UNBALANCED LARGE SCALE MULTIPLE SITE DIVERSITY PERFORMANCE IN SATELLITE COMMUNICATION NETWORKS

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ABSTRACT

Frequency bands well above 10GHz are of primary importance for current and, more importantly, future user oriented satellite communication networks. In this course, well known rain fade mitigation techniques such as site diversity are reviewed and considered for use in a different context. This paper extends previous analytical methodologies to the case of large scale site diversity, that is, satellite networks employing cooperative earth terminals at distances higher than 50km to combat the severe effects of rain attenuation. The general case of an unbalanced diversity configuration is considered with different climatic input for each earth station, obtained from the latest rainfall statistics of the ITU-R. The proposed model is successfully tested against experimental results coming from Japan.

INTRODUCTION

Commercial fixed satellite communication (satcom) networks already operate or will operate in the near future at frequencies well above 10GHz (Ku, Ka and V bands). At these frequency bands, rain attenuation is the dominant fading mechanism [1]. To combat rain attenuation several fade mitigation techniques have been developed such as diversity protection schemes, power control and adaptive transmission techniques [2]. Among these countermeasures, the most efficient is site diversity (SD) [3], which achieves a significant availability improvement. SD takes advantage of the spatial characteristics of the rainfall medium by engaging two or more earth stations (ESs) to ensure that the probability of attenuation due to rain occurring simultaneously on the alternative Earth-space paths is significantly less than the relevant probability of the individual paths. Depending on the distance between ESs, SD is distinguished into micro, short and long scale diversity [4], [5]. Recently, large-scale SD (LSSD) schemes have also been proposed in the literature [6], [7], utilizing earth terminals (particularly major gateway stations) separated by more than 50km and up to 1000km, aiming at further increasing the service time. LSSD is also considered as a mean to provide alternative feeder links to the satellite network.

The purpose of this paper is to introduce a new analytical model for the estimation of the joint exceedance probability of two or three earth stations at a distance larger than 50km. The suggested methodology is based on the fundamental assumption that rainfall rate and rain attenuation follow the lognormal distribution. The long-term rain rate statistics of the two or three terminals are considered generally different and are obtained from the ITU-R rainmaps recommended in P.837 [8]. In this recommendation, the annual rainfall rate percentage is provided for every geographical longitude and latitude. Furthermore, the different rain height values at every earth terminal location are taken from the ITU-R Recommendation P.839 [9]. The lognormal statistical parameters of rain attenuation are evaluated using the convective raincells model [10]. In view of the above, the LSSD configuration investigated in this specific work is considered unbalanced. Finally, the spatial inhomogeneity of the induced rain attenuation on the Earth-space paths is taken into account through the incorporation of the logarithmic correlation coefficient proposed by Paraboni-Barbaliscia [11] for distances greater than 50km. The proposed model is compared with experimental data coming from Japan with encouraging results.

THE ANALYSIS

Consider the LSSD configuration in Fig.1, where ESs are separated by more than 50km apart (distances between ESs are denoted by $D_{ij}$, $i,j=1,2,3$).

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In this figure, the case of a triple LSSD scheme is shown; however, the analysis that follows covers double LSSD as well.

For SD of smaller scale, elevation angles from ESs to the satellite can be considered equal and, in turn, the scheme is balanced. However, for LSSD, where distances between ESs are in the range of 50km to 1000km, this assumption does not hold. As a result, LSSD must be treated as an unbalanced geometry with different elevation angles $\theta_i$, $i=1,2,3$ for each participating station.

The joint exceedance probability of the triple and the double LSSD scheme is respectively defined as

$$ P_{1,2,3} = \Pr[A_1 \geq x_1, A_2 \geq x_2, A_3 \geq x_3] = \int \int \int f_{A_1,A_2,A_3}(A_1, A_2, A_3) \, dA_1 \, dA_2 \, dA_3 $$

$$ P_{1,2} = \Pr[A_1 \geq x_1, A_2 \geq x_2] = \int \int f_{A_1,A_2}(A_1, A_2) \, dA_1 \, dA_2 $$

where $A_i$ [dB], $x_i$ [dB], $i=1,2,3$, are the rain attenuation lognormal random variables for slant path $i$ and the corresponding fade margin thresholds, respectively. The fact that the latter are different for every earth-to-satellite connection designates that the system is unbalanced. In (1), (2) the triple $f_{A_1,A_2,A_3}$ and double $f_{A_1,A_2}$ joint lognormal probability density functions (pdf) appear. Under the assumptions of the convective raincells model [10], the final expression for the probabilities in (1), (2) is given by

$$ P_{1,2,3} = \frac{1}{2} \int \int f_{U_1, U_2}(u_2, u_3) \text{erfc} \left[ \frac{u_1 - m_1}{\sqrt{2} \sigma_1} \right] \, du_2 \, du_3 $$

$$ P_{1,2} = \frac{1}{2} \int f_{U_2}(u_2) \text{erfc} \left[ \frac{u_1 - m_1}{\sqrt{2} \sigma_1} \right] \, du_2 $$

where

$$ f_{U_1,U_2}(u_1,u_2) = \frac{1}{2\pi \sqrt{1-\rho_{u_1u_2}^2}} \exp \left[ -\frac{u_1^2 + u_2^2 - 2\rho_{u_1u_2}u_1u_2}{2(1-\rho_{u_1u_2}^2)} \right] $$

is the joint two dimensional pdf (the single pdf in (5) is derived similarly) of the normalized random variable

$$ u_i = \frac{\ln A_i - \ln A_{mi}}{S_{ui}} $$

All the unknown terms that appear in (3-6) are obtainable from [10].

Nevertheless, for the LSSD case investigated here, one must take into consideration two significant factors that differentiate the analysis in comparison to the conventional medium range SD. First, the statistical parameters of the lognormal distribution $A_{mi}$, $S_{mi}$ can no longer be calculated using the same climatic input from [8], which is a database providing detailed rainfall statistics grouping regions of the Earth in 1.5°x1.5° squares. Hence, besides the dependence on frequency of operation, polarization tilt angle, effective path length and rain height, $A_{mi}$, $S_{mi}$ differ, also, in rainfall rate statistics assumed for each terminal. Second, the correlation properties
of the rainfall medium, represented by the lognormal correlation coefficient $\rho_{nij}$ for pairs of Earth-satellite paths $i, j$, follow a different pattern at large distances. To treat this, we take advantage of the contribution in [11] to give an overall expression for $\rho_{nij}$ for use in short-, long-, and large-distance SD fade mitigation

$$\rho_{nij} = \begin{cases} \left( S_{ai} S_{aj} \right)^{\frac{1}{2}} \ln \left[ \rho_{ij} \sqrt{\exp\left\{ S_{ai}^2 - 1 \right\} \exp\left\{ S_{aj}^2 - 1 \right\} + 1} \right] & \text{for } 1.7 \text{ km} < D_{ij} < 50 \text{ km} \\ 0.94 \exp\left\{-D_{ij} / 30\right\} + 0.6 \exp\left\{-D_{ij} / 500\right\} & \text{for } D_{ij} \geq 50 \text{ km} \end{cases}$$

(7)

Note that an expression for $\rho_{nij}$ in the case of $D_{ij} < 1.7$ km (micro-scale SD) has not been proposed to date.

The most insightful parameter to quantify the improvement resulting from SD is the SD gain (SDG). For either the double or triple SD scheme, SDG is defined as

$$SDG = A_{i} - A_{DorT}$$

(8)

In (8), $A_i$ is the rain attenuation over the reference link $i$ and $A_D, A_T$ are the rain attenuation values jointly exceeded in two (double SD) or three (triple SD) links, respectively.

**NUMERICAL IMPLEMENTATION AND VALIDATION OF THE MODEL**

In this section, we first present a hypothetical implementation of the above LSSD methodology for a 40GHz downlink from the Hellas-Sat geostationary satellite at 39°E. Receiving ESs are located in Athens (ES#1), Lamia (ES#2), and Ioannina (ES#3) in Greece and use the relevant data from [8], [9] for rain rate and rain height data, respectively. The corresponding elevation angles formed are $\theta_1 = 43.46^\circ$, $\theta_2 = 42.06^\circ$, and $\theta_3 = 40.52^\circ$, while $D_{12} = 209$ km, $D_{13} = 235$ km, and $D_{23} = 444$ km. The huge improvement in terms of exceedance probability resulting from this particular LSSD scheme is evident from Fig.2, where the exceedance probability vs. rain attenuation curves are drawn for the triple and the double (between ES#1 and ES#2) LSSD case, together with average single site probability of the three ESs.

Next, the physical LSSD model presented in the previous section is compared in Fig.3 against experimental data of a double SD configuration operating at 14GHz between Tohuku Gakuin University (TGU) and Waseda University (WU) in Japan [7]. The distance between the two stations is 300 km. The test is carried out for SDG vs. single site attenuation values. Although the predicted curve falls quite close to the reported data, much more experimental results and comparison tests are needed to definitely conclude on the suitability of the expression in (7), since this specific experiment lasted for only six months (May-Nov 1995). Deviation of the proposed model from the experimental results is due to the fact that Japan’s climate, belonging to a subtropical area, is quite different in comparison to Mediterranean areas (Italy), for which the lower part of (7) was derived.

![Fig.2 Application of the proposed LSSD model (both double and triple) between HellasSat (39°E) and ESs located in Athens, Lamia, and Ioannina, GR. V band downlink frequency (40GHz).](image-url)
CONCLUSIONS

In this paper, some early experimental work on large-scale SD as a fade mitigation technique were employed to test the convective rain cells statistical model for the joint double and triple statistics of rain attenuation. In comparison to the typical medium range application of the model, the correlation coefficient proposed by Paraboni-Barbaliscia for distances between ESs greater than 50km was used, as well as different rainfall related statistics for every location of the LSSD configuration, yielding a general unbalanced system.

REFERENCES