Path Loss Modelling in Industrial Environment

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Abstract — In the paper adjusted selected propagation models as well as the new path loss model have been evaluated in terms of designing mobile radio networks in investigated environment.

Index Terms — path loss modelling, radio waves propagation, measuring research, container terminal environment

I. INTRODUCTION

The container port area is a particular example of the industrial environment and should be treated as a very difficult radio waves propagation environment. There are a number of propagation models, mainly for urban, suburban or rural environments. There is also propagation model destined for container port environment, but this model has been developed for designing only fixed radio links. So there was a need to adjust existing models and to develop new propagation model based on results of measurement research. Such tests have been carried out by author in Gdansk Deepwater Container Terminal (hereinafter called DCT Gdansk) in accordance with normative requirements [1, 2], that have to be met during research. The analysis contained in [3] has been also taken into account. During research in DCT Gdansk nearly 290 thousand propagation cases have been collected. These cases concern propagation routes with various lengths (up to 620 m), various frequencies of test signal (from a range of 500 MHz up to 4 GHz), various heights of transmitting antenna installation (from a range of 12 m up to 36 m) and various average heights of container stacks (from a range of 2.6 m up to 8.7 m). It should be noted that width of the streets (transport routes between containers stacks) as well as theirs length are not variables and equal 10 m and 620 m, respectively.

In the paper adjusted selected propagation models have been evaluated in terms of designing mobile radio networks in investigated environment. These models are: ITU-R P.1411 models for the case of propagation over roof-tops for urban and suburban areas [4], COST231 – Walfisch-Ikegami model [5] and the multi-variant empirical model for designing fixed radio systems in container terminal [6]. The new propagation model for designing mobile radio links in container terminal has also been evaluated [7]. At the end of the paper results have been summarized and discussed.

II. ADJUSTED PROPAGATION MODELS

Analysis contained in [8] has pointed the necessity of statistical adjustment of the selected models. In order to increase accuracy of path loss estimation in investigated environment, a method of statistical adjustment of selected models has been proposed. This method relies on adding functional correction factors to original path loss formulas. Coefficients of these functions have been calculated on the basis of empirical data and using multivariate linear regression. The statistical significance of particular coefficients has been proved (with 95% confidence) using the Student's t-test.

A. Adjusted COST 231 Walfisch-Ikegami

The COST231 Walfisch-Ikegami model has been developed as a result of COST 231 Project [5]. The model allows to improved path loss estimation by consideration of more data to characterized of the urban environment, namely: heights of buildings, widths of roads, buildings separation and road orientation with relation to the direct radio path. For NLOS situation the basic transmission loss is depended on a free space loss \( L_{0\text{fs}}[^{\text{dB}}] \), a multiple screen diffraction loss \( L_{\text{msd}}[^{\text{dB}}] \), and a roof-top-to-street diffraction and scatter loss \( L_{\text{rts}}[^{\text{dB}}] \) [5].

The Walfisch-Ikegami model has been modified by adding two functional correction factors to original equation: \( \Delta L_c(f, d, A_{h_b}, A_{h_t}, \phi) \) and \( \Delta L_{c_2}(f, d) \), as follows:

\[
L_{\text{mod}}[^{\text{dB}}] = \begin{cases} 
L_{0\text{fs}} + L_{\text{msd}} + \Delta L_c & \text{for } L_{\text{mod}} > 0, \\
L_{0\text{fs}} + \Delta L_{c_2} & \text{for } L_{\text{mod}} \leq 0.
\end{cases}
\] (1)

These factors are expressed by following polynomials:

\[
\Delta L_c[^{\text{dB}}] = \begin{cases} 
-17.9\log(f) - 151\log(d) - 12.9\log(A_{h_b}) + 5.2\log(A_{h_t}) - 0.08\phi + 48.2, & \text{for suburban areas original scenario} \\
-31.9\log(f) - 16.7\log(d) - 8.8\log(A_{h_b}) + 5.5\log(A_{h_t}) - 0.09\phi + 86.7, & \text{for urban centres original scenario}
\end{cases}
\] (2)

\[
\Delta L_{c_2}[^{\text{dB}}] = \begin{cases} 
2.31\log(f) - 9.11\log(d) - 8.7, & \text{for suburban areas original scenario} \\
5.91\log(f) - 7.5\log(d) - 16.8, & \text{for urban centres original scenario}
\end{cases}
\] (3)

where \( f[^{\text{MHz}}] \) – signal frequency, \( d[^{\text{km}}] \) – distance between base station antenna and mobile terminal, \( A_{h_b}[^{\text{m}}] \) - difference between average height of containers stacks and height of mobile terminal, \( A_{h_t}[^{\text{m}}] \) - difference between height of base station antenna and average height of containers stacks and \( \phi[^{\circ}] \) - street orientation angle.
B. Adjusted ITU-R P.1411 (§4.2.1)

Recommendation [4] includes propagation models destined for designing short-range outdoor radio communication systems for different types of environments. Two models for typical cases (called NLOS1), where the base station antenna is mounted above roof-top level, have been selected. For these situations radio wave propagation is mainly over the roof-tops.

The first one is the model described in §4.2.1 of [4]. It is a modified version of the Walfisch-Ikegami model, extending the frequency range of its applicability up to 5 GHz. In addition, this model describes situations in which the length of the path covered by buildings is less than so called “settled field distance”. This situation hasn’t been taken under consideration in Walfisch-Ikegami model.

In case of propagation model, described in §4.2.1 of ITU-R P.1411, adjustment has been done by adding to original model equation one functional correction factor \( \Delta L_{1411,4.2.1}^C [\text{dB}] \), as it is outlined below:

\[
\Delta L_{1411,4.2.1}^C [\text{dB}] = \Delta L_{c3} + \begin{cases} 
L_0 + L_{\text{mod}} & \text{for } L_{\text{mod}} + L_0 > 0, \\
L_0 & \text{for } L_{\text{mod}} + L_0 \leq 0.
\end{cases}
\]  

This factor is expressed by following equation:

\[
\Delta L_{c3} [\text{dB}] = \begin{cases} 
-6 \lg \left( f \right) + 19.7 \lg \left( d \right) - 6.9 \lg \left( \Delta h_b \right) + 0.7 \lg \left( \Delta h_v \right) - 0.2 \phi + 10, & \text{for suburban areas original scenario:} \\
-6 \lg \left( f \right) - 20 \lg \left( d \right) - 9.4 \lg \left( \Delta h_b \right) + 0.1 \lg \left( \Delta h_v \right) - 0.2 \phi + 12, & \text{for urban centres original scenario:}
\end{cases}
\]

Function parameters have the same meaning as in (2) and (3).

C. Adjusted ITU-R P.1411 (§4.2.2)

The third model has been characterized in §4.2.2 of [4]. It may be used to calculate the basic transmission loss in suburban environment. Depending on the distance between base station and mobile station this model distinguishes three regions in terms of dominant arrival waves at the mobile station: a direct wave dominant region (with \( L_0 [\text{dB}] \)), a reflected wave dominant region (with \( L_{\text{ref}} [\text{dB}] \)) and a diffracted wave dominant region (with \( L_{\text{dif}} [\text{dB}] \)).

Adjustment of this model was done by adding to original equation three functional correction factors: \( \Delta L_{c4}(d, \lambda, \Delta h_v, \Delta h_b, \phi) \), \( \Delta L_{c5}(d, \lambda, \Delta h_v, \Delta h_b, \phi) \) and \( \Delta L_{c6}(d, \lambda, \Delta h_v, \Delta h_b, \phi) \), as follows:

\[
L'_{1411,4.2.2} [\text{dB}] = \begin{cases} 
L_0 + \Delta L_{c4} & \text{(direct wave dom. reg.),} \\
L_{\text{ref}} + \Delta L_{c5} & \text{(reflected wave dom. reg.),} \\
L_{\text{dif}} + \Delta L_{c6} & \text{(diffracted wave dom. reg.).}
\end{cases}
\]

These factors are expressed by following polynomials:

\[
\Delta L_{c4} [\text{dB}] = -6.5 \lg \left( d \right) + 0.81 \lg \left( \lambda \right) + 21.5,
\]
\[
\Delta L_{c5} [\text{dB}] = -22.5 \lg \left( d \right) + 15.6 \lg \left( h_b - h_v \right) - 16.6 \lg \left( h_b - h_v \right) - 0.2 \phi + 46.2,
\]
\[
\Delta L_{c6} [\text{dB}] = -3.8 \lg \left( d \right) + 0.71 \lg \left( \lambda \right) + 1.71 \lg \left( h_b - h_v \right) + 15.1 \lg \left( h_b - h_v \right) - 0.2 \phi + 6.2,
\]

where \( \lambda \) [m] – wavelength, \( d \) [m] – distance between base station antenna and mobile terminal, \( h_b \) [m] - height of base station antenna, \( h_v \) [m] – average height of containers stacks, \( h_b \) [m] - height of mobile terminal. Other parameters have the same meaning as in the previous cases.

D. Adjusted Empirical Model

There is also known the empirical model for designing fixed radio links in container terminal. This model makes the basic transmission loss dependent on: frequency \( f \) [MHz], propagation path length \( d \) [km], path type qualification (LOS or NLOS condition) and difference between transmitter antenna height \( h_v \) [m] above terrain level and average height \( h_{av} \) [m] of containers stacks [6, 9]. From among four variants, two describes propagation situations that occurred during tests (both for \( h_v \geq h_{av} \)), namely: LOS1 and NLOS1.

This model has been modified by adding functional correction factors: \( \Delta L_{c7}(f, d, h_b-h_{av}) \) and \( \Delta L_{c8}(f, d, h_{av}) \) to two investigated variants, namely:

\[
L'_{\text{LOS}1} [\text{dB}] = L_{\text{LOS}1} [\text{dB}] + \Delta L_{c7} [\text{dB}],
\]
\[
L'_{\text{NLOS}1} [\text{dB}] = L_{\text{NLOS}1} [\text{dB}] + \Delta L_{c8} [\text{dB}].
\]

These factors are expressed by following polynomials:

\[
\Delta L_{c7} = -0.2 \lg \left( f \right) + 14 \lg \left( d \right) + 11.3 \lg \left( h_b - h_{av} \right),
\]
\[
\Delta L_{c8} = -0.2 \lg \left( f \right) + 11.9 \lg \left( d \right) - 11.6 \lg \left( h_{av} - h_b \right) + 22.5.
\]

III. NEW EMPIRICAL MODEL FOR MOBILE RADIO LINKS

The environment under investigation has a relatively regular structure. However, the diversity of conditions occurring in different places of the container terminal was taken into account in the new model (named the MCT model, as an abbreviation for: mobile, container, terminal). For this reason, the terminal was divided into three subareas, where different propagation mechanisms have a crucial influence on basic transmission loss, namely: LOS Area, Containers Area and Off-Terminal Area [7].

Based on preliminary analysis of propagation conditions, the relevant factors affecting the basic transmission loss value in a container terminal environment were defined, namely: frequency \( f \) [MHz] of the radio signal, propagation path length \( d \) [m], base station antenna height \( h_b \) [MHz]), angle
\( (\phi [^\circ]) \) of radio wave arrival. The characteristic parameters for the investigated industrial environment are also very important. These are:

- terminal surface occupancy ratio \((S_i)\), defined as a ratio of surface occupied by containers to all terminal surface destined for container storage,
- \(i\)-th row surface occupancy ratio \((S_i)\), defined as a ratio of surface occupied by containers in \(i\)-th row to all surface destined for container storage in this row,
- average height of container stacks \( (h_{c,i})\) throughout the terminal,
- average height of container stacks \( (h_{c,i})\) in \(i\)-th row,
- average height of container stacks \( (h_{c,i})\) over a propagation path length,
- average height of container stacks \( (h_{c,i})\) in the row behind the mobile station and causing the reflection of radio waves.

On the basis of the analysis of propagation conditions in each subarea of the terminal under investigation, the basic transmission loss \((L_{\text{MCT}})\) in such an environment may be expressed by the following equation:

\[
L_{\text{MCT}} \ [dB] = \begin{cases} L_{\text{LOS}} & \text{for } d \leq d_i \text{ (LOS Area)}, \\ L_{\text{cont}} & \text{for } d_i < d \leq d_s \text{ (Containers Area),} \\ L_{\text{off}} & \text{for } d > d_s \text{ (Off-Terminal Area).} 
\end{cases}
\]

The particular components are:
- for the LOS Area:
  \[
  L_{\text{LOS}} \ [dB] = L_0 - 4.2 \log (h_b - h_{s,i}) + 11.6,
\]
where the \(L_0\) factor is related to the direct wave, expressed by the well-known equation:

\[
L_0 \ [dB] = 20 \log (f) + 20 \log (d) - 27.6,
\]
and the \((h_b-h_{s,i})\) factor is related to the wave reflected from containers in the first row of storage fields;
- for the Containers Area:
  \[
  L_{\text{cont}} \ [dB] = 20 \log (f) + 25 \log (d) - 18 \log (h_b - h_{c,i}) + 4 \log (\phi) - 21.8,
\]
where the \((h_b-h_{c,i})\) factor is related to the path loss due to diffraction at the edges of containers on the propagation path over the containers, where:

\[
L_{\text{cont}} \ [dB] = 20 \log (f) + 25 \log (d) - 18 \log (h_b - h_{c,i}) + 4 \log (\phi) - 21.8,
\]

and the \((h_b-h_{c,i})\) factor is related to the wave reflected from the containers in the next row behind the mobile station;
- for the Off-Terminal Area:
  \[
  L_{\text{off}} \ [dB] = 20 \log (f) + 30 \log (d) - 18 \log (h_b - h_{c,i}) + 13.5 \log (S_i) + 4 \log (\phi) - 21.8,
\]
where the \((h_b-h_{c,i})\) factor is related to the path loss due to diffraction at the edges of containers on the propagation path over the containers, where:

\[
h_{c,i} = \frac{\sum_{i=1}^{R} h_{c,i} \cdot S_i}{\sum_{i=1}^{R} S_i}
\]
and the \(S_i\) factor reflects the influence of the number of containers in the whole container terminal area.

In the above equations \(r=1,2...,R-1\) means the number of the last row of storage fields before the mobile station and \(R\) is the number of all rows of storage fields.

Coefficients of the above equations were calculated on the basis of empirical data and using multivariate linear regression with the least-squares method, which minimizes the sum of squared differences between measured path loss value and the regression function. Statistical significance of particular coefficients was proved with 95% confidence interval (5% level of significance) using the t-test with Student’s distribution, and statistical significance of regression functions was proved with the same confidence interval using the F-test with Fisher-Snedecor distribution.

IV. THE EVALUATION

Above described models were evaluated in order to use them for designing mobile radio links in container terminal environment. This evaluation was based on the measure of matching measured data to mathematical models, namely standard error of estimate (SEE), which is used to verify accuracy of the path loss models [10] and it is defined as follows:

\[
\text{SEE} \ [dB] = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (L_{\text{m},i} \ [dB] - L_{c,i} \ [dB])^2},
\]
where \(L_{\text{m},i}\) is measured value of the basic transmission loss in \(i\)-th position of the receiver \((i=1,2...,N)\), \(L_{c,i}\) means the basic transmission loss value computed using propagation model for \(i\)-th position, and \(N\) is a sample size.

Apart from this parameter, very important is a coefficient of determination \(R^2\), which is a statistical measure of how well the adjusted model approximates the real path loss values and it is expressed by following equation [11]:

\[
R^2 = \frac{\sum_{i=1}^{N} (L_{c,i} - L_{\text{m},i})^2}{\sum_{i=1}^{N} (L_{\text{m},i} - L_{\text{m},\text{av}})^2},
\]
where \(L_{\text{m},\text{av}}\) – averaged value of measured basic transmission loss.
TABLE 1 VALUES OF STANDARD ERROR OF ESTIMATE AND COEFFICIENT OF DETERMINATION FOR SELECTED PROPAGATION MODELS

<table>
<thead>
<tr>
<th>Model</th>
<th>Original scenario</th>
<th>SEE [dB]</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjusted COST 231&lt;br&gt;Walfisch-Ikegami</td>
<td>Suburban areas</td>
<td>5.2</td>
<td>0.758</td>
</tr>
<tr>
<td></td>
<td>Urban centers</td>
<td>5.7</td>
<td>0.718</td>
</tr>
<tr>
<td>Adjusted ITU-R P.1411 NLOS1&lt;br&gt;(§4.2.1 of [4])</td>
<td>Suburban centers</td>
<td>7.6</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Urban centers</td>
<td>7.8</td>
<td>0.46</td>
</tr>
<tr>
<td>Adjusted ITU-R P.1411 NLOS1&lt;br&gt;(§4.2.2 of [4])</td>
<td>Suburban areas</td>
<td>5.0</td>
<td>0.785</td>
</tr>
<tr>
<td>Adjusted Empirical Model for&lt;br&gt;Fixed Radio Systems</td>
<td>LOS1</td>
<td>5.3</td>
<td>0.752</td>
</tr>
<tr>
<td></td>
<td>NLOS1</td>
<td>5.3</td>
<td>0.752</td>
</tr>
<tr>
<td>The MCT Model</td>
<td>LOS Area</td>
<td>4.40</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>Containers Area</td>
<td>4.53</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>Off-Terminal Area</td>
<td>4.30</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>All Areas</td>
<td>4.45</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Comparison of $SEE$ and $R^2$ values for described selected propagation models is presented in Table 1. It is seen, that the best results were obtained for the MCT model for each area of the container terminal and for all areas in general.

V. CONCLUSION

Since there was no propagation model for designing mobile radio networks in a container terminal environment, in practice other models were used. Therefore, there was a need to adjust existing models and to develop new empirical propagation model for mobile radio links working in such a difficult environment as is the container terminal. The new model takes into account all essential factors that occur in this environment and that affect basic transmission loss of radio wave.

The MCT model is the first model for the accurate estimation of path loss in the investigated environment. It was developed on the basis of almost 290 thousand propagation path measurements in a real container terminal environment, collected in accordance with the appropriate requirements. The obtained standard error of estimate is 4.45 dB. What is more, the obtained value of the coefficient of determination is 0.82, what additionally proves the accuracy and usefulness of the MCT model.

The MCT model may be used for frequencies from a range of 500 MHz up to 4 GHz, propagation path length between 50 m and 620 m and the base station antenna height between 12 m and 36 m.

Described model is a prelude to elaborate more universal model for the outdoor industrial environments in general. For this reason a comprehensive measurement research in different environments should be carried out. For obvious reasons this should be done in international cooperation.

REFERENCES