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SHADOWING CORRELATION FOR MOBILE SATELLITE DIVERSITY IN URBAN AREAS

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1. INTRODUCTION

In order to enhance the availability of mobile satellite systems, it is necessary to minimise the effects of shadowing or blockage effects. One of the major approaches to achieving this is to apply satellite diversity, where signals from multiple satellites are selected or combined to improve the composite availability. In order to maximise the benefit of this approach it is necessary for the paths to show low or negative correlation between their shadowing states. Reliable prediction of this correlation is therefore a key requirement for the design of mobile satellite systems. This paper reviews existing methods for predicting the correlation, and finds that they are inadequate in their ability to generalise to a wide range of environments and to account quantitatively for the influence of the local geometry around the mobile. Two new approaches are introduced and compared and shown to yield benefits, particularly within built-up areas.

2. OVERVIEW OF OTHER SATELLITE DIVERSITY STUDIES

A brief summary of existing methods for predicting the correlation as well as satellite diversity gain can be given as follows.

a) In [1] an extension of the two-state model proposed in [2] for a single satellite-mobile link to two angle-spaced links was proposed. A campaign in rural, suburban and urban environments using a video-camera to record the landscape was carried out. The outcome of this study was the formulation of an empirical model for the correlation coefficient for a number of environments which were modelled by using circular scans with "0" or "1" representing obstruction or visibility respectively.

b) The two-state model proposed in [2] was extended by the same author to model two correlated links [3][4]. Lutz proposed a 4-state Markov model to describe the possible combinations of good and bad states in two different links. Equilibrium state and transition probabilities for a four-state model were computed for the correlated and the uncorrelated cases in terms of the individual two-state model probabilities and of the correlation coefficient, r.

c) A complete analysis of path diversity for LEO Satellite-PCS networks in urban environments is presented in [5]. The method consisted of taking fisheye photos at potential user locations; extracting from the images path-state information (clear/shadowed/blocked) as a function of look angles, and combining each path-state for single or multiple satellites in a specific constellation using appropriate statistical fade models. Once the model was accomplished, independent links were assumed and consequently the calculation of k-fold diversity gain was performed in a straightforward fashion. For example, significant diversity gains of 10 dB and 9 dB were obtained for Globalstar (Mid-latitude).

d) A similar approach can be found in [6]. A three-state Markov model is assumed to account for the large dynamic range of the received signal. The use of uncorrelated Markov models, one per satellite link was proposed and results of this study showed a notable improvement in service availability thanks to the diversity effect.

e) In [7], the availability of the ICO and Globalstar systems was analysed using the correlated four-state model developed by Lutz. From fisheye pictures taken in Guilford, Southampton, London and Los Angeles, blockage and correlation statistics were extracted. In this study it was observed that for azimuth separations smaller than 30º, satellite channels tend to be correlated.

In summary, available studies on correlation are referred to a scarce number of measurements from which no conclusions can be drawn and correlation is not taken into consideration in those studies providing complete methodologies to compute diversity gain.

3. SHADOWING CORRELATION MODELLING

Two different approaches to shadowing correlation modelling are presented here. One is based on the use of a physical-statistical model and the other one is based on a semi-deterministic model. Both approaches start off with the same definition of the stochastic $S_i(t)$ for each satellite-*i* which takes the value 0 when shadowing conditions are present and 1 when there is direct visibility to the satellite. The two approaches are:

1. A physical-statistical model, which adapts existing work by the authors [8] yielding an explicit formulation for the correlation between shadowing states associated with pairs of satellites as a function of the path geometry and the statistics of surrounding buildings.
2. A semi-deterministic model [9] which proposes a possible correlation description parameter: the azimuth correlation angle, B(Df, Dq, q_{ref}) where Df is the azimuth separation, Dq is the elevation separation and q_{ref} is a reference elevation. This is the mean angular separation for two satellites to become uncorrelated in a given environment type. Simulations using synthetic environments are used to compute the correlation angle. Fig. 1 shows the typical shape of the correlation coefficient as a function of Df and Dq for a given q_{ref}. It can be observed that the correlation behaviour for any pair of satellites can be described by the azimuth correlation angle which contemplates the effect of the environment.

The correlation coefficient is calculated in both approaches according to the mathematical expectation and ensemble averaging respectively. Mathematical expressions are given as follows

$$r_{Approach\ 1} = \frac{COV(S_1,S_2)}{s_1 s_2} = \frac{E\left[\left(S_1-\bar{S}_1\right)\left(S_2-\bar{S}_2\right)\right]}{\sqrt{E\left[\left(S_1-\bar{S}_2\right)^2\right]}\sqrt{E\left[\left(S_2-\bar{S}_2\right)^2\right]}}; \quad r_{Approach\ 2} = \frac{COV(S_1,S_2)}{s_1 s_2} = \frac{\left\langle\left(S_1-\bar{S}_1\right)\left(S_2-\bar{S}_2\right)\right\rangle}{\sqrt{\left\langle\left(S_1-\bar{S}_1\right)^2\right\rangle}\sqrt{\left\langle\left(S_2-\bar{S}_2\right)^2\right\rangle}} \tag{2}$$

The models were compared and found to yield exact agreement within the same environment [10], thus verifying the validity of both approaches. The semi-deterministic model has been then used to produce statistics of variability of the correlation with mobile. The advantage of the two proposed approaches over the use of measurements and other techniques (e.g. fish eye photos) is that they are based on the statistical formulation involved and therefore can be totally simulated. In order to carry out the simulations, canyon streets were used since built up areas are of primary interest to benefiting from satellite diversity. To do this, statistical analysis of the parameters involved such as building heights was addressed first. Then, since it was possible to easily generate synthetic canyon streets, averaging of the correlation coefficient was performed. Finally, statistical behaviour of Df and Dq for a given q_{ref} and its dependency with constellation was investigated.

Environment Parameterisation

Urban environments from two European countries were studied and found to follow different yet well known distributions. Namely, high and medium built-up density areas from England and Spain were analysed. London and Guildford building heights were found to be log-normally distributed with means of 17.6 and 7.2 m., and standard deviations of 0.31 and 0.26 m, respectively. Contrasting with this result, two different sectors of Madrid were analysed and in this case heights were found to be normally distributed. Particularly, it was studied the business area of Madrid (La Castellana Street) characterised by very high buildings and a residential district of the city centre (Chamberí). The obtained Gaussian distributions present means of 21.45 and 12.56 m, and standard deviations of 8.97 and 3.78 m, respectively. Fig 2 shows the fitting of the latter case. Note that the fitting was performed by using number of stores instead of heights. According to the information included in the official database, 2 m per store were considered. Study of widths of buildings, lanes, sidewalks and other effects such as frequency of squares were also investigated.

Correlation Coefficient Averaging

The results obtained for $\overline{B}$ (Df, Dq, q_{ref}) in the simulations are summarised in Table 1 where correlation values have not been included but only azimuth ranges for the correlation to be considered important. Log-normal street canyons were used and the threshold correlation coefficient was set to 0.3. For links having angle separations greater than $\overline{B}$, no correlation and negative correlation could be expected. It can be observed that for satellites at the same elevation, loss of correlation is reached around Df = 30º. It can also be observed how correlation is lost for two satellite links with elevation offsets greater than 20º. Note that azimuth separation in the vicinity of 180º are specially relevant, as it could be expected for a canyon street geometry. Nevertheless, it is worth to clarify that averaging is not as meaningful as it would be expected since correlation coefficients tend to vary about their mean value presenting an important percentage of small and even negative values. In order to further illustrate the correlation coefficient variability Fig. 3 shows the distribution of the correlation coefficient variations at different points along the route.

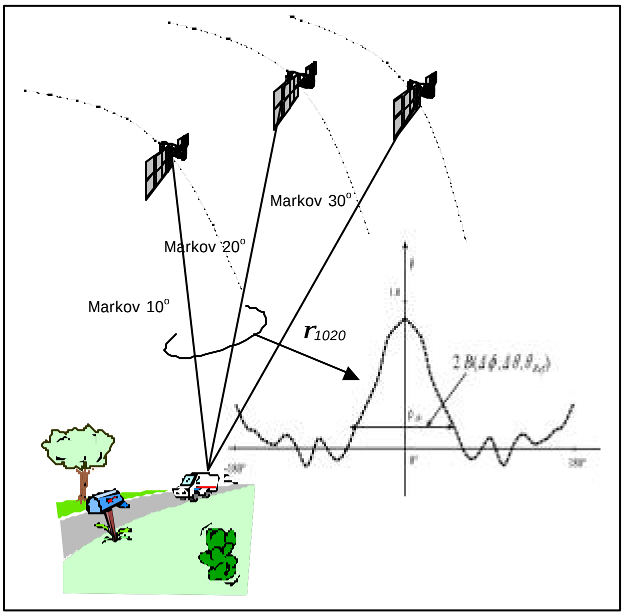

Fig.1. Illustration of the azimuth correlation angle concept.

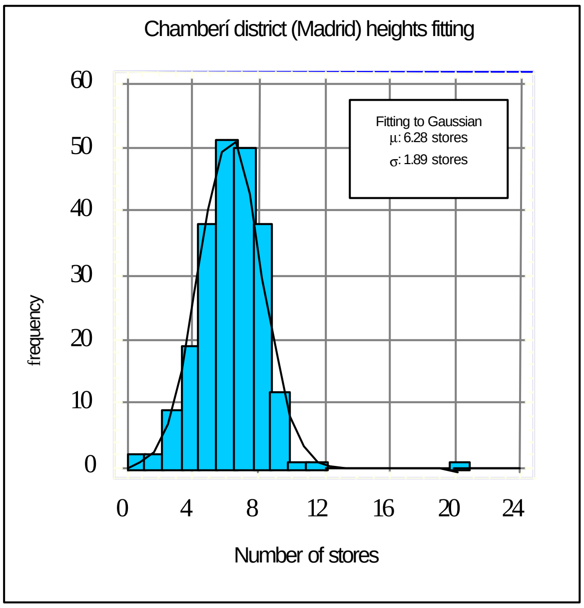

Fig.2. Fitting of heights of Chamberí (Madrid) to a Gaussian distribution.

Table 1. Summary of geometrical conditions for which correlation can be expected in street canyon scenarios

Reference Elevation	Elevation Increment	Azimuth Increment	Existence of Correlation
$10^o \leq q_{ref} < 50^o$	$Dq = 0^o$	$\lvert D f\rvert < 30^o$ $170^o < \lvert D f\rvert < 180^o$	Yes
$10^o \leq q_{ref} < 50^o$	$Dq = 0^o$	$30^o < \lvert D f\rvert < 170^o$	No
$10^o \leq q_{ref} < 50^o$	$0^o < Dq \leq 20^o$	$\lvert D f\rvert < 15^o$ $170^o < \lvert D f\rvert < 180^o$	Yes
$10^o \leq q_{ref} < 50^o$	$Dq > 20^o$	any	No
$q_{ref} \geq 50^o$	any	any	LOS

It can be observed that for satellites at the same elevation, loss of correlation is reached around $Df = 30^o$. It can also be observed how correlation is lost for two satellite links with elevation offsets greater than 20. It can be also inferred from the simulations that for azimuth separations around 90º, negative correlation is found. Nevertheless, it should be noted that averaging is not as meaningful as it would be expected since correlation coefficient tend to vary about the mean as the mobile moves along the route. In order to further illustrate this correlation coefficient variability Fig. 3 shows the distribution of the correlation coefficient variations at different points along the route. A very promising feature can be observed as it is the fact that negative values of this parameter occur with significant probabilities.

Satellites Separation

In the last section, angular satellite separations were calculated for which it is possible to know the expected correlation. It would therefore be of interest to assess whether the obtained angular separations are likely to occur. Satellite constellations of Iridium and Globalstar were used since their updated two-line-elements can be easily obtained on the web. In order to have different latitudes, distributions of angular separations were calculated for Madrid, London and Rome. Total time of simulation was 480' to comprise both orbital periods and enough number of events. Elevations were divided into five different reference azimuths (10º - 50º) and all of them were compared one to each other so as to comprise all possible elevation separations. For example, if 10º is compared to 30º and q_{ref} is set to 10º (10&30), then the elevation separation is Dq=20º. Interesting results were obtained as it is illustrated in Fig. 4 where only (10&20) and (10&30) are plotted.

4. CONCLUSIONS

In this paper two new approaches are presented for satellite correlation modelling. The semi-deterministic model is used to produce statistics of variability of the correlation with mobile position along a street. The results show that significant negative correlation is obtained in a number of situations, and this information can be used to optimise satellite constellations for maximum diversity gain. Significant efforts have been made to parameterise built-up scenarios and satellite separations for real constellations giving rise to a deeper insight into the satellite correlation topic.

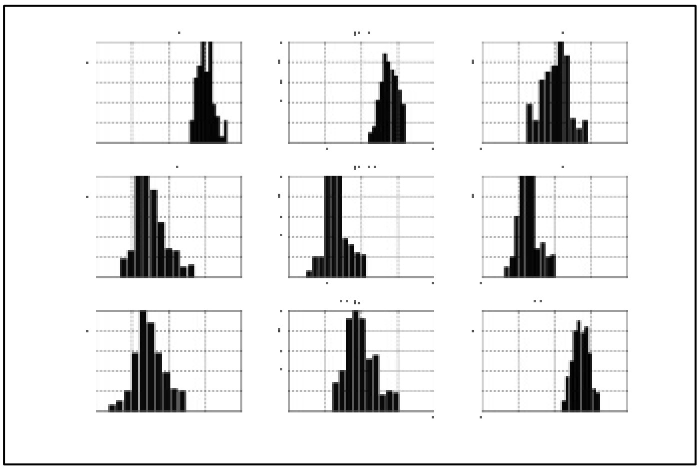

Fig. 3. Histograms showing the variability along the mobile route of ***r*** for different values of ***Df***.

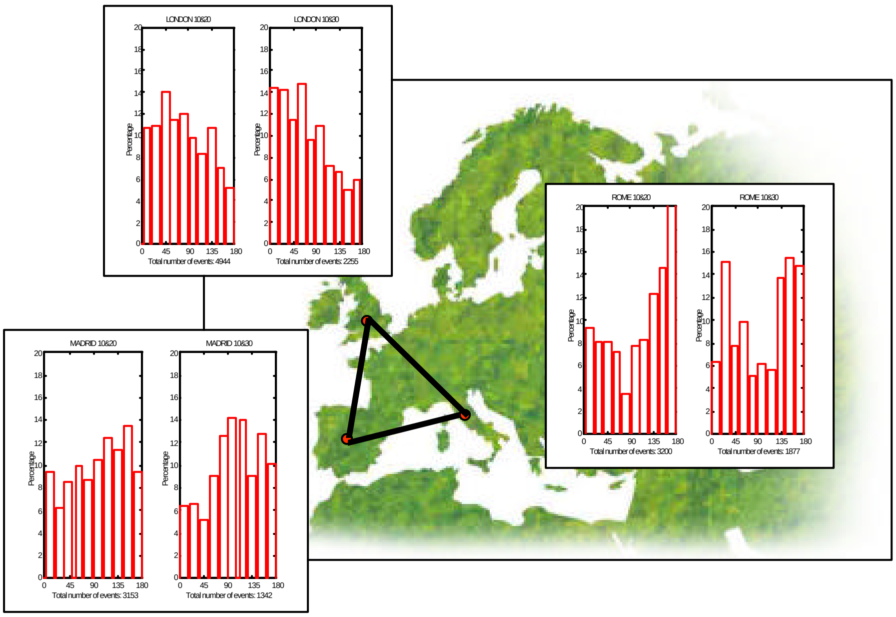

Fig. 4. Histograms showing the distribution of ***Df*** for q_{ref}=10° and ***Dq*** *= 10º,20º* , for Madrid, London and Rome.

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