressed as:

$$P[A_1 \geq A_{th}, A_2 \geq A_{th}, A_3 \geq A_{th}] = 1 - u_1 - u_2 - u_3 + C_{1,2}(u_1, u_2, \theta_{12}) + C_{1,3}(u_1, u_3, \theta_{13}) + C_{2,3}(u_2, u_3, \theta_{23}) + C_{1,2,3}(u_1, u_2, u_3, \theta_{123}) \quad (5.31)$$

The three copula functions $C_{1,2}$, $C_{1,3}$, $C_{2,3}$ can be calculated from Eq. (5.27) and the values θ_{12} , θ_{13} and θ_{23} are determined from either Eq. (5.29) or (5.30) by taking into account the distances d_{12} , d_{13} , d_{23} , the baseline angles b_{12} , b_{13} , b_{23} , and the elevation angles ψ_{12} , ψ_{13} , ψ_{23} , belonging to the corresponding pairs of the stations. For the tri-variate copula $C_{1,2,3}$ only a single parameter θ_{123} has to be determined. It represents inter-dependency of the three variables u_1 , u_2 , u_3 of the three stations and as such cannot be expressed directly from expressions (5.29) or (5.30). Thus, applying the HAC structure from (5.19), the joint CCDF becomes

$$P[A_1 \geq A_{th}, A_2 \geq A_{th}, A_3 \geq A_{th}] = 1 - u_1 - u_2 - u_3 + C_{1,2}(u_1, u_2, \theta_{12}) + C_{1,3}(u_1, u_3, \theta_{13}) + C_{2,3}(u_2, u_3, \theta_{23}) - C_4(C_{1,2}(u_1, u_2, \theta_{12}), u_3, \theta_4) \quad (5.32)$$

Since the θ_4 of the copula C_4 expresses the dependency between variables $v = C_{1,2}(u_1, u_2)$, and u_3 , i.e., $C_4(v, u_3, \theta_4) = C_4(C_{1,2}(u_1, u_2), u_3, \theta_4)$ and since the equations (5.29) and (5.30) are to be applied, a meaningful definition of θ_4 based on parameters d_4 , b_4 and ψ_4 has to be found. For equation (5.29), we propose the distance d_4 to be calculated as the distance between the station 3 and the middle point (M) between stations 1 and 2, as illustrated in Figure 5.24. For equation (5.30), baseline angle b_4 and elevation angle ψ_4 are needed in addition to d_4 . The same logic is followed in this case; baseline angle b_4 is proposed to represent the angle between the ground projection of

satellite path to station 3 and the line which connects this station with the middle point M, whereas elevation angle ψ_4 is the elevation angle of the ground station 3. Note that baseline and elevation angles are assumed to be equal for both locations (stations) in any of the station pairs, which is a consequence of much larger distance between the satellite and Earth stations compared to the distances among the Earth stations. Thus for example, the baseline angle b_4 and elevation angle ψ_4 could be determined also at the middle point M.

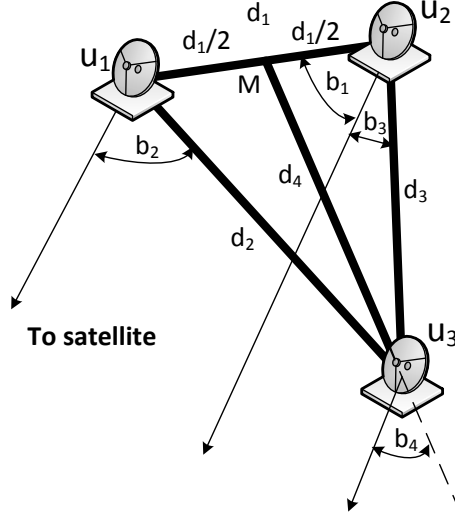


Figure 5.24: A general three-site diversity configuration.

Considering that $C_{1,2}$ and C_4 are from the same family of copulas, we need to guarantee that $\theta_4 < \theta_{12}$. If Eq. (5.29) is applied, the condition is fulfilled when d_4 is greater than d_1 . In general, this can be achieved by varying the station numbers, i.e., the distance d_4 has to be chosen properly among the three options. However, in the case of a triangle with equal sides, this is impossible. One of the advantages of using Eq.(5.30) is that the condition $\theta_4 < \theta_{12}$ relies also on values of b and ψ which can make the condition achievable also for equilateral triangles.

Based on hyperbolic cosecant generator in Eq. (5.22) and expressions (5.19) and (5.27), the joint CCDF for three-site diversity in Eq. takes the form:

$$\begin{aligned}
 P[A_1 \geq A_{th}, A_2 \geq A_{th}, A_3 \geq A_{th}] &= 1 - u_1 - u_2 - u_3 \\
 &+ \left[\operatorname{acsch}(\operatorname{csch}(u_1^{\theta_{12}}) + \operatorname{csch}(u_2^{\theta_{12}}) - \operatorname{csch}(1)) \right]^{\frac{1}{\theta_{12}}} \\
 &+ \left[\operatorname{acsch}(\operatorname{csch}(u_1^{\theta_{13}}) + \operatorname{csch}(u_3^{\theta_{13}}) - \operatorname{csch}(1)) \right]^{\frac{1}{\theta_{13}}} \\
 &+ \left[\operatorname{acsch}(\operatorname{csch}(u_2^{\theta_{23}}) + \operatorname{csch}(u_3^{\theta_{23}}) - \operatorname{csch}(1)) \right]^{\frac{1}{\theta_{23}}} \\
 &- \left[\operatorname{acsch} \left(\operatorname{csch} \left[\operatorname{acsch}(\operatorname{csch}(u_1^{\theta_{12}}) + \operatorname{csch}(u_2^{\theta_{12}}) - \operatorname{csch}(1)) \right]^{\frac{\theta_4}{\theta_{12}}} + \operatorname{csch}(u_3^{\theta_4}) \right. \right. \\
 &\quad \left. \left. - \operatorname{csch}(1) \right) \right]^{\frac{1}{\theta_4}}
 \end{aligned} \tag{5.33}$$

Two examples of joint attenuation CCDF prediction are shown hereafter for the three-site case. The first example involves two Earth stations located approximately

7.8 km apart in Chilbolton and Sparsholt in the southern UK and the third station in Dundee, Scotland, approximately 600 km north of the two [109]. The operating frequency is 20.7 GHz. In order to ensure that $d_1 < d_4$, u_1 and u_2 were chosen to correspond to rain attenuation CDFs of Chilbolton and Sparsholt, while u_3 was the CDF of Dundee. The parameters θ_{12} , θ_{13} , θ_{23} , and θ_4 were then calculated from Eq. (5.29) and the joint CCDF from Eq. (5.33). Experimental and predicted CCDFs are depicted in Figure 5.25. In this example, the prediction model Hyperbolic (d) gave satisfactory results, also confirming our assumption about the relation between θ_4 and the distance d_4 .

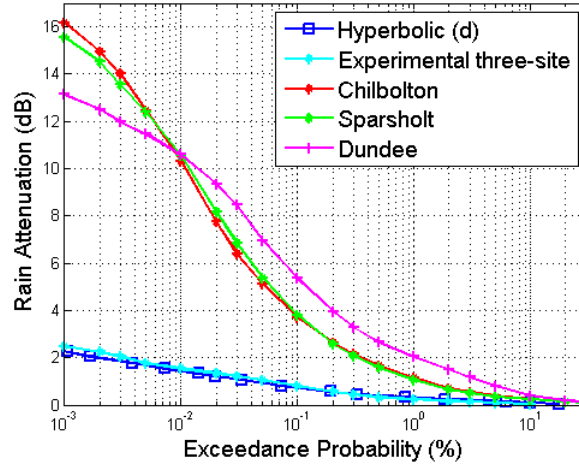


Figure 5.25: Three-site diversity attenuation in Chilbolton, Sparsholt, Dundee, in UK.

In the next example, the strength of the Hyperbolic (deb) method is demonstrated. The analysis is based on the dataset of our own experiment, performed in Slovenia and in Austria [108]. The Slovenian stations in Ljubljana and in Lisec are around 40 km apart, while the Austrian station in Graz is about 140 km away from them. The stations 1, 2 and 3 were chosen to correspond to Ljubljana, Lisec and Graz, respectively. By applying the expression (5.29), the parameter values $\theta_{12} = 83.58$ and $\theta_4 = 12.02$ were obtained, while the expression (5.30) returned $\theta_{12} = 72.7$ and $\theta_4 = 5.10$. Thus in both cases, the condition $\theta_4 < \theta_{12}$ is satisfied. The graph in Figure 5.26 shows clearly that in this case, the Hyperbolic (deb) prediction method outperforms the Hyperbolic (d).

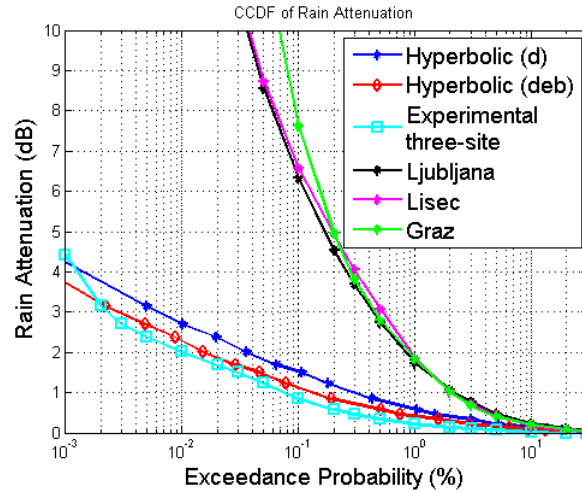


Figure 5.26: Three-site diversity attenuation in Ljubljana, Lisec, Graz.

The presented hyperbolic cosecant copula prediction method can be applied to diversity systems with an arbitrary number of sites, in a similar manner as for the three-site case, by using the equations (5.17), (5.21), and with proper utilization of the HAC structures. Any of the three presented HAC structures can be used, as long as the dependence parameters θ , defined by equation (5.29) or (5.30), decrease with the hierarchy level. Single site CDFs $u_i = 1 - P[A_i \geq A_{th}]$ can be derived from CCDFs of experimental data or by following Recommendation ITU-R P.618-12, paragraph 2.2.1.1 [18].

In order to apply the proposed procedure for the calculation of the joint CCDFs for two, three and more site diversity systems the following step-by-step procedure is given:

- calculate the parameters θ using Eq. (5.29) or Eq. (5.30).
- for every slant path use the single site CDF (u_i),
- for two-site diversity, calculate the joint CCDF using Eq. (5.28),
- for three site diversity assign u_1, u_2, u_3 to the sites to fulfil $\theta_4 < \theta_{12}$, $\theta_{1,2} > (\theta_{13}, \theta_{23})$, and calculate CCDF using (5.33)
- for multiple-site diversity, use the equations (5.17), (5.21), (5.22), (5.23), express the multivariate copula in (5.21) by any HAC structure and assign the u_i that the copula parameters decrease with hierarchy level.

5.3.4 Comparative tests and error performance of prediction models – two-site diversity systems

Both versions of the proposed prediction method were validated by comprehensive tests in terms of error performance. The predicted joint exceedance probability distributions were compared to experimental distributions for 53 mentioned two-site diversity experiments and additionally to a one year data distribution for three new ongoing experiments in Slovenia and Austria. Therefore altogether 56 two-site diversity experiments are included in the error performance comparison. Single site CDFs were taken from experimental data. The errors were computed according to ITU-R P.311-15 error criterion and expressed as mean errors, standard deviations and rms values [110]. For comparative purposes, the same evaluation was done for the model proposed in ITU-

R P.618-12, paragraph 2.2.4.1 [71] and the recently proposed models based on copula theory, the Clayton copula [8] and the both versions of the Gaussian copula [120, 121].

Since there are a small number of experiments with data at percentages above 1%, the analysis for two-site diversity is given only for the probability range between 0.001% and to 1% which are the most important exceedance probabilities for Earth-satellite propagation studies.

Table 5.5 summarizes the error performance in terms of mean error, standard deviation and rms value, over all 56 experiments and six considered models. In the overall analysis, the Hyperbolic (deb) model performs better than Hyperbolic (d), whereas both models based on Gaussian copula performs the best. Moreover in Figure 5.27, Figure 5.28 and Figure 5.29, the mean value, std and rms of the error are depicted respectively for different percentages separately for all experiments. From a closer review of the rms error in Figure 5.29 it can be observed that for 56 experiments the Hyperbolic (deb) outperforms all the models within the range 0.01% up to 0.1%, while out of this range two models based on the Gaussian copula performs the best. Hyperbolic (d) shows similar performance to Clayton, and slightly worse performance compared to Hyperbolic (deb) for almost all percentages.

Table 5.5: Total error performance comparison for 56 two-site diversity experiments.

Model	$\epsilon_{\text{mean}}(\%)$	$\epsilon_{\text{std}}(\%)$	$\epsilon_{\text{rms}}(\%)$
ITU-R P.618-12	-19.35	26.66	32.94
Clayton	9.81	20.51	22.74
Gaussian (d)	1.22	17.76	17.80
Gaussian (deb)	4.61	16.55	17.18
Hyperbolic (d)	5.57	20.58	21.32
Hyperbolic (deb)	4.83	18.63	19.25

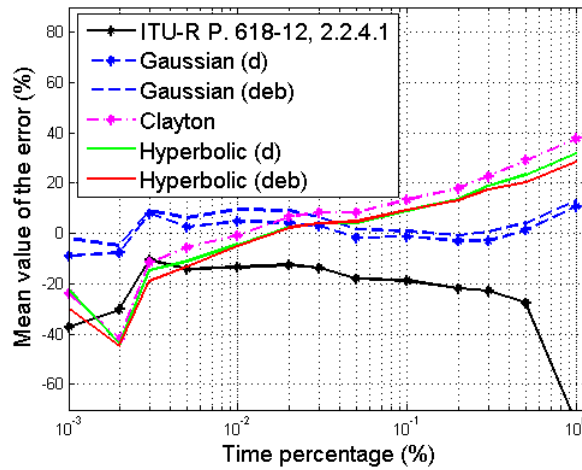


Figure 5.27: Mean value of error for various probabilities for 56 experiments.

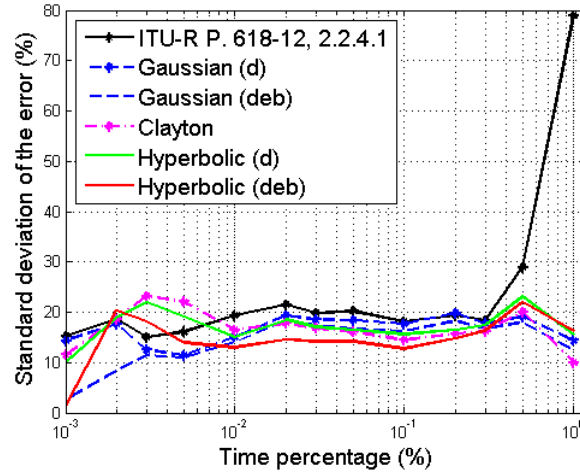


Figure 5.28: Standard deviation of error for various probabilities for 56 experiments.

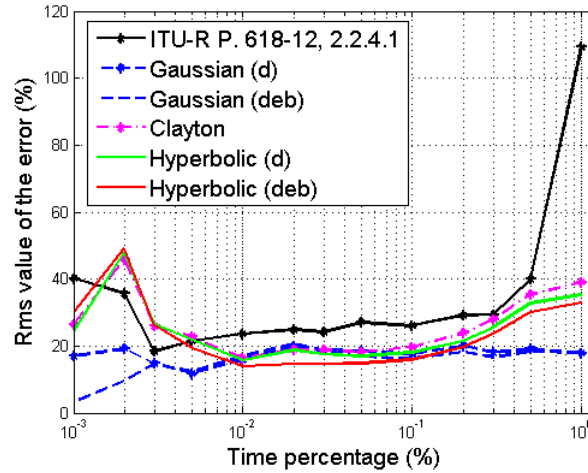


Figure 5.29: Rms value of error for various probabilities for 56 experiments.

Since the strength of the Hyperbolic (deb) is in its capability to account for system's angular geometry, further investigation was performed on the impact of angular values on the model's accuracy. The purpose of this investigation was to find out for which type of system configurations it is particularly important to choose Hyperbolic (deb) instead of Hyperbolic (d). A detailed analysis of all available data showed that the error performance was particularly improved for 28 two-site experiments with intermediate inter-site distances between 10 km and 150 km, low elevation angles which do not exceed 40° , and high baseline angles above 40° . The rms value of error for the Hyperbolic (deb) in this case was 17.46% compared to 21.71% for the Hyperbolic (d). Moreover, for this set of experiments, better performance of the Hyperbolic (deb) was expressed also in comparison to the Gaussian (d) model with rms 18.56%. However the Gaussian (deb) performs the best with rms value 15.51%. The error performance for this group of experiments is given in Table 5.6.

Table 5.6: Error performance for 28 two-site diversity experiments.

Model	$\epsilon_{\text{mean}}(\%)$	$\epsilon_{\text{std}}(\%)$	$\epsilon_{\text{rms}}(\%)$
ITU-R P.618-12	-20.55	26.03	33.17
Clayton	10.59	20.83	23.37
Gaussian (d)	-0.09	18.56	18.56
Gaussian (deb)	1.67	15.41	15.51
Hyperbolic (d)	7.86	20.23	21.71
Hyperbolic (deb)	5.39	16.61	17.46

In Figure 5.30, Figure 5.31 and Figure 5.32, the error analysis is also given for different probabilities. Figure 5.31 clearly shows a stable behaviour of the Hyperbolic (deb), as its standard deviation is lower compared to all other models for almost all percentages. The rms error analysis in Figure 5.32 shows that the Hyperbolic (deb) performs better than the Clayton, the Hyperbolic (d) and the ITU-R model for almost all percentages, while compared to the Gaussian models, it performs slightly better for percentages $0.01\% < p < 0.1\%$.

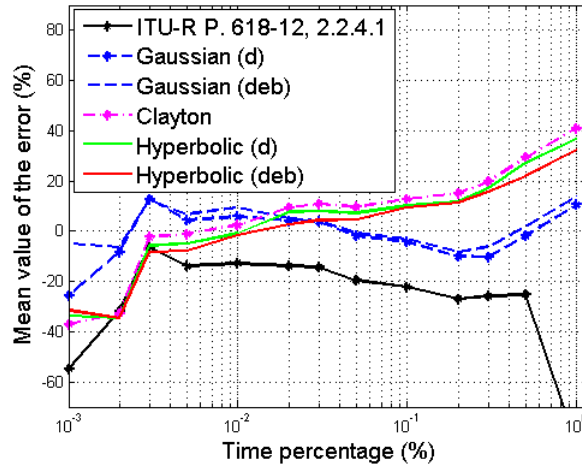


Figure 5.30: Mean values of error for various probabilities for 28 experiments.

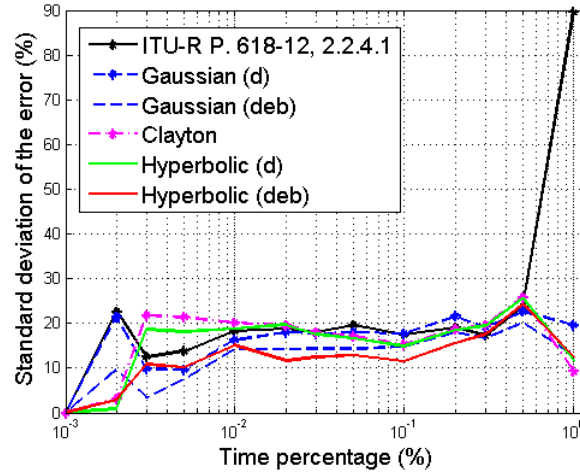


Figure 5.31: Standard deviation of error for various probabilities for 28 experiments.

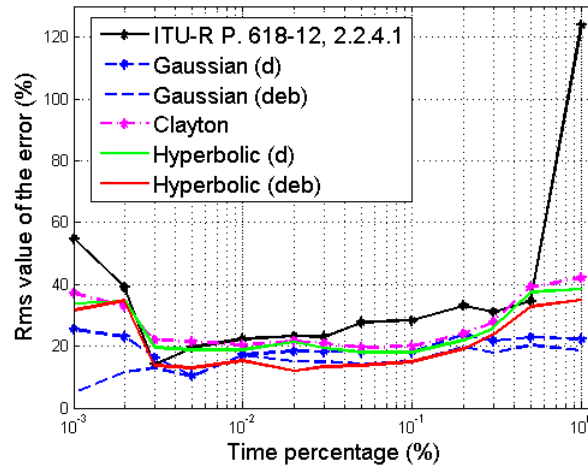


Figure 5.32: Rms value of error for various probabilities for 28 experiments.

The subset of the 28 experiments analysed above was chosen based on the performance comparison of the Hyperbolic (d) and the Hyperbolic (deb). For the performance comparison between Hyperbolic (deb), Gaussian (d) and Gaussian (deb), as the three best models in the overall performance, we studied representative subsets of the experiments for which every model performs the best.

Detailed analyses of all experiments revealed that for the majority of the experiments which are located in Canada, the USA and Japan, the Hyperbolic (deb) performs the best. The total error analyses of the 31 experiments located in these three countries are depicted in Table 5.7, while the mean, standard deviation and rms of the errors as a function of different time probabilities are depicted in Figure 5.33, Figure 5.34 and Figure 5.35, respectively. From Figure 5.34 and Figure 5.35 it is evident that the best performance of the Hyperbolic (deb) is expressed within probability range 0.01% to 0.2%.

Table 5.7: Error for two-site diversity experiments from USA, Canada and Japan.

Model	$\epsilon_{\text{mean}}(\%)$	$\epsilon_{\text{std}}(\%)$	$\epsilon_{\text{rms}}(\%)$
ITU-R P.618-12	-25.09	21.40	32.98
Clayton	4.10	18.88	19.32
Gaussian (d)	-4.73	21.01	21.54
Gaussian (deb)	1.62	18.74	18.81
Hyperbolic (d)	1.51	19.47	19.53
Hyperbolic (deb)	3.90	16.06	16.53

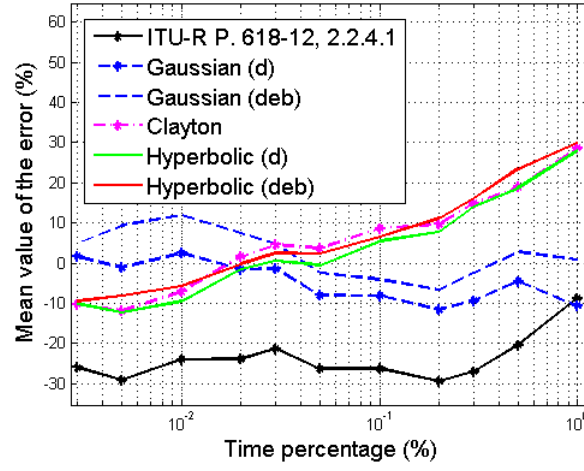


Figure 5.33: Mean value of error for experiments from USA, Canada and Japan.

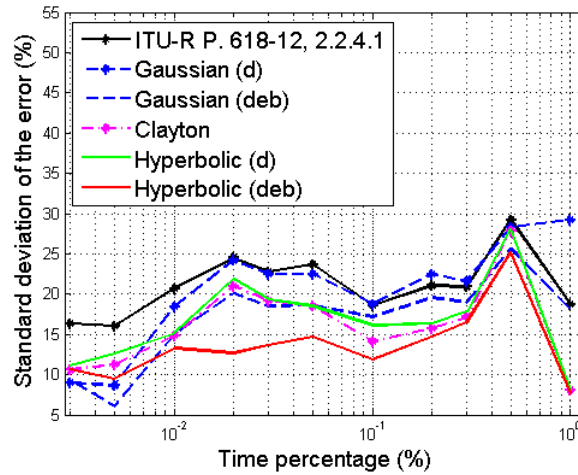


Figure 5.34: Standard deviation of error for experiments from USA, Canada and Japan.

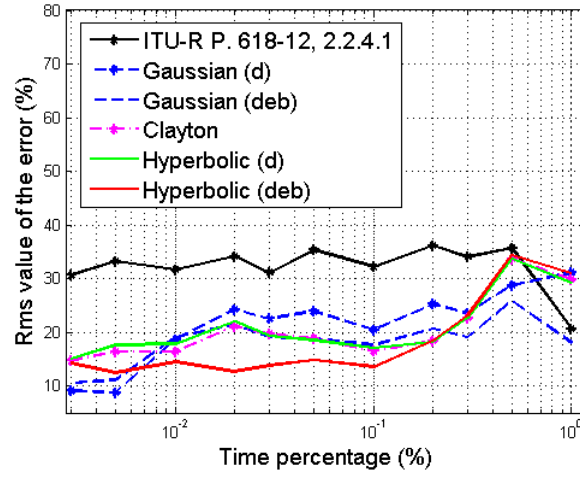


Figure 5.35: Rms value of error for experiments from USA, Canada and Japan.

The error performances of the 24 experiments which are located in European countries are presented in Table 5.8. Results show that the Gaussian (d) outperforms all other tested models. The mean, standard deviation and rms of the errors as a function of different time probabilities are depicted in Figure 5.36, Figure 5.37 and Figure 5.38, respectively.

Table 5.8: Error for two-site diversity experiments from from Europe.

Model	$\epsilon_{\text{mean}}(\%)$	$\epsilon_{\text{std}}(\%)$	$\epsilon_{\text{rms}}(\%)$
ITU-R P.618-12	-15.65	29.71	33.58
Clayton	13.61	20.50	24.61
Gaussian (d)	5.96	11.54	12.99
Gaussian (deb)	7.03	14.13	15.79
Hyperbolic (d)	8.04	20.79	22.30
Hyperbolic (deb)	5.13	20.41	21.05

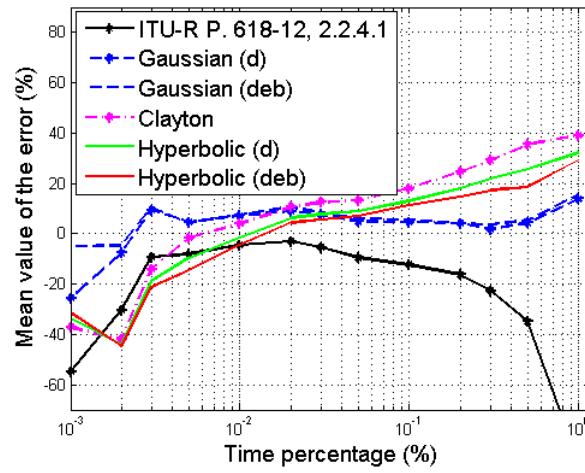


Figure 5.36: Mean value of error for experiments from Europe.

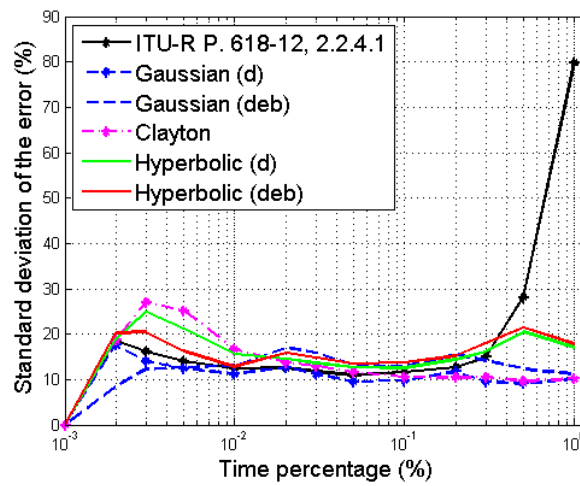


Figure 5.37: Standard deviation of error for experiments from Europe.

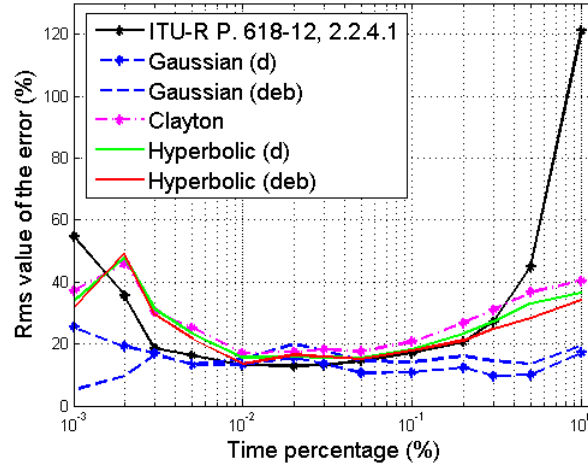


Figure 5.38: Rms value of error for experiments from Europe.

For the last set of two-site diversity analyses 26 experiments with distances larger than 10 km and baseline orientation angles greater than 45° were chosen. The total errors for this group are given in Table 5.9, while the analysis with respect to different probabilities is given in Figure 5.39, Figure 5.40 and Figure 5.41. It is evident that Gaussian (deb) gives the smallest rms error and standard deviation.

Table 5.9: Error performance for experiments with $b > 45^\circ$ and $d > 10$ km.

Model	$\epsilon_{\text{mean}}(\%)$	$\epsilon_{\text{std}}(\%)$	$\epsilon_{\text{rms}}(\%)$
ITU-R P.618-12	-18.70	22.74	29.44
Clayton	9.99	20.38	22.70
Gaussian (d)	1.07	17.21	17.24
Gaussian (deb)	2.30	13.57	13.77
Hyperbolic (d)	7.71	20.09	21.52
Hyperbolic (deb)	5.02	16.88	17.61

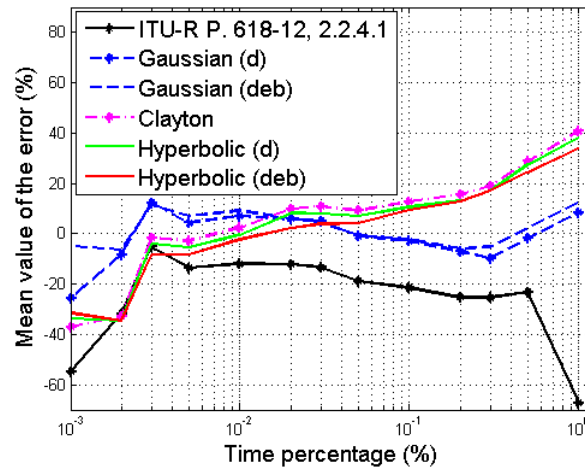


Figure 5.39: Mean value of error for experiments with $b > 45^\circ$ and $d > 10$ km.

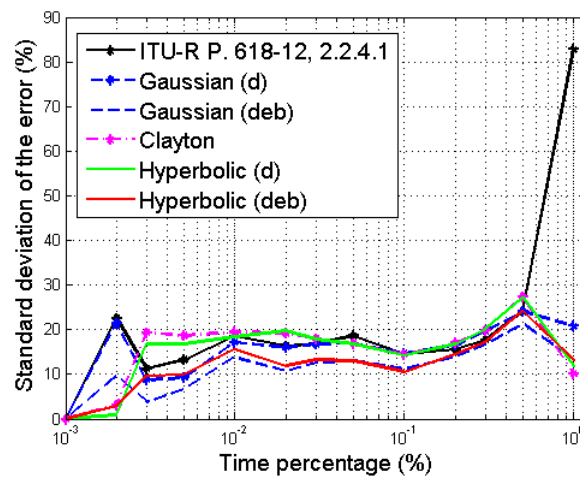


Figure 5.40: Standard deviation of error for experiments with $b > 45^\circ$ and $d > 10$ km.

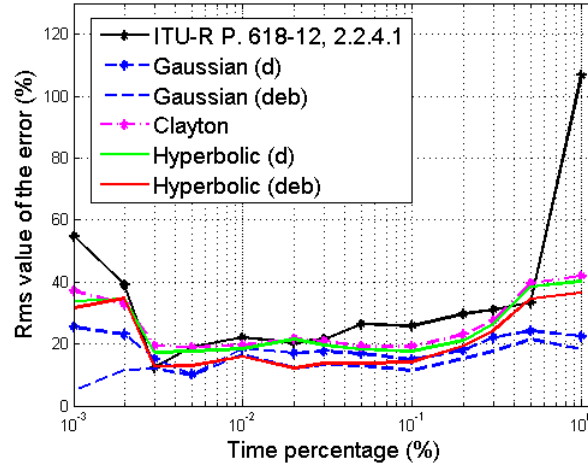


Figure 5.41: Rms value of error of experiments with $b > 45^\circ$ and $d > 10$ km.

Experiments from the tropical regions are not available or are very rare. Due to the geographical location, the climate in this region is characterized by high humidity and abundant rainfall and severe attenuations are evident for high percentages of the time. We have tested the performance of the four models with data from a recent two-site diversity experiment performed in Malaysia where the climate is classified as equatorial. The distance between two Earth-stations is 70 km, with elevation angle 25.24° and 26.15° , respectively. They measure beacon at frequency of 20.245 GHz from Syracuse 3A satellite with the orbital position 47°E [122]. In Figure 5.42 are depicted the joint CCDFs obtained from four models and compared to experimental data. The single site CCDFs for both locations are also depicted. High attenuation values exceeding 25 dB for 0.1% of time are evident. The curves of the predicted joint CCDFs show that the Gaussian models perform very well, while the Hyperbolic models overestimate the joint CCDF. This experiment indicates that the Gaussian models may be appropriate for prediction in these regions, however the evaluation of the models with the data from future experiments are needed.

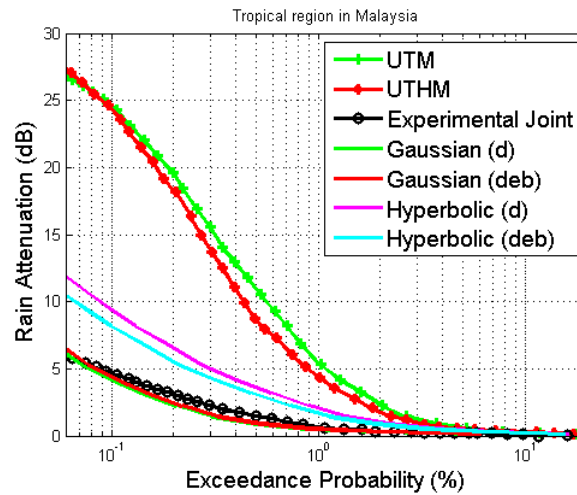


Figure 5.42: Single site and two-site diversity CCDFs of attenuation in Malaysia.

5.3.5 Comparative tests and error performance of prediction models – three-site diversity systems

The error performance of the proposed models was analysed also for three-site diversity systems. Unlike the two-site experiments, three-site experiments are very rare and altogether only eleven experiments from Europe and the USA were analysed. The European experiments consist of five three-site diversity systems in Slovenia-Austria, one experiment from Norway [97] and one from the UK [109]. The USA experiments consist of one experiment in [96] based on beacon signal data and three experiments with radiometer data of rain attenuation [123].

In Table 10 the total error performance for all eleven three-site diversity systems is depicted. Generally, the Gaussian models perform better than hyperbolic models. The Hyperbolic (deb) performs better than Hyperbolic (d) and Gaussian (deb) performs the best of all. The mean value, standard deviation and rms for different time percentages are shown in Figure 5.43, Figure 5.44 and Figure 5.45. It is evident that the two Gaussian models perform the best for percentages higher than 0.02%, while for percentages lower than 0.02% the Hyperbolic (deb) and Gaussian (deb) models show the best performance in terms of rms error.

Table 5.10: Comparison of total three-site diversity prediction performance.

Model	$\epsilon_{\text{mean}}(\%)$	$\epsilon_{\text{std}}(\%)$	$\epsilon_{\text{rms}}(\%)$
Gaussian (d)	-1.66	14.13	14.23
Gaussian (deb)	-1.59	13.51	13.60
Hyperbolic (d)	25.91	25.10	36.07
Hyperbolic (deb)	17.69	21.98	28.23

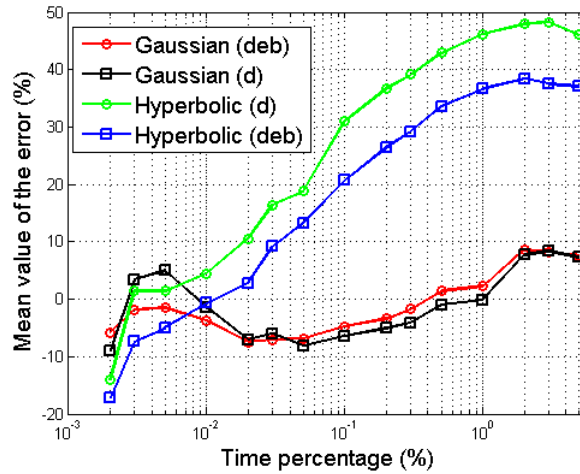


Figure 5.43: Mean value of error for experiments from Europe and the USA.

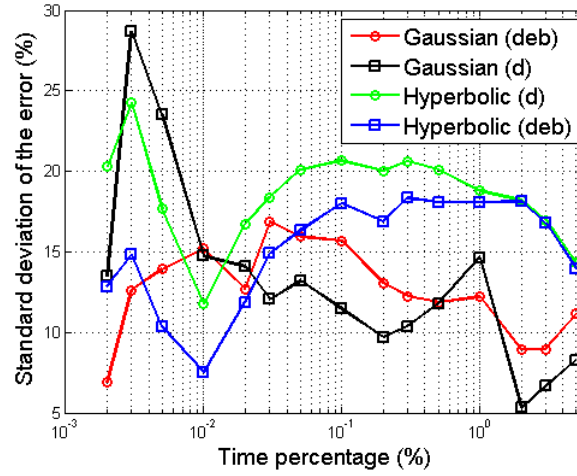


Figure 5.44: Standard deviation of error for experiments from Europe and the USA.

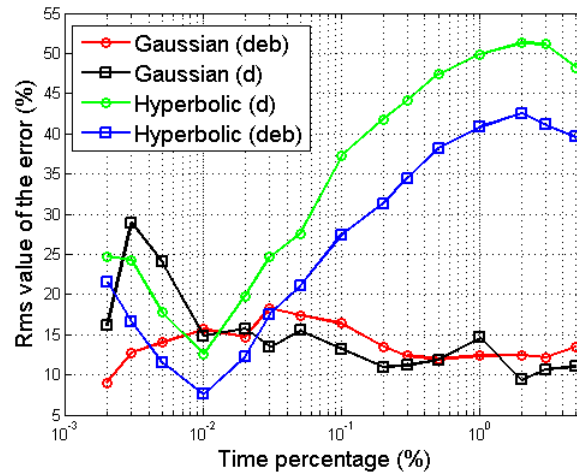


Figure 5.45: Rms value of error for experiments from Europe and the USA.

Considering that the experiments are from two temperate regions, Europe and the USA, in the following subsections the prediction performance for both regions is analysed separately.

5.3.5.1 Comparison of the three-site diversity experiments from the USA

Four experiments are included in analysis of error performance from the USA. Note that for available attenuation data within the given percentages interval, depending on the model the prediction may appear in a different time percentage interval. Therefore, the error performances are depicted separately in Figure 5.46, Figure 4.47 and Figure 4.48 in terms of mean, standard deviation and rms for concurrent percentages of CCDF intervals between each model and experimental data.

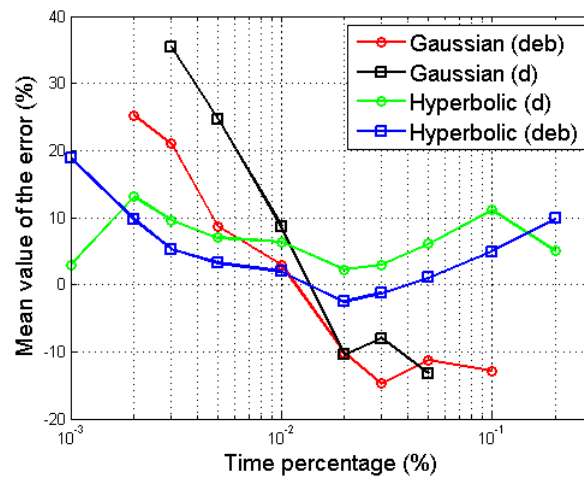


Figure 5.46: Mean values of error for experiments from the USA.

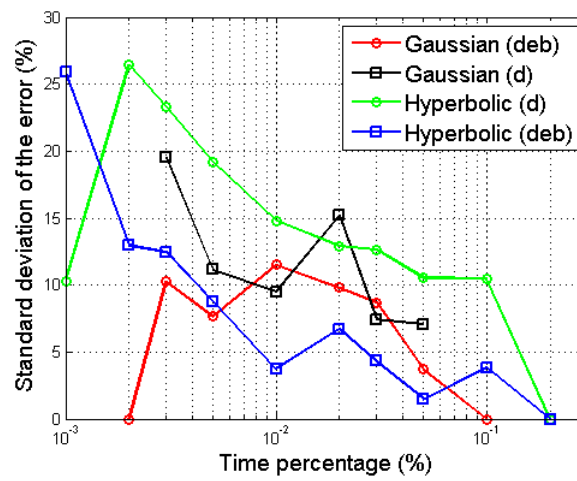


Figure 5.47: Standard deviation of error for experiments from the USA.

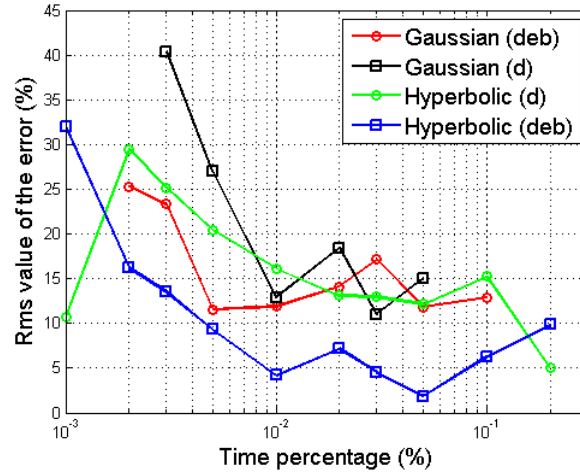


Figure 5.48: Rms value of error for experiments from the USA.

From Figure 5.48 it is clear that the Hyperbolic (deb) performance is quite good at demonstrating small rms errors. However, for general comparison of models the total error is calculated taking into account for each experiment only percentages where the attenuation data predicted from all models and experimental data exists. This is in compliance with the only method comparison which is used in the thesis for total error computation. The complete error comparison performance is given in Table 5.11.

Table 5.11: Total error performance of three-site diversity experiments from USA.

Model	$\epsilon_{\text{mean}}(\%)$	$\epsilon_{\text{std}}(\%)$	$\epsilon_{\text{rms}}(\%)$
Gaussian (d)	2.89	21.62	21.82
Gaussian (deb)	-4.22	12.35	13.06
Hyperbolic (d)	6.91	14.68	16.22
Hyperbolic (deb)	1.17	5.93	6.05

While the Hyperbolic (deb) has the smallest error values and performs the best, Gaussian (deb) model performs better than Gaussian (d) and Hyperbolic (d) models which consider only distance between the stations. Because the distances between stations are small in these experiments, the Hyperbolic (deb) model is recommended for the prediction of joint rain attenuation CCDF for small range three-site diversity systems. An example of the attenuation prediction for three-site diversity system [123] is shown in Figure 5.49. The CCDF of joint rain attenuation predicted by Hyperbolic (deb) best fits the experimental data joint CCDF.

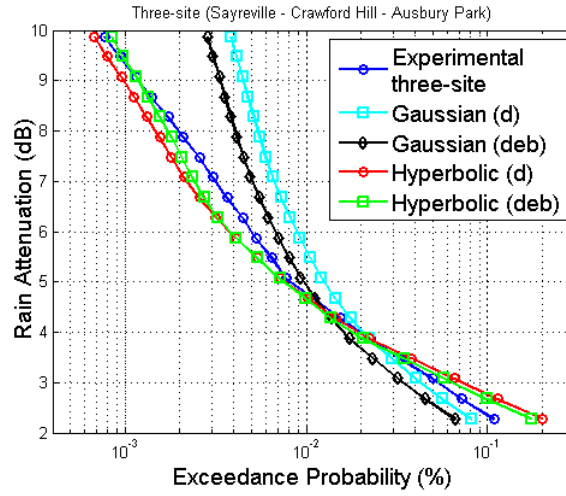


Figure 5.49: The measured and predicted CCDFs of a three-site diversity in the USA.

5.3.5.2 Comparison of the three-site diversity experiments from Europe

The error performance of four prediction models is analysed and compared to experimental data for seven European three-site diversity experiments. The error performance in terms of mean, standard deviation and rms values is presented for various prediction models for all experiments. The complete error comparison performance is given in Table 5.12. It is evident that both Gaussian models outperform both Hyperbolic models. In addition, in terms of standard deviation and rms error the Gaussian (d) performs slightly better than Gaussian (deb). Figure 5.50, Figure 5.51 and Figure 5.52 show the mean, standard deviation and rms error for different time percentages for all experiments. For percentages higher than 0.02%, the Gaussian (d) has the lowest error values. Low percentages are especially interesting in a high availability system. For percentages within range 0.005% up to 0.02% the Hyperbolic (deb) has the lowest rms error, while for percentages under 0.005% the Gaussian (deb) outperforms all other models.

Table 5.12: Total error performance of three-site diversity experiments from Europe.

Model	$\epsilon_{\text{mean}}(\%)$	$\epsilon_{\text{std}}(\%)$	$\epsilon_{\text{rms}}(\%)$
Gaussian (d)	-2.43	12.43	12.67
Gaussian (deb)	-1.14	13.71	13.76
Hyperbolic (d)	29.14	25.12	38.48
Hyperbolic (deb)	20.47	22.54	30.45

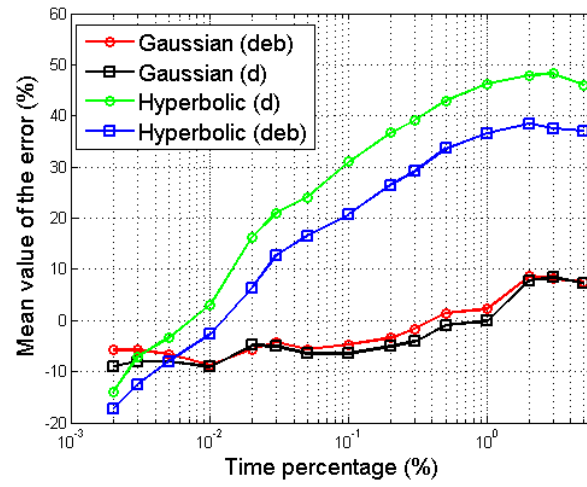


Figure 5.50: Mean value of error for experiments from Europe.

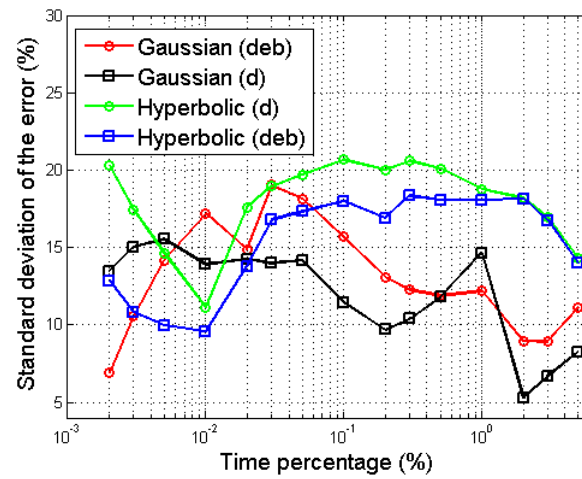


Figure 5.51: Standard deviation of error for experiments from Europe.

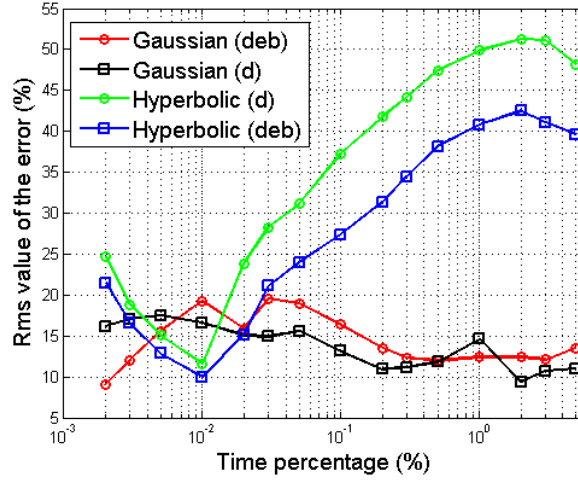


Figure 5.52: Rms value of error for experiments from Europe.

Among the seven experiments investigated in Europe, in six experiments the distances between two pairs of stations exceeds 100 km. The distances between two stations pairs of five experiments located in Slovenia-Austria are above 120 km, while the distances between the two pairs of stations in the UK three-site diversity experiment are around 600 km. Although the number of experiments is small for a general conclusion, it seems that the Gaussian models are the most suitable for prediction of the joint rain attenuation CCDF for three-site diversity systems with larger distances between stations. An example of the prediction of the three-site performance for three-site diversity system Ljubljana-Krvavec-Graz is shown in Figure 5.53. It is evident that the CCDFs of joint rain attenuation, predicted by Gaussian models fit better to the experimental data of joint CCDF than the Hyperbolic models.

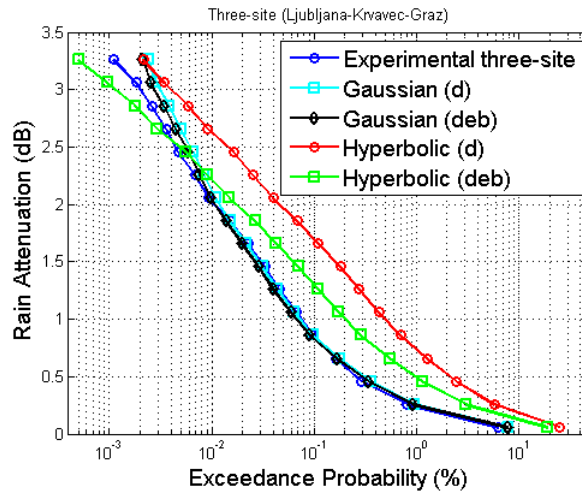


Figure 5.53: The measured and predicted CCDFs of a three-site diversity in Europe.

The geometrical characteristics of all three-site diversity configurations, namely, distances, elevations and baseline orientation angles, and assignments of the CDFs u_1, u_2, u_3 to corresponding stations, are given in Table 5.13. Two experiments with the same geometrical configurations and locations have been performed in Ljubljana, Lisec

and Graz. During the first experiment, which includes one years' measured data, the Graz station measured the beacon signal at Ka-band from Alphasat while the other two stations measured the signals from Astra 3B. In the second experiment all three stations were receiving the signal from Astra 3B. The satellites are close to each other in orbit and similar elevation and baseline angles are assigned for both experiments.

Table 5.13: Geometry characteristics and parameters for three-site diversity systems.

Stations (u_1, u_2, u_3)	distances (km)				elevations ($^\circ$)				baseline angles ($^\circ$)			
	d_{12}	d_{13}	d_{23}	d_4	ψ_{12}	ψ_{13}	ψ_{23}	ψ_4	b_{12}	b_{13}	b_{23}	b_4
Ljubljana Lisec Graz	40.7	138.1	141.4	138	36.5	36.3	35.4	35.4	50	47	29	37
Krvavec Ljubljana Lisec	28.5	58.2	40.7	48.2	36	36.3	35.5	35.5	17	23	50	34
Ljubljana Krvavec Graz	28.5	138.1	113.2	125.7	36.3	36	35.4	35.4	17	47	53	49
Krvavec Lisec Graz	58.2	113.2	141.4	124.8	36.3	36	35.4	36.4	22.4	53	29	37.5
Nittedal Kjeller Eggemoen	23	29.7	50.1	39.5	22	21.7	22	21.7	36	73	57	63.3
Chilbolton Sparsholt Dundee	7.8	601	608	604	27	23	23	23	30	21	21	21
Comsat Virginia APL	30.5	33	44.5	40	38.8	39.1	38.7	38.7	25	66	24	41
Ausbury Park Crawford Hill Perrineville	19	33	27	28.6	32	32	32	32	90	35	0	19
Temple Palmetto Major	16	47	31	39	38.2	38.2	38.2	38.2	90	90	90	90
Sayreville Crawford Hill Ausbury Park	11	30	19	24.5	32	32	32	32	90	90	90	90

5.3.6 Comparative tests and error performance of prediction models – four-site diversity system

The availability of data for evaluation of the proposed models in site diversity systems with more than three stations is not sufficient. To the best of our knowledge we established the only existing four-site diversity experimental configuration which has available CCDFs data [124].

The joint CCDF in four-site diversity is given by

$$\begin{aligned}
 P[A_1 \geq A_{th}, A_2 \geq A_{th}, A_3 \geq A_{th}, A_4 \geq A_{th}] = & 1 - u_1 - u_2 - u_3 - u_4 \\
 & + C_{1,2}(u_1, u_2) + C_{1,3}(u_1, u_3) + C_{2,3}(u_2, u_3) + C_{1,4}(u_1, u_4) + C_{2,4}(u_2, u_4) \\
 & + C_{3,4}(u_3, u_4) - C_{1,2,3}(u_1, u_2, u_3) - C_{1,2,4}(u_1, u_2, u_4) - C_{1,3,4}(u_1, u_3, u_4) \\
 & - C_{2,3,4}(u_2, u_3, u_4) + C_{1,2,3,4}(u_1, u_2, u_3, u_4)
 \end{aligned} \quad (5.34)$$

The copula functions in the Eq. (5.34) are expressed using expression (5.6) when predicted by Gaussian models, and the parameters are calculated from expression (5.12) and (5.16) for Gaussian (d) and Gaussian (deb), respectively. In case of Hyperbolic models the two-variate copulas are expressed by (5.27), three-variate copulas and four-variate copula are expressed by HAC structure as described in subsubsection 5.3.3.3. Copula $C_{1,2,3,4}$ is expressed by HAC structure as:

$$C_{1,2,3,4}(u_1, u_2, u_3, u_4) = C[C_1(C_{1,2}(u_1, u_2), u_3), u_4] \quad (5.35)$$

The variables u_1, u_2, u_3 , and u_4 correspond to Ljubljana, Krivavec, Lisec and Graz, respectively. In Figure 5.54 the joint CCDFs obtained from measurements and from four models are depicted. The Gaussian models perform better than the Hyperbolic models.

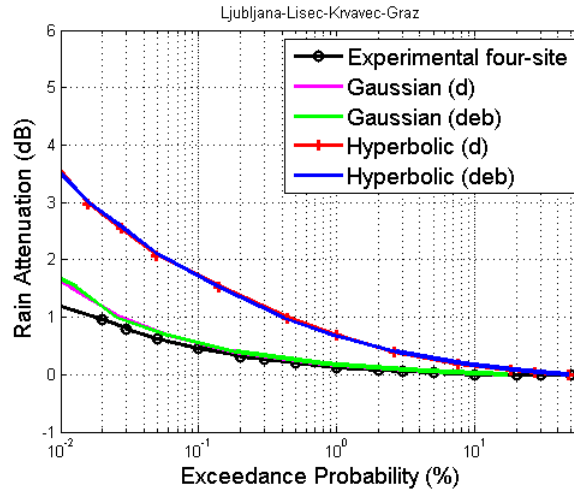


Figure 5.54: Four-site diversity CCDFs of rain attenuation prediction.

Chapter 6

Conclusions and Outlook

In this thesis four new methods for prediction of joint rain attenuation CCDF for multisite diversity systems were proposed.

The first two methods are based on the Gaussian copula. We call them the “Gaussian (d)” and the “Gaussian (deb)”. The Gaussian (d) method predicts the CCDF in relation to the distance between the ground stations. It has been extended to predict the joint attenuation not only for two-site systems but also for multisite systems with an arbitrary number of sites. The Gaussian (deb) is even more enhanced as it is upgraded with the capability to account for the baseline angle and elevation angle as input parameters. Extensive tests of the two models were conducted for two-site and three-site diversity systems. The analysis shows that the proposed methods outperform the existing models in terms of the error in prediction. The joint rain attenuation CCDFs are predicted more accurately compared to the ITU-R P.618 model and to the Clayton-based copula model. The total rms error value of the Gaussian (deb) method is slightly lower compared to the Gaussian (d). The improvement is more evident for a group of analysed experiments with baseline angle higher than 45° and distance larger than 10 km. The results confirm that consideration of the system angles also offers additional accuracy improvements for three-site diversity systems. In some cases, the elevation angle and the baseline angle have a notable impact. The models are thus more accurate and can be used in multisite diversity with an arbitrary number of sites, which was not an adequately supported feature up to now. The only recognized disadvantage of the Gaussian-based copula models is the calculation complexity, since the method involves multiple integrals, whose number increases even further with an increasing number of stations in system. Without the aid of a computer, the calculation may be very difficult.

In order to address the complexity of calculation, we investigated also the Archimedean copula families. Their function structure is simpler. A thorough analysis has been made on the adequacy of several different Archimedean copula functions. We found that the appropriate family for the joint rain attenuation prediction proves to be the hyperbolic cosecant copula. We have proposed two new prediction methods, called the “Hyperbolic (d)” and the “Hyperbolic (deb)”. They were extended from the usage for two-site systems to the prediction in the multisite systems by applying the HAC structures. The Hyperbolic (d) method takes into account only the distance between the stations. By also including the dependency on the baseline angle and the elevation angle, we get the improved version of the method, the Hyperbolic (deb).

Comprehensive tests have been conducted comparing the error performance of the proposed methods with respect to the previously known Clayton-based copula model and the ITU-R model. For this purpose, experimental data were used, involving the database

of 56 two-site diversity experiments. For the three-site diversity, the error performance was analysed by including 11 accessible experiments.

The analysis of the two-site diversity systems shows that the proposed models perform notably better than the ITU-R model, and slightly better than the Clayton-based copula model. The models which account for the dependency on the system's angular geometry have a slightly better performance compared to the corresponding models which account only for the distance. Both Gaussian models perform better than the hyperbolic models, and the Gaussian (deb) shows the best performance overall. Nevertheless, in certain cases the Hyperbolic (deb) proves to be the best. For example, it predicts the joint attenuation the most accurately for the probabilities in the range of 0.01% up to 0.1%. Further comparison of the Hyperbolic (deb) to the Hyperbolic (d) revealed that total error performance is particularly improved for 28 two-site experiments with inter-site distance between 10 km and 150 km, elevation angles which do not exceed 40° and baseline angles above 40°.

By comparing the three best models overall, i.e., the Hyperbolic (deb), the Gaussian (d) and the Gaussian (deb), we found that their performance can differ depending on the studied experiment subsets. For example, for the 31 experiments located in Canada, the USA and Japan, the Hyperbolic (deb) performs best, while for the 24 experiments located in Europe, the best total error performance is shown by using the Gaussian (d). The Gaussian (deb) outperformed the other models notably when we considered the experiments with the distance larger than 10 km and baseline angles above 45°.

The analysis of the eleven three-site diversity experiments included seven experiments from Europe and four from the USA. The results showed that both Gaussian models perform better compared to both hyperbolic models. Once again, a different behaviour was noted for the case of American experiments. For this subset, the Hyperbolic (deb) performed best. Because the distances between the stations are short in the USA experiments, we can say that the Hyperbolic (deb) is appropriate for small range three-site diversity systems. The European experiments confirmed the Gaussian (d) as the best model, especially the experiments in Austria-Slovenia and in UK, where the distances are large, i.e. 110 km and 600 km, respectively. The Gaussian (d) model seems to be the best for the large range systems.

In addition, the Gaussian models perform well for a two-site diversity experiment in tropical region and also for a four-site diversity experiment while the hyperbolic models are less accurate compared to Gaussian models.

It can be concluded that each of the proposed models shows valuable performance for certain conditions. The Gaussian models are more complex but show the better performance in general. On the other hand, the Hyperbolic methods are simpler to use and may outperform even the Gaussian model in specific scenarios. Moreover, the HAC structure procedure used with the Hyperbolic method is generic, meaning that the multi joint CCDF can be predicted with any future Archimedean copula family, yet to be explored. Furthermore, a combination of different families can be used in HAC structures, as long the required monotonic conditions are fulfilled.

For future research in the area, more experimental data are needed, especially for tropical regions and for the diversity systems with three stations or more. Note that experiments with four sites or more are not available at all, except for the single four-site experiment established by Jozef Stefan Institute in Slovenia and in Austria. It is expected that the design of commercial diversity systems with more than three stations will be necessary, if high availabilities are desired. A high number of new experiments with different site diversity characteristics are also needed in order to deepen the knowledge about the possible impact of other parameters on the system performance, such as

operating frequency and spatial heterogeneity of rainfall in different geographical locations.

The joint attenuation prediction modelling research could be extended in the future by involving radar data, which provide more information about atmospheric attenuation in terms of continuous 3D space as opposed to the beacon data which are more accurate, but cover only particular links. Investigation of the second order statistics of joint attenuation time series could also be an interesting topic. More particularly, the combination of copulas which describe joint statistics of rain attenuation on temporal and spatial domain will help in the derivation of multisite space-time correlated rain attenuation time series. Such synthesizers may help implementing a combination of the site diversity technique with additional FMTs, such as ACM. Another topic of research which is based on the results of this thesis is the study of interference through the differential rain attenuation and, in particular, for the coexistence of satellite communication systems on the same spectrum. Finally, copulas methodology could be used for the derivation of joint statistics for the co-polar attenuation and XPD.

References

- [1] P. Thompson, B. Evans, L. Castanet, M. Bousquet and T. Mathiopoulos, "Concepts and technologies for a terabit/s satellite," in *Proceeding of the Third International Conference on Advances in Satellite and Space Communications*, Budapest, Hungary, 2011.
- [2] Recommendation ITU-R V.431-8, "Nomenclature of the frequency and wavelength bands used in telecommunications," International Telecommunication Union, Geneva, Switzerland, 2015.
- [3] C. I. Kourogiorgas, "Channel modeling and performance evaluation of high data rate next generation wireless terrestrial and satellite communication systems," PhD Thesis, National Technical University of Athens, Athens, Greece, 2015.
- [4] G. Berretta, "KA-SAT, a reality," in *Proceeding of 17th Ka and Broadband Communications Conference*, Palermo, Italy, 2011.
- [5] D. Freyer, "Ka-Band: Ready to make a business impact?," *Via Satellite Magazine*, vol. 23, no. 9, pp. 26-32, 2008.
- [6] N. Jeannin, L. Castanet, J. Radzik, M. Bousquet, B. Evans and P. Thompson, "Smart gateways for terabit/s satellite," *International Journal of Satellite Communications and Networking*, vol. 32, pp. 93-106, 2014.
- [7] A. D. Panagopoulos, P.-D. M. Arapoglou and P. G. Cottis, "Satellite communications at Ku, Ka, and V bands: Propagation impairments and mitigation techniques," *IEEE Communications Surveys & Tutorials*, vol. 6, no. 3, 2004.
- [8] S. N. Livieratos, C. I. Kourogiorgas, A. D. Panagopoulos and G. E. Chatzarakis, "On the prediction of joint rain attenuation statistics in Earth-space diversity systems using copulas," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 4, pp. 2250-2257, 2014.
- [9] C. Kourogiorgas, A. Kelmendi, A. D. Panagopoulos and A. Vilhar, "On rain attenuation time series generation: a new simple copula-based channel model for satellite slant paths," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 7, pp. 3206-3211, 2016.
- [10] C. Kourogiorgas, A. Kelmendi, A. D. Panagopoulos, S. N. Livieratos, A. Vilhar and G. E. Chatzarakis, "Rain attenuation time series synthesizer based on copula functions," in *Proceedings of the 9th European Conference on Antennas and Propagation (EuCAP)*, Lisbon, Portugal, 2015.
- [11] L. Luini and C. Capsoni, "MultiEXCELL: a new rain field model for propagation applications," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 11,

- pp. 4286-4300, 2011.
- [12] L. J. Ippolito, Radiowave propagation in satellite communications, Springer Science & Business Media, 2012.
 - [13] R. Medhurst, "Rainfall attenuation of centimeter waves: Comparison of theory and measurement," *IEEE Transactions on Antennas and Propagation*, vol. 13, no. 4, pp. 550-564, 1965.
 - [14] R. Olsen, D. V. Rogers and D. Hodge, "The aR b relation in the calculation of rain attenuation," *IEEE Transactions on Antennas and Propagation*, vol. 26, no. 2, pp. 318-329, 1978.
 - [15] M. S. Assis and C. M. Einloft, "A simple method for estimating rain attenuation distribution," *Annals of Telecommunications*, vol. 32, no. 11, pp. 478-480, 1977.
 - [16] G. H. Bryant, I. Adimula, C. Riva and G. Brussaard, "Rain attenuation statistics from rain cell diameters and heights," *International Journal of Satellite Communications and Networking*, vol. 19, no. 3, pp. 263-283, 2001.
 - [17] C. Capsoni, L. Luini, A. Paraboni and C. Riva, "Stratiform and convective rain discrimination deduced from local P (R)," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 11, pp. 3566-3569, 2006.
 - [18] Recommendation ITU-R P.618-12, "Propagation data and prediction methods required for the design of Earth-space telecommunication systems," International Telecommunication Union, Geneva, Switzerland, 2015.
 - [19] J. D. Kanellopoulos and S. G. Koukoulas, "Analysis of the rain outage performance of route diversity systems," *Radio Science*, vol. 22, no. 4, pp. 549-565, 1987.
 - [20] A. D. Panagopoulos, P.-D. M. Arapoglou, J. D. Kanellopoulos and P. G. Cottis, "Long-term rain attenuation probability and site diversity gain prediction formulas," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 7, pp. 2307-2313, 2005.
 - [21] C. I. Kourogiorgas, A. D. Panagopoulos and J. D. Kanellopoulos, "On the Earth-space site diversity modeling: A novel physical-mathematical outage prediction model," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 9, pp. 4391-4397, 2012.
 - [22] R. K. Crane, "An algorithm to retrieve water vapor information from satellite measurements," Final report, Monterey, California, USA, 1976.
 - [23] H. J. Liebe, "Modeling attenuation and phase of radio waves in air at frequencies below 1000 GHz," *Radio Science*, vol. 16, no. 06, pp. 1183-1199, 1981.
 - [24] H. J. Liebe, "An updated model for millimeter wave propagation in moist air," *Radio Science*, vol. 20, no. 5, pp. 1069-1089, 1985.
 - [25] H. J. Liebe, "MPM—An atmospheric millimeter-wave propagation model," *International Journal of Infrared and Millimeter Waves*, vol. 10, no. 6, pp. 631-650, 1989.
 - [26] R. A. Harris, "COST Action 255: Radiowave propagation modelling for SatCom services at Ku-Band and above-Final Report," in *ESA Special Publication*, 2002.
 - [27] Recommendation ITU-R P.676-11, "Attenuation by atmospheric gases,"

- International Telecommunication Union, Geneva, Switzerland, 2016.
- [28] Recommendation ITU-R P.835-5, "Reference standard atmospheres," International Telecommunication Union, Geneva, Switzerland, 2012.
 - [29] Recommendation ITU-R P.836-5, "Water vapour: surface density and total columnar content," International Telecommunication Union, Geneva, Switzerland, 2013.
 - [30] E. E. Altshuler and R. A. Marr, "Cloud attenuation at millimeter wavelengths," *IEEE Transactions on Antennas and Propagation*, vol. 37, no. 11, pp. 1473-1479, 1989.
 - [31] F. Dintelmann and G. Ortgies, "Semiempirical model for cloud attenuation prediction," *Electronics Letters*, vol. 25, no. 22, pp. 1487-1488, 1989.
 - [32] E. Salonen and S. Uppala, "New prediction method of cloud attenuation," *Electronics Letters*, vol. 27, no. 12, pp. 1106-1108, 1991.
 - [33] A. Dissanayake, J. Allnutt and F. Haidara, "A prediction model that combines rain attenuation and other propagation impairments along Earth-satellite paths," *IEEE Transactions on Antennas and Propagation*, vol. 45, no. 10, pp. 1546-1558, 1997.
 - [34] L. Luini and C. Capsoni, "Modeling high-resolution 3-D cloud fields for Earth-space communication systems," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 10, pp. 5190-5199, 2014.
 - [35] L. Luini and C. Capsoni, "Efficient calculation of cloud attenuation for Earth-space applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 1136-1139, 2014.
 - [36] Recommendation ITU-R P.840-6, "Attenuation due to clouds and fog," International Telecommunication Union, Geneva, Switzerland, 2013.
 - [37] R. E. Stewart, J. D. Marwitz, J. C. Pace and R. E. Carbone, "Characteristics through the melting layer of stratiform clouds," *Journal of The Atmospheric Sciences*, vol. 41, no. 22, pp. 3227-3237, 1984.
 - [38] P. T. Willis and A. J. Heymsfield, "Structure of the melting layer in mesoscale convective system stratiform precipitation," *Journal of the Atmospheric Sciences*, vol. 46, no. 13, pp. 2008-2025, 1989.
 - [39] W. Zhang, S. I. Karhu and E. T. Salonen, "Predictions of radiowave attenuations due to a melting layer of precipitation," *IEEE Transactions on Antennas and Propagation*, vol. 42, no. 4, pp. 492-500, 1994.
 - [40] S. Das and A. Maitra, "Some melting layer characteristics at two tropical locations in Indian region," in *Proceedings of the XXXth URSI General Assembly and Scientific Symposium*, Istanbul, Turkey, 2011.
 - [41] G. O. Ajayi and F. Barbaliscia, "Prediction of attenuation due to rain: Characteristics of the 0 C isotherm in temperate and tropical climates," *International Journal of Satellite Communications and Networking*, vol. 8, no. 3, pp. 187-196, 1990.
 - [42] A. W. Dissanayake and N. J. McEwan, "Radar and attenuation properties of rain and bright band," in *Proceedings of the International Conference on Antennas and*

- Propagation*, London, England, 1978.
- [43] P. J. Hardaker, "A study of the melting layer in single polarisation radar echoes with application to operational weather radar," PhD Thesis, The University of Essex, 1992.
 - [44] R. Teixeira and A. Rocha, "Scintillation prediction models compared with one year of measurements in Aveiro, Portugal," in *Proceedings of the Loughborough Antennas & Propagation Conference (LAPC)*, Loughborough, United Kingdom, 2007.
 - [45] I. E. Otung, "Prediction of tropospheric amplitude scintillation on a satellite link," *IEEE Transactions on Antennas and Propagation*, vol. 44, no. 12, pp. 1600-1608, 1996.
 - [46] M. M. J. L. van de Kamp, J. K. Tervonen, E. T. Salonen and J. P. V. P. Baptista, "Improved models for long-term prediction of tropospheric scintillation on slant paths," *IEEE Transactions on Antennas and Propagation*, vol. 47, no. 2, pp. 249-260, 1999.
 - [47] E. C. Johnston, D. L. Bryant, D. Maiti and J. E. Allnutt, "Results of low elevation angle 11 GHz satellite beacon measurements at Goonhilly," in *Proceedings of the Seventh International Conference on Antennas and Propagation, ICAP 91 (IEE)*, York, UK, 1991.
 - [48] Y. Karasawa, M. Yamada and J. E. Allnutt, "A new prediction method for tropospheric scintillation on Earth-space paths," *IEEE Transactions on Antennas and Propagation*, vol. 36, no. 11, pp. 1608-1614, 1988.
 - [49] H. Vasseur, "Prediction of tropospheric scintillation on satellite links from radiosonde data," *IEEE Transactions on Antennas and Propagation*, vol. 47, no. 2, pp. 293-301, 1999.
 - [50] A. Aragon-Zavala, *Antennas and propagation for wireless communication systems*, John Wiley & Sons, 2008.
 - [51] V. Pozhidayev and F. Dintelmann, "Letter: Evaluation of total radiowave attenuation statistics for slant path links from phenomenon-based attenuation distributions," *Transactions on Emerging Telecommunications Technologies*, vol. 8, no. 3, pp. 259-263, 1997.
 - [52] L. Castanet, J. Lemorton, T. Konefal, A. K. Shukla, P. A. Watson and C. L. Wrench, "Comparison of various methods for combining propagation effects and predicting loss in low-availability systems in the 20-50 GHz frequency range," *International Journal of Satellite Communications and Networking*, vol. 19, no. 3, pp. 317-334, 2001.
 - [53] Recommendation ITU-R P.1623-1, "Prediction method of fade dynamics on Earth-space paths," International Telecommunication Union, Geneva, Switzerland, 2005.
 - [54] M. M. J. L. van de Kamp and L. Castanet, "Propagation impairment mitigation for millimeter wave radio systems: Fade dynamics review," in *Proc. PM3018, COST Action 280 1st Int. Workshop*, 2002.
 - [55] J. Goldhirsh, "Rain-rate duration statistics over a five-year period: a tool for assessing slant path fade durations," *IEEE Transactions on Antennas and*

- Propagation*, vol. 43, no. 5, pp. 435-439, 1995.
- [56] A. Safaai-Jazi, H. Ajaz and W. L. Stutzman, "Empirical models for rain fade time on Ku-and Ka-band satellite links," *IEEE Transactions on Antennas and Propagation*, vol. 43, no. 12, pp. 1411-1415, 1995.
 - [57] E. Matricciani, "Prediction of fade durations due to rain in satellite communication systems," *Radio Science*, vol. 32, no. 3, pp. 935-941, 1997.
 - [58] A. Paraboni and C. Riva, "A new method for the prediction of fade duration statistics in satellite links above 10 GHz," *International Journal of Satellite Communications and Networking*, vol. 12, no. 4, pp. 387-394, 1994.
 - [59] M. M. J. L. van de Kamp, "Statistical analysis of rain fade slope," *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 8, pp. 1750-1759, 2003.
 - [60] F. Dintelmann, G. Ortgies, F. Ruecker and R. Jakoby, "Results from 12-to 30-GHz German propagation experiments carried out with radiometers and the Olympus satellite," *Proceedings of the IEEE*, vol. 81, no. 6, pp. 876-884, 1993.
 - [61] J. D. Laster and W. L. Stutzman, "Frequency scaling of rain attenuation for satellite communication links," *IEEE Transactions on Antennas and Propagation*, vol. 43, no. 11, pp. 1207-1216, 1995.
 - [62] S. Bertorelli and A. Paraboni, "Modelling of short-term frequency scaling for rain attenuation using ITALSAT data," *International Journal of Satellite Communications and Networking*, vol. 25, no. 3, pp. 251-262, 2007.
 - [63] D. B. Hodge, "An improved model for diversity gain on Earth-space propagation paths," *Radio Science*, vol. 17, no. 06, pp. 1393-1399, 1982.
 - [64] J. E. Allnut and D. V. Rogers, "Novel method for predicting site diversity gain on satellite-to-ground radio paths," *Electronics Letters*, vol. 18, no. 5, pp. 233-235, 1982.
 - [65] J. Goldhirsh, "Space diversity performance prediction for Earth-satellite paths using radar modeling techniques," *Radio Science*, vol. 17, no. 6, pp. 1400-1410, 1982.
 - [66] E. Matricciani, "Prediction of site diversity performance in satellite communications systems affected by rain attenuation: Extension of the two layer rain model," *Transactions on Emerging Telecommunications Technologies*, vol. 5, no. 3, pp. 327-336, 1994.
 - [67] A. V. Bosisio and C. Riva, "A novel method for the statistical prediction of rain attenuation in site diversity systems: Theory and comparative testing against experimental data," *International Journal of Satellite Communications and Networking*, vol. 16, no. 1, pp. 47-52, 1998.
 - [68] J. Mass, "A simulation study of rain attenuation and diversity effects on satellite links," *Cosat Technical Review*, vol. 17, no. 1, pp. 159-187, 1987.
 - [69] A. D. Panagopoulos, P.-D. M. Arapoglou, G. E. Chatzarakis, J. D. Kanellopoulos and P. G. Cottis, "A new formula for the prediction of the site diversity improvement factor," *International Journal of Infrared and Millimeter Waves*, vol. 25, no. 12, pp. 1781-1789, 2004.
 - [70] A. Paraboni and F. Barbaliscia, "Multiple site attenuation prediction models based

- on the rainfall structures (meso-or synoptic-scales) for advanced TLC or broadcasting systems,” in *XXVII URSI General Assembly*, Maastricht, 2002.
- [71] Recommendation ITU-R P.837-6, “Characteristics of precipitation for propagation modelling,” International Telecommunication Union, Geneva, Switzerland, 2012.
 - [72] "ITU-R Databank DBSG3," 2015. [Online]. Available: <http://www.itu.int/publ/R-SOFT-SG3/en>. [Accessed 2015].
 - [73] L. Castanet, J. Lemorton and M. Bousquet, “Fade mitigation techniques for New SatCom services at Ku-band and above: a review,” in *Proceedings of the Fourth Ka-band Utilization Conference*, Venice, Italy, 1998.
 - [74] L. Castanet, A. Bolea-Alamañac and M. Bousquet, “Interference and fade mitigation techniques for Ka and Q/V band satellite communication systems,” in *Proceedings of the 2nd International Workshop of COST Action*, 2003.
 - [75] A. Bolea-Alamanac, M. Bousquet, L. Castanet and M. M. J. L. Van de Kamp, “Implementation of short-term prediction models in fade mitigation techniques control loops,” in *Joint COST 272/280 Workshop*, 2003.
 - [76] Recommendation ITU-R S.1061-1, “Utilization of fade countermeasures strategies and techniques in the fixed-satellite service,” International telecommunication Union, Geneva, Switzerland, 2007.
 - [77] P. F. Hartigan and A. P. Gallois, “The use of satellite imagery for forecasting rain attenuation,” in *Proceedings of the Eighth International Conference on Antennas and Propagation*, Edinburgh, UK, 1993.
 - [78] M. Filip and E. Vilar, “Adaptive modulation as a fade countermeasure. An Olympus experiment,” *International Journal of Satellite Communications and Networking*, vol. 8, no. 1, pp. 31-41, 1990.
 - [79] L. Luini and C. Capsoni, “Spatial correlation of rainfall over Europe investigated through statistical dependence index,” *Electronics Letters*, vol. 49, no. 3, pp. 230-231, 2013.
 - [80] C. Capsoni, E. Matricciani and M. Mauri, “SIRIO-OTS 12 GHz orbital diversity experiment at Fucino,” *IEEE Transactions on Antennas and Propagation*, vol. 38, no. 6, pp. 777-782, 1990.
 - [81] E. Matricciani and M. Mauri, “Italsat-Olympus 20-GHz orbital diversity experiment at Spino d’Adda,” *IEEE transactions on antennas and propagation*, vol. 43, no. 1, pp. 105-108, 1995.
 - [82] F. Carassa, G. Tartara and E. Matricciani, “Frequency diversity and its applications,” *International Journal of Satellite Communications and Networking*, vol. 6, no. 3, pp. 313-322, 1988.
 - [83] D. Chakraborty, F. Davarian and W. L. Stutzman, “The Ka-band propagation measurements campaign at JPL,” *IEEE Antennas and Propagation Magazine*, vol. 35, no. 1, pp. 7-13, 1993.
 - [84] S. Ventouras, R. Reeves, E. Rumi, F. Perez-Fontan, F. Machado, V. Pastoriza, A. Rocha, S. Mota, F. Jorge, A. D. Panagopoulos, A. Z. Papafragkakis, C. Kourogiorgas, O. Fiser, V. Pek, P. Pesice, M. Grabner, A. Vilhar and A. Kelmendi et al., “Large scale assessment of Ka/Q band atmospheric channel across Europe

- with Alphasat TDP5: the augmented network,” in *Proceedings of the 11th European Conference on Antennas and Propagation (EuCAP)*, Paris, France, 2017.
- [85] A. Paraboni, C. Riva, L. Valbonesi and M. Mauri, “Eight years of ITALSAT copolar attenuation statistics at Spino d'Adda,” *Space Communications*, vol. 18, no. 1,2, pp. 59-64, 2002.
 - [86] C. Riva, “Seasonal and diurnal variations of total attenuation measured with the ITALSAT satellite at Spino d'Adda at 18.7, 39.6 and 49.5 GHz,” *International Journal of Satellite Communications and Networking*, vol. 22, no. 4, pp. 449-476, 2004.
 - [87] S. Ventouras, S. A. Callaghan and C. L. Wrench, “Long-term statistics of tropospheric attenuation from the Ka/U band ITALSAT satellite experiment in the United Kingdom,” *Radio Science*, vol. 41, no. 2, 2006.
 - [88] F. Jorge, A. Rocha and S. Mota, “Evaluation of inter-annual variability of rainfall rate and rain attenuation based on the ITU Rec P. 678,” in *Proceedings of the 9th European Conference on Antennas and Propagation (EuCAP)*, Lisbon, Portugal, 2015.
 - [89] J. M. Garcia-Rubia, J. M. Riera, P. Garcia-del-Pino, G. A. Siles and A. Benarroch, “Experimental assessment of slant-path rain attenuation variability in the Ka-band,” *International Journal of Satellite Communications and Networking*, vol. 34, no. 2, pp. 155-170, 2016.
 - [90] T. Ishida, N. Fugono, J. Tabata, M. Ohara and T. Ishizawa, “Propagation experiment with Japanese satellite, ETS-II (KIKU-2),” *Acta Astronautica*, vol. 7, no. 3, pp. 357-370, 1980.
 - [91] Y. Karasawa and Y. Maekawa, “Ka-band Earth-space propagation research in Japan,” *Proceedings of the IEEE*, vol. 85, no. 6, pp. 821-842, 1997.
 - [92] D. V. Rogers and R. K. Crane, “Review of propagation results from the Advanced Communications Technology Satellite (ACTS) and related studies,” *IEICE Transactions on Communications*, vol. 84, no. 9, pp. 2357-2368, 2001.
 - [93] X. Boulanger, F. Lacoste and L. Castanet, “Small and large scale site diversity experiment at Ka-band in the south of France,” *International Journal of Satellite Communications and Networking*, In press. doi:10.1002/sat.1190.
 - [94] P. Garcia-del-Pino, A. Rocha, J. M. Riera, J. M. Garcia-Rubia and A. Benarroch, “Joint statistics of rain attenuation at 20 GHz in Madrid and Aveiro,” *IEEE Antennas and Wireless Propagation Letters*, vol. 9, pp. 799-802, 2010.
 - [95] M. Buti and U.-C. Fiebig, “Joint statistics of slant-path attenuation in distant sites measured with ITALSAT at 40 GHz,” *Electronics Letters*, vol. 42, no. 18, pp. 1014-1015, 2006.
 - [96] J. Goldhirsh, B. H. Musiani, A. W. Disannayake and K.-T. Lin, “Three-site space-diversity experiment at 20 GHz using ACTS in the Eastern United States,” *Proceedings of the IEEE*, vol. 85, no. 6, pp. 970-980, 1997.
 - [97] M. Rytir, P. A. Grotthing, T. Tjelta, L. E. Bråten and C. Riva, “Three-Site Diversity on Low-Elevation 20 GHz Links in Norway,” in *Proceedings of the 21st Ka and Broadband Communications Conference*, Bologna, Italy, 2015.

- [98] A. Hrovat, G. Kandus, U. Kuhar, A. Kelmendi and A. Vilhar, "A Ka-band Satellite Beacon Receiver for Propagation Experiment," *Electronic Components and Materials*, vol. 46, no. 1, pp. 13-23, 2016.
- [99] U. Kuhar, G. Kandus and A. Vilhar, "Low-cost frequency-stable beacon receiver based on software defined radio," in *Proceedings of the 20th International Conference on Software, Telecommunications and Computer Networks*, Split, Croatia, 2012.
- [100] A. Vilhar, A. Hrovat, U. Kuhar and G. Kandus, "Four Channel Alphasat Ka- and Q- Band Receiver Station in Ljubljana," in *Proceedings of the 21st Ka and Broadband Communications Conference*, Bolonja, Italy, 2015.
- [101] F. Teschl, F. Cuervo, A. Martellucci, J. R. Castro, C. Riva, G. Codispoti, K. Plimon and M. Schönhuber, "The Ka/Q-band Alphasat ground propagation terminal-first months of operation," in *Proceedings of the 8th European Conference on Antennas and Propagation (EuCAP)*, The Hague, Netherlands, 2014.
- [102] A. Vilhar, A. Kelmendi and A. Hrovat, "Satellite Propagation Experiment in Ljubljana: Beacon Measurements at Ka- And Q-band," in *Proceedings of the 11th European Conference on Antennas and Propagation (EuCAP)*, Paris, France, 2017.
- [103] A. Vilhar, A. Kelmendi, A. Hrovat and G. Kandus, "First year analysis of Alphasat Ka-and Q-band beacon measurements in Ljubljana, Slovenia," in *Proceedings of the 22nd Ka and Broadband Conference*, Cleveland, Ohio, USA, 2016.
- [104] R. B. Nelsen, *An introduction to copulas*, Springer, 2006.
- [105] S.-H. Huang, M.-N. L. Huang, K. T. Wong and T.-C. Tseng, "Copula-to model multi-channel fading by correlated but arbitrary Weibull marginals, giving a closed-form outage probability of selection-combining reception," *IET Microwaves, Antennas & Propagation*, vol. 9, no. 15, pp. 1698-1705, 2015.
- [106] I. N. Bronštejn, K. A. Semendjajev, G. Musiol and H. Mühlig, *Matematicni priročnik*, Ljubljana: Tehniška založba, 1997.
- [107] A. Kelmendi, C. Kourogorgas, A. Hrovat, A. D. Panagopoulos, G. Kandus and A. Vilhar, "Modeling of joint rain attenuation in Earth-space diversity systems using Gaussian copula," in *Proceedings of the 10th European Conference on Antennas and Propagation (EuCAP)*, Davos, Switzerland, 2016.
- [108] A. Vilhar, G. Kandus, A. Kelmendi, U. Kuhar, A. Hrovat and M. Schönhuber, "Three-site Ka-band diversity experiment performed in Slovenia and Austria," in *Proceedings of the 9th European Conference on Antennas and Propagation (EuCAP)*, Lisbon, Portugal, 2015.
- [109] "British Atmospheric Data Center," 2014. [Online]. Available: <http://badc.nerc.ac.uk/home/index.html>. [Accessed 2014].
- [110] Recommendation ITU- R P.311-15, "Acquisition, presentation and analysis of data in studies of tropospheric propagation," International Telecommunication Union, Geneva, Switzerland, 2015.
- [111] S. Bertorelli and M. Buti, "Radar derived joint statistics of rain attenuation in multiple locations at various distances: data, models and applications," in *Proceedings of the 2nd European Conference on Antennas and Propagation (*

EuCAP), Edinburgh, UK, 2007.

- [112] C. Nagaraja and I. Otung, "Spatial rain correlation analysis for application in site diversity design," *Radio Science*, vol. 44, no. 2, 2009.
- [113] D. Gray, "Earth-space path diversity: Dependence on base line orientation," in *Proceeding of the Antennas and Propagation Society International Symposium*, Boulder, CO, USA, 1973.
- [114] H. Bal and V. Najjari, "Archimedean copulas family via hyperbolic generator," *Gazi University Journal of Science*, vol. 26, no. 2, pp. 195-200, 2013.
- [115] O. Okhrin, Y. Okhrin and W. Schmid, "On the structure and estimation of hierarchical Archimedean copulas," *Journal of Econometrics*, vol. 173, no. 2, pp. 189-204, 2013.
- [116] M. Hofert, "Sampling nested Archimedean copulas with applications to CDO pricing," PhD Thesis, Ulm University, Ulm, Germany, 2010.
- [117] K. Aas and D. Berg, "Models for construction of multivariate dependence-a comparison study," *The European Journal of Finance*, vol. 15, no. 7-8, pp. 639-659, 2009.
- [118] S. Nicklas, "Pair constructions for high-dimensional dependence models in discrete and continuous time," PhD Thesis, University of Koln, 2013, Koln, Germany, 2013.
- [119] T. Tjelta, J. Mamen, L. E. Bråten and P. A. Grotthing, "Measured and modeled spatial rain rate correlation to improve the prediction method for satellite site diversity," *Radio Science*, vol. 49, no. 12, pp. 1232-1244, 2014.
- [120] A. Kelmendi, C. Kourogiorgas, A. Hrovat, A. D. Panagopoulos, G. Kandus and A. Vilhar, "Prediction of joint rain attenuation statistics induced on Earth-satellite multiple site diversity systems using Gaussian copula," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 95-98, 2017.
- [121] A. Kelmendi, G. Kandus, A. Švigelj, A. Vilhar, A. Hrovat and E. Leitgeb, "Evaluation of the Gaussian copula prediction method for joint rain attenuation statistics in Earth-satellite site diversity systems," in *Proceedings of the International Conference on Broadband Communications for Next Generation Networks and Multimedia Applications (CoBCom)*, Graz, Austria, 2016.
- [122] F. Cuervo, M. Schoenhuber, L. Yin, J. .. Jong, J. B. Din and A. Martelluci, "Ka band propagation campaign in the tropical regions of peninsular Malaysia - statistical analysis," in *Proceedings of the 22nd Ka and Broadband Communication Conference*, Cleveland, Ohio, USA, 2016.
- [123] S. H. Lin, H. J. Bergmann and M. V. Pursley, "Rain attenuation on Earth-satellite paths—summary of 10-year experiments and studies," *Bell System Technical Journal*, vol. 59, no. 2, pp. 183-228, 1980.
- [124] A. Kelmendi and A. Vilhar, "Preliminary statistical analysis of four site diversity experiment at Ka-band," in *Proceedings of the 11th European Conference on Antennas and Propagation (EuCAP)*, Paris, France, 2017.

Bibliography

Publications Related to the Thesis

Journal Articles

- A. Kelmendi, C. Kourogiorgas, A. Hrovat, A. D. Panagopoulos, G. Kandus and A. Vilhar, "Prediction of joint rain attenuation statistics induced on Earth-satellite multiple site diversity systems using Gaussian copula," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 95-98, 2017.
- C. Kourogiorgas, A. Kelmendi, A. D. Panagopoulos and A. Vilhar, "On rain attenuation time series generation: a new simple copula-based channel model for satellite slant paths," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 7, pp. 3206-3211, 2016.
- A. Hrovat, G. Kandus, U. Kuhar, A. Kelmendi and A. Vilhar, "A Ka-band Satellite Beacon Receiver for Propagation Experiment," *Electronic Components and Materials*, vol. 46, no. 1, pp. 13-23, 2016.
- A. Kelmendi, G. Kandus, A. Hrovat, C. Kourogiorgas, A. D. Panagopoulos, M. Schönhuber, M. Mohorčič and A. Vilhar, "Rain attenuation prediction model based on hyperbolic cosecant copula for multiple site diversity systems in satellite communications," *IEEE Transactions on Antennas and Propagation*, [submitted manuscript, September 2016. In review with minor modifications required].

Conference Papers

- A. Kelmendi, G. Kandus, A. Švigelj, A. Vilhar, A. Hrovat and E. Leitgeb, "Evaluation of the Gaussian copula prediction method for joint rain attenuation statistics in Earth-satellite site diversity systems," in *Proceedings of the International Conference on Broadband Communications for Next Generation Networks and Multimedia Applications (CoBCom)*, Graz, Austria, 2016.
- A. Kelmendi, C. Kourogiorgas, A. Hrovat, A. D. Panagopoulos, G. Kandus and A. Vilhar, "Modeling of joint rain attenuation in Earth-space diversity systems using Gaussian copula," in *Proceedings of the 10th European Conference on Antennas and Propagation (EuCAP)*, Davos, Switzerland, 2016.
- A. Kelmendi and A. Vilhar, "Preliminary statistical analysis of four site diversity experiment at Ka-band," in *Proceedings of the 11th European Conference on Antennas and Propagation (EuCAP)*, Paris, France, 2017.
- A. Vilhar, G. Kandus, A. Kelmendi, U. Kuhar, A. Hrovat and M. Schönhuber, "Three-site Ka-band diversity experiment performed in Slovenia and Austria," in *Proceedings of the 9th European Conference on Antennas and Propagation (EuCAP)*, Lisbon, Portugal, 2015.
- C. Kourogiorgas, A. Kelmendi, A. D. Panagopoulos, S. N. Livieratos, A. Vilhar and G. E. Chatzarakis, "Rain attenuation time series synthesizer based on copula functions,"

- in *Proceedings of the 9th European Conference on Antennas and Propagation (EuCAP)*, Lisbon, Portugal, 2015.
- A. Vilhar, A. Kelmendi, A. Hrovat and G. Kandus, "First year analysis of Alphasat Ka- and Q-band beacon measurements in Ljubljana, Slovenia," in *Proceedings of the 22nd Ka and Broadband Conference*, Cleveland, Ohio, USA, 2016.
- S. Ventouras, R. Reeves, E. Rumi, F. Perez-Fontan, F. Machado, V. Pastoriza, A. Rocha, S. Mota, F. Jorge, A. D. Panagopoulos, A. Z. Papafragkakis, C. Kourogorgas, O. Fiser, V. Pek, P. Pesice, M. Grabner, A. Vilhar, A. Kelmendi, A. Hrovat, D. Vanhoenacker-Janvier, A. Graziani, L. Quibus and G. Goussetis, "Large scale assessment of Ka/Q band atmospheric channel across Europe with Alphasat TDP5: the augmented network," in *Proceedings of the 11th European Conference on Antennas and Propagation (EuCAP)*, Paris, France, 2017..
- A. Vilhar, A. Kelmendi and A. Hrovat, "Satellite Propagation Experiment in Ljubljana: Beacon Measurements at Ka- And Q-band," in *Proceedings of the 11th European Conference on Antennas and Propagation (EuCAP)*, Paris, France, 2017.

Other Publications

Conference Paper

- A. Kelmendi, T. Javornik, I. Ozimek, A. Vilhar, A. Hrovat, G. Kandus, "Performance evaluation of ITU-R P.1546 Propagation Model," in *Proceedings of the 6th Jožef Stefan International Postgraduate School Students Conference*, Ljubljana, Slovenia, 2014.

Biography

Arsim Kelmendi was born on July 19, 1980 in Pejë, Kosovo. He attended the Faculty of Electrical and Computer Engineering, Section Computers and Telecommunications, University of Prishtina in Kosovo. He was nominated as Eminent Student of the University of Prishtina. In 2006, he received his Graduate Electrical Engineer Degree with the highest average grade of the year.

After graduation, he spent seven years as an IT Systems and Database Administrator in Elkos Group, International Trade Company, Kosovo. His main activities in the company were configuration, efficient and reliable operation of computer and server systems, network infrastructure maintenance and security and database administration for the company.

At the same time, Arsim was involved in teaching and in research work. In 2010/2012, he was an assistant professor at University of Prizren and in 2012/2013, a teaching assistant at University of Prishtina, Faculty of Applied Science in Mitrovica.

In 2013, he received 3-year scholarship from Slovene Human Resources Development and Scholarship Fund for Postgraduate Studies of Nationals of Western Balkan States for Study in the Republic of Slovenia and enrolled in the PhD study “Information and Communication Technologies” at the Jožef Stefan International Postgraduate School in Ljubljana, Slovenia. During his study, he actively participated in the Department of Communication Systems, Jožef Stefan Institute in the project “Ka/Q-band Propagation Measurements and Modelling - Slovenian Contribution to the Alphasat TDP#5 Scientific Mission - SatProSi Alpha”, financed by the European Space Agency. He was involved in the analysis and modelling of site diversity performance at Ka-band and above.

In the past few years, Arsim has published several articles, including two papers in IEEE journals.