Measuring Research on Radio Wave Propagation


**Abstract**

Telecommunication connections are increasingly based on the wireless links, both fixed and mobile, carried out under different radio systems. This kind of solution has many advantages. However, the propagation medium is a factor that causes many difficulties in designing wireless networks, because of large diversity of propagation environments. Transmission loss in each environment is determined by many variables phenomena and factors. It is essential to determine the transmission loss to a specified accuracy, which is necessary for designing of radio links to meet energy requirements [1]. Therefore, there is a need to create empirical propagation models for different environments, based on measuring research results. So far a number of such models have been developed, mainly for urban and indoor environments. However, the environments in these groups may also differ within. Because of this, the issue of radio wave propagation measuring research is a current topic, especially for the radio networks in specific environments. At present, the Department of Radiocommunication Systems and Networks in the Gdansk University of Technology is carrying out the wide research on radio wave propagation. Very important are normative requirements - as described in literature, such as ITU-R Recommendations [2-5] - that have to be met during the research. At the outset of paper, radio links have been characterized in scope of transmission loss and its components. Then the next to be discussed is requirements concerning measuring equipment, its calibration process, measurement methodology, as well as the processing and presentation of their results. In the last part of the paper an exemplary mobile measuring station is presented. It was developed and implemented for use in research in diverse propagation environments.

1. Measuring radio link description

As known, power of signal transmitted in the radio link is significantly reduced. The effect of this is the large difference between signal power on output of transmitter and power of the same signal available at input of the receiver. This difference depends on many factors, mainly transmission loss of propagation medium, as well as the power losses in the transmission feeder lines, the losses due to measuring devices, the antenna losses due to the impedances or polarization mismatch, etc. Therefore, there is a necessity to systematize terminology and symbols used in analyzing the transmission loss and its components. It can be presented using a graphical depiction of terms used in the measuring transmission loss concept, shown in Fig. 1, which considered all essential factors affecting the energy level in radio link, such as:

- total loss of a measuring radio link between transmitter output and receiver input,
- system loss between input of transmitting antenna and output of receiving antenna,
- basic transmission loss of a radio link,
- free-space basic transmission loss, that is a basic component of transmission loss.

1.1 Total loss of a measuring radio link

The total loss $L_L$ [dB] of a measuring radio link is defined as a difference between power $P_{MT}$ [dBW] supplied by measuring transmitter and power $P_{MR}$ [dBW] available at input of measuring receiver in real installation, propagation and operational conditions [2]. The total loss may be expressed by:

$$L_L[dB] = P_{MT}[dBW] - P_{MR}[dBW] = 10 \log \left( \frac{P_{MT}[W]}{P_{MR}[W]} \right), \quad (1)$$

where lowercase letters, i.e. $P_{MT}$ and $P_{MR}$, are power on the output of transmitter and power on the input of receiver, respectively. They can be expressed in absolute values, such as [W], or in relative values, such as [dBW], in that case they are written as uppercase letters, $P_{MT}$ and $P_{MR}$, respectively.

Total loss includes all factors affecting the power of received signal, i.e. basic transmission loss of propagation medium, gains of antennas , loss in feeder lines, etc.
Knowledge of the total loss components is necessary to correctly determine the value of the basic transmission loss.

### 1.2 System loss

The system loss $L_s$ [dB] is defined as a difference between power $P_s$ [dBW] supplied at terminals of the transmitting antenna and power $P_r$ [dBW] available at terminals of the receiving antenna [2]. By analogy with equation (1), it may be written as follows:

$$L_s[dB] = P_s[dBW] - P_r[dBW] = 10\log\left(\frac{P_s}{P_r}\right). \tag{2}$$

In addition to basic transmission loss, the system loss also includes effects of circuits associated with the measuring antennas, such as ground losses, dielectric losses, antenna loading coil losses and terminating resistor losses. But on the other hand, the system loss excludes losses in feeder lines, both in the transmitting section ($L_s$ [dB]) and in the receiving section ($L_w$ [dB]). Considering Fig. 1, it can be written as follow:

$$L_s[dB] = L_w[dB] - L_{aw}[dB] - L_{aw}[dB]. \tag{3}$$

### 1.3 Basic transmission loss

The basic transmission loss $L_w$ [dB] consists of free-space basic transmission loss $L_{sf}$ [dB] and additional loss $L_{add}$ [dB], resulting from real conditions of propagation environment, different from ideal free space. From this point of view, the basic transmission loss may be expressed by:

$$L_w[dB] = L_{sf}[dB] + L_{add}[dB]. \tag{4}$$

The additional loss $L_{add}$ includes phenomena occurring in real propagation environments. In terms of measurement procedures, the most important are: loss dependent on path clearance, diffraction fading, attenuation due to rain, other precipitation and fog, fading due to multipath. Equation (4) is a case of isotropic radiation, i.e. it excludes characteristics of real antennas, especially its directivity and power efficiency, which are described by power gain [1].

Taking into consideration the link power budget, in case of free-space environment, the basic transmission loss may be expressed by:

$$L_w[dB] = P_s[dBW] - P_r[dBW] + G_r[dBi] + G_s[dBi]. \tag{5}$$

where $G_r$ and $G_s$ (in [dBi]) are the isotropic (absolute) gains of the transmitting and receiving antennas, respectively, in the direction of propagation. Table 1 gives the power gains for typical reference antennas.

### 1.4 Free-space basic transmission loss

As known, free space is an ideal case of propagation environment, open and without any propagation obstacles. It is a perfectly dielectric, homogenous and unlimited environment, characterized by a lack of influence of Earth surface on radio wave propagation and non-absorbing the energy of the electromagnetic field [1].

Assuming that free-space propagation environment and distance $d$ [m] between antennas of the measuring radio link is much larger than wavelength $\lambda$ [m] of test signal, the free-space basic transmission loss $L_{sf}$ [dB] may be expressed by a well-known equation [3]:

$$L_{sf}[dB] = 20\log\left(\frac{4\pi \cdot d[m]}{\lambda[m]}\right). \tag{6}$$

### 2. Standardization of measuring apparatus

In order to ensure accurate measurement results in frequency range 9 kHz to 3 GHz and above (up to 40 GHz), the ITU-R recommends (in document [4]) the method of installation and calibration of measuring systems. The document also determines the accuracy, that are expected in field-strength measurements, assuming no noise of receiver, atmospheric noise or external interference. Taking these assumptions into account, the expected accuracy of measurements should be:

- for frequency band 9 kHz to 30 MHz: ±2 dB,
- for frequency band 30 MHz to 3 GHz: ±3 dB.

If recommended values are not obtainable (for various reasons, such as limitation of the measuring
receiver, interference, instability of the test signal, etc.), nevertheless the accuracy specified above should be taken into consideration [4].

Depending on the electrical parameters, on which the receiving antenna and the measuring receiver are calibrated, the measuring receiver may measure the following quantities:

- signal power at the receiver input resulting from the power flux density of electromagnetic wave at point of reception (the point of the receiving antenna placement),
- voltage at the receiver input resulting from the electric field intensity at point of reception,
- current at the receiver input resulting from the magnetic field intensity at point of reception.

And so, for the receiving antenna calibrated for power flux density of electromagnetic wave, at the receiver input are available and measured power $P_{MR}$ (Fig. 1), which is the basis of determining the basic transmission loss $L_0$ according to equation (8). Similar equations may be written for the case of the receiving antennas, calibrated for electric or magnetic component of electromagnetic field.

### 2.1 Measuring antennas installation

Type of the receiving antenna may affect the type of the measuring receiver – the electrical signal, measured by the measuring receiver should correspond to the electrical signal (to which the antenna was calibrated) available at output terminals of the receiving antenna. For example, for the short monopole antenna of a specified length, the receiver should measure voltage of test signal, and for the inverted cone type vertical antenna the receiver should measure power of test signal. Recommendation [4] contains examples of antennas for different frequency ranges. For frequencies below 30MHz it is recommended to use vertical or loop antennas. In case of the vertical antenna, the monopole antenna shorter than one-quarter of a wavelength may be used with a RF ground system, built with radial conductors at least twice the length of the antenna and spaced 30° or less. Instead of radial conductors, an equivalent RF ground screen may be used. There is also a possibility to use an inverted cone type vertical antenna with similar construction of RF ground system. This allows to obtain a greater power gain of measuring antenna than the quarter wave monopole antenna.

For frequency range 30MHz to 1GHz it is recommended to use a short monopole antennas, half-wave dipoles or high-gain directional antennas, but it is essential to ensure the same polarization of receiving antenna as the transmitting antenna. For field-strength measurements at frequencies above 1GHz it is recommended to use directional antennas with matched polarization.

It should be noted that the height of antennas installation has a significant influence on the measurement results, due to the fact that the signal attenuation is dependent on surface wave propagation [6]. And so, if antennas are installed in close proximity to the ground, the electromagnetic waves take the form of surface waves, which takes effect to the wave depolarization, consequently there is wave attenuation resulting to the polarization mismatch in the radio links. In addition, the radio wave attenuation increases due to losses related to the penetration of radio waves into the propagation ground [1]. To minimize the influence of the Earth surface on test signal, transmitting antenna has to be installed at a height that enables space waves propagation [6]. Therefore, the ITU-R recommends that for frequency range 30MHz to 1GHz, the installation of the transmitting antenna should be at least 10m high [4]. The recommended height of the receiving antenna is 1.5 m up to 3 m [5].

### 2.2 Measuring receiver

The measuring receiver primarily should have stable parameters (gain, frequency, bandwidth, attenuation), that have an influence on accuracy of the measurements (its voltage, current or power).

#### The required bandwidth and detector functions for various signal types

<table>
<thead>
<tr>
<th>Example of signal types</th>
<th>Minimal bandwidth (kHz)</th>
<th>Detector function</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM DSB</td>
<td>9 or 10</td>
<td>Linear average</td>
</tr>
<tr>
<td>AM SSB</td>
<td>2.4</td>
<td>Peak</td>
</tr>
<tr>
<td>FM broadcast signal</td>
<td>170 or greater</td>
<td>Linear average (or log)</td>
</tr>
<tr>
<td>TV carrier</td>
<td>200 or greater</td>
<td>Peak</td>
</tr>
<tr>
<td>GSM signal</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>DAB signal</td>
<td>1 500</td>
<td></td>
</tr>
<tr>
<td>DVB-T signal Systems:</td>
<td>6 MHz</td>
<td>r.m.s.</td>
</tr>
<tr>
<td></td>
<td>7 MHz</td>
<td>6 000</td>
</tr>
<tr>
<td></td>
<td>8 MHz</td>
<td>7 000</td>
</tr>
<tr>
<td></td>
<td>15 MHz</td>
<td>8 000</td>
</tr>
<tr>
<td>TETRA signal</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>UMTS signal</td>
<td>3 840</td>
<td></td>
</tr>
<tr>
<td>Narrow-band FM radio</td>
<td>7.5</td>
<td>Linear average (or log)</td>
</tr>
<tr>
<td>Channel spacing:12,5kHz</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>20kHz</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>25kHz</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

Local oscillators should have low phase noise, the operating dynamic range should be greater than 60dB and the bandwidth should be wide enough to allow reception of essential parts of the test signal spectrum. Type of detector depends on the bandwidth and the modulation mode of test signal. The required bandwidth and detector functions for various signal types are compiled in Table 2 [5].

Properly configured spectrum analyzer may be used as the measuring receiver, whose work may also be automated. The measuring receiver, with remainder of the receiving section, may be mounted
on a vehicle or a hand-cart, that enables mobile measurements in the area of propagation research.

2.3 Measuring devices calibration

Each of measuring devices and circuits (feeder lines, filters, etc.), that affect total loss of a measuring radio link, are usually calibrated in accordance with certain standards, as one of the stages of their production. Nevertheless it is recommended to calibrate transmitting and receiving section as a single entities [4]. The above allows to take into account the influence of all elements of the measuring radio link, including attenuation due to the ground, masts, etc.

The calibration procedures, presented below, deal with the case of the basic transmission loss calculation based on the power measurement. Calibration of the transmitting section lies in set-up of the power \( P_{MT} \) value, to obtain required value of \( P \) at the input terminals of the transmitting antenna. The calibration process of the receiving section deals with calculation of the difference (in logarithmic scale) between power of test signal available at the output terminals of the receiving antenna and the power of test signal at the input of the measuring receiver. After taking into account the power gain of receiving antenna, it is possible to calculate a correction factor \( F \) as follows (see Fig. 1):

\[
\] (7)

Considering equation (5) and Figure 1, which implies that \( P_t = P_{MT} + L_{op} \) after simple transformation, the basic transmission loss may be calculated using following equation:

\[
\] (8)

The equation (8) is very important in measuring research and calculation of the basic transmission loss on the basis of measurements of power \( P_{MT} \) at input of the measuring receiver. To calculate basic transmission loss it is necessary to know the following values:

- the power gain \( G_c \) of the transmitting antenna,
- the power \( P_t \) on input of the transmitting antenna – set during calibration process of the transmitting section,
- the correction factor \( F \) – calculated during calibration process of the receiving section.

Fixed measuring apparatus should be recalibrate at least once a year or every time after change any of its parts [4].

2. Standardization of measuring procedures

There may be many various reasons for measuring research on radio wave propagation, inter alia: to create empirical propagation models or to estimate coverage of radio networks. This information may be useful in increasing efficiency of radio resources management or for controlling proper use of this resources by particular entities, and so on. Considering the above-cited, ITU-R recommends to unify methodology of measuring procedures and presentation of its results.

3.1 Requirements for measurements

The measurement results should include information about slow and fast changes of the power flux density of electromagnetic field (slow and fast fading, respectively). So it is recommended to choose the measurement points in an appropriate manner. Measurements points should be spaced every \( 0.8\lambda \) along a route of radio waves propagation.

It is recommended that the results should be averaged every \( 40\lambda \) [7].

Measurements may also be done automatically when the measuring receiver is mobile, but speed \( V[km/h] \) of the receiver is not arbitrary. It depends on the frequency \( f[MHz] \) of test signal and minimum time \( t[s] \) given by the receiver specifications to revisit a single frequency. It may be expressed by following equation [5]:

\[
V[km/h] \leq \frac{864}{f[MHz] \cdot t[s]}. \quad (9)
\]

3.2 Positioning systems

In order to find relations between the basic transmission loss and the distance from the transmitting antenna, result of each measurement should be correlated to the place of its execution. For this reason, the positioning system should be used for reading current position of measuring receiver. It is recommended to use one of three systems specified in the ITU-R Recommendation [5]. The GPS is a preferred positioning system, although its accuracy is limited in tunnels, narrow streets or valleys. Accuracy in position determining should be a few meters, which in most cases can be provided.

If unable to determine the position using the GPS system, it is recommended to use dead reckoning system. The position is determined basing on information about the starting point, the direction of movement and the distance covered by the receiver. It is also possible to use the complex navigation system, which is the combination of the above-mentioned systems.

3.3 The measurement data processing

Due to the large instability of propagation environment, the result of single measurement is not reliable or repeatable. Therefore, the measurements results should be classified in terms of probability of exceeding a particular value by the power of received
signal. This probability may be in range of 1-99%, but typical values for this parameter are as follows: 1%, 10%, 50%, 90% and 99%. During research on radio wave propagation, the median value is recommended, i.e. the value from a ordered subset of measurement results, which is exceeded by 50% of the other values from this subset [5].

In practice, for each \( i \)-th subset of measurement data, it is necessary to calculate the median of test signal power \( P_{MR,i} \) at the receiver input. Each subset of data is created on the basis of \( n \) measurement results, collected along the route at 40\( \lambda \) spacing [5] in accordance with the following equation:

\[
P_{MR,i}^i = \begin{cases} 
      P_{MR,i+1/2}^i, & \text{if } n \text{ is odd,} \\
      \frac{1}{2} \left( P_{MR,i+1/2}^i + P_{MR,i+2}^i \right), & \text{if } n \text{ is even,}
\end{cases}
\]

(10)

where \( P_{MR,1}^i \leq P_{MR,2}^i \leq P_{MR,3}^i \leq \ldots \leq P_{MR,n}^i \) is the subset of measurement results in non-descending order, and \( n \) is the number of measurement results taken on the \( i \)-th (\( i = 1, 2, 3 \ldots \) section of the route of radio waves propagation.

Calculation of median values of measurement results may be done in real time during research, but only calculated median values are recorded. It is also possible to record all results and calculate median values after measuring research. Results obtained using both methods may be used to basic transmission loss modeling or estimating coverage of radio networks in the area under research.

### 3.4 Presentation of the measurement results

There are three, recommended by ITU-R [5], methods of the measurement results presentation. The first one and the easiest is a table containing descriptions of devices types and feeders lengths. This way of data presentation helps to illustrate changes of the basic transmission loss in dependence on the distance from transmitting antenna.

The second possibility is graphical representation of the pre-processed median values – as a function of distance – in the Cartesian coordinates. This way of data presentation helps to illustrate changes of the basic transmission loss in dependence on the distance from transmitting antenna.

The third one is a digital map of the area under research with marked colored points, that are representing a range of measured values of test signal power at input of the measuring receiver, assuming a known value of the radiated signal power, which is equal to the signal power \( P_t \) [dBW] supplied to the terminals of the transmitting antenna plus power gain \( G_t \) [dBi] of this antenna. Map scale is dependent on the area where research is carried out. The advantage of this method is a simultaneous view on the value of received signal power and localization of measurement. It is also possible to interpolate the results of measurements in order to estimate the radio coverage in the area (Fig.2).

![The estimated radio coverage in the Gdynia Container Terminal](image)

It should be noted, that on the basis of power measurements at the receiver input and using the equation (8) it is easy to calculate the basic transmission loss in given propagation environment.

### 3. Exemplary equipment for propagation measurements

Multipurpose mobile equipment for propagation measurements has been developed and implemented in the Gdansk University of Technology. This equipment allows to carry out the research in accordance with described normative requirements. It has been used to research in the container terminal environments in Tricity.

Measurement equipment consists of two parts: immobile transmitting section (Fig. 3) and mobile receiving section (Fig. 4). Block diagrams exclude descriptions of devices types and feeders lengths.

![The block diagram of the transmitting section](image)

The transmitting section of the equipment for propagation measurements consists of signal generator connected to transmitting antenna through the RF amplifier and the attenuator. The generator is a source of the test signal, that is going to be investigated. The attenuator protects the amplifier from damage caused of high level signals. The signal generator and the amplifier are a source of test signal with power of \( P_{MT} \) (see Fig. 1), which is supplied to input terminals of transmitting antenna. The transmitting antenna is a monopole vertical antenna with electrical length of one-quarter of a wavelength. It has been developed and implemented in a manner, that allows to change its linear length, so it may be used to research on various frequencies. During the
research antenna was installed on various heights, but always higher than 10 meters above a ground level [4], to minimize the influence of the Earth surface on the test signal attenuation.

In order to prepare the transmitting section for tests, the calibrating spectrum analyzer should be connected in place of transmitting antenna. The desirable value $P_t$ of test signal should be set by changing settings of the generator and RF amplifier and taking into account attenuation of the attenuator.

![Fig. 4 The block diagram of the receiving section](image)

The spectrum analyzer is used as the measuring receiver. It is also equipped with GPS receiver, which allows to determine the test vehicle position and assign it to appropriate measurement result. The receiving antenna is the same type as the transmitting antenna. During research the receiving antenna was installed at a height of 2 meters above ground level. The transmitting section is carried by test vehicle (e.g. hand-cart). It is moving along a route of radio wave propagation with velocity not exceeding the value resulting from equation (9). The rotary encoder is used to determine the distance from starting point and to determine the point where the measurement should be triggered. This encoder is connected to the test wheel and the encoder controller. For every distance of 0.8s, the encoder controller sends an impulse to the industrial computer, which triggers next measurement of signal power $P_{MR}$ at the receiver input. The industrial computer is responsible for the spectrum analyzer configuring, measurements triggering and recording its results. The LCD display shows the following data: current measurement result, distance from the starting point, current velocity of test vehicle. The receiving section is powered by battery with sufficient capacity.

It is very important to ensure safety of people during research in industrial environments. For this reason, the receiving section is equipped with pulsing safety lighting to make the test vehicle more visible. This lighting is mounted in the possible highest point of the test vehicle, at the antenna mast.

**Conclusion**

The paper presents normative requirements concerning methodology of measurement research on radio wave propagation. This requirements are in accordance with current ITU-R Recommendations. On the basis of these recommendations the research in the container terminals in Tricity were made.

In the Gdynia Container Terminal there were collected about 5 thousand measurement results in band 1GHz to 4GHz. On the basis of these results a novel analytical propagation model was developed using multidimensional linear regression analysis with multiple independent variables [8]. During the research in the DCT Gdansk Container Terminal data about nearly 290 thousand of propagation cases were collected. These cases concern propagation routes with various lengths, four frequencies of test signal and three heights of transmitting antenna installation. The results of these research will be used for verification and extending existing propagation models for atypical propagation environments, such as container terminals.

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