Irregular Terrain Attenuation in the Medium Frequency Band: Planning for Digital Radio Systems

D. de la Vega, S. López, U. Gil, D. Guerra, P. Angueira, A. Arrinda and J.L. Ordiales

Abstract— Some basic rules and values to include the attenuation effect of terrain obstacles in the Medium Wave (MW) band are presented. The analysis applies to ground wave propagated signals and focuses on the new digital broadcasting systems (HD-RADIO/IBOC and DRM) that require accurate predictions for appropriate network planning. This study is based on field strength data from a measurement campaign and the results represent a complementary approach to numerical solutions for planning purposes. A simple but efficient classification of the terrain prominences is presented and attenuation curves are calculated.

Index Terms— Prediction methods, Ground wave, Irregular terrain, Channel characterization, Digital radio.

I. INTRODUCTION

The recently developed digital radio broadcasting standards for the LF, MF and HF bands, HD-RADIO/IBOC [1] and DRM [2], [3], provide coverage areas due to the specific propagation mechanisms in those bands. Several countries have already carried out both experimental and pioneer commercial transmissions [4], [5] in the MW band using these new systems. One of their most remarkable planning requirements is an increase in planning accuracy due to the brick wall behavior of any digital system. Factors not considered so far by broadcasters in the MW band such as irregular terrain and environmental factors in the vicinity of the receiver, can cause service unavailability, and must be included in the prediction techniques.

A method for calculating the attenuation associated to irregular terrain paths as a function of the degree of obstruction is proposed. The study has been based on field data recorded in a measurement campaign in the MW band, and the results have been validated against independent data collected along a second measurement campaign.

II. METHODS FOR FIELD STRENGTH PREDICTION IN MW

In 1909 Sommerfeld [6] obtained a solution for the attenuation function of the ground wave propagation for a vertical short dipole on the plane interface between an insulator and a conductor, considering flat, lossy Earth, describing two propagation components: a space wave and a surface wave. The surface wave propagates along the Earth’s surface and it is the dominant propagation component at low frequencies. The contributions of Norton in 1936 [7], and Van der Pol and Bremmer in 1937 [8], enabled the calculation of field strength values on the spherical surface of the Earth and a paper by Norton [9] proposed practical expressions to be used in network planning.

In these expressions, the field strength is calculated as a function of the distance between the transmitter and the receiver and the electric properties of the ground (conductivity \(\sigma\) and permittivity \(\varepsilon\)). Millington introduced in 1949 a semi-empirical method that extended the application range in the case of variation of the ground electric properties along the path [10]. Later on, Hufford developed an integral equation to calculate the field strength for a smoothly varying, inhomogeneous terrain, but very difficult to solve numerically for practical planning [11].

During the 70s, new computer methods were proposed to solve this integral equation including an attenuation function to account for the influence of the irregular terrain features [12]-[16]. The comparison with empirical values showed that the influence of the topography can be in the same range of decibels and sometimes even greater than the influence of conductivity [12], [17]. The results from those studies concluded that the predictions were improved, but the predicted values still differed from the measurements [18].

The theoretical approach to the prediction problem has been developed by some authors in the last decade [19]-[21]. The most cited approaches in the ground-wave propagation modeling, for non-flat terrain and atmospheric refractivity affects, are the split-step parabolic equation method (widely known as PEM and SSPE), the Method of Moments (MoM), and the Finite-Difference Time-Domain method (FDTD) [20]. These methods have been scarcely used by broadcasters for network planning purposes in wide areas (regional or national networks), mainly due to their complexity and computational requirements. Nevertheless, the latest steps towards practical implementations make them an interesting tool for the broadcast industry in the next years [21]. The results of this study aim at being a complementary tool to this theoretical approach.

Finally, it should be noted that due to the complexity and computational cost of theoretical methods, most broadcasters carry out network planning based on ITU-R Recommendations[22] based on Norton’s and Millington’s models. The new systems in the MF and HF bands (HD-RADIO/IBOC and DRM) need an improvement in the propagation prediction methods at these bands. In this way, field trials in different countries have been carried out in the recent years [4], [5], [23], some of their conclusions have been considered by ITU-R [24]-[26], and new prediction tools are being developed for these bands [19]-[21], [27].

III. METHODOLOGY

A. Measurement campaigns and field databases

This work has been based on the data obtained in experimental DRM (Digital Radio Mondiale) networks in Spain, set up in 2004 and 2007. Table I and Table II show the main transmission and reception features of each experiment. A detailed description of the trial carried out in 2004 can be found in [5] and [23]. The second trial was carried out also in
Spain in 2007 to validate the curves and empirical expressions obtained from the first set of data. The DRM transmission of this experimental network used a different frequency and transmitter site, and the reception area was also different, in order to use uncorrelated data to validate the results from the first experiment. The measurements were collected along different radial routes from the transmitter in both campaigns.

The recorded field strength samples along each route were first referenced geographically and a 500 m x 500 m grid was used to obtain 500 m x 500 m geographical areas, which will be referred as cells. Only cells with a statistically significant number of instantaneous measurements were considered to estimate the median value of each cell (the mean of the instantaneous values per cell is 65). The calculated median value excludes sharp signal variations due to other factors, such as the influence of traffic, bridges, or high voltage power lines. More than 600 cells and 40,000 instantaneous field strength values in heterogeneous reception conditions were analyzed. In the first stage of the analysis, the behavior of the paths with terrain irregularities was inspected.

### TABLE I
**NETWORK CONFIGURATION AND MEASUREMENT CAMPAIGN 1**

<table>
<thead>
<tr>
<th>Broadcaster</th>
<th>Radio Nacional de España (RNE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter station</td>
<td>Arganda del Rey (Madrid), Spain</td>
</tr>
<tr>
<td>Channel center frequency</td>
<td>1359 kHz ($\lambda = 221$ m)</td>
</tr>
<tr>
<td>Nominal bandwidth</td>
<td>$9$ kHz</td>
</tr>
<tr>
<td>Transmitted digital power</td>
<td>$4$ kW RMS</td>
</tr>
<tr>
<td>Transmitter antenna</td>
<td>1.1 dBi vertical monopole</td>
</tr>
<tr>
<td>Height</td>
<td>$30$ m</td>
</tr>
<tr>
<td>Receiver antenna</td>
<td>Short monopole active antenna</td>
</tr>
<tr>
<td>Height</td>
<td>$3$ m</td>
</tr>
<tr>
<td>Total extent of the</td>
<td>$2200$ km in rural environment</td>
</tr>
<tr>
<td>measurement campaign</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE II
**NETWORK CONFIGURATION AND MEASUREMENT CAMPAIGN 2**

<table>
<thead>
<tr>
<th>Broadcaster</th>
<th>Cadena SER (Unión Radio)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter station</td>
<td>Pozuelo (Madrid), Spain</td>
</tr>
<tr>
<td>Channel center frequency</td>
<td>$1251$ kHz ($\lambda = 240$ m)</td>
</tr>
<tr>
<td>Nominal bandwidth</td>
<td>$9$ kHz</td>
</tr>
<tr>
<td>Transmitted digital power</td>
<td>$12.5$ kW RMS</td>
</tr>
<tr>
<td>Transmitter antenna</td>
<td>2 dBi vertical monopole</td>
</tr>
<tr>
<td>Height</td>
<td>$60$ m</td>
</tr>
<tr>
<td>Receiver antenna</td>
<td>Short monopole active antenna</td>
</tr>
<tr>
<td>Height</td>
<td>$3$ m</td>
</tr>
<tr>
<td>Total extent of the</td>
<td>$60$ km in rural environment</td>
</tr>
<tr>
<td>measurement campaign</td>
<td></td>
</tr>
</tbody>
</table>

As an illustration of this first inspection of the database, Fig. 1 is presented. This figure shows the measurement route values depicted with their corresponding range height profiles. The route crosses the Somosierra mountain range. The route is virtually radial from the transmitter and includes 12 km before and 28 km after the summit of Somosierra. A tunnel goes through the mountain range near the summit, causing a deep fading in the field strength signal. There is a remarkable field strength attenuation in Fig. 1 at the “shadowed” side of the mountain (more than $10$ dB if median values are considered).

![Fig. 1. Variation of the field strength median values (in 500 x 500 m cells) as a function of the distance to the transmitter, for a route of the measurement campaign. Terrain elevation values recorded by the GPS receiver are shown.](image)

This drop in the signal level was found after every significant obstacle in the measurement campaign, suggesting that the attenuation due to terrain irregularities can lead to significant field strength attenuation that might lead to reception failures and audio dropouts in some cases. At the shadow side of the obstacle, as the receiver runs away from the transmitter, the field strength values follow an upward trend (see Fig. 1). This behavior of the field strength in the vicinity of the terrain irregularities, as a function of the distance to the transmitter, is explained by Ott [12], and previously predicted by Wait [13], as a constructive interference of a direct diffracted ray and a diffracted ray traveling along the surface.

Following the analysis on Fig. 1, the next field strength drop was measured at km 109.5, and is due to a second lower obstacle, which is not very high ($\lambda/4$ height, where $\lambda$ is 221 m) but is very close to the receiver location. The short distance from the obstacle to the receiver location appears to be a very influential parameter.

As a result of the first analysis of the database this communication proposes the following methodology to evaluate and quantify the effect of terrain irregularities in a transmitter – receiver profile. First, it is suggested to use the path length $d$, the obstacle height $h$ and the distance from the obstacle to the receiver $d'$ as the key parameters. In a second phase the field data (measured median values corresponding to more than 600 different 500 m² terrain cells) will be classified into different profile categories as a function of $h$ and $d'$. Finally a family of curves for different $h$ and $d'$ values will be derived showing the normalized received field strength versus the path length $d$. 

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**Note:** The table images and the figure are placeholders and need to be replaced with actual images.
B. Path profile classification

Three types of path profiles were considered in the analysis. First, terrain profiles including an obstacle noticeably higher than the rest of the terrain irregularities along the path profile were used to empirically characterize the influence of the terrain obstruction on the field strength mean values. The main irregularity within this type of profile will be referred as “primary obstacle”. Second, line-of-sight reception locations were considered as a reference to evaluate the attenuation values. Last, profiles including several significant terrain irregularities show situations where the influence of the irregularities is greater.

Obstacles of the path profile were classified according to the height of the terrain prominence and the proximity of that obstacle to the receiver location. The height of the obstacle was calculated as the difference between the elevation of the obstacle and the receiver location.

The proximity to the receiver was categorized according to the results of a previous study [28]. It was obtained that the attenuation caused by irregularities is less than 4 dB, if the distance between the primary obstacle and the receiver is longer than 4 km - 12 km (depending on the height of the obstacle). If the receiver and the obstacle are closer than 10 km the attenuation can rise up to 10 dB depending on the distance and the obstacle height. Subsequently, the range of influence of the terrain variations can be limited to a distance of 10 km - 12 km. When the distance is longer than this range of influence, the attenuation in the received field strength is negligible. A similar value for this range of influence of the terrain variations has been established in [19]. Table III summarizes a classification and the number of available records for each category.

It was possible to obtain values for receiver locations placed at distances up to 60 km to the transmitter for “LoS” and “N” cases; up to 75 km for “F” cases; and finally, up to the coverage limit for “Mult” case. In order to avoid accumulative effects, only reception points with just one obstacle in the path profile (“N” and “F” cases in Table III) were taken into consideration in the estimation of attenuation. All the reception locations with more than one representative obstacle (“Mult” case) were used only for comparison purposes.

### Table III

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>Obstacle Height (h)</th>
<th>N° of (E_{\text{median}}) samples</th>
<th>N° of instantaneous samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>LoS</td>
<td>Unobstructed reception points</td>
<td>-</td>
<td>110</td>
<td>8,360</td>
</tr>
<tr>
<td>N cases</td>
<td>N (&lt;(\lambda/2))</td>
<td>(\lambda/4 &lt; h &lt; \lambda/2)</td>
<td>150</td>
<td>10,318</td>
</tr>
<tr>
<td></td>
<td>N ((\lambda/2-\lambda))</td>
<td>(\lambda/2 &lt; h &lt; \lambda)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N ((\lambda-2\lambda))</td>
<td>(\lambda &lt; h &lt; 2\lambda)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F cases</td>
<td>F (&lt;(\lambda/2))</td>
<td>(\lambda/4 &lt; h &lt; \lambda/2)</td>
<td>115</td>
<td>7,048</td>
</tr>
<tr>
<td></td>
<td>F ((\lambda/2-\lambda))</td>
<td>(\lambda/2 &lt; h &lt; \lambda)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mult</td>
<td>Multiple obstacles between transmitter and receiver</td>
<td>(h_i &gt; \lambda)</td>
<td>252</td>
<td>15,154</td>
</tr>
</tbody>
</table>

### IV. RESULTS AND DISCUSSION

The attenuation due to the varying degrees of obstruction (described in Table III) was analyzed separately for each type of obstacle. Finally, the results were compared and an estimation of the values of attenuation due to irregular terrain was made.

A. Line-of-sight reception

This subsection considers line of sight reception. Those data was the reference to later evaluate the impact of obstructions. Fig. 2 shows LoS values vs distance between transmitter and receiver, with a curve fit using logarithmic interpolation. The estimation curve proposed by ITU-R (σ = 25mS/m, \(\varepsilon = 30\)) is also displayed in the figure, only as a reference of the distance attenuation [29].

The interpolation curve from the line-of-sight measurements follows quite well the ITU-R tendency curve. Fluctuations around the interpolated curve probably have their origin in the variation of intermediate electric properties between transmitter and receiver, and on the reception environment. Nevertheless, this fluctuation is very low, and the curve can be considered an adequate representation of the field data.

The figure shows a group of points with a black background taken from the set of locations, not only in the line of sight but also with the mobile unit climbing a mountainside (positive slope). This empirical subset confirms that the predictions by

![Fig. 2. Median values of field strength measurements for reception locations with no terrain obstruction.](image-url)
Wait and Ott are fulfilled [12], [13], that is, the field level increases on the lit side of the crest due to the focusing of the direct and surface rays [12].

B. Influence of irregular terrain: general results

Fig. 3 compares the field strength measurements in unobstructed and obstructed locations. The obstructed points in Fig. 3 correspond to locations with a primary obstacle close to the receiver (N cases) and also those with multiple obstacles in the terrain profile (Mult). Results for F cases were noticeably lower, thus will be presented separately.

As illustrated in Fig. 3, reception locations with irregular terrain paths present lower field strength values than reception points with unobstructed line of sight. In some cases, the difference is higher than 10 dB for the same distance to the transmitter. This difference suggests the existence of an additional attenuation due to terrain obstacles in the vicinity of the receiver.

The independence of the conductivity was assumed provided the high range of conductivity values of the geographical area. Independently of the accuracy of the data provided by the ITU-R, the region under study has a large number of very heterogeneous conductivity zones in a relatively small area. The recommended conductivity ranges from values lower than 1 mS/m to quite high values, 55 mS/m, in the study area. This heterogeneous set of values for $\sigma$ provides a full range of conductivity situations in the LoS, N and MULT profiles.

C. Effect of the distance between obstacle and receiver

Fig. 4 shows the values and the interpolation curve for the set of values corresponding to $N(<\lambda/2)$ and $N(\lambda/2-\lambda)$ cases. Almost all the situations with obstructed reception show values lower than the interpolation curve of line of sight reception. It is observed that attenuation increases with the height of the terrain obstacle. The interpolation curve for case $N(<\lambda/2)$ is around 3 dB below the curve obtained for the unobstructed condition. The mean value of the difference between the $N(<\lambda/2)$ case values and the interpolation curve of unobstructed cases is 3.2 dB. Higher obstacles belonging to the case $N(\lambda/2-\lambda)$ show even higher attenuation for similar distances to the transmitter. The mean value of the difference between the $N(\lambda/2-\lambda)$ case values and the unobstructed cases interpolation curve is 6.8 dB. Fluctuations associated to each particular location around the interpolation curve are due to the different heights of the obstacles in each group, distance to the receiver, and the possible variation of the electric properties of the ground.

The mean value of the difference between the values of $N(\lambda/2-\lambda)$ case and the interpolation curve of unobstructed cases has been calculated, obtaining a figure of 13.5 dB. This value suggests a significant influence of the irregular terrain, and confirms again the need to take into account this influence in the coverage prediction algorithms.

Finally, a relation between the attenuation and the obstacle-receiver distance and the transmitter-receiver distance ratio was derived. The attenuation values rise as this ratio decreases. Being obstacles near the receiver the only ones studied in this section, a similar degree of obstruction causes a rising attenuation value as the distance to the transmitter increases. These results agree with the theory of the constructive interference of a diffracted ray and a diffracted ray traveling along the surface, developed by Wait and Ott [12].

Paths including obstacles far from the receiver (distance > 10 km), showed different behavior than nearby obstacles [19], [28]. It was observed that the values were similar to those obtained in unobstructed reception, with virtually negligible attenuation values. The maximum difference between the LoS interpolation curve and the F case interpolation curves was 1.5 dB. Thus, it is suggested that obstacles lower than a wavelength where the distance to the receiver is longer than 10 km are not considered as relevant for planning purposes.

D. Proposal of Attenuation Curves

To sum up, Fig. 5 shows the curves obtained for each of the cases. Likewise, Table IV contains expressions of the aforementioned interpolation curves. Next to each expression, the dispersion value of the field level values around its interpolation curve is indicated, expressed in the form of Root Mean Square Error. It is remarkable the low dispersion values
obtained in this study.

The mean attenuation values of each case are also indicated (‘Mean attenuation’ in Table IV), calculated as the average difference between the field level values in each obstructed reception case, and the curve representative of reception in line of sight. The values set out in the table show that attenuation grows with the height of the primary obstacle, provided that terrain irregularities near the receiver are involved. As the distance between the obstacle and the receiver increases, the attenuation decreases, and tends towards a negligible value for large distances (greater than 10 km) and primary obstacles lower than 1λ height.

**TABLE IV**

<table>
<thead>
<tr>
<th>Case</th>
<th>Interpolation curve – equation (x: transmitter–receiver distance, in km)</th>
<th>RMSE</th>
<th>Mean Attenuation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LoS</td>
<td>-14.29·ln(x) + 130.4</td>
<td>1.85</td>
<td>-</td>
</tr>
<tr>
<td>N (&lt;λ/2)</td>
<td>-14.03·ln(x) + 126.35</td>
<td>1.88</td>
<td>3.2</td>
</tr>
<tr>
<td>N (λ/2-λ)</td>
<td>-18.46·ln(x) + 138.3</td>
<td>2.50</td>
<td>6.8</td>
</tr>
<tr>
<td>N (&lt;λ/2) and N (λ/2-λ)</td>
<td>-16.33·ln(x) + 132.65</td>
<td>2.85</td>
<td>4.8</td>
</tr>
<tr>
<td>N (3-2λ)</td>
<td>-</td>
<td>-</td>
<td>13.5</td>
</tr>
<tr>
<td>LoS + F</td>
<td>-15.17·ln(x) + 132.62</td>
<td>2.06</td>
<td>-</td>
</tr>
<tr>
<td>Mult</td>
<td>-</td>
<td>-</td>
<td>17.6</td>
</tr>
</tbody>
</table>

**E. Validation of the results**

The second set of data from the measurement campaign in 2007 was used to validate the proposed curves. Reception locations where LoS, N (<λ/2), and N (λ/2-λ) cases occur were selected. A total of 29 cells were measured (7 cells of LoS case, 11 of N (<λ/2) case, and 11 of N (λ/2-λ) case), and the median value of each cell calculated.

In Fig. 6, the field strength median values of the cells are compared to the interpolation curves obtained in Fig. 5 and Table IV. For a proper comparison, field data of both measurement campaigns have been normalized to a transmitted power of 1 kW. As illustrated, the field strength values of the second measurement campaign are adequately represented by the interpolation curves of Fig. 5. The goodness of fit of the prediction curves has been also assessed numerically. The ITU-R Rec. SM.1447 [30] states that the coverage estimations are validated if measurements statistically agree with calculated values. The criterion for simulation in rural area is ±4 dB in 90% of measurements. Differences between estimations and measurements have been calculated, and the measurements included between 5th and 95th percentile provide differences between (-3.5 dB, +3.3 dB). These values verify the criterion specified by the ITU-R Rec. SM.1447.

Consequently, the set of data of the second measurement campaign validates the expressions of the interpolation curves of Table V, which define the influence of the irregular terrain in ground wave propagation.

**V. CONCLUSIONS**

The communication presents the results of a study to quantify the attenuation caused by irregular terrain in the MW band (two frequencies around 1.3 MHz). The procedure has been based in establishing a classification of terrain profiles. This classification considered an identification of the main (“primary”) obstacle at each terrain profile and the analysis of the associated attenuation value.
When analyzing the obstructed profile cases two relevant parameters were identified: the obstacle height and its position along the path profile. The results show that attenuation grows with the height of the primary obstacle, provided that terrain irregularities near the receiver are involved. As the distance between the obstacle and the receiver increases, the attenuation decreases. When the primary obstacles are of less than 1λ height, attenuation tends towards a negligible value, for distances greater than 10 km.

The attenuation values for profiles with obstacles that are higher than λ and close to the receiver, or those with multiple obstacles between the transmitter and the receiver are, in most cases, greater than 10 dB.

Expressions to calculate the attenuation as a function of the distance have been obtained for each obstruction scenario. The trend with the distance of the interpolation curves is logarithmic.

An independent measurement campaign was carried out to validate the results and the fit between the interpolation curves and the independent data describe adequately the influence of the irregular terrain. Moreover, the statistical criterion defined by the ITU-R to validate the coverage estimations is fulfilled.

This study has described the importance of taking terrain irregularities into consideration to ensure the adequate planning of the new digital services in MF and LF bands, and offer the necessary characterization of irregular terrain paths, allowing a more reliable estimation of the attenuation that produce in the field level of the received signal.

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