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A physical–statistical hybrid model for Land Mobile Satellite propagation channel at Ku/Ka band

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Abstract— This paper presents an optimized Land Mobile Satellite (LMS) propagation channel model for Ku/Ka band. Here, a physical–statistical hybrid approach is proposed in order to simplify as much as possible the synthetic environment and the electromagnetic model, while keeping a good representation of the satellite propagation channel. This approach is complementary of full statistical approach [1] as a specific environment can now be tackled instead of a mixture of different propagation conditions. An original validation of the model is presented here, with an innovative method based on 360° panoramic images analysis in order to rebuild a simple synthetic environment.

Index Terms— LMSS, Ku/Ka band, Physic – statistic

I. INTRODUCTION

The current trend of telecommunication services towards high data rate mobile or nomadic multimedia services should result in the saturation of the currently used frequency bands (L and S bands). The limited broadband capacity of these frequency bands lead to use higher frequencies such as Ku and Ka bands for the extension of the existing services or for the development of new services for different types of nomadic or mobile users such as pedestrians, terrestrial vehicles, trains, ships, and aircrafts. In these higher frequency bands, the margins to be implemented in wideband mobile communication links will be limited and the air interface should be more complex. A fair understanding and modeling of the propagation channel dynamic are necessary for the design and optimization of these systems (waveform...) and the possible implementation of Propagation Impairment Mitigation Techniques. For this type of mobile satellite communication systems operated at Ku or Ka bands, two propagation media may have a significant influence on the propagation channel: the local environment of the receiver (i.e. obstacles in the vicinity of the receiver) and the troposphere (especially rain or clouds). This paper focuses on the effects of the local environment.

Several models have been developed and compared to measurements to characterize the Land Mobile Satellite (LMS) propagation channel and to assess the impact of the local environment of the receiver on the RF signal. The prediction method described in Section 6 of

Recommendation ITU-R P.681-11 [1] proposes a statistical modeling of the LMS channel suitable for frequencies between 1 to 30 GHz, and for several environments (train, highway, sub-urban, wooded ...). As far as Ku/Ka bands are concerned, this model has been built thanks to extensive measurements campaigns [2], [3]. It provides reliable results for selected overall environments and frequencies, and can be used for receiver testing and link budget estimation. However, the model takes into account a mixture of different propagation conditions and also a specific antenna diagram (the one used during the campaigns). Thus, this model cannot reproduce the RF effects of a specific environment or take into account another antenna diagram.

To take into account the effect of the local environment on the propagation channel with a deterministic approach, the common approach uses an accurate 3D database containing a description of the electromagnetic properties of the materials. Knowing the position of the transmitter, the field is computed within the 3D database using ray-launching or ray-tracing techniques. Nevertheless, those tools are not completely relevant in the case of mobile satellite communication systems, as the modeling of the entire coverage area is out of reach of those tools. The main issue in the case of mobile SatCom systems is to have a flexible description of the channel in different environment and geometrical configurations. To overcome the limitations that are inherent to those methods, physical-statistical hybrid models have been proposed. They rely on the use of a rough modeling of the environment constituted of different canonical elements. Efficient EM methods are then used to compute the effects of each canonical element of the channel. This method combines the benefits offered by the statistical models in terms of computing time with the flexibility offered by direct computation on 3D environment (environment type, elevation ...).

This paper will present an optimized LMS propagation channel for Ku/Ka band. The main assumptions and the model itself will be described in section II. The validation process, based on 360° panoramic images to rebuild the synthetic environment, is presented in section III. Finally, conclusions will be highlighted in section IV.

II. THE PHYSIC – STATISTIC MODEL FOR KU/KA APPLICATION

In order to propose an efficient model for SatCom applications, the following assumptions have been made:

Antenna:

The reception of satellite signal for the LMS case in Ku and Ka bands is technologically conditioned to the use of high gain and thus very directive antennas. This choice was not necessary at lower frequency bands and most of the channel models for LMS contain the underlying assumption of an almost isotropic antenna. For the provision of SatCom services in the case of mobile receivers at Ku or Ka bands, different kinds of terminals are considered for different kind of mobile vehicles namely, public transportation (train, tramway, buses), large and high standard individual vehicles (civilian security vans or 4x4) and individual vehicles. The main difference between mobile receivers to be boarded on different classes of vehicles concerns the size of the antenna. This will greatly affect the gain and the aperture of the terminal and consequently the received signal in different situations. To get a clearer idea of the different terminals that will be used for each of those types of vehicles, the following antenna gain values are considered here:

- Public transportation vehicles: 30-35 dBi,
- High standard individual vehicles 15-20 dBi,
- Individual vehicle 6 dBi.

Considering the antenna gain for the different usage cases, and assuming a parabolic reflector antenna with a uniform illumination and an efficiency of 0.7, the antenna directivity may change from 2.71° to 48.2° .

Modeling of the interaction between the local environment and EM wave:

The interaction of the EM wave with the local environment has been modelled for different canonical elements using various techniques.

- Building diffraction

In order to be able to perform diffraction computations on long trajectory, the use of a fast methodology for the simulator has been searched. In this study, the use of Fresnel-Kirchhoff (FK) methodology for the computation of the diffraction has been favored to other methodologies such as UTD (Uniform theory of Diffraction [5]) or GTD (Geometric Theory of Diffraction [4]), even if Fresnel-Kirchhoff methodology does not account for polarization. In order to assess the accuracy of this method, the results have been compared to those obtained with a reference tool: the Physical Optics and the Equivalent Current Method modules of the SE RAY EM - FERMAT software. The chosen configuration is illustrated on Figure 1. The first simulations

are done considering an azimuth angle $\varphi=90^\circ$ and an elevation $\theta = 30^\circ$. Different values for the distance D ranging from 4 m to 44 m were considered with frequencies of 12 and 20 GHz. Examples of comparison results are proposed in Figure 2, where computation of the power diffracted by a building using SE RAY EM - FERMAT and KF methodology is plotted at 20 GHz for two distances from the building (here metallic building). It has to be noticed that the highest differences between the results given by SE RAY EM - FERMAT and FK methods occur in deep shadowing areas. In this case, multipath are likely to be some orders of magnitude higher than the direct path. Consequently, the impact of the inaccuracy in those deep shadowing conditions is very small.

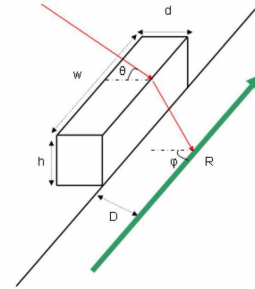


Figure 1: Geometry of the scenario, $h = 20\text{m}$, $w = 40\text{m}$ and $d = 10\text{m}$

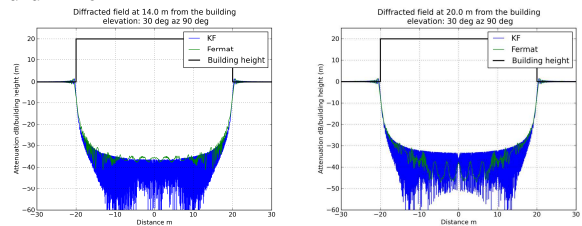


Figure 2: Power diffracted by a building using SE RAY EM - FERMAT and KF at distances 14 m (left) and 20m (right) from the building. $F = 20\text{ GHz}$

- Pole diffraction

The diffraction by rail poles and lamp poles can be computed using a 2D Fresnel Kirchhoff diffraction method using the same approximation. Realistic 3D poles models have been used to assess the impact of the simplification of the geometry in the software. In Figure 3, the left pole is modelled by a cylinder of the same diameter for the computation using Fresnel Kirchhoff diffraction method. There is no substantial difference between the diffracted powers computed using the SE RAY-Fermat and FK for thin configurations (Figure 4).

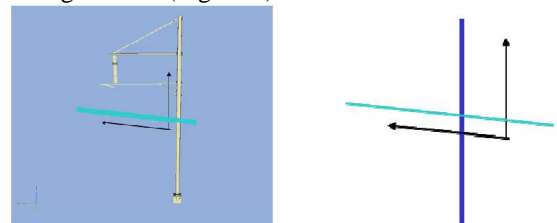


Figure 3: 3D pole model for computation using SE RAY EM - FERMAT and equivalent cylinder for the computation using Fresnel-Kirchhoff diffraction

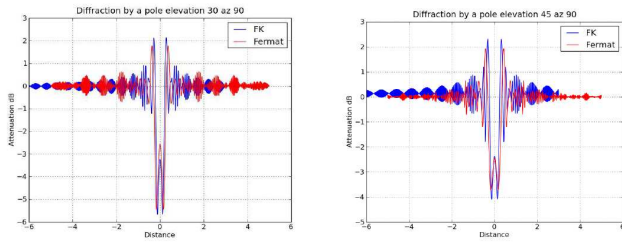


Figure 4: Power diffracted by a pole using SE RAY EM - FERMAT and KF for two elevation angles: 30° (left) and 45° (right). F = 20 GHz

- Electric wires

As the wavelengths at Ku or Ka bands are approximately of the same size as the diameter of electric wires, a possible interaction between the wires and the EM waves has to be considered. The size of the wires with regard to the wavelength prevents the use of a simple approach to compute the power radiated by the electric wire. Nevertheless, a quick check can be made in order to assess the impact of the presence of electric wires. Considering that the antenna is a reflector antenna of diameter D and of half power beamwidth, θ , equal to 3° at 20 GHz, the size of the reflector is given by: $D = 70 \lambda / \theta = 35 \text{ cm}$ (which leads to a surface approximately equal to 1000 cm^2). If the plane wave coming from the satellite is intercepted by an electrical wire, the proportion of power intercepted by the wire is approximately the ratio between the surface of the projection of the wire on the reflector with the surface of the reflector as illustrated on Figure 5.

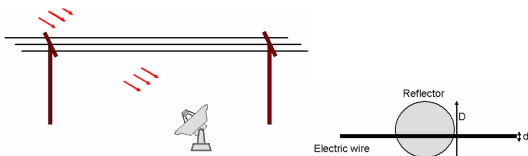


Figure 5: Interception of the wave front by an electric wire and 2D projection of the problem

The worst case happens if all the power incoming on the wire is radiated outside of the antenna diagram of the receiver. If a wire diameter of 2 cm is considered, the maximum loss equals to the following evaluation:

$$A = -10 \log_{10} \left(\frac{\pi \left(\frac{D}{2}\right)^2 - dD}{\pi \left(\frac{D}{2}\right)^2} \right)$$

Thicker wires are not frequent, at least in an urban environment, so the value of 0.3 dB can be considered as the maximum attenuation caused by an electric wire. With the half power beamwidth defined at Ku band, the same conclusion holds. This attenuation of 0.3 dB is marginal

with regards to other attenuating components i.e. lamp pole, trees or masking by building and should be neglected in the present case in order to reduce the complexity of the scenarios.

- The effect of trees on the channel

When an incoming EM wave reaches a tree, the following contributions are computed: trunk and large branches diffraction, direct signal attenuation and scattering within canopy.

As far as diffraction is concerned, the same module based on the Fresnel-Kirchhoff methodology is used. For signal attenuation and scattering, Recommendation ITU-R P.833-9 [6] is employed. To generate the multipath from the trees, the point scattering methodology presented and validated in [7] is used.

Multipath modeling:

Multipaths are due to multiple bounces on the environment and are causing fast fluctuations of the channel by creating constructive or destructive interferences. It also contributes to enlarge the Doppler spectrum of the signal. If the contribution of multipath is very significant in the case of small receiver using almost isotropic antennas, the impact is less pronounced for the present application where directive antennas are considered. Considering that the multipath coming from outside the main lobe can be neglected and that the main lobe is characterized by a width of $2 \times \theta_{3dB}$, and assuming an isotropic angle of arrival for multipath, the useful to multipath power ratio caught by the main lobe of the antenna can approximately be given by:

$$\frac{P_R}{P_0} = \left(\frac{2\theta_{3dB}}{360} \right)^2$$

where P_R is the multipath power received by the antenna and P_0 is the overall multipath power. The generation of the multipath power is made assuming a Ricean channel considering the attenuation of the direct path, and a multipath power extracted from the available data. A first extraction has been done on the OLYMPUS database collected in Darmstadt [8]. The average multipath power in different shadowing conditions has been computed for different shadowing states namely, LOS, shadowed and blocked. Those results have been obtained from regression using the methodology described in [9]. The results in different environments are summarized in Table 1.

Table 1: Average Multipath power (dB/LOS) received in different environments [8] and state of attenuation of the direct signal

	Average Multipath power (dB/LOS) received in different environment type and state of attenuation of the direct signal		
	LOS	Shadowed	Blocked
Urban	-15.2	-14.9	-26.1
Rural	-15.2	-15.1	-23.2
Highway	-15.2	-14.6	-26.7

III. MODEL VALIDATION

The main issue for the validation of the model is the generation of the 3D synthetic environment. During the OLYMPUS experimentation [8], only the calibrated time series were available, without additional information on the 3D environment. Thus, the model cannot be validated with this dataset. From the 20 GHz campaign highlighted in [2], concurrent RF and 360° panoramic images data were collected. Thus, the images information can be used in order to help in the 3D reconstruction. As a matter of fact, a deep learning processing has been performed to automatically detect trees, buildings, poles and sky on the pictures as illustrated in Figure 6.

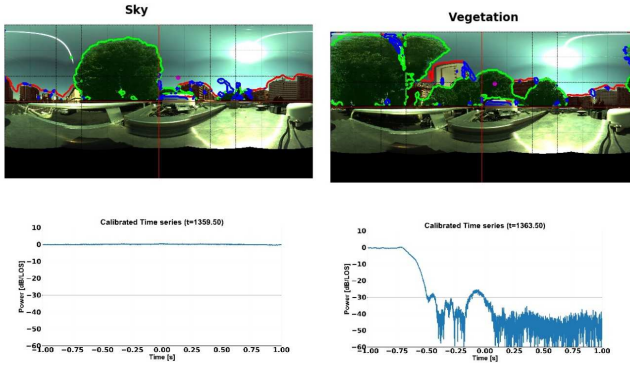


Figure 6: Deep learning classification vs signal power. LOS situation left, NLOS (signal blocked by vegetation) right

Thus, the images can be used in order to identified canonical elements of the model. The model has been tested in four situations (assumed to be independent): LOS (i.e. sky detection, same as Figure 6 left), signal blocked by vegetation (i.e. tree detection, same as Figure 6 right), signal blocked by pole and signal blocked by building. In Figure 7, the RF time series and the results of image classification are presented. From then, it is easy to sort the time series samples as a function of each situation. Then, a point-to-point comparison between the experimental and simulated time series can be performed as well as a comparison of power Cumulative Distribution Function (CDF).

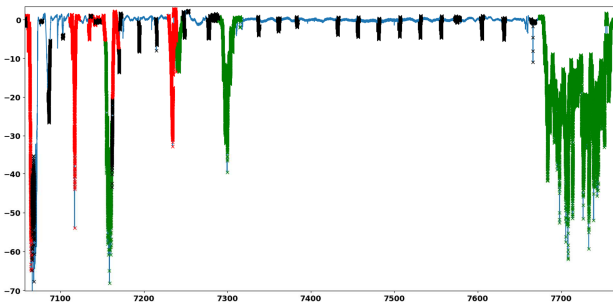


Figure 7: RF time series vs image classification : blue = Sky, green = vegetation, black = pole and red = building

The first goal is to validate the software in LOS situation. This is equivalent to check that the images classification works properly, and that time series are well calibrated. Indeed, almost no multipath should occur here due to the antenna pattern, and the time series is impacted only by noise. Figure 8 highlights the CDF associated to LOS situation. Measurement and simulation curves are in a fair agreement.

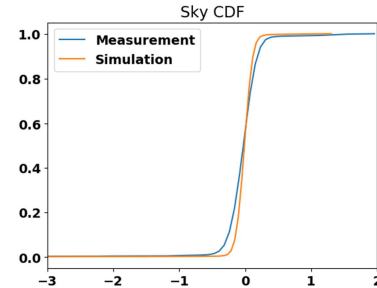


Figure 8: Experimental vs simulated CDF in LOS (i.e. sky detection)

When an obstacle is detected on the images, we can put a canonical object of the same size. However, the range between the object and the road cannot be estimated. Here, we assume that the ranges between the objects and the road are uniformly distributed between 5 and 10 meters. For building obstruction, the model provides reliable results without additional tuning. In Figure 9, experimental and simulated time series and CDF are compared, and provide a similar pattern.

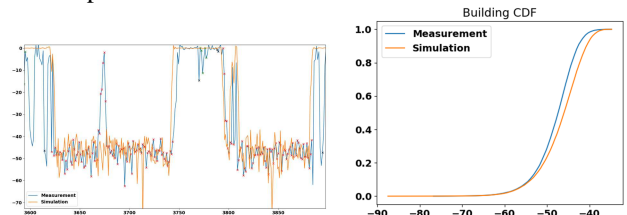


Figure 9: Experimental vs simulated: Example in signal bloc by building. Time series example left, CDF right

About the trees effect, it is necessary to estimate the path length inside the canopy based on the attenuation series restricted to canopy shadowing situations. By denoting R the canopy radius, the density function of R can be estimated thanks to the tree attenuation measurement and a specific attenuation given by the Recommendation ITU-R P.833 [6]. After optimization of the R density function, the experimental and simulated CDF look similar as observed in Figure 10.

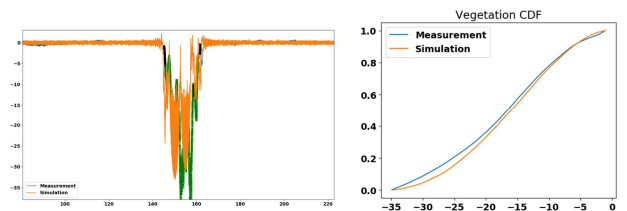


Figure 10: Experimental vs simulated: Example in signal blocked by tree. Time series example left, CDF right

For the poles, it is not possible to estimate CDF as the number of samples tagged as “pole” is not enough to provide reliable statistical results. We can only have a visual inspection between the experimental and simulated time series as in Figure 11. Note that the size of the pole has been fixed to 0.3 m.

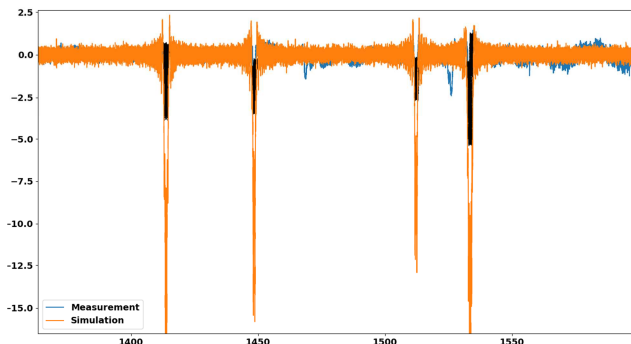


Figure 11: Experimental vs simulated time series in pole situation

Consequently, the tools can be validated in several canonical situations which demonstrate that the propagation channel output is relevant.

It was possible to test the model on selected trajectories of [2], but for some trajectories of [2], the final results are not as good as expected. For example, Figure 12 presents another example of experimental and simulated time series. Even if an overall visual inspection seems to be satisfying, there are several impairments which bias the final statistics. Among all the impairments which are mostly due to the experimental issue, the sampling rate of the video (10fps) is much smaller than the RF signal (1.5kHz). Thus, some object cannot be detected with the images as pointed out in Figure 13 (up left). In Figure 13 (up right), small fluctuation on the experimental time series can be observed, probably due to the antenna tracking system. This effect cannot be taken into account in the model, and that explains the small differences on the CDF associated with the LOS situation (Figure 8). The worst issue is illustrated in Figure 13 (bottom). Here, sever obstructions were simulated but they cannot be seen in the experimental data. The issue here was a bad estimation of the satellite position on the images, which lead to a simulated building blockage. In reality, the satellite elevation was a few degrees higher and LOS situation should have been simulated.

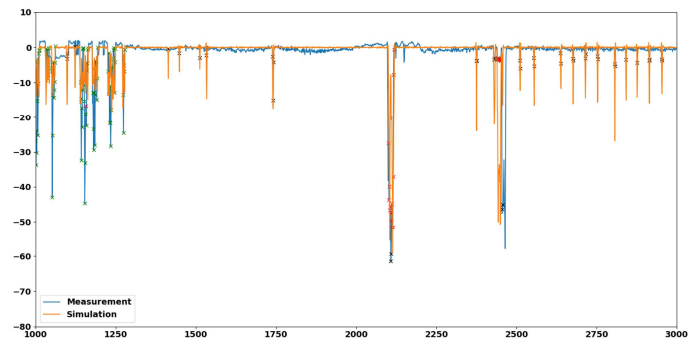


Figure 12: Experimental vs simulated time series on a full trajectory

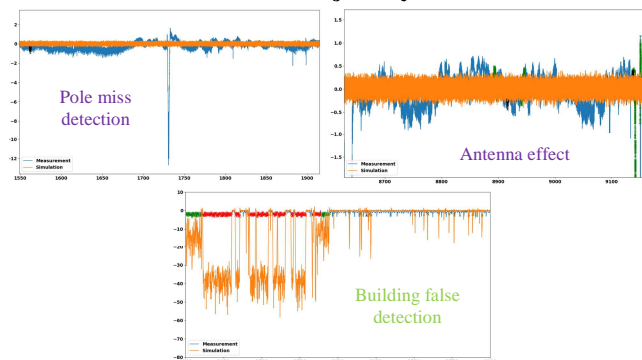


Figure 13: Experimental vs simulated time series. Reconstruction issue

IV. CONCLUSIONS

This paper has presented an optimized Land Mobile Satellite (LMS) propagation channel model for Ku/Ka band. A physical–statistical hybrid approach has been proposed, complementary of the full statistic approach [1] in order to tackle specific environment. An original validation of the model has been highlighted, with an innovative method based on 360° panoramic images analysis in order to rebuild a simple synthetic environment. It was possible to validate the model in canonical situations such as LOS, vegetation, pole and building. However, the synthetic 3D reconstruction is a major issue in the validation of the physical-statistical hybrid model, and this point should be improved in a near future to assess the performances on a long trajectory (>50 km).

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