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Rain Attenuation Prediction Model Based on Hyperbolic Cosecant Copula for Multiple Site Diversity Systems in Satellite Communications

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***Abstract*—The paper presents a novel model for prediction of site diversity system performance in millimeter-wave satellite communications. The model predicts the joint exceedance probability of rain attenuation based on a new family of Archimedean copulas, called the Hyperbolic Cosecant Copula. Furthermore, employing the Hierarchical Archimedean Copula (HAC) structures, the proposed methodology can be used for the prediction of joint first order statistics of rain attenuation for dual and multiple site diversity satellite communication systems. The proposed method has been tested on an extensive dataset of site diversity experiments with various system configurations. Moreover, in addition to the common approaches, where the dependency of rain attenuation induced on multiple links is based solely on the distance between ground stations, elevation and baseline angle are also taken into account for the modeling of the dependence parameter. Both versions of the model outperform the existing model for two-site diversity systems given in ITU-R Recommendation P.618-12. The version which accounts for the system's angles, shows a better performance also in comparison to the state-of-the-art models such as the models based on the Archimedean Clayton Copula and the Gaussian Copula.**

***Index Terms*— Copula, hyperbolic cosecant copula, site diversity, prediction, modeling, rain attenuation.**

I. Introduction

The requirements for high capacity satellite communication services such as voice, video, data transmissions, internet connection, and even earth observation, are pushing towards employment of higher and higher operational frequencies. At high frequency bands, especially at Ka-band and above, satellite communications benefit from wider bandwidth and channel capacity performance, smaller and lighter terminals, avoidance of channel congestion, etc. However, significant atmospheric impairments are present at these bands, caused primarily by rain, which attenuate electromagnetic waves. The impact is increasing with the increasing frequency [1].

Fade Mitigation Techniques (FMTs) are employed to compensate of these effects. Common FMTs based on power control cannot be used to counteract large signal fades caused by heavy rain. Site diversity proves to be the most effective FMT method to overcome such conditions [2]. A site diversity system consists of two or more ground stations spatially separated and interconnected by terrestrial (e.g. optical, wireless or wireline) links. Considering that short term heavy rainfall decorrelates with increasing distance between ground stations [3], 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 employing a site diversity system with appropriate selection of the separation distance between the stations, proper system geometry and a suitable algorithm for selection of a ground station with the best conditions at any instant of time.

In order to design an efficient site diversity system and accurately plan its performance in advance, the prediction of long term joint rain attenuation exceedance probability, improvement factor and site diversity gains are needed. Several models for prediction of site diversity performance have been proposed. Most of them are based on an assumption that both the single link and joint link rain attenuation follow a certain distribution function. In [4], a prediction model for calculation of the site diversity gain is proposed, assuming that Complementary Cumulative Distribution Function (CCDF) of rain attenuation on a single link follows the Weibull distribution. In the paragraph 2.2.4.1. of ITU-R. P. 618-12 [5] a model for prediction of the joint exceedance probability for two-site diversity systems is described, which assumes a Lognormal distribution of rain attenuation, as proposed in [6]. The same assumption was made also by the authors of the model in [7], while the model proposed in [8] assumes that rain attenuation follows Inverse Gaussian distribution. Two models based on simulation of rain cells have been proposed

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in [9] and [10], assuming that they have an exponential shape.

Recently, a theory of copula functions has been employed in satellite propagation modeling. A model for prediction of joint exceedance probability of rain attenuation for two-site diversity systems based on Archimedean copulas has been proposed [11]. Gaussian copulas have also been studied. A rain attenuation time series synthesizer was proposed in [12], [13], while a model for prediction of joint rain attenuation CCDF for multiple site diversity systems is presented in [14].

In this paper, firstly, a new family of Archimedean copula known as hyperbolic cosecant copula is used for the prediction of joint attenuation distributions in two- and multi-site diversity systems. For the multi-site diversity systems the HAC structures are used in order to extend the ability of copulas to model joint first order statistics for multiple random variables. Moreover, two expressions are derived through an extensive investigation of datasets for calculating of copula's dependence parameter as a function of the separation distance for the first one and as a function of baseline and elevation angles for the second expression.

The remainder of the paper is organized as follows. In Section II, the basic theory of multivariate Archimedean copulas with special emphasis on hyperbolic cosecant copula family is presented. In Section III, joint rain CCDF modeling by fitting to experimental data for two-site diversity systems is presented. Two versions of prediction method for modeling the copula parameter and an extension to multi-site modeling are described in Section IV. In Section V, results of comparative tests with statistical error performance are discussed. The paper concludes in Section VI.

II. Probability Theory and Multivariate Archimedean Hyperbolic Cosecant Copula

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 [15], there exists a unique copula function C, by which n marginal distributions $F_1(x_1)$, $F_2(x_2)$,…, $F_n(x_n)$ are combined into an n-dimensional distribution function H:

$$H\left[x_1, x_2, \ldots, x_n\right] = C(F_1(x_1), F_2(x_2), ..., F_n(x_n)). \quad (1)$$

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

$$P\left[X_1 \le x_1, X_2 \le x_2 \ldots, X_n \le x_n\right] = C(u_1, u_2, ..., u_n). \quad (2)$$

The joint CCDF for n variables can be calculated from CDFs as [16]:

$$P\left[X_1 \ge x_1, \ldots, X_n \ge x_n\right] = 1 - \sum_{k=1}^{n} P[X_k \le x_k] + \sum_{k=2}^{n}\left\{(-1)^k \sum_{1 \le i_1 < i_2 \cdots < i_k \le n} P[X_{i_1} \le x_{i_1}, X_{i_2} \le x_{i_2}, \cdots, X_{i_k} \le x_{i_k}]\right\}. \quad (3)$$

From (2) and (3) the joint CCDF can be expressed by using copulas as:

$$P\left[X_1 \ge x_1, \ldots, X_n \ge x_n\right] = 1 - \sum_{k=1}^{n} u_k + \sum_{k=2}^{n}\left\{(-1)^k \sum_{1 \le i_1 < i_2 \cdots < i_k \le n} C_{i_1, i_2, \cdots, i_k}(u_{i_1}, u_{i_2}, \cdots, u_{i_k})\right\}. \quad (4)$$

Among various families of copula functions, the Archimedean copulas are a family of wide usage in practical applications. A large number of copula functions belonging to this family exists and the number is increasing. Their advantage is that they can be easily generated. The n-dimensional Archimedean copula is expressed as:

$$C\left(\mathbf{u};\theta\right) = \varphi^{[-1]}(\varphi(u_1;\theta) + \varphi(u_2;\theta) ... + \varphi(u_n;\theta);\theta), \quad (5)$$

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

$$\varphi^{[-1]}(t;\theta) = \begin{cases} \varphi^{-1}(t;\theta), & 0 \le t \le \varphi(0;\theta) \\ 0, & \varphi(0;\theta) < t \le \infty \end{cases}. \quad (6)$$

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 in (5) is called a strict Archimedean copula. In order to be a proper copula generator, the function φ needs to be completely monotone [15].

In general, multivariate Archimedean copulas depend on a single parameter θ which is not always applicable for $n \ge 3$. Therefore, a method for expressing multivariate copulas with $n \ge 3$ has been proposed, by employment of Hierarchical Archimedean Copula (HAC) structure [17]. 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:

$$\begin{aligned} C(u_1, u_2, u_3, \theta) &= \varphi^{-1}(\varphi(u_1) + \varphi(u_2) + \varphi(u_3)) \\ &= C_4(C_1(u_1, u_2, \theta_1), u_3, \theta_4) \\ &= \varphi_4^{-1}(\varphi_4 \circ \varphi_1^{-1}(\varphi_1(u_1) + \varphi_1(u_2)) + \varphi_4(u_3)). \end{aligned} \quad (7)$$

Similarly, for multivariate copula of any level, the general HAC is expressed as [18]:

$$C(u_1, ..., u_n) = \varphi_{n-1}^{-1}\left\{\varphi_{n-1} \circ \varphi_{n-2}^{-1}\left[\ldots\left(\varphi_2 \circ \varphi_1^{-1}\left[\varphi_1(u_1) + \varphi_1(u_2)\right] + \varphi_2(u_3)\right)\right] + \ldots + \varphi_{n-2}(u_{n-1}) + \varphi_{n-1}(u_n)\right\}. \quad (8)$$

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

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Copulas (PNAC). A combined structure of FNAC and PNAC can also be used. Note that the equation (8) represents a general expression of the FNAC structure. Fig. 1 illustrates the three different strategies for building a HAC structure of a six variate copula.

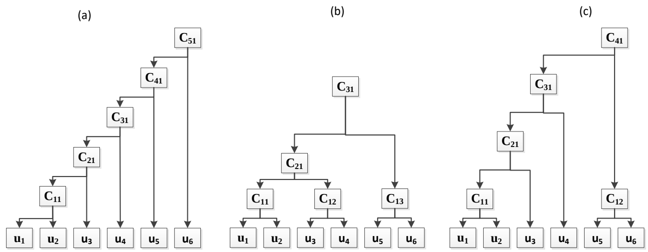

Fig. 1. HAC structure examples: a) FNAC, b) PNAC and c) mixed

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 decrease with the hierarchy level [19], e.g. if $\theta_4<\theta_1$ in equation (7). For the sake of adaptability, it could be beneficial to use different copula families in the HAC structure. This case is also possible but the monotonic conditions must be verified separately [20].

In order to predict the joint rain attenuation CCDFs we analyzed the adequacy of several different Archimedean copula families not used till now. The results revealed that an appropriate family for the calculation of joint CCDF of rain attenuation for site diversity systems is family of Archimedean copulas via hyperbolic generator [21] which was subsequently used in our study. The multivariate copula functions in equation (4) are expressed with HAC structure, which proves to be an effective solution for site diversity systems with three stations or more.

The hyperbolic strict generator is expressed via hyperbolic cosecant function:

$$\varphi(t) = csch(t^{\theta}) - csch(1) \tag{9}$$

and its inverse function:

$$\varphi^{-1}(t) = \left[acsch\left(t + csch(1)\right)\right]^{\frac{1}{\theta}}, \tag{10}$$

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

$$csch(x) = \frac{2}{e^{x} - e^{-x}} \tag{11}$$

and *acsch* is an inverse hyperbolic cosecant function.

III. Modeling of Joint Rain Attenuation Statistics

The joint exceedance probability of rain attenuation for two site diversity system based on equation (4) can be expressed as

$$P\left[A_1 \geq A_{th}, A_2 \geq A_{th}\right] = 1 - u_1 - u_2 + C(u_1,u_2) \tag{12}$$

using single CDFs of rain attenuation, $u_1=P[A_1\leq A_{th}]$ and $u_2=P[A_2\leq A_{th}]$, and a bivariate copula function $C(u_1,u_2)$.

By the definition (5), the two-dimensional copula function is:

$$C\left(u_1,u_2\right) = \varphi^{-1}(\varphi(u_1)+\varphi(u_2)) . \tag{13}$$

By insertion of strict generator and its inverse function as defined in (9) and (10), the following expression is obtained [21]:

$$C\left(u_1,u_2,\theta\right) = \left[acsch\left(csch(u_1^{\theta}) + csch(u_2^{\theta}) - csch(1)\right)\right]^{\frac{1}{\theta}} . \tag{14}$$

Therefore, dual joint CCDF in (12) takes the form:

$$P\left[A_1 \geq A_{th}, A_2 \geq A_{th}\right] = 1 - u_1 - u_2 + \left[acsch\left(csch(u_1^{\theta}) + csch(u_2^{\theta}) - csch(1)\right)\right]^{\frac{1}{\theta}} , \tag{15}$$

where u_1 and u_2 correspond to CDFs of attenuation of both stations and θ is a 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 modeling the joint statistics of rain attenuation, an optimal value of θ parameter must be determined. Thus, at first investigation stage, the parameter is obtained by fitting the modeled joint CCDF of rain attenuation derived from expression (15) to the experimental data joint CCDF. Since (15) is a nonlinear function, the non-linear least squares regression fitting is used, taking into account the predefined θ boundaries $[0,\infty)$. The theoretical joint CCDF is calculated by using measured single site CDFs u_1 and u_2 and the obtained parameter θ as an input to expression (15).

Two examples of modeling joint CCDF of rain attenuation for dual site systems are presented hereafter, based on the database of ITU-R's study group 3 (DBSG3) [22]. The first example is from Austin and Bee Caves in USA, with the operating frequency of 13.6 GHz, the separation distance equal to 15.8 km, the baseline orientation angle 79° and the elevation angles 52°. Fig. 2 depicts rain attenuation CCDFs obtained for this setup. The measured single links CCDFs and experimental joint CCDF were taken as an input to (15). The value of θ =172.82 was obtained from the fitting procedure. As a result, a very accurate fitting of the hyperbolic copula model to the experimental data was achieved.

Measurements from the stations in Vernet and La Conception in Canada were taken as the second example [22], with rather different configuration parameters. The operating frequency is 13 GHz, the elevation angle 18°, the baseline orientation angle 65° and the separation distance between the stations is 31.8km. The experimental and the modeled rain attenuation CCDFs are depicted in Fig. 3. The obtained copula parameter θ of this experiment was 155.72, which is lower compared to the first experiment. This can be ascribed to different experimental configuration parameters, among which the distance is believed to play a crucial role. Note that for the higher distance, lower θ is obtained.

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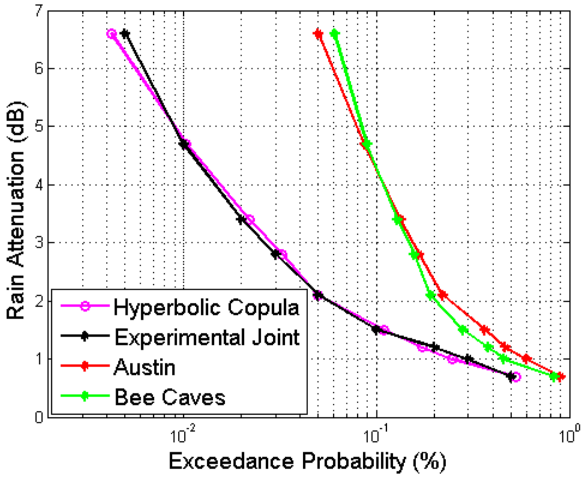

Fig. 2. CCDFs of single and joint attenuation for a two-site diversity system in Austin and Bee Caves in USA.

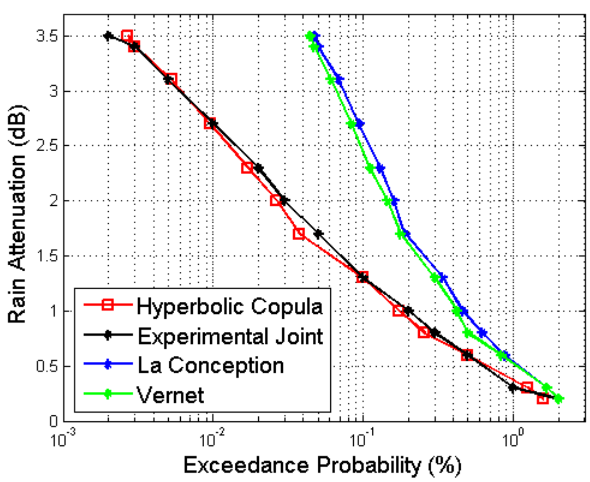

Fig. 3. CCDFs of single and joint attenuation for a two-site diversity system in Vernet and La Conception in Canada.

The same fitting procedure as described above was repeated for forty-four experiments taken from DBSG3 [22] with sufficiently accurate representation of single site rain attenuation distributions, i.e. those that are represented by at least five data points. In addition, nine more dual site experiments from [23], [24], [25] and [26] were investigated, some of which are operated at exceptionally large distances. Therefore, altogether fifty-three double site diversity experiments were included in the analysis.

The parameters θ were extracted for all the 53 analyzed experiments. The errors between theoretical expressions (15) and experimental joint exceedance probabilities were then calculated according to ITU-R P. 311-15 [27]:

$$\varepsilon_i(P) = \begin{cases} \left(\dfrac{A_{m,i}(P)}{10}\right)^{0.2} \ln\left(\dfrac{A_{p,i}(P)}{A_{m,i}(P)}\right), & A_{m,i}(P) < 10dB \\ \ln\left(\dfrac{A_{p,i}(P)}{A_{m,i}(P)}\right), & A_{m,i}(P) \geq 10dB \end{cases} \quad (16)$$

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 (16) was repeated for all fifty-three experiments at all available probabilities P. Mean value, standard deviation and rms were then expressed. The resulting total mean value of error is 0.90%, standard deviation 13.02% and rms 13.05%.

Similarly we analyzed several other Archimedean copula families not been used before for the prediction of the joint rain attenuation CCDFs. The fitting procedure resulted in a worse error performance compared to the hyperbolic cosecant copula. Therefore, the hyperbolic copula was chosen for modeling of joint exceedance probability of rain attenuation. In the next section, a prediction model of joint rain attenuation statistics for dual and multisite diversity systems is proposed.

IV. Joint CCDF Rain Attenuation Prediction Method

For the prediction of joint exceedance probability of rain attenuation for dual site diversity system based on expression (15), 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 the 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 include different operating frequencies, spatial heterogeneity of rainfalls in different geographical locations. As shown in [28], the weather direction may also play a notable role.

In this paper, we propose and analyze two versions of prediction model. First, θ is modeled only as a function of the separation distance d. Second, the model is extended by including the dependency on the elevation angle e and the baseline angle b.

A. *Modeling parameter θ as a function of the separation distance*

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

$$\theta(d) = A\exp\left(-\frac{d}{\alpha}\right) + B\exp\left(-\frac{d^2}{\beta^2}\right), \quad (17)$$

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 (17) and from measurements data as a function of distance is for distances up to 150 km depicted in Fig.4.

Dual site diversity experiments from which the expression (17) is proposed are located at mid-latitudes zones. The distance between Earth stations varies from 1.7 km to 608 km. The frequency of the links ranges from 11.4 GHz to 30 GHz, baseline orientation from 0° to 90° and elevation angle from 6° to 83°. These limitations have to be taken into account when expression (17) is used for the prediction of parameter θ.

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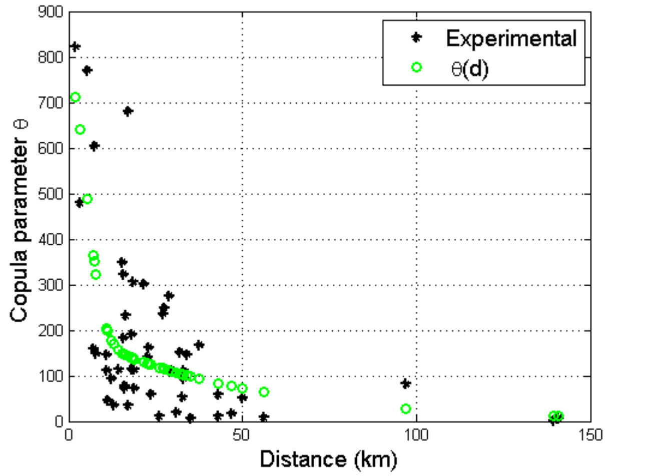

Fig. 4. Comparison of the theoretical and experimental copula parameter

An example prediction of joint rain attenuation CCDF was performed by using the experimental data from Crawford Hill and Sayreville in USA. Fig. 5 depicts the predicted curve in comparison to the experimental joint CCDF and the accompanying measured single site CCDFs. Equation (17) returned $\theta = 102.49$ for the separation distance of 33 km between the Earth stations. The θ parameter was then used as an input to equation (15) 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 1.

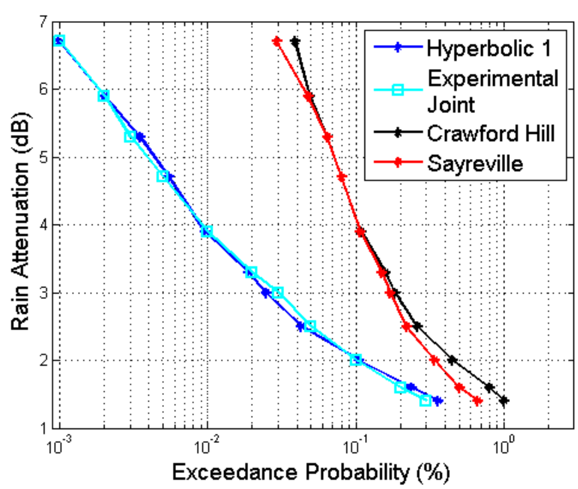

Fig. 5. Measured single and joint attenuation CCDFs and predicted joint CCDF for a two-site diversity experiment in Crawford Hill and Sayreville, USA.

B. *Modeling parameter θ as a function of the separation distance, the baseline angle and the elevation angle*

An assumption was made that the mathematical description of θ parameter in (17) could be improved even further by including additional input configurational variables which increase the accuracy of the model. Therefore, besides the separation distance, the elevation angle and the baseline angle are included. The baseline angle is an angle between the ground projection of the satellite path to one of the stations and the horizontal line connecting both stations. Based on the investigated experiments, we noted that by increasing the baseline orientation angle and the elevation angle, the performance of site diversity system was improved, which is expressed by a decreased value of θ. A few attempts to find an impact of the baseline angle have been performed before [29], [30], whereas the Hodge model [31] shows an improvement in the diversity gain by increasing both the baseline orientation angle and the elevation angle.

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:

$$\theta(d,b,e) = A\exp\left(-\frac{d}{\alpha-\lambda b-\gamma e}\right) + B\exp\left(-\frac{d^2}{\beta^2}\right), \qquad (18)$$

where $A=340$, $\alpha=67$, $\lambda=0.34$, $\gamma=0.59$, $B=300$, $\beta=10$, d is distance expressed in km, and b and e are the baseline and the elevation angles expressed in degrees, respectively, where b is always lower than 90 degrees. The values of b and e must satisfy the condition $\alpha-\lambda b-\gamma e > 0$. The condition is not very restrictive, as all of the 53 analyzed experiments comply with it. This version of prediction method, which depends on d, b and e, is referred to as the Hyperbolic 2.

An example prediction is shown in Fig. 6. CCDFs for a dual site diversity system in Atlanta and in Cobb County, USA [22] are depicted. The predictions were made using both the Hyperbolic 1 and the Hyperbolic 2 method. As expected, a more accurate prediction was achieved by the Hyperbolic 2. A comprehensive error performance analysis and comparison of both methods is given in section V.

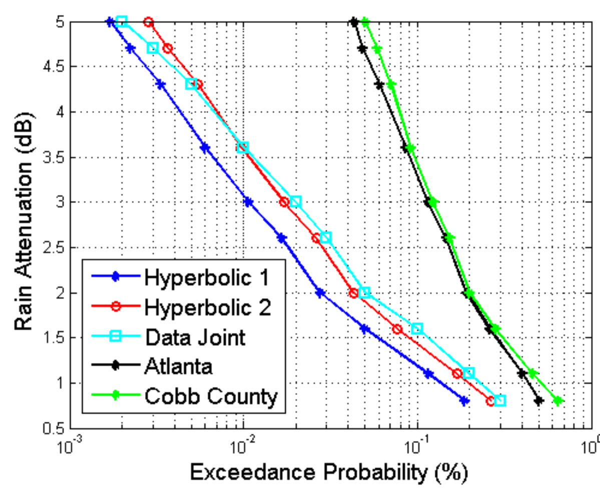

Fig. 6. Measured single and joint attenuation CCDFs and predicted joint CCDFs, by applying both versions of proposed method, for a two-site diversity experiment in Atlanta and Cobb County, USA.

C. *Multiple site diversity prediction model using HAC (Hierarchical Archimedean Copula)*

The methodology is extended from the common dual 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 equation (4), the joint CCDF of rain attenuation for three sites can be expressed as:

$$P[A_1 \geq A_{th}, A_2 \geq A_{th}, A_3 \geq A_{th}] = 1 - u_1 - u_2 - u_3 + \sum_{1 \leq i_1 < i_2 \leq 3} C_{i_1,i_2}(u_{i_1}, u_{i_2}) - \sum_{1 \leq i_1 < i_2 < i_3 \leq 3} C_{i_1,i_2,i_3}(u_{i_1}, u_{i_2}, u_{i_3}) . \tag{19}$$

The condition $1 \leq i_1 < i_2 \leq 3$ implies that i_1 and i_2 form the pairs (1,2), (1,3) and (2,3), whereas for $1 \leq i_1 < i_2 < i_3 \leq 3$, we obtain (1, 2, and 3). Hence, the equation (19) takes the form:

$$P[A_1 \geq A_{th}, A_2 \geq A_{th}, A_3 \geq A_{th}] = 1 - u_1 - u_2 - u_3 + C_{1,2}(u_1, u_2, \theta_{12}) + C_{1,3}(u_1, u_3, \theta_{13}) + C_{2,3}(u_2, u_3, \theta_{23}) - C_{1,2,3}(u_1, u_2, u_3, \theta_{123}) . \tag{20}$$

The three copula functions $C_{1,2}$, $C_{1,3}$, $C_{2,3}$ can be calculated from (14) and the values θ_{12}, θ_{13} and θ_{23} can be determined from either (17) or (18), 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 e_{12}, e_{13}, e_{23}, belonging to the corresponding pairs of the stations. For the three-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 (17) or (18). Thus, applying the HAC structure from (7), the joint CCDF becomes:

$$P[A_1 \geq A_{th}, A_2 \geq A_{th}, A_3 \geq A_{th}] = 1 - u_1 - u_2 - u_3 + C_{1,2}(u_1, u_2, \theta_{12}) + C_{1,3}(u_1, u_3, \theta_{13}) + C_{2,3}(u_2, u_3, \theta_{23}) - C_4(C_{1,2}(u_1, u_2, \theta_{1,2}), u_3, \theta_4) . \tag{21}$$

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 (17) and (18) are to be applied, a meaningful definition of θ_4 based on parameters d_4, b_4 and e_4 has to be found. For equation (17), 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 Fig. 7. For equation (18), baseline angle b_4 and elevation angle e_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 e_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 e_4 could be determined also at the middle point M.

Considering that $C_{1,2}$ and C_4 are from the same family of copula, we need to guarantee that $\theta_4 < \theta_{1,2}$. If equation (17) 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 case of a triangle with equal sides, this is impossible. One of the advantages of using equation (18) is that the condition $\theta_4 < \theta_{1,2}$ relies also on values of *b* and *e*, which makes the condition achievable also for equilateral triangles.

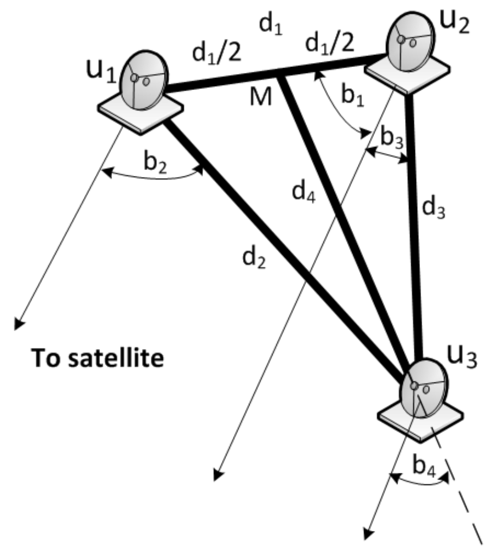

Fig. 7. A general three site diversity configuration with denoted distances and baseline orientation angles.

Based on hyperbolic cosecant generator in (9) and expressions (7) and (14), the joint CCDF for three site diversity in (21) takes the form:

$$\begin{aligned}
&P[A_1 \geq A_{th}, A_2 \geq A_{th}, A_3 \geq A_{th}] = 1 - u_1 - u_2 - u_3 + \\
&+ \left[acsch\left(csch(u_1^{\theta_{1,2}}) + csch(u_2^{\theta_{1,2}}) - csch(1) \right) \right]^{\frac{1}{\theta_{1,2}}} \\
&+ \left[acsch\left(csch(u_1^{\theta_{1,3}}) + csch(u_3^{\theta_{1,3}}) - csch(1) \right) \right]^{\frac{1}{\theta_{1,3}}} \\
&+ \left[acsch\left(csch(u_2^{\theta_{2,3}}) + csch(u_3^{\theta_{2,3}}) - csch(1) \right) \right]^{\frac{1}{\theta_{2,3}}} \\
&- \left[acsch\left(csch\left[acsch\left(csch(u_1^{\theta_{1,2}}) + csch(u_2^{\theta_{1,2}}) - csch(1) \right) \right]^{\frac{\theta_4}{\theta_{1,2}}} \right.\right. \\
&\qquad \left.\left. + csch(u_3^{\theta_4}) - csch(1) \right) \right]^{\frac{1}{\theta_4}} .
\end{aligned} \tag{22}$$

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 southern UK and the third station in Dundee, Scotland, approximately 600 km north of the two [26]. 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 $\theta_{1,2}$, $\theta_{1,3}$, $\theta_{2,3}$ and θ_4 were then calculated from (17) and the joint CCDF from (22). Experimental and predicted CCDFs are depicted in Fig. 8. In this example, the prediction model Hyperbolic 1 gave satisfactory results, confirming also our assumption about the relation between θ_4 and the distance d_4.

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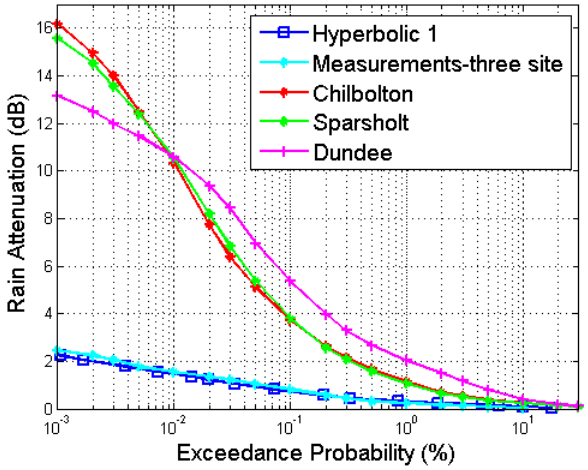

Fig. 8. CCDFs of joint attenuation from measurements and from prediction model for the three site diversity system in UK.

In the next example, the strength of the Hyperbolic 2 method is demonstrated. The analysis is based on the dataset of our own experiment, performed in Slovenia and in Austria [23]. The Slovenian stations in Ljubljana and in Lisec are 43 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 (17), the parameter values $\theta_{1,2}$=83.58 and θ_4=12.02 were obtained, while the expression (18) returned $\theta_{1,2}$=72.7 and θ_4=5.10. Thus in both cases, the condition $\theta_4<\theta_{1,2}$ is satisfied. The graph in Fig. 9 shows clearly that in this case, the Hyperbolic 2 prediction method outperforms the Hyperbolic 1.

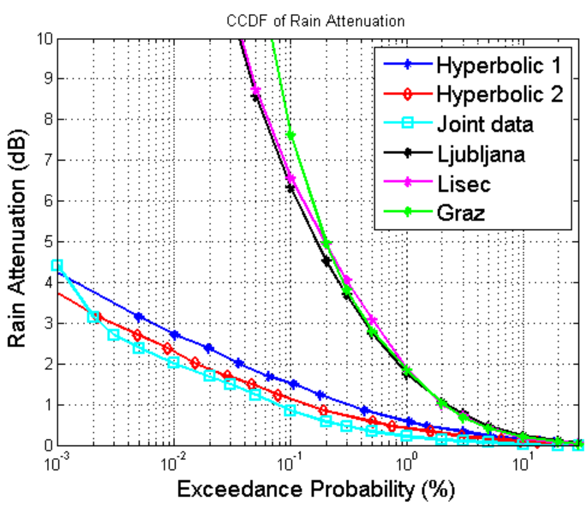

Fig. 9. CCDFs of joint attenuation from measurements and from both versions of the cosecant hyperbolic model for the three-site diversity system in Slovenia and Austria.

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 (4), (5), (9) 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 (17) or (18), 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 Section (2.2.1.1) [5].

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 (17) or (18),
- for every slant path use the single site CDF (u_i),
- for two site diversity, calculate the joint CCDF using (15),
- for three site diversity assign u_1, u_2 and u_3 to the sites to fulfill $\theta_4<\theta_{12}$, $\theta_{12}\geq(\theta_{13}, \theta_{23})$, and calculate CCDF using (22),
- for multiple site diversity, use the equations (4), (5), (9), (10), express the multivariate copula in (4) by any HAC structure and assign the u_i that the copula parameters decrease with hierarchy level.

V. Comparative Tests And Error Performance of Prediction Models

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 all 53 studied dual site diversity experiments. 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 [27]. For comparative purposes, the same evaluation was done for the model proposed in ITU-R P.618-12 (Section 2.2.4.1) [5] and the recently proposed models based on copula theory, the Clayton copula [11] and the Gaussian copula [14].

Since there are a small number of experiments with data at percentages above 1%, the analysis in this paper 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 I summarizes the error performance in terms of mean error, standard deviation and rms value, over all the 53 experiments and five considered models. In the overall analysis, the Hyperbolic 2 performs the best. The Gaussian method shows slightly higher standard deviation and rms error compared to Hyperbolic 2, but lower than the Hyperbolic 1.

TABLE I
TOTAL ERROR PERFORMANCE COMPARISON

Model	ε_{mean}(%)	ε_{std} (%)	ε_{rms}(%)
ITU-R P.618-12	-19.65	23.59	30.70
Gaussian	0.35	18.18	18.19
Clayton	5.60	19.95	20.72
Hyperbolic 1	1.59	19.80	19.87
Hyperbolic 2	2.06	17.72	17.84

A closer insight of the error performance is revealed in Fig. 10, where the rms error for different time percentages is shown. It can be observed that Hyperbolic 2 outperforms all

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the models within the time percentages of range 0.008% up to 0.2%. The error analyses of all experiments confirmed that within this range Hyperbolic 2 with rms 13.03% performs notably better than Gaussian with rms 18.61% which has just slightly higher rms compared to Hyperbolic 2 as evident in Table I. Hyperbolic 1 shows similar performance to Clayton, and worse compared to Hyperbolic 2 for almost all percentages.

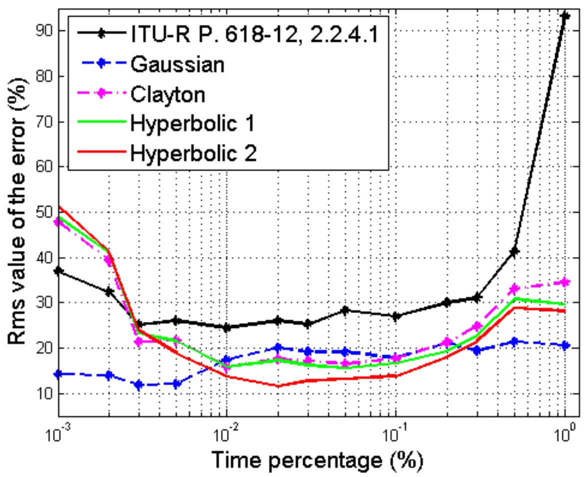

Fig. 10. Rms values of error (%) for various time percentages for 53 experiments.

Since the strength of the Hyperbolic 2 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 2 instead of Hyperbolic 1. A detailed analysis of all the available data showed that the error performance was particularly improved for 27 dual-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 Hyperbolic 2 in this case was 16.61% compared to 20.11% of the Hyperbolic 1. Moreover, for this set of experiments, the better performance of the Hyperbolic 2 was more expressed also in comparison to the Gaussian model, as shown in Table II.

TABLE II
27 EXPERIMENTS $e < 40°$, $b > 40°$, $10\text{km} < d < 150\text{km}$

Model	ε_{mean}(%)	ε_{std} (%)	ε_{rms}(%)
ITU-R P.618-12	-20.41	22.43	30.33
Gaussian	-1.13	19.44	19.47
Clayton	6.87	19.96	21.11
Hyperbolic 1	4.71	19.54	20.11
Hyperbolic 2	3.95	16.14	16.61

In Fig. 11, Fig. 12 and Fig. 13, the error analysis is given also for different probabilities. Fig. 12 clearly shows a stable behavior of the Hyperbolic 2, as its standard deviation is lower compared to all the models for almost all percentages. The rms error analysis in Fig. 13 shows that the Hyperbolic 2 performs better than the Clayton, the Hyperbolic 1 and the ITU-R model for almost all percentages, while compared to the Gaussian, it performs significantly better for percentages 0.005%<p<0.3%.

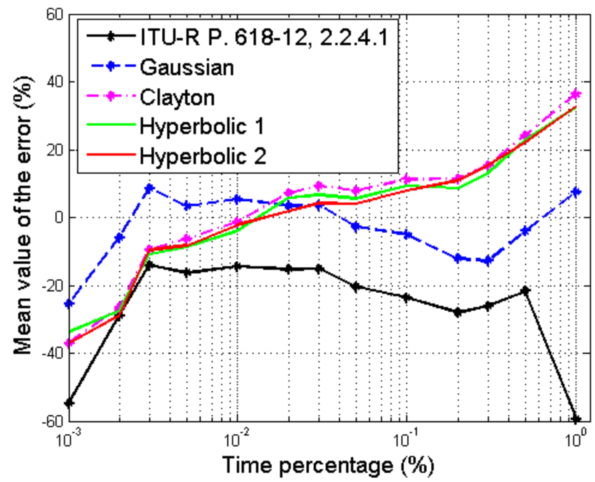

Fig. 11. Mean values of error (%) for various time percentages for 27 experiments with $e < 40°$, $b > 40°$ and $10\text{km} < d < 150\text{km}$.

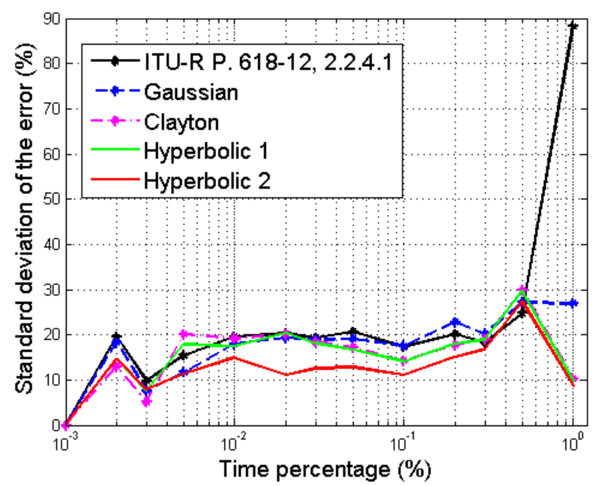

Fig. 12. Standard deviation of error (%) for various time percentages for 27 experiments with $e < 40°$, $b > 40°$ and $10\text{km} < d < 150\text{km}$.

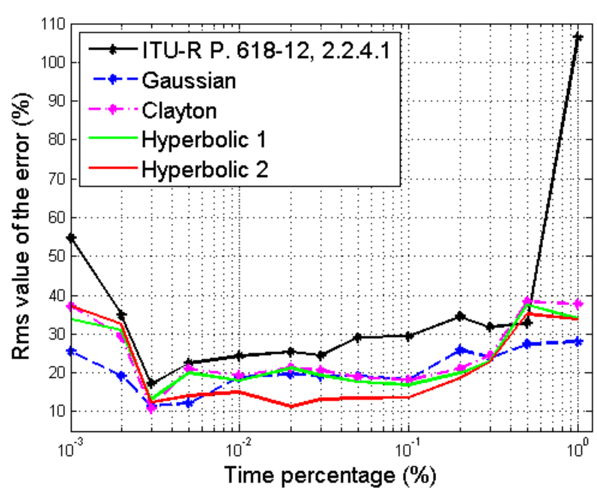

Fig. 13. Rms error (%) for various time percentages for 27 experiments with $e < 40°$, $b > 40°$ and $10\text{km} < d < 150\text{km}$.

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The subset of the 27 experiments analyzed above was chosen based on the performance comparison of the Hyperbolic 1 and the Hyperbolic 2. For the performance comparison of the Hyperbolic 2 and the Gaussian, as the second best model in the overall performance, another representative subset of experiments was chosen and analyzed.

In this case, the difference in performance was especially significant for the group of 29 experiments with distances between stations from 15 km up to 100 km, elevation angles lower than 50° and baseline orientation angles greater than 15°. The total errors for this group are given in Table III, while the analysis with respect to different probabilities is given in Figs. 14-16. For this subset, the Hyperbolic 2 outperformed the Gaussian model for 3.41 percentage points in terms of the total rms error.

TABLE III
29 EXPERIMENTS $e < 50°$, $b > 15°$, 15km < d < 100km

Model	ε_{mean}(%)	ε_{std} (%)	ε_{rms}(%)
ITU-R P.618-12	-23.80	20.33	31.30
Gaussian	-4.04	19.42	19.84
Clayton	2.41	18.78	18.93
Hyperbolic 1	1.34	19.17	19.22
Hyperbolic 2	2.61	16.22	16.43

The conclusions for this subset are similar as for the one above; when the elevation angle is low and the baseline angle is high, the prediction method considering angular geometry notably improves the predictions. The difference is evident regardless of the applied function family (Archimedean or Gaussian) and is expressed especially in terms of better stability.

In addition, we have analyzed the total error performance for the experiments which do not fulfil the conditions valid for Table II and III. The results showed that Gaussian performs slightly better compared to Hyperbolic 2 as the second model in the performance for these cases. It must be also pointed out that the additional analyses of all experiments for time percentages lower than 0.01% and higher than 0.1 % were performed. The results which are also confirmed by Fig. 10 shows that Gaussian performs better compared to Hyperbolic 2.

In general the main advantage of the Hyperbolic 2 method against Gaussian is the simplicity of the numerical implementation. When referring to two site diversity prediction performance, the Hyperbolic 2 should be used if conditions valid for Table II and III are fulfilled or if the joint CCDF is required within the range 0.01% and 0.1%.

Finally, the error performance of the proposed model was analyzed also for the three-site diversity systems. Unlike the dual-site experiments, three-site experiments are very rare. Four accessible experiments were analyzed here [23], [24], [26], [32], based on which we compared the Hyperbolic 1, the Hyperbolic 2 and the Gaussian. Note that the existing version of the Clayton model and the ITU-R do not enable multiple-site prediction. The results are summarized in Table IV. The Hyperbolic 2 method outperformed the other two methods, however, considering the sparse experimental data, more experiments are needed in the future, in order to corroborate the conclusions.

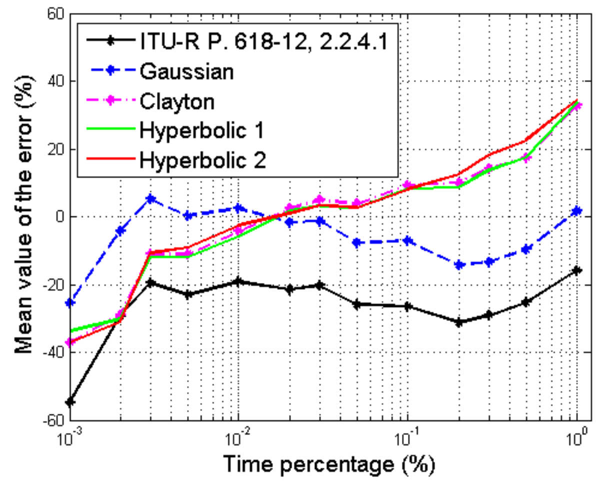

Fig. 14. Mean values of error (%) for various time percentages for 29 experiments with $e < 50°$, $b > 15°$ and 15km < d < 100km.

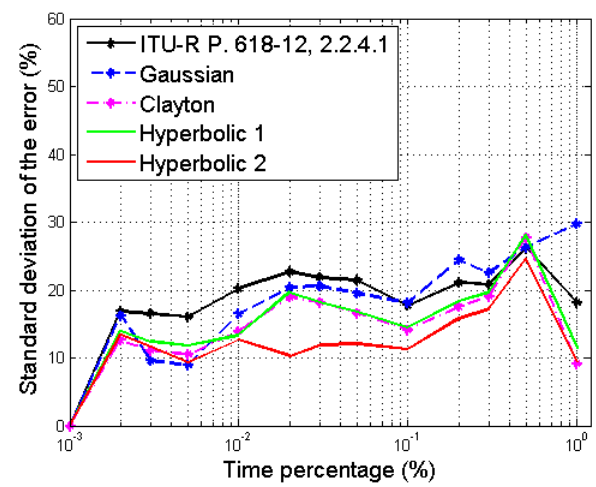

Fig. 15. Standard deviation of error (%) for various time percentages for 29 experiments with $e < 50°$, $b > 15°$ and 15 km < d < 100km.

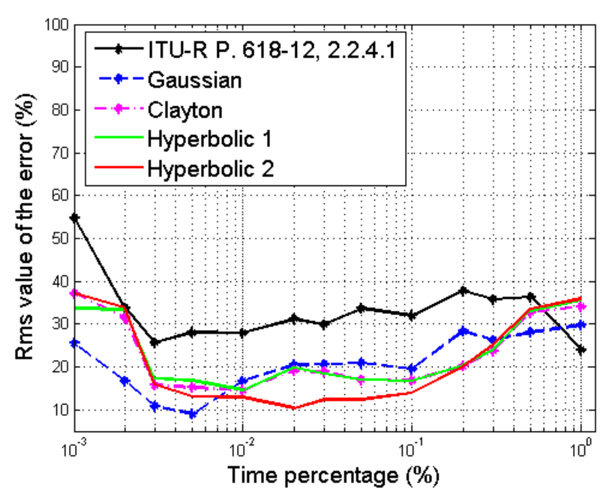

Fig. 16. Rms error (%) for various time percentages for 29 experiments with $e < 50°$, $b > 15°$ and 15km < d < 100km.

TABLE IV
ERROR PERFORMANCE COMPARISON FOR 4 THREE-SITE EXPERIMENTS

Model	ε_{mean}(%)	ε_{std} (%)	ε_{rms}(%)
Hyperbolic 2	3.06	16.34	16.63
Hyperbolic 1	6.56	19.44	20.51
Gaussian	-13.05	11.63	17.48

VI. CONCLUSIONS

In this paper, a new method for prediction of joint rain attenuation CCDF for site diversity systems was proposed. It is based on a new family of Archimedean copulas, the Hyperbolic Cosecant Copula. Besides the new family, two other novel features have been introduced. First, the method has been extended from joint attenuation prediction for dual-site systems to prediction in multi-site systems with an arbitrary number of sites. For this purpose, the HAC structure of Archimedean copula has been applied. Second, the prediction method has been improved by the capability to account for the dependency on the system's angular geometry. The model thus includes the elevation angle and the baseline angle as the input parameters.

Extensive tests were performed in order to validate the proposed model, involving databases of 53 two-site and 4 three-site diversity experiments. An error performance evaluation were conducted, focusing on two aspects: comparison of the proposed model with the other existing models and evaluation of the benefits of modeling the angular dependency.

The analysis showed that the elevation angle and the baseline angle may have a notable impact, making them suitable for inclusion in the model. According to our study, this is relevant especially for the experiments with intermediate distances, low elevation angles and high baseline angles. In such cases, an average improvement of about 3.5 percentage points was achieved in comparison to other families from Archimedean copulas and in comparison to Gaussian copulas, whereas the improvement compared to the current ITU-R model was in the order of 13 percentage points. The proposed method seems to be more accurate also for the three-site diversity modeling, however to confirm this result more experimental data are needed.

The proposed method has also practical advantages. For multi-site diversity, the HAC structure can be used and thus the joint probability can be expressed as an algebraic function. This simplifies the procedure, which could otherwise involve complex multiple integrals (e.g. in the Gaussian copula). The presented procedure is generic, meaning that the multi joint CCDF prediction can be used with any future Archimedean family, yet to be proposed. In fact, a combination of different families can be used, as long as the composite generator functions are completely monotonic.

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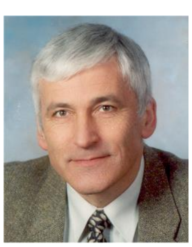
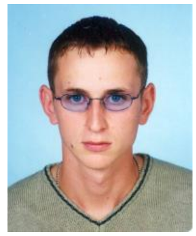


Gorazd Kandus (M’85-SM’10-LSM’17) was born in Ljubljana in 1947. He received B.Sc., M.Sc., and Ph.D. degrees in Electrical Engineering from University of Ljubljana, Slovenia, in 1971, 1974 and 1991, respectively. He spent one year at Worchester Polytechnic Institute, Worchester, MA, USA as a Fulbright Fellow, 3 months as CEC Fellow at the University of Karlsruhe, 3 months at Forschungszentrum Informatik in Karlsruhe, and 2 months at German Aerospace Center (DLR) in Oberpfaffenhofen, Germany as DAAD Visiting Scientist. He is Emeritus Scientist of the Jozef Stefan Institute and a Full Professor at the Jožef Stefan International Postgraduate School, Ljubljana, Slovenia teaching courses in Mobile Communications. He has published more than 80 papers in international journals and more than 180 papers in conference proceedings. He holds 2 US patents. He was national representative in 6 COST Actions and EU TP ISI and eMobility. He participated to EU FP projects CAPANINA, SatNEx, AgroSense, and several national projects.

His research interest includes radio propagation, radio channel modelling, wireless optical communications, satellite and HAP communications, adaptive coding and modulation, adaptive routing, and self-organizing networks. He is Honour member of Upsilon Pi Epsilon.



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His research and working experience are in the field of telecommunications, focusing on development and performance analysis for fixed and mobile systems including terrestrial, stratospheric and satellite systems, radio channel modelling for fixed and mobile narrowband and broadband radio communication systems. He works on several projects connected with professional mobile communication systems, 2/3/4G, WiFi and WiMAX technologies, satellite and sensor networks, including several COST actions, Framework Program projects, H2020 projects, European Space Agency (ESA) projects and numerous national research and applicative projects. He is author or co-author of more than 50 peer-reviewed journal and conference papers.

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Andrej Vilhar (M’11) was born in Ljubljana, Slovenia, in 1979. He received the Diploma degree and the Ph.D. degree in electrical engineering from the University of Ljubljana in 2004 and 2009, respectively. In 2009/2010, he spent one year as a post-doc at the French Aerospace Lab ONERA. He currently works as a research fellow at the Jozef Stefan Institute in Slovenia, Department of Communication Systems. He has published more than 50 papers in international refereed journals and conferences. His main research field is radio wave propagation. He has been involved in various industrial and research projects, covering terrestrial and satellite propagation, including the PECS projects for the European Space Agency. He took part in various international working groups dealing with Earth-space propagation, such as COST IC0802 and the ASAPE.