BLOCKAGE AND MULTIPATH MODELING FOR THE MULTI-SATELLITE NAVIGATION CHANNEL IN URBAN AREAS

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ABSTRACT

Existing satellite navigation systems like GPS, or future like Galileo, require the simultaneous reception of at least four satellites in the constellation to perform range and position calculations effectively. Prior to quantifying signal distortion caused by multipath, it is important to asses the availability for those satellites given that building blockage probabilities are high in built-up areas. In this paper, a multi-satellite channel model for urban areas is presented. The model tackles two aspects: availability and multipath time-spreading. Modeling results can be readily used in signal and system simulation work by defining tapped delay-lines, one for each non-blocked satellite.

INTRODUCTION

The objective of the work reported here is to adapt an existing [1] wide-band statistical model for the land mobile satellite (LMS) communications channel in urban areas for its use in satellite navigation system studies. The main difficulty found in this process has been that the available wide-band measured data was obtained using a channel sounder with an insufficient time-resolution from the point of view of the new application of interest: the chip rate of the channel sounder used was 10 Mcps which is insufficient looking at the expected chipping rates (up to 30 Mcps) of future navigation systems, e.g., Galileo. It must be born in mind that the most damaging multipath contribution are those arriving within one or at most two chip intervals of the direct ray. While higher time-resolution measured data becomes available, an attempt to upgrade the existing statistical model [1] can be performed by including in the modeling simple geometrical and electromagnetic considerations that may mitigate the lack of this type of experimental data for the time being.

Two aspects have been addressed, one is the introduction of higher resolutions in the modeling of multipath time-spreading and the other is the generation of multiple time-series corresponding to signals form the various satellites in the navigation constellation visible from the receiver at a given point in time. For this purpose, basic/canonical urban scenarios are defined, namely, street canyons, street crossings, T-junctions and single walls, where simplified ray-tracing can be performed to verify the existence of line-of-sight (LOS) or non-LOS conditions caused by building blockage. Ray-tracing allows the preservation in the modeled results of the possible correlation of building blockage effects experienced by the signals from different satellites. The statistics of the variability of blockage and multipath conditions may be brought into the model if the statistics of building heights, street widths, etc, are considered [2]. Ray-tracing also allows the identification of a small number of traceable rays responsible, in part, for the overall channel time-spreading. Each of these rays is assumed to be accompanied by a cluster of diffuse echoes whose amplitudes and delays cannot be determined by pure ray-tracing: non-deterministic contributions. To model those contributions statistical assumptions and measurements are needed. Currently available experimental data has been used to work out the model parameters describing these non-deterministic contributions. In a final step, the multipath structures generated are converted to tapped delay-line form −one TDL per satellite− suitable for signal and system simulation studies.

MULTI-SAT MODELING IN URBAN AREAS

Urban areas are better suited for geometrical modeling than rural or suburban areas given that their main component parts, i.e., buildings, can be described in terms of boxes of different sizes. This is an underlying assumption behind most ray-tracing based propagation modeling tools. These tools, especially those used for cellular network deployment, rely on building databases consisting of boxes of different sizes and shapes. In such a framework, more or less sophisticated ray-tracing and electromagnetic models (e.g. GTD/UTD) are applied to compute the received signal level for a grid of equally spaced sampling points to generate coverage maps. In many cases, time-dispersion calculations are also carried out to identify areas with potential problems due to signal distortion caused by multipath. For each point in the grid a large number of operations must be carried out to compute the received power (or power delay profile). For each point the existence of all possible types of rays: direct, diffracted, double diffracted, ..., reflected, double reflected, ..., reflected-diffracted, ... must be tested for each edge/plane in the database. This requires large computation times. This is so because in the terrestrial case, given the low elevation angles involved and the fairly large link margins (larger that those in the satellite case), it is possible that echoes arrive at the receiver after long delays and several interactions with the environment, e.g., double, triple, ... reflections. This is not the case in the satellite channel where most interactions of the transmitted signal with the environment occur on features belonging to the same street where the receiver is located.

Furthermore, the wanted model is not focusing on a particular environment (a specific part of a given city) but on generic urban scenarios so that conclusions on availability and positioning errors may be drawn on a statistical basis. Physical-statistical [2] or virtual city [3] models have already been proposed where the urban features: building heights, street widths, etc. are characterized statistically, i.e., their distributions are taken into account. A similar approach is followed here. To further simplify this study only a small number, in this case four, of canonical urban configurations are considered to describe such propagation scenarios: street canyons, street crossings, T-junctions and single walls. These basic scenarios may be tailored to describe urban areas with different building densities by using the so called masking angle, MKA (º) [4]. A given urban area can be described, as a first approximation, by an average **masking angle**, MKA (º), indicating the elevation for which a satellite would be visible from the user terminal for a street orientation perpendicular to the link. The masking angle will not be constant throughout the urban environment under consideration, it will thus follow a given distribution. It is easier to characterize the distribution of building heights as in ITU-R Rec. 1410-1 [5]. This Recommendation deals with terrestrial point to multipoint system planning, a Rayleigh pdf was found to fit well the distribution of building heights. Similarly, ITU-R Rec. 681-5 [6] reports Rayleigh distributed building heights.

Once the urban environment has been adequately parameterized in terms of observable magnitudes: heights, widths, etc, it is possible to carry out simple channel modeling. Two complementary studies can be carried out on the canonical scenarios defined above:

1. An availability study where building blockage effects are assessed.
2. A time-dispersion study in which the different contributions reaching the receiver are classified according to their times of arrival with respect to the direct signal. The results of this study can be transformed into a tapped delay line from appropriate for simulation work.

RAY-TRACING AND AVAILABILITY

To evaluate the existence of a non-blocked direct LOS signal in any of these basic scenarios **masking functions**, MKFs, can be defined representing the angles for which visibility/non-visibility conditions exist. The masking functions corresponding to the four canonical urban scenarios are shown in Fig. 1 where the ordinates indicate elevation angles and the abscissas azimuths or, rather, street orientations, ξ, with respect to the link. The top half-plane refers to positive orientations and the bottom half-plane corresponds to negative orientations. A MKF indicates the regions in the celestial hemisphere where the link is blocked or not.

For a given point in time the satellite positions of the navigation system constellation can be placed on the masking function for the scenario of interest giving a clear picture of the availability conditions for that particular moment, having in mind that availability, in this case, means having at least four satellites in non-blocked conditions. This can be repeated for a sufficient number of times in order to fully characterize the constellation availability, for example, the study could be performed for a whole constellation period. This approach helps preserve the partial correlation between the shadowing effects on signals from the various satellites. This approach has also been applied to the modeling of the cross-correlation coefficient of building blockage effects using a 3-segment model [4] describing the evolution of the cross-correlation coefficient as a function of the angle spacing between the two links.

When rays other than the direct need to be found, the use of ray-tracing is advised. In addition to determining the existence or not of a direct non-shadowed signal, it is possible to perform simple ray-tracing to verify the existence of reflected/diffracted rays. Fig. 2 illustrates a street crossing scenario where the terminal is receiving signals from two satellites approximately 180º apart. In the figure the rays corresponding to first order interactions (single diffractions/reflections) are illustrated. In this manner it is possible to identify the "deterministic" rays contributing to the overall received signal. The evaluation of their magnitudes can be performed using simple models: knife-edge for diffracted rays and theoretical coefficients for reflected rays. A simpler alternative is to assume a constant reflection loss. This study (identification of signal blockage plus identification of traceable rays) can be both performed for small areas (several wavelengths to tens of wavelengths) or for larger areas. In the small area case, ray-tracing may be performed only once since the various rays will basically keep their amplitudes constant while their phases change.

MULTIPATH TIME-SPREADING

After ray-tracing what is needed is to place the various rays adequately on the time-delay axis. The reference time is that of the direct signal, $\Delta\tau=0$ μs. Only first order contributions have been considered, i.e., single reflections/diffractions. Other higher order rays are highly unlikely to be traced from a geometrical point of view and, if they existed, their amplitudes would show very small levels. In this case priority has been placed on the generation of diffuse multipath clusters accompanying each of the previously traced rays as illustrated in Fig. 3 for the scenario in Fig. 2. The modeling of these multipath structures is not a task easily handled using deterministic models, thus it was decided to make a number of statistical assumptions as in [1] while the parameters giving rise to these diffuse multipath structures have been derived from experimental data. In [1] the following parameters were used to describe the multipath channel:

- a_{Dir}: magnitude of the direct ray (lin. units, $1 \equiv$ LOS)
- MP: R.M.S. value of signal variations (Rayleigh) due to multipath (dB/LOS);
- τ_{av}: average of exponential distribution of times of arrival of multipath echoes (μs);
- Sp: decay rate of multipath components (dB/μs).

To generate a cluster of non-deterministic contributions, a sufficiently large number of rays, N>100, is produced. Their excess delays are assumed to follow an exponential distribution with parameter τ_{av}. These echoes are attenuated according to a linear decay rate Sp and, finally, the power sum of all rays must amount to a total of MP (dB), i.e., if the diffuse echoes have amplitudes a_i with i=1, ..., N,

then
$$mp = \sum_{i=1}^{N} a_i^2 \quad \text{and} \quad MP\ (\text{dB}) = 10 \log (mp). \tag{1}$$

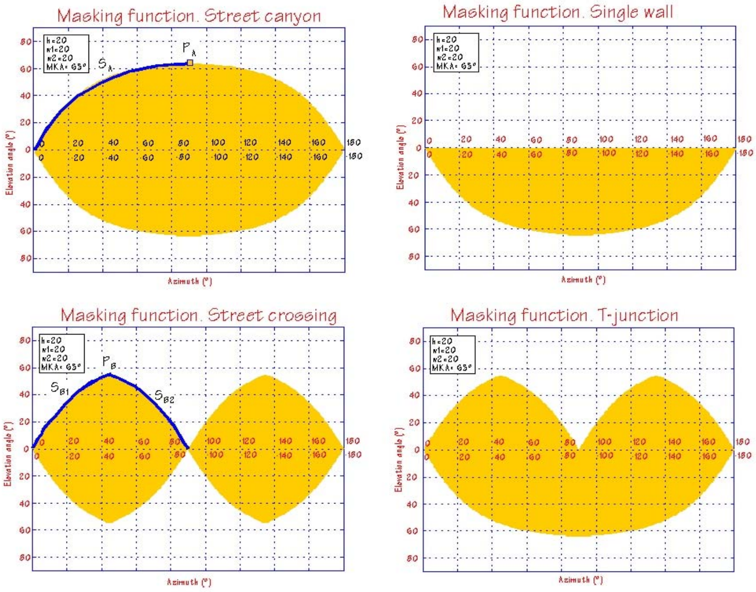

Fig. 1. Masking functions for the four basic scenarios and for a stationary terminal.

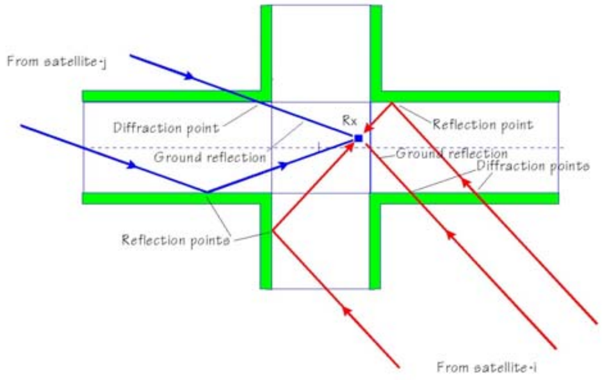

Fig. 2. Ray-tracing on a canonical representation of a street crossing for signals from two satellites.

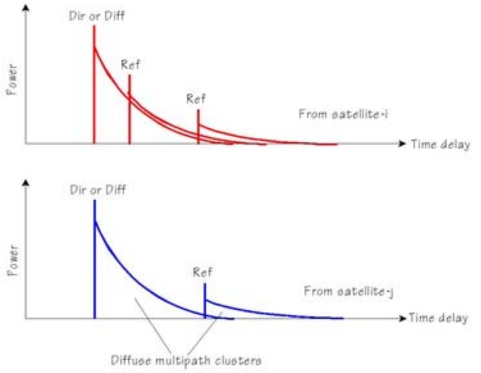

Fig. 3. Adding multipath clusters to traced rays.

When traceable rays other than the direct are introduced in the model some changes must be made to remain consistent with previous versions of the model, especially as regards empirically derived parameters. In the case of having to add only one reflected ray of amplitude a_{Ref} (street canyon case), the following corrections must be made:

$$mp = mp_{\text{Dir}} + a_{\text{Ref}}^2 + mp_{\text{Ref}} \qquad \left(\frac{a_{\text{Dir}}}{a_{\text{Ref}}}\right)^2 = \frac{mp_{\text{Dir}}}{mp_{\text{Ref}}} \qquad a_{\text{Ref}} = |R| \tag{2}$$

where $|R|$ is the reflection coefficient on the building faces of the opposite side of the street and $MP = 10 \log(mp) = 10 \log(2\sigma^2)$ with

$$p(x) = \frac{x}{\sigma^2} \exp\left(-\frac{x^2 + a^2}{2\sigma^2}\right) I_0\left(\frac{a\,x}{\sigma^2}\right) \quad \text{and} \quad K\ (\text{dB}) = 10 \log\left(\frac{a^2}{2\sigma^2}\right) \tag{3}$$

corresponding to the Rice pdf, where I_0 is a modified Bessel function of the first kind and of zero order and to the carrier-to-multipath ratio in dB. The parameter mp_{Dir} is the power of the diffuse multipath cluster accompanying the direct signal of amplitude a_{Dir}, and mp_{Ref} is the power of the diffuse multipath cluster following the reflected signal of amplitude a_{Ref}.

MP, τ_{av} and Sp remain constant and thus parameters drawn form experimental data [1] can be used with new versions of the model. Typical values for these parameters in urban environments are $MP = -8$ to -10 dB, $\tau_{av} = 0.05$ to $0.1\ \mu$s, Sp: = -10 dB/µs.

In the case of the street canyon scenario, the direct ray and a reflected ray on the opposite side of the street can be traced. It is assumed that the radiation pattern of the receive antenna (and the vehicle itself) significantly attenuate reflections on the ground (in case they exist). It is also assumed that these two rays are each accompanied by a diffuse multipath structure (Fig. 3).

EXAMPLE

To illustrate the problems caused by the lack of time-resolution mentioned in the Introduction, Fig. 4.a shows six measured power delay profiles. Given that the chip rate was 10 Mcps, the base of the correlation peak in the channel sounder is ±0.1 µs wide. Echoes arriving before can not be appreciated using simple techniques. In the figure the shape of the sounding pulse is clearly observed for the first 0.1 µs; only a slight broadening of the pulse due to echoes in this range is observed in some cases. Echoes in the 0.1-0.2 µs range are greatly attenuated. These contributions can either be due to specular or diffuse echoes, depending on the scenario. These measurements correspond to an urban area and an elevation of 60º. The region of excess delays of most interest for navigation purposes lies within the 0-0.1 µs range where almost no features of interest can be appreciated on the available measurements. Simulations with the modified model are shown below where traced rays within the region of delays of interest appear together their accompanying non-deterministic clusters. Fig. 4.b shows simulated power delay profiles for three different satellites. Fifty samples (taps) in the 0.5 µs range have been generated, sufficient for the envisaged application. The simulation results show power delay features within the delay range of interest while consistency with the parameters of the original model (which were derived from wide-band measurements with lower resolution) is maintained. The power delay profile in Figure 4.b corresponds to the ideal case, i.e., it is made up of deltas. For direct comparisons to be made the sounding equipment response has to be accounted for.

SUMMARY

An upgrade of an existing wide-band statistical model for the LMS channel in urban areas has been presented. The objective was to introduce higher time-resolutions in the current model in order to make it usable in navigation system analyses. Currently, no high time-resolution experimental data is available to the authors. The model upgrading has been made using simple ray-tracing techniques applied to a small number of canonical scenarios. Backward compatibility has been preserved with regard to the model parameters obtained from the analysis of wide-band data with lower time-resolution. Furthermore, the model has also been upgraded to include the multi-satellite case thus allowing the assessment of multi-satellite system availabilities.

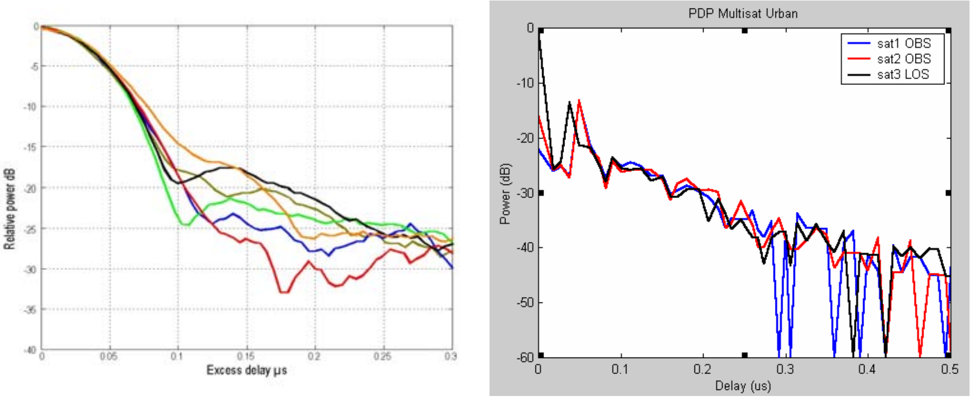

Fig. 4. (a) Measured power delay profiles in an urban area with 60º elevation and at L-Band. (b) Multi-satellite urban. Power delay profiles of two partially obstructed paths and one LOS path.

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